Systematic Survey on the Development of Aluminum Alloys for Aircraft

Hideo Yoshida

Abstract

Before World War II, Japan's aluminum industry was mainly focused on the production of aircraft materials. In the process of developing these materials, the world's strongest aluminum alloy was invented. The use of this material in the main wings of the Zero fighter, named after the Type Zero Carrier-Based Fighter, dramatically improved its performance, helping it achieve spectacular results in the early stages of the Pacific War. In an attempt to unlock the secrets of the Zero fighter, the U.S. military examined Zero fighter planes that had been crash-landed and discovered that their main wings were made of an Al-Zn-Mg-Cu alloy called Extra Super Duralumin (ESD), and had Alcoa produce almost the same alloy. This is 7075 alloy, which became the typical aircraft alloy after the war and is still used today. It can be said that ESD is the originator of 7075. Focusing on the development of alloys from the discovery of aluminum to the development of ESD, we conducted a systematic survey of the development of aluminum alloys for aircraft in Japan. The relationship between the development of materials and aircraft in the postwar period was also clarified. The main points are summarized below.

The first is the discovery of aluminum. In the 1820s, the first metallic aluminum was extracted by H. C. Ørsted and F. Wöhler. Then, in 1855, Sainte-Claire Deville, encouraged by Napoleon III, built a plant capable of mass production. In 1886, C.M. Hall in the United States and P. Héroult in France both invented the method of molten salt electrolysis at about the same time, which enabled mass production and significantly reduced costs. Thus, in the 20th century, aluminum began to be widely used in kitchenware, construction, cars, etc.

Second, in 1906, A. Wilm in Germany serendipitously discovered the phenomenon of age hardening, which occurred when aluminum with copper and magnesium was quenched and left at room temperature to harden naturally. This Al-Cu-Mg alloy was named Duralumin. It was Count Zeppelin who applied this material to the framework of airships. In World War I, Germany used Zeppelin airships to bomb London and other cities. At the same time, however, faster airplanes than airships were developed, and airplanes went from being made of wood to being made of all-metal with Duralumin. In order to win the war, lighter and faster fighter planes were needed, and the aluminum alloy had to be even stronger than Duralumin. In response to these demands, the Al-Cu-Mg based alloy, Super Duralumin 24S (2024) was developed by Alcoa in the United States.

Third, the Japanese Navy requested Sumitomo to develop an alloy with even higher strength than 24S. The result was the development of Extra Super Duralumin (ESD). IGARASHI Isamu and his colleagues at Sumitomo achieved high strength with an Al-Zn-Mg-Cu alloy. However, the problem of stress corrosion cracking remained. They established an evaluation method for stress corrosion cracking and thoroughly investigated the effects of trace elements. As a result, they found that addition of Cr was the most effective countermeasure and applied for a patent within a year of starting the development. This alloy attracted the attention of HORIKOSHI Jirō, a chief engineer at Mitsubishi who was working on the design of the Zero fighter prototype. After hearing Igarashi's explanation, he realized that the weight of the plane could be reduced by 30 kg, and he immediately requested permission from the Navy to use the alloy in extruded materials. As a result, he succeeded in reducing the weight of the Zero fighter by using ESD as a spar of the main wing.

Fourth, at the time of World War I, Japan did not have the machinery, equipment, or human resources to mass produce aluminum alloy sheets. Since Japan was the victor against Germany in World War I, it was able to learn German technology as part of the reparations. After World War I ended, Alcoa expanded into Japan to sell primary aluminum, and worked with Sumitomo to build a plant to manufacture aluminum sheets, extrusions, and forgings. Japan's manufacturing technology was based on those of Germany and the United States. However, by the time of World War II, Alcoa had further developed its manufacturing technology, perfecting continuous casting technology and tandem hot rolling technology, and the Pacific War created a huge technological gap between Japan and the United States.

Fifth, after World War II, Japan was prohibited from manufacturing and researching aircraft, and many aircraft engi-

neers moved on to railway vehicles, automobiles, and motorcycles. The use of aluminum for the railway vehicles was considered, and Al-Zn-Mg-Cr extrusions, which had been researched and developed before the war, were applied. Cr was added to prevent stress corrosion cracking, but this time it was difficult to obtain high strength when the cooling rate was slow because of high quench sensitivity. BABA Yoshio, who continued the research of Igarashi, developed Al-Zn-Mg-Zr alloy 7N01 (7204) with low quench sensitivity by adding Zr, ahead of the rest of the world. In addition, Baba developed 7003, which has improved extrudability, achieved as a result of reducing the amount of Mg in 7204, and this has since been used in Shinkansen vehicles, automobile bumpers, trailer containers, and motorcycle rims.

■ Profile

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●1975	Graduate School of Engineering (MA), Kyoto University
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●2007	Executive Officers Research and Development Center, Executive Researcher
●2009	Vice President, Japan Institute of Light Metals
●2013	Advisor, Research and Development Center, Sumitomo Light Metal Industries, Ltd merged into UACJ Corporation, Advisor, Research and Development Division
●2015	Awarded the Japan Institute of Light Metals Award
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■ Contents

1 Introduction

Before World War II, Japan's aluminum industry was mainly focused on the production of aircraft materials. In the process of developing these materials, Extra Super Duralumin (ESD), the strongest aluminum alloy in the world, was invented. The use of this material in the Zero fighter dramatically improved its performance, helping it achieve spectacular results in the early stages of the Pacific War. In an attempt to unlock the secrets of the Zero fighter, the US military examined Zero fighter planes that had crash-landed and discovered that their main wings were made of ESD, an Al-Zn-Mg-Cu alloy, and had Alcoa produce almost similar alloy. This is 7075 alloy, which became the typical aircraft alloy after the war and is still used today.

Tracing back to the discovery of aluminum and the development of Duralumin, this systematic survey of the development of aluminum alloys for aircraft in Japan sheds light on why this ESD was invented in Japan, and how such a discovery was possible despite the fact that Japan was considered to be behind Europe and the United States in R&D capabilities. The development of aluminum alloys for aircraft after the war was almost entirely the work of Europe and the U.S., because few commercial aircraft other than YS-11 have been developed in Japan, so this document will only give a brief overview.

Aluminum was first identified by Davy in England and extracted through chemical methods by Ørsted and Wöhler. Then, for a period of approximately 30 years until mass production by Deville in France, aluminum was hailed "the silver of the clay" due to its extremely high price. Approximately 30 years later, Hall in the United States and Héroult in France invented the method of molten salt electrolysis, making aluminum inexpensive to manufacture and widely available to the public. This systematic survey discusses the background of achieving such inexpensive production.

In the pursuit of high-strength alloys, Wilm in Germany serendipitously discovered the phenomenon of age hardening, which occurs when aluminum with copper and magnesium added thereto is quenched from high temperature and left at room temperature to harden naturally. With aluminum, such a phenomenon was found to occur in Al-Cu-Mg, Al-Mg-Si, and Al-Zn-Mg alloys, which stimulated alloy development. The Al-Cu-Mg alloy discovered by Wilm was named Duralumin.

It was Count Zeppelin in Germany who turned his attention to this material. The material was applied to the Zeppelin airship he developed. This survey reveals how this hard Duralumin was deformed. In World War I, Germany used Zeppelin airships in air raids on London and other cities, and so military officials in many countries took notice and attempted to build airships in their own countries. This led to improvements in performance not only in airships, but in fighter planes and other aircraft as well. In particular, lighter and faster fighter planes were needed, and thus an even stronger Duralumin had to be developed. In Britain and Germany, Super Duralumin was developed by adding silicon to Duralumin. In response, in the United States, 24S was developed by Alcoa by increasing the amount of magnesium in Duralumin. This was first used in the DC-3, and countries around the world followed suit. In this survey, we clarify why the 24S was developed in the United States and why its development was not achieved in the United Kingdom, Germany, or Japan.

The Japanese Navy initially followed the British and German lead in developing silicon-containing Super Duralumin, but switched abruptly to 24S in 1935. At the same time, the Japanese Navy requested that Sumitomo develop an alloy with even higher strength than 24S, as high as 60 kg/mm^2. Sumitomo pursued alloy development under the leadership of IGARASHI Isamu and achieved favorable results within a short period of time, less than a year. The key to alloy development was two-fold: a composition that combined strength and workability and an alloy that did not cause stress corrosion cracking. Strength and workability were achieved by combining alloys studied in the past. The problem was stress corrosion cracking. For this, Igarashi and his colleagues at Sumitomo clearly defined a cracking evaluation method and thoroughly investigated the effects of load stress and corrosive environments. The result of this endeavor was the addition of chromium and the development of Extra Super Duralumin (ESD), an Al-Zn-Mg-Cu-Mn-Cr alloy. In this survey, we clearly identify how development was achieved in such a short period of time.

This alloy attracted the attention of HORIKOSHI Jirō of Mitsubishi. After estimating that use of this alloy could reduce the weight of a plane by 30 kg, he requested permission from the Navy to use the material and received approval for its use in extruded materials. Horikoshi succeeded in reducing the weight of the prototype 12 Carrier Fighter (a prototype of the Zero fighter), which he was working on at the time, by utilizing ESD for the main spar of the wing.

After the war, ESD was no longer used for aircraft materials, and developers moved to a high-strength, easy-to-extrude Al-Zn-Mg-Zr alloy for the body structure of railway vehicles. In this alloy, zirconium was used in place of chromium. BABA Yoshio, who continued the research of Igarashi, contributed to this development with his ingenious work.

Currently, more than 80% of aircraft materials are imported to Japan, and the percentage of domestically produced materials is minuscule. With the market for aircraft materials being so small compared to other aluminum products, Japan has been unable to develop related technology and materials and is now completely behind Europe, the United States, and China. Breaking this deadlock is important for Japan in the future. Although we propose technical measures for this purpose in this survey, it is first necessary to develop talent capable of developing high-strength materials, such as IGARASHI Isamu and BABA Yoshio.

If, through the history of the development of Extra Super Duralumin in prewar Japan, we heed and adopt its lessons in the development of future materials and create a world-class material having the highest strength, the study of the history of technology and its systemization has a meaningful purpose well worth the effort.

2 Discovery of Aluminum and Establishment of Smelting Technology in the 19th Century

2.1 Discovery of Aluminum

In ancient Egypt, a type of alumen obtained from mining was used as a color enhancing and color fixing agent (mordant) and as a tanning agent in the dyeing of textiles and leather. With its antiseptic and astringent properties, alumen was also used for hemostasis, sterilization, and deodorization.[1] The use of alumen is described in detail in Pliny's Natural History.[2] Forbes' "Studies in Ancient Technology" states that in Mesopotamia alumen was also made by boiling alunite in water.[3] According to Beckmann's "History of Inventions, Discoveries, and Origins," what the Romans called alumen was melanterite (green sulfate of iron).[4] This is because natural alumen is rarely found in the ground. According to Beckmann, the technology for manufacturing alumen was introduced from the East in the 12th century and spread to Syria and Turkey, and alumen factories were built in Italy in the 15th century. As the technology for refining alunite from melanterite advanced, high-quality alumen was referred to as "alum." Agricola's "De Re Metallica" describes in detail how alum was manufactured in the 16th century, as illustrated in Figure 2.1.[5, 6]

Figure 2.1 Manufacture of Alum
(G. Agricola, De Re Metallica, Dover, p. 567)[5, 6]

In the 18th century, alum was considered an oxide of metal and was called alumina in England. In 1808, Humphry Davy of England gave the metal the name alumium based on the name alum. The metal was later renamed aluminum, and subsequently officially named aluminium by Henri Sainte-Claire Deville of France.[1] Since then, there have been and still are two types of academic notation for aluminum: aluminium is commonly used in Europe, while aluminum is mainly used in the United States (see Note).

(Note) In the United States, the Noah Webster's Dictionary of 1828 adopted aluminum, but both terms were still in use until the mid-1890s. Officially, aluminum was adopted by The American Chemical Society in 1925. On the other hand, globally, the International Union of Pure and Applied Chemistry (IUPAC) has officially adopted aluminium, and both terms are currently used in scientific and technical papers.[7]

2.2 Chemical Reduction Process

Davy attempted to extract the metal in alumina using voltaic pile, but without success. Later, Hans Christian Ørsted of Denmark is said to have been the first to extract metallic aluminum from aluminum chloride and potassium amalgam in 1825. In 1827, Friedrich Wöhler of Germany isolated aluminum by reacting aluminum chloride with potassium.[1] In 1854, Henri Sainte-Claire Deville of France reduced aluminum chloride with sodium, a less expensive alternative to potassium, to isolate aluminum. The aluminum at this time was about the size of a teaspoon. With the backing of Emperor Napoleon III, Deville built a plant in the suburbs of Paris in 1856 with a production capacity of two tons, which became the first aluminum smelting plant.[1, 8]

The raw material of alumina used by Deville was bauxite. Bauxite was discovered and named by Pierre Berthier in Les Baux-de-Provence, France (see Column) in 1821. When red soil was found on the property and analyzed by mineralogist Berthier, it was found to be low in iron, much to the dismay of the steelmakers, but high in alumina. Thirty-five years later, it was Deville who turned his attention to this.[9]

Deville's chemical reduction process involves the reduction of aluminum chloride with sodium. As illustrated in Figure 2.2, aluminum chloride is made by passing chlorine through a mixture of alumina, sodium chloride, and crushed coal that has been heated. The mixture is then mixed with flux, sodium, and aluminum chloride and fed from E into the heated furnace illustrated in Figure 2.2 to melt the mixture and accelerate the reaction, resulting in slag settling to the bottom of the furnace. When the brick D is removed, slag and aluminum flow into the crucible J.[9, 10] The average purity of the aluminum he made was 97%. The aluminum made by Deville was called “*l’argent issu de l’argile* [the silver from the clay]” at the Paris Exposition of 1855 and was very expensive. Napoleon III, who originally wanted to lighten the weight of his armor, was a great lover of aluminum, and there is a famous anecdote that he entertained his most important guests with aluminum forks, knives, and spoons instead of gold or silver. However, Deville’s chemical reduction process still required the use of expensive sodium and had limited applications due to the high content of impure iron and silicon and poor corrosion resistance. For this reason, electrochemical extraction processes were tried, but they required large amounts of electricity and were not industrially feasible. Just then, in 1870, the electric generator was invented by Gramme in Belgium, and in 1878, the world’s first hydroelectric power was generated in the U.K..

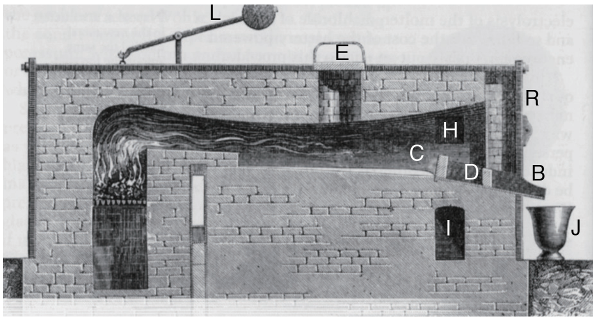


Figure 2.2 Chemical Reduction Process by Deville[9, 10]

Column: Les Baux-de-Provence

Les Baux is located between Arles and Avignon in the Provence region of France. The ruins of a castle ruled by the Baux family (Figure 1) remain on a small white rocky hill. I (author) visited this site in June 2006 to find out why bauxite (Figure 2) was discovered here. (For more information, see “Visiting Les Baux,” *Journal of The Japan Institute of Light Metals* 57 (2007), p. 389.) Note that the ruins of this castle are a tourist attraction and the setting for Matsumoto Seichō’s novel “*The Poetic Castle Traveler*” [Japanese title: Shijo no Tabibito] (Japan Broadcast Publishing, 1989).

This area is located at the edge of the Alpilles, a limestone formation that was uplifted from the sea floor by tectonic movements during the formation of the Alps and Pyrenees. Bauxite deposits are generally classified into karst bauxite deposits and lateritic bauxite deposits based on the host rock and formation. Karst deposits are aluminum oxide deposits formed by the decomposition of carbonates and the subsequent concentration of residual aluminum derived from the weathering of Al silicates. The bauxite at Les Baux was formed by the weathering of limestone from the Early Cretaceous or Jurassic periods. After the deposit was formed, it sank and was submerged into the sea, limestone from the Middle to Late Cretaceous period was deposited on top, and then it was uplifted again. The main distribution areas of karst deposits are the northern Mediterranean, Jamaica, and the United States. The deposits at Les Baux have been mined out. Lateritic deposits are formed by the lateritic weathering of Al silicate rocks under subtropical or tropical climatic conditions and account for about 90% of the world’s bauxite. The main distribution areas of lateritic deposits are North and Southwest Australia, West Africa (mainly Guinea), South America (Guiana shield, Brazilian shield), India, and Southeast Asia. (SHIMAZAKI Yoshihiko and OKANO Takeo, “Geological Survey of Japan,” AIST, *Geological News*, No. 122 (Oct. 1964), pp.28-39.)

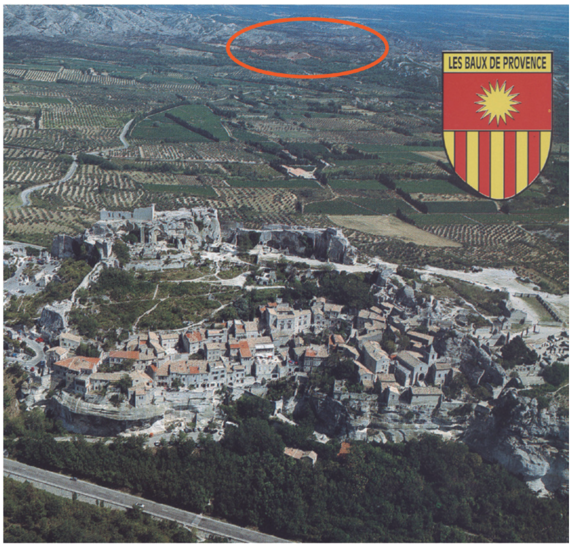


Figure 1: Ruins of Baux Castle (the reddish-brown area in the upper photo is the mining site; from the tourist information book *Les Baux*).

Figure 2: Bauxite Ore (on display at the entrance to the tourist information center in Les Baux[10])

https://www.lesbauxdeprovence.com/en/tourist-office (2021.8.31)
https://commons.wikimedia.org/wiki/File:140606_Les-Baux-12.jpg (2021.8.31)

2.3 Molten Salt Electrolysis

On February 23, 1886, 23-year-old Charles Martin Hall (left in Figure 2.3) of the United States successfully produced aluminum by electrolysis. He worked on aluminum isolation at Oberlin College in Ohio under his advisor, Professor Frank Fanning Jewett (see Note), and continued his research after graduation from the college in 1885.[11, 12] His process was revolutionary in that he used cryolite as a solvent to melt alumina, and then electrolyzed the molten salt to reduce and extract aluminum. Cryolite discovered in Greenland in 1795 lowered the melting point of alumina (2,050°C) by more than 1,000°C, allowing it to melt at 980 to 1,000°C, facilitating aluminum production. At about the same time as Hall's invention, Paul Louis Toussaint Héroult of France (right in Figure 2.3) discovered the same process. Héroult learned about Deville's aluminum studies at Sainte-Barbe Academy and read his famous dissertation when he was 15. He attempted electrolysis of various aluminum compounds using the steam engine and dynamo of a small tannery he inherited in 1885, and succeeded in separating aluminum.[8, 9] Figure 2.4 illustrates the smelting facility of Alcoa's predecessor, Pittsburgh Reduction Company, and its electrolytic furnace. Hall's process was patented in the United States in 1889, and Héroult's process was patented in France, Belgium, the U.K., and other countries in 1888. Schematic diagrams of their electrolytic furnace structures are illustrated in Figure 2.5.[13, 14] A schematic diagram of the structure of a modern prebake electrolytic furnace is illustrated in Figure 2.6. Their process is called the "Hall-Héroult process" because it is virtually the same process. They were born in the same year, created the same invention in the same year, and died in the same year, 1914, a coincidence of history. For this reason, they were called The Aluminum Twins.[9]

(Note) F. F. Jewett: Born in 1844, studied chemistry and mineralogy at Yale University, graduating in 1870; studied chemistry at the University of Gottingen in Germany, from 1873 to 1875, where he met Professor Wöhler, who had successfully isolated aluminum. In 1876, he was nominated by the president of Yale University to teach science at the Tokyo Imperial University, and the following year he joined the faculty of the Tokyo Imperial University. In 1880, he left Japan to become a professor of chemistry and mineralogy at Oberlin College at the age of 36. When Hall

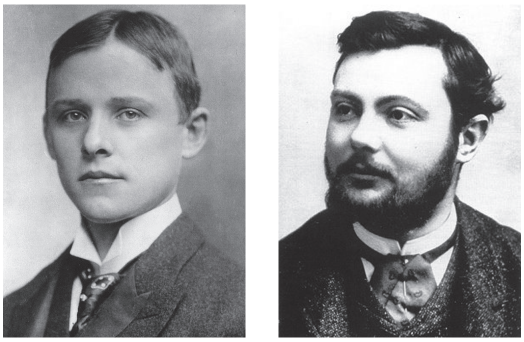


Figure 2.3 Hall (left)[15] and Héroult (right)[16]

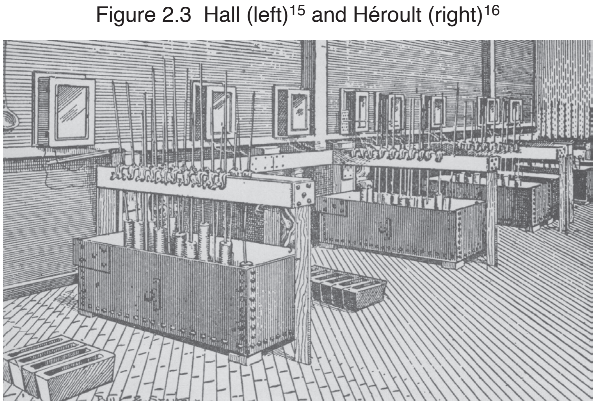
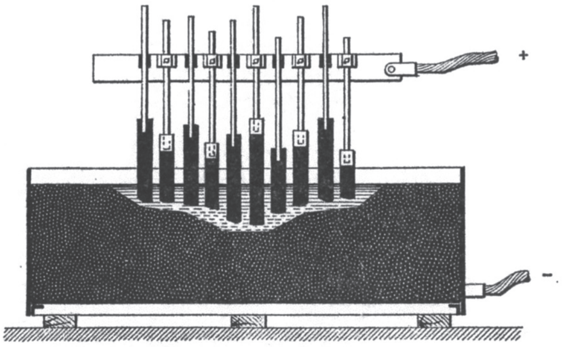
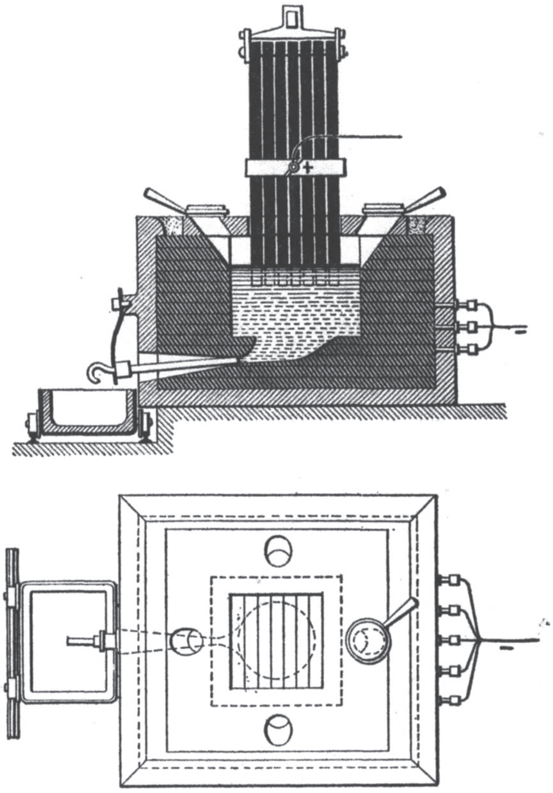


Figure 2.4 Electrolytic Furnace of Alcoa's Predecessor, Pittsburgh Reduction Company[13]



(a) Hall's Electrolytic Furnace



(b) Héroult's Electrolytic Furnace

Figure 2.5 Schematic Drawings of Hall's and Héroult's Electrolytic Furnace Structures[17] entered the university, he met Jewett, who showed him a small piece of aluminum given to him by Professor Wöhler and told him that whoever invents an economical way to produce aluminum will not only benefit mankind, but will also gain great wealth, deepening Hall's interest in aluminum.[15]

The Hall-Héroult process is significantly less expensive than the conventional Deville chemical reduction process, and improved the purity to about 99.7%.[13] This invention is largely associated with the inventions of hydroelectric power, the direct current generator by Z. T. Gramme of Belgium used for this hydroelectric power, and the cryolite discovered in Greenland. With cryolite added to alumina, the melting point can be lowered to about the same temperature as that of copper, making it much easier to manufacture industrially.

Héroult established AIAG, a joint venture between Swiss and German capital, built a plant in Neuhausen, Switzerland, upstream from the Rhine River, and began smelting using electricity from the Rhine River Falls.

Meanwhile, Hall established a company in Pittsburgh and began smelting. The company started out with thermal power, but when the Niagara Falls power plant was built, was their first customer. This company would later become Alcoa. In 1888, K. J. Bayer of Austria invented the Bayer process to obtain alumina by using bauxite, as illustrated in Figure 2.7, which became the raw material for the Hall-Héroult process. In this process, bauxite is dissolved in caustic soda to make a sodium aluminate solution, which is hydrolyzed to crystallize aluminum hydroxide, which is then calcinated to remove water to produce alumina. Alumina is found not only in alunite but also in various ores such as haze stone and alum shale, but bauxite is particularly low in silicic acid and contains more than 50% alumina.

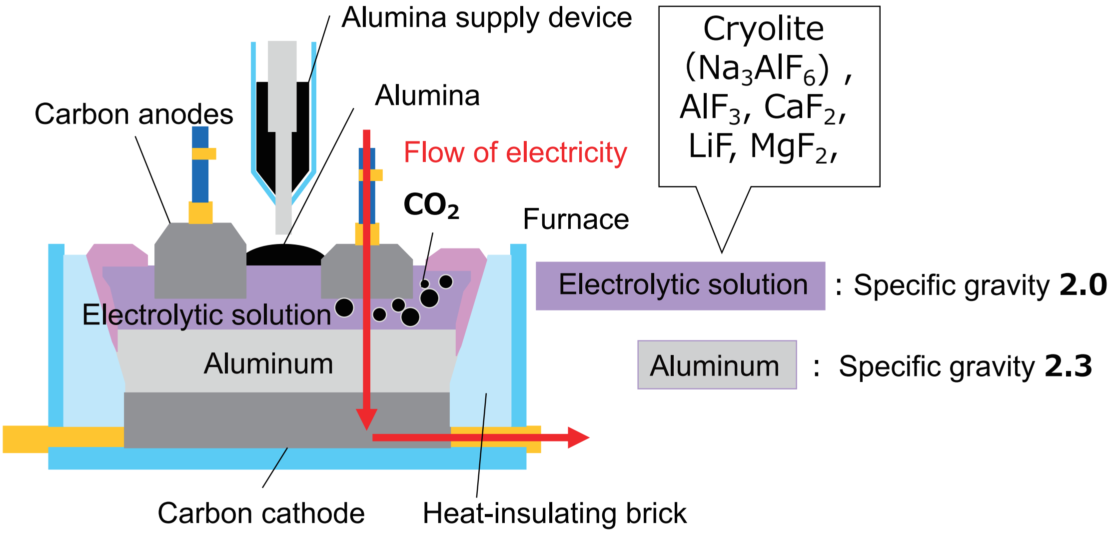


Figure 2.6 Schematic Drawing of Modern Electrolytic Furnace (Prebake Type)

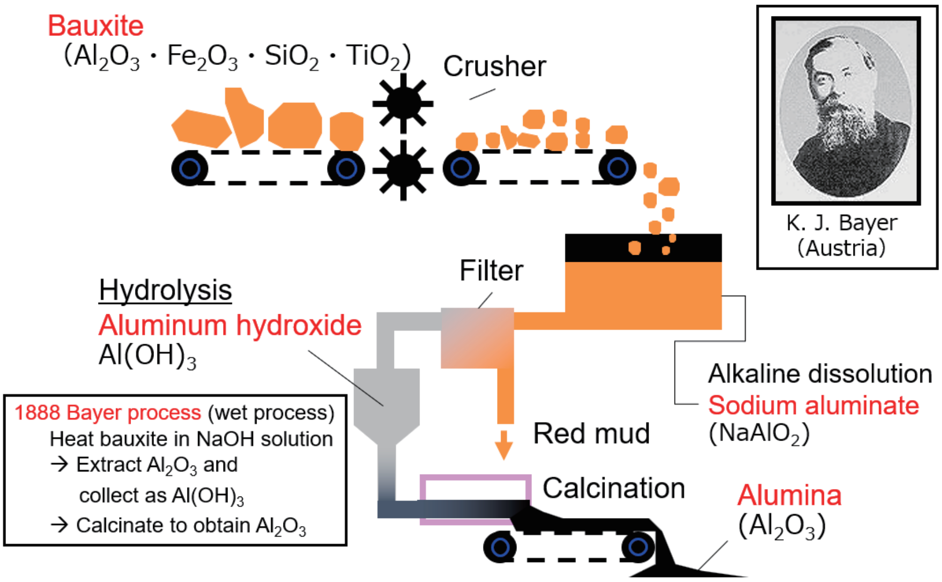


Figure 2.7 Bayer Process

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3 Rapid Production of Primary Aluminum and Market Formation in the 20th Century

3.1 Formation of Aluminum Industry

3.1.1 Start of Production of Aluminum by Hall-Héroult Method

To industrialize the new method of molten salt electrolysis, Héroult attempted to sell his patent to A.R. Pechiney of *Produits Chimiques d'Alais et de la Camargue*, which initially manufactured aluminum by chemical reduction, but Pechiney refused the offer. In 1888, as a joint venture of Swiss and German capital, Héroult founded Aluminium Industrie A.G. (AIAG, later Swiss Aluminium), built a factory in Neuhausen, Switzerland, and began to produce aluminum by utilizing the hydroelectric power generated by the waterfalls of the Rhine River. Subsequently, Héroult granted a license to the *Société Électrométallurgique Française* in France and established its first aluminum plant in Froges, near Grenoble, in 1889.[1, 3]

A.R. Pechiney, who refused Héroult's offer, felt threatened by the production in Froges, closed his own company, and bought the Froges company in 1897 in order to switch to electrolytic production. In 1921, the company was renamed AFC (*Compagnie des Produits Chimiques et Électrométallurgique d'Alais*, *Froges et Camargue*, then Pechiney).[2]

In the U.K., British Aluminium Co., Ltd. was established in 1894 and began production in Foyers, Scotland, after taking over Héroult's patent. Under the protection of Héroult's patent rights, the number of manufacturing companies was limited to four. Aluminum production in Europe increased from 150 tons in 1890 to 4,100 tons in 1900. Figure 3.1 illustrates the change in primary aluminum prices from 1860 to 1900.[4] The graph shows that the price of aluminum also declined by about 1/10 in the decade following 1889. Molten salt electrolysis made it possible to significantly reduce the cost of primary aluminum.

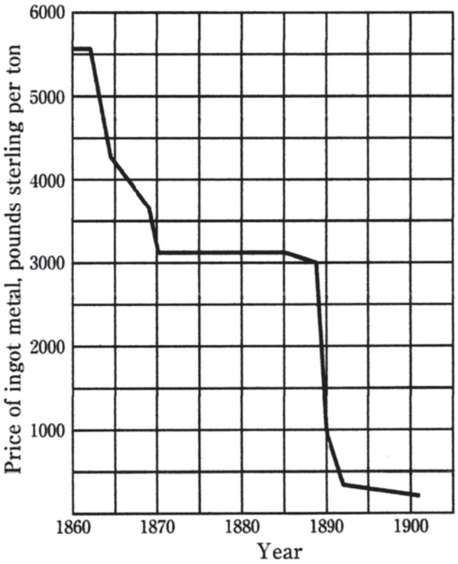


Figure 3.1 Price of Primary Aluminum from 1860 to 1900 (*1GBP=$5, 1880-1920)[4]

When Héroult's patent expired in 1901, numerous companies launched operations. In Europe, the number of companies and factories reached 11 and 20, respectively, in 1913, accounting for 57% of world production.[1]

Meanwhile, Hall established a new company in Pittsburgh on July 31, 1888. Initially named Pittsburgh Aluminium Company (Note 1),[5] the company changed its name two months later to The Pittsburgh Reduction Company on October 1, 1888,[6] and to today's Aluminum Company of America (Aluminum Company of America = ALCOA) in 1907.[6]

> (Note 1) Interestingly, Alcoa's first name uses Aluminium instead of Aluminum, indicating that both spellings were in use in the United States at the time. The reason for the change to Aluminum, according to an anecdote of uncertain authenticity, was that the printer inadvertently omitted the "i" in aluminium from one of its letterheads. The printer went bankrupt, however, so Alcoa decided to keep using the term without the "i" rather than spend $300 for reprinting.[5] The fact was that Alcoa at the time was unable to pay out even $300.

According to Deville, the price of primary aluminum was $90/lb at the Paris Exposition of 1855 (Note 2), down to $27/lb two years later, $17/lb in 1859, and $8/lb in 1886, the year of Hall's invention ($1 in 1886 = $29.21 in 2020). Hall's process brought the price down to $2/lb in 1889, then to $1.50/lb in 1891, and $0.75/lb in 1893 as mass production progressed.[7]

> (Note 2) In comparison with current prices, $1 then is $28.18 today ($1 in 1855 = $28.18 in 2020). See citation 8 for a comparison of past and current dollar values.
> Assuming $90/lb = $5,586/kg (2021.5.5), 1 lb = 0.454 kg, and $1 = ¥109.34 (May 5, 2021), then the price is equivalent to ¥610,773/kg today. Compared with current gold and silver, the price falls between Au: ¥7000/g and Ag: ¥100/g. During the reign of Napoleon III, aluminum was called "the silver from the clay." The current (September 1, 2021) London Metal Exchange (LME) price for primary aluminum is $2.718/kg (= ¥299.64/kg)[9] ($1 = ¥110.24).

In December 1888, Alcoa's production yielded six pounds per day, but increased to 3,200 tons in 1900 with the construction of new plants. Electricity was initially generated by thermal power, but was later switched to low-cost hydroelectric power. In 1893, Alcoa bought power from the Niagara Falls Power Co., and acquired this company in 1896. Later, Alcoa expanded production by acquiring power companies in various regions. The company then built an electrolysis plant in Massena, New York, in 1903, and entered into a long-term contract with the St. Lawrence Water & Power Co. for electric power, eventually purchasing the company in 1906. In 1910, Alcoa began hydroelectric power generation for the entire Tennessee Valley area and, in 1914, completed an electrolysis plant in Tennessee.

In 1899, Alcoa built a smelting plant in Shawinigan, Canada, which began operations in 1901. Production at this plant was carried out by Northern Aluminium Co., which changed its name to ALCAN (Aluminium Company of Canada) in 1925. Criticism of the Alcoa monopoly gained momentum in the 1920s, and the company accepted the government's recommendation and established Aluminium Limited Co. (renamed Alcan Aluminium Limited in 1966) and transferred its holdings to the new company. Northern Aluminium Co. (ALCAN) became its core company. As for bauxite, the company initially purchased alumina, but it became important to secure raw materials. The company acquired Georgia Bauxite, which had mined bauxite in Georgia since 1889, and built an alumina plant in Illinois in 1903. The company then acquired, in Arkansas, the General Bauxite Co. in 1904, followed by the Republic Mining Co. in 1909, giving it a monopoly on bauxite deposits throughout the United States. Later, the company expanded its mining operations to Suriname, Guiana, and other locations in South America.

Aluminum production in North America increased dramatically from 3,200 tons in 1900 to 27,400 tons in 1913. Around 1900, household utensils accounted for 50% of the aluminum market, followed by steel deoxidizers (25%), but later aluminum was used for power transmission lines, automobile parts, machine parts, and container lids.[1]

3.2 Age of Mass Production

In 1925, approximately half of all aluminum was used for casting, and the other half for pure sheet, wire, bar (square and round), and tubing aluminum products, as well as powder, foil, and granular aluminum products. In the United States, 40% of aluminum consumption was used for automotive products. The applications for sheet products included kitchenware, containers, tanks, cooking utensils, various chemical industry equipment, and automobile bodies. As a wire material, aluminum was used for the wiring of electrical products and for high-voltage power transmission lines. Cast materials were used in sand molds, dies, and die castings to make products and, as automotive parts, used for crankcases, oil pans, pistons, housings, manifolds, car bodies, and small parts.

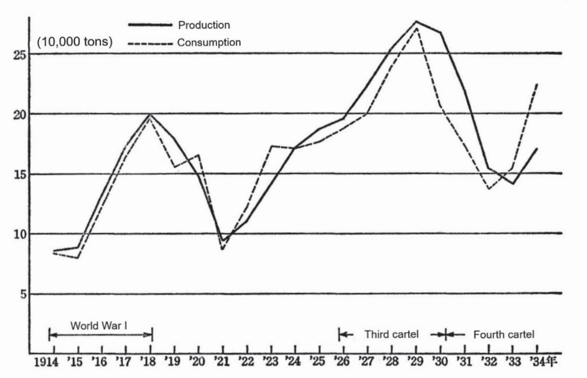
Table 3.1 shows the trends in production of primary aluminum in various countries from 1900 to 1943.[10] Figure 3.2 shows the trends in world primary aluminum production and consumption of primary aluminum from 1914 to 1934.[11]

World War I provided the United States with a huge munitions market, and production of primary aluminum production in the United States jumped from 41,100 tons in 1915 to 58,300 tons in 1919. After the end of the war, countries had surplus stocks, and exports from Europe to the United States increased, leading the United States to strengthen the Alcoa monopoly by establishing tariff barriers to defend its domestic market. Further, in the 1920s, Alcoa also expanded into Europe, taking a stake in a Norwegian company and acquiring companies in France and Italy. Alcoa also acquired bauxite resources and hydroelectric power generation in European countries and built aluminum manufacturing plants and fabricated aluminum products in various locations. In this way, Alcoa developed bauxite mines, hydroelectric power plants, alumina production plants, electrolysis plants, and manufac-

Table 3.1 Global Production of Primary Aluminum (1900 - 1943)[10]

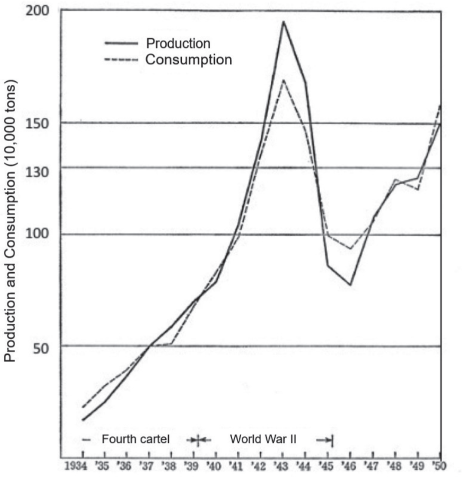
	Production of Primary Aluminum (1,000 tons)									
Year	1900	1905	1910	1915	1920	1925	1930	1935	1940	1943
Unites States	3.2	5.1	15.4	45.0	62.9	63.0	103.9	54.1	187.1	834.8
Canada			3.5	8.5	12.0	14.1	34.9	21.0	99.0	449.7
Austria				2.5		3.0	3.0	2.4	6.7	44.2
France	1.0	3.0	9.5	7.5	12.3	20.0	24.6	70.8	61.7	46.5
Germany				2.0	31.2	27.2	30.7	13.8	204.8	203.1
Italy			0.8	0.9	1.7	1.9	8.0	15.3	38.8	46.2
Norway			0.9	3.5	5.6	21.3	27.4	1.2	27.8	23.5
Switzerland	2.5	3.0	8.0	12.5	14.0	21.0	20.5	15.1	28.3	18.5
United Kingdom	0.6	1.0	5.0	6.0	8.0	15.0	13.2		19.3	56.6
Yugoslavia									2.0	2.0
Spain							1.1	1.8	1.3	0.8
Sweden								11.7	1.6	3.6
Soviet Union								15.5	59.9	62.3
Hungary								0.3	3.2	9.5
Japan								2.6	45.9	149.7
World total	7.3	12.1	43.1	88.4	147.7	186.5	267.3	247.6	787.4	1952.3

Data from *The Twenty Years History of Nippon Light Metal Co., Ltd.*. Figures for Japan include Korea, Taiwan, and China (Manchuria).



Source: *The Twenty Year History of Nippon Light Metal Co., Ltd.*

Figure 3.2 Trend in Global Production and Consumption of Primary Aluminum (1914 - 1934)[11]



Source: *The Twenty Year History of Nippon Light Metal Co., Ltd.*

Figure 3.3 Trend in Global Production and Consumption of Primary Aluminum (1934 - 1950)[11]

turing plants such as rolling and casting plants. Alcoa grew into the world's largest aluminum company, with mines and smelting plants affiliated not only in the United States but also on the North American continent even after World War I. This diversification of overseas activities led to separate management of domestic and overseas operations. In 1928, Aluminium Limited (renamed Alcan Aluminium Limited in 1966) was established in Canada and overseas operations were transferred to this company. Although formally separated as a separate company, Aluminium Limited was effectively under the control of Alcoa since it shared the same major shareholders. Later, it was completely divested in 1950 under the Trust Act. The Great Depression of 1931 halved production in the United States and Canada, but international cartels and military expansion led to rapid expansion after 1936, and North American production reached 223,000 tons in 1939, accounting for one-third of the world's total.[1]

Figure 3.3 shows the trends in production and consumption of primary aluminum from 1934 to 1950.[12] It can be seen that the peak was just under two million tons in 1943 during World War II. Most of the demand was for aircraft. For reference, global production of primary aluminum as of 2016 amounted to 57.55 million tons, 30 times the production in 1943.[12] China produces about 55% of the total, followed by Russia and Canada, which account for about two-thirds of total production.

The increase in military demand resulting from World War II led to the dramatic development of the aluminum industry, as illustrated in Figure 3.3.[11] In order to further expand its facilities, the United States government provided loans to Reynolds Metals Corp., which had been producing aluminum foil for cigarette packaging since 1926, to enter the aluminum smelting business, effectively breaking Alcoa's monopoly. This resulted in an annual capacity of 440,000 tons for Alcoa and 85,000 tons for Reynolds Metals in 1943.

The government also established a system whereby the Defense Plant Corporation built new facilities by itself and leased them to aircraft manufacturers and aluminum manufacturers. In the aluminum sector, DPC invested $700 million to build two alumina plants, nine electrolysis plants, and 25 manufacturing plants, which it outsourced to private contractors. Alcoa designed, built, and operated most of these. In 1943, the company produced 834,800 tons.

In Canada, Aluminium Limited developed its overseas operations, and Alcan, a direct subsidiary of Aluminium Limited, developed as the only Canadian aluminium company. The driving force behind this is Canada's abundant and low-cost hydroelectric power sources in the country. In 1925, the company built a 200,000 kW hydroelectric plant on the Saguenay River and a new plant four miles away in Arvida (named after the initials of founder Arthur Vining Davis). The company continued to build power plants and expand its facilities, and by 1943 it produced 450,000 tons, making it the second largest producer in the world, and making Canada the world's largest exporter of aluminum. Of the country's production from 1940 to 1944 during World War II, 55% was exported to the United Kingdom, 32% to the United States, and 7% to other countries, with only 6% consumed domestically.

Until before World War I, Germany's production of primary aluminum was only 800 tons per year, produced by the Swiss-owned Rheinfelden smelter, and domestic consumption at that time, which amounted to 14,000 tons, depended on imports. With the outbreak of World War I, three smelting plants were built, and the state-owned Vereinigte Aluminium Werke (VAW) was established in 1917, making the three smelters and three newly built plants state and semi-state owned.[13] Against the backdrop of military expansion, Germany's production increased from 14,100 tons in 1918 to 27,200 tons in 1925, 70,700 tons in 1936, and 203,100 tons in 1943, making it the third largest producer in the world after the United States and Canada during World War II. Japan was the fourth largest producer in the world in 1943, but produced one-eighth of the United States and about half of Germany's production.

Germany, like Japan, does not have bauxite resources, so sought bauxite raw materials overseas, mainly from European countries.[14] Prior to World War II, bauxite was produced in Europe primarily by France, Hungary, Italy, Yugoslavia, and Greece. Before World War II began in 1939, German bauxite

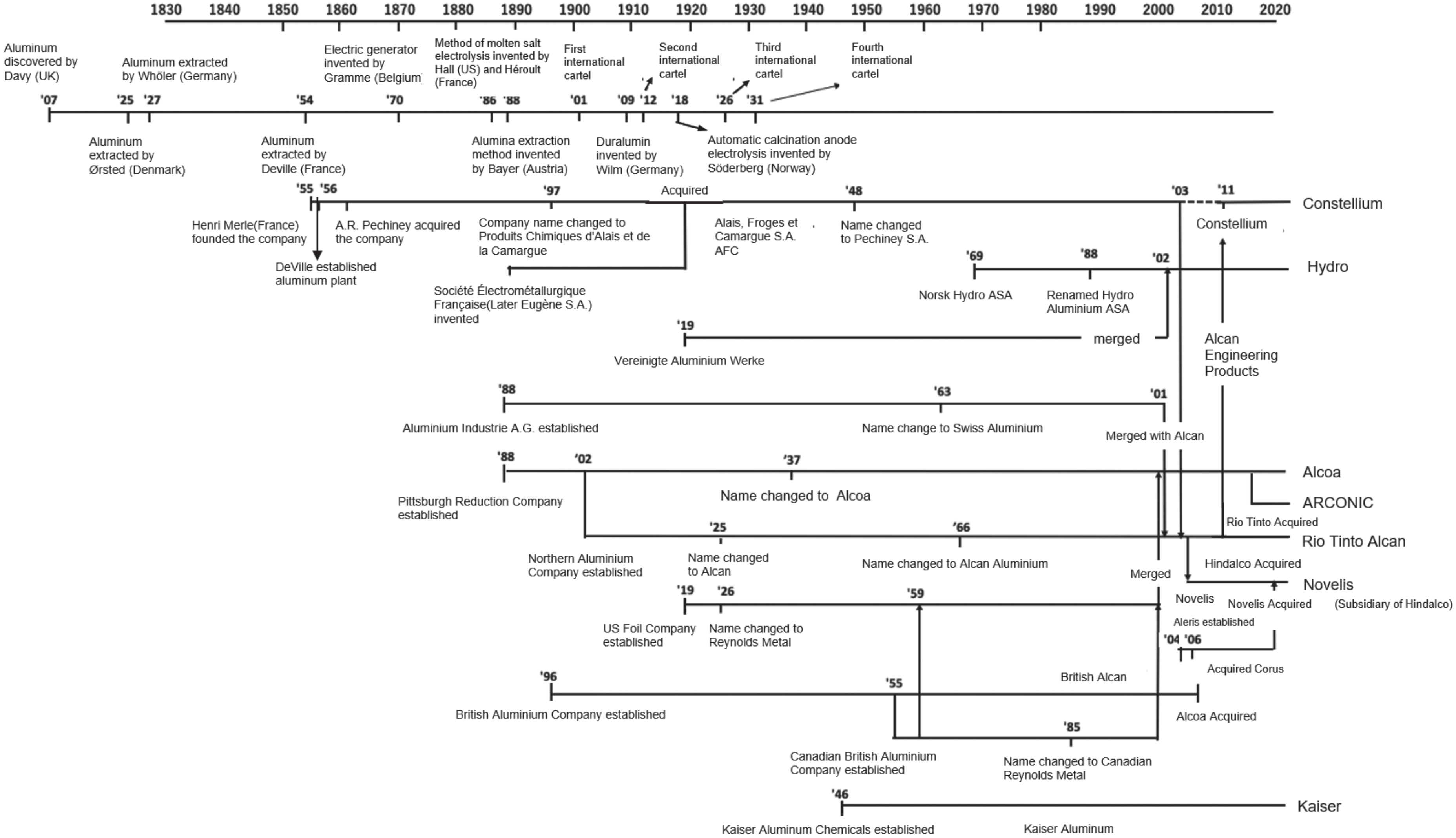


Figure 3.4 Development Flow of the World's Major Companies[1] (author's additions to original figure after 1970)

imports came mostly from Hungary and Yugoslavia, but after the start of World War II, imports increased from France under the Vichy regime and Italy, an Axis country, in addition to Hungary. German imports accounted for half of European production before World War II, but increased to 70% of European bauxite production during the war.[13] The development process of the world's major companies is illustrated in Figure 3.4.[1]

3.3 Development of Production Technology

3.3.1 Casting Technology

(1) Tilt Casting Method

Before the start of the continuous casting method, casting was carried out in square or round molds using the book mold method. This casting method is called the tilt casting method. In this method, molten metal is cast from a crucible into a mold as if pouring beer. Figure 3.5 illustrates a principle diagram of the casting process and the shape of the mold.[15] The mold was initially tilted and then stood upright while pouring. The mold used had a flow channel as illustrated in Figure 3.5(a). An iron wire mesh was used for the flow channel, and molten metal poured from the opening, passed through this wire mesh, and gradually flowed into the mold from the bottom. A runner was also attached at first, but due to the cutting loss and man-hours required for cutting, the end face was made into a roof shape as illustrated in (b).

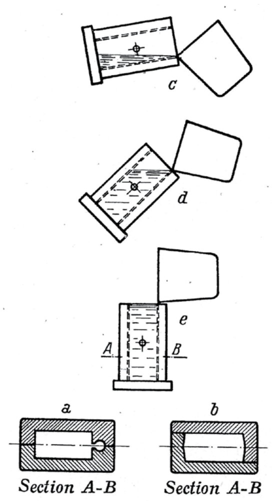
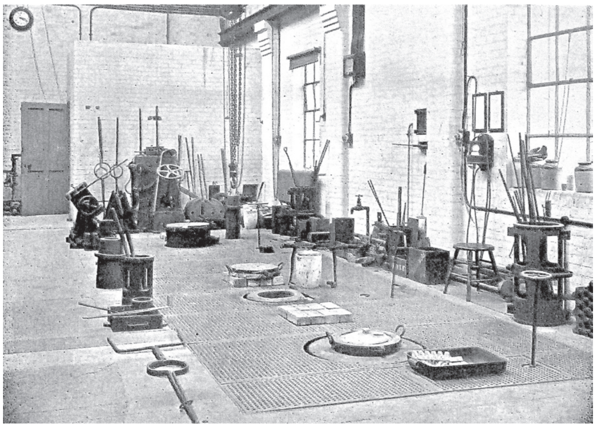
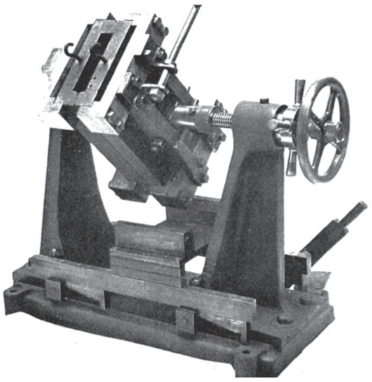


Figure 3.5 Principle Diagram of Tilt Casting Machine and Mold Shape[15]

Figure 3.6 illustrates the tilt casting method devised by W. Rosenhain of the National Physical Laboratory in the U.K.[16] The upper photo shows his casting laboratory and the lower photo shows the tilt casting machine. His method was one of tilting the mold with a handle. Figure 3.7 shows the casting of ingots at the Alcoa foundry.[17] Molten aluminum melted in a tilt-type furnace is cast into square molds for sheets.



(a) Experimental Foundry at NPL



(b) NPL Tilt Casting Machine

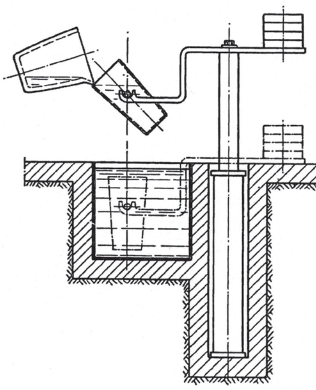
Figure 3.6 Experimental Foundry and Tilt Casting Machine at National Physical Laboratory, U.K.[16]

Figure 3.7 Alcoa Foundry Casting Ingots for Sheets[17]

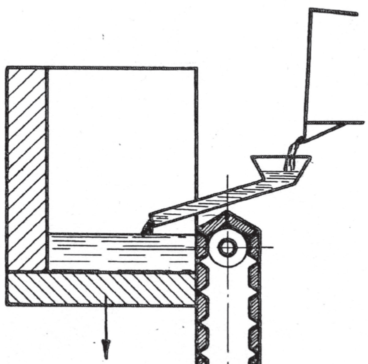
3.3.2 Continuous Casting Technology

In Germany and the United States, to increase the productivity of aluminum, larger ingots for rolling, forging, and extrusion were required. The conventional casting method of casting in a mold caused problems such as inclusions, segregation, cavities, shrinkage cavities, columnar crystals, pipes (shrinkage nests), and other casting defects, making it necessary to develop a new casting method. In particular, it was necessary to increase the cooling rate to achieve grain refinement and reduce reverse segregation.

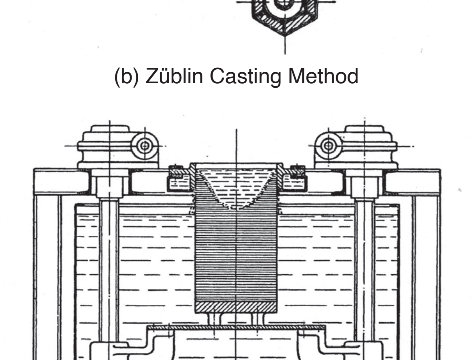
For this reason, as illustrated in Figure 3.8(a), bucket casting was developed in which molten metal was poured into a 1/8-inch (3-mm) thick steel mold and water-cooled at a constant rate. However, there was a problem of solidification and shrinkage of the aluminum in contact with the mold, creating gaps and reducing heat transfer.[18] In response, Züblin invented the casting method illustrated in Figure 3.8(b). This method involves opening one side of the mold, closing the side with a movable flat plate, lowering the mold vertically, and then pouring the molten metal on top of the previously solidified layer sequentially, with each layer being one to two inches deep.[18, 19] Later, improved versions of such methods were developed. Figure 3.8(c) illustrates the method developed by Zunckel, in which the bottom table moves downward to make long billets.[20]



(a) Bucket (Bag) Casting Method



(b) Züblin Casting Method



(c) Zunckel Casting Method

Figure 3.8 Trends in Casting Methods[18]

Alcoa, too, had been limited to an ingot size of 121 x 305 x 508 mm (4.75 x 12 x 20 in.) by the conventional method of casting iron in molds since around 1930, and larger ingots were required to increase productivity. Larger ingots also had the effect of reducing the amount of cutting in the scalping process. In 1930, a new DC casting method was considered by W.T. Ennor at the Massena plant. In 1934, Ennor devised a method to increase the solidification speed and refine the microstructure by using a mold without a bottom and directly applying coolant to the solidified shell.[21] This method was found to be suitable for softer alloys such as 2S, but cracking occurred during the cooling of harder alloys such as 17S and 24S. The problem could no longer be solved by plant personnel alone, resulting in a joint collaboration with Physical Testing Division in Aluminum Research Laboratories (ARL). With the plant accumulating data on casting speed, water temperature and volume, temperature of metal in contact with the mold, and alloy composition, and ARL proceeding with thermal stress analysis, the problems were solved. By the end of 1937, the DC casting process had been applied to up to half of the Alcoa rolling mills and, during World War II, all high-strength alloys were produced by the DC casting process, although they still included some cracking. Ennor's casting process was reported at a meeting of Alcoa metallurgical researchers in 1937, and Ennor was called the "Daddy of the DC Ingot."[21] Figure 3.9 illustrates the DC casting method described in a patent filed in 1938.[22]

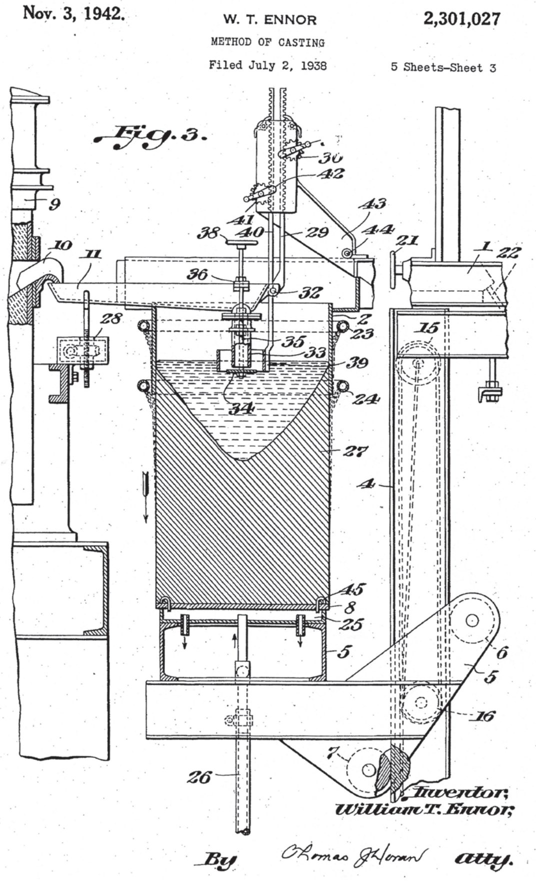


Figure 3.9 DC Casting Method of Ennor of Alcoa[21, 22]

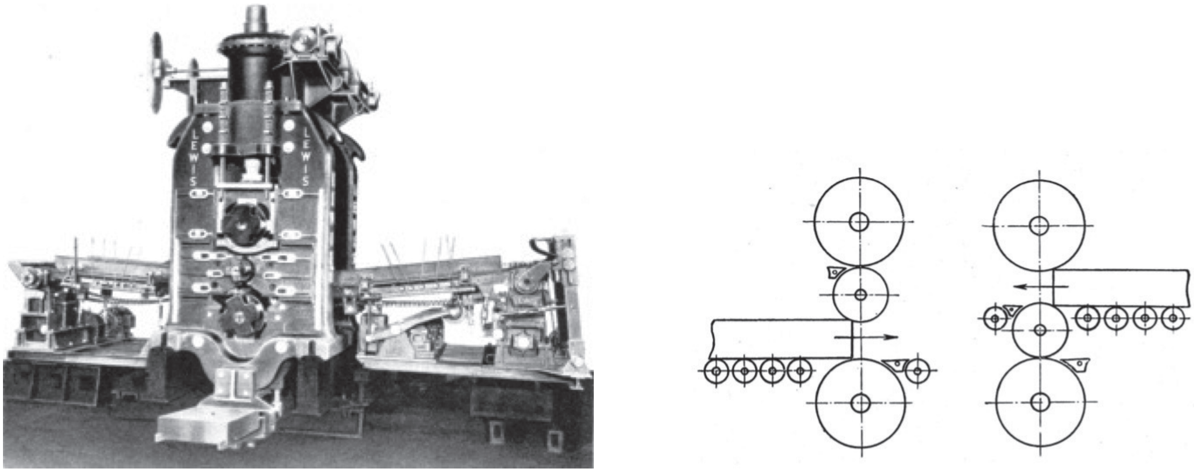


Figure 3.10 Three-High Hot Rolling Mill and its rolling schematic diagram[24]

3.3.3 Rolling Technology

Hot rolling needs to be performed as quickly as possible to increase productivity. For this reason, manufacture at an optimum rolling temperature is important, but the speed must be slowed at the start of hot rolling to prevent hot cracking during rough rolling. A vertical edging roll was introduced to prevent edge cracking.[23] Hot rolling is usually carried out with two rolling mills: a roughing mill and a finishing mill. The rolling conditions for Duralumin at that time involved a process of rolling an 8-inch thick slab in a two-high hot roughing mill at a speed of 130 ft/min in 10 passes of 50 seconds to a 4-inch thickness, followed by rolling in a three-high hot finishing mill at a speed of 450 ft/min in 20 passes of 15 seconds to a 0.280-inch thickness. Figure 3.10 shows a three-high rolling mill used for hot rolling.[24] Rolling can be done in one direction without changing the rolling direction of the plate as in a two-high or four-high rolling mill. A comparison of production speeds for two-, three-, and four-high rolling mills is shown in Figure 3.11.[24] The high productivity of the four-high rolling mill is evident from the figure.

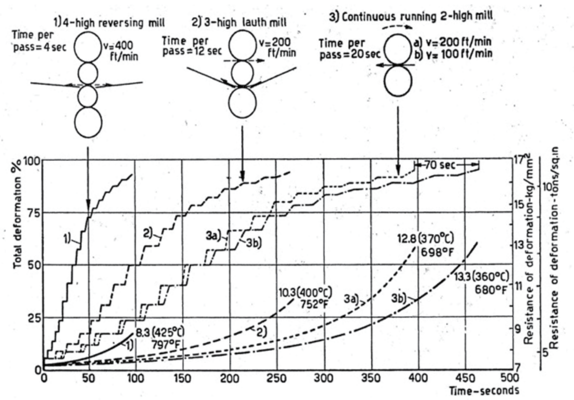
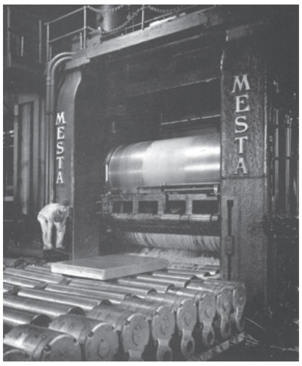


Figure 3.11 Comparison of Production Speeds for Two-, Three-, and Four-High Rolling Mills[24]

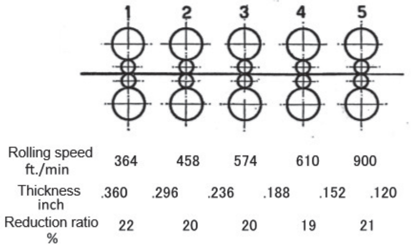
3.3.4 Tandem Rolling Technology[23-26]

Figure 3.12 shows a hot roughing mill[23, 24] and a hot tandem rolling mill. Figure 3.12(c) shows a tandem rolling mill at the Trentwood mill, which was built by the United States government's Defense Plant Corporation (DPC) during World War II, outsourced to Alcoa for management and operation, and then sold to Kaiser Aluminum after the war.[25] While a typical hot rolling mill consists of two units for roughing and finishing (or one unit for both roughing and finishing), the state-of-the-art hot rolling mill at that time consisted of seven hot rolling mills in total (two one-stand four-high rolling mills and one five-stand tandem four-high rolling mill). Pure aluminum is attached to both sides of the surface-machined ingot, which is then placed in a furnace and heated to 495–516°C. After a certain time, the ingot is taken out of the furnace, the rolling temperature is lowered to 427–454°C, and rolling begins in the rough rolling mill. For wide rolled material, the rolling mill has a turntable, which rotates 90° for width rolling. The temperature drops, so the rolled material is reheated and transferred to the next roughing mill for rolling.[26] The first rough rolling can be devoted to breaking the cast structure, and the remaining rolling mills are highly productive and very rational production equipment, which are considered optimal for the hot rolling and heat treatment of high-strength aluminum alloys. The rolling mill was said to be 50 times faster than a conventional rolling mill.[27]

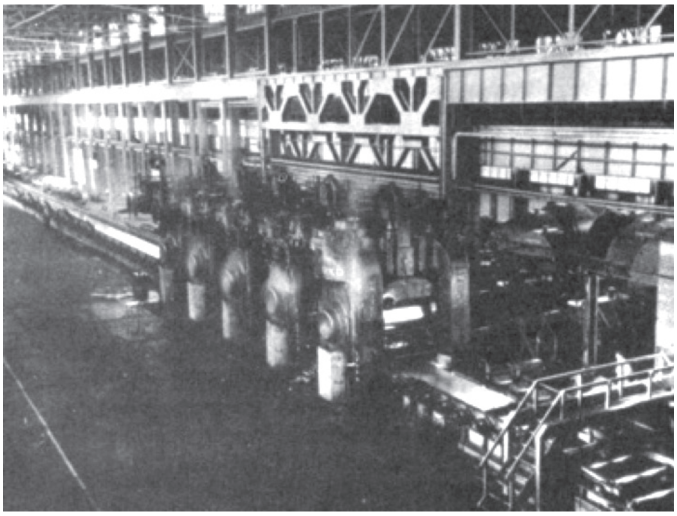
The roughing mill is a reversible, four-high hot roughing mill (from 8 to 3 in.) with a 5,000 hp DC motor capable of rolling speeds from 130 to 450 ft/min. Between that roughing mill and the five-stand tandem hot finishing mill is a four-high intermediate hot rolling mill of the same type (from 3 to 1 in. or less), with a reheating process before the intermediate rolling mill. Finally, the process involves rolling to 0.100–0.120 inches in a five-stand tandem four-high finishing mill. The roll speed, thickness, and reduction ratio for a five-stand tandem rolling mill are shown in Figure 3.12(b).[24]



(a) Four-High Hot Roughing Mill [23]



(b) Rolling Conditions of Five-Stand Tandem Four-High Hot Finishing Mill[24]



(c) Five-Stand Tandem Four-High Hot Finishing Mill of Trentwood Mill [25]

Figure 3.12 Four-High Hot Roughening Mill and Five-Stand Tandem Four-High Hot Finishing Mill

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4 Development of Duralumin and Super Duralumin

4.1 Development of Duralumin and Zeppelin Airship

4.1.1 Discovery of Age Hardening

In 1901, Alfred Wilm (Figure 4.1) of Germany was invited to the *Zentralstelle für wissen-schaftliche-technische Untersuchungen* (Central Institute of Science and Engineering) in Neubabelsberg, near Berlin. The following year, he was commissioned by *Deutsche Waffen und Munitions Fabriken* (DWM) to develop an aluminum alloy to replace brass casings. Wilm quenched the Al-4%Cu alloy in the same manner as steel, obtaining tensile strengths of 152 to 225 MPa and elongations of 5 to 7%, but not enough to replace brass. In 1903, he applied for a patent for this heat treatment method (DRP 170,085). He continued his research and discovered the age-hardening phenomenon in 1906. The following anecdote concerning this discovery is a well-known story.[1, 2]

Figure 4.1 Alfred Wilm[3]

On a Saturday in September 1906, a 3-mm thick sheet of Al-4%Cu-0.5%Mn alloy with 0.5% Mg was prepared, heated in a salt bath furnace at 520°C, and quenched. Wilm ordered his assistant Jablonski, who was about to leave, to measure the hardness at about one o'clock in the afternoon, and when he did so, the change was slight. Wilm followed up on this on the following Monday and was surprised to find a marked increase, so checked the measurement equipment and repeated the experiment. The results showed that the change in hardness was only slight up to two hours after quenching and then increased over the next four days, after which the hardness was constant. This heat treatment resulted in a tensile strength of 390 MPa and elongations of 20 to 25%.

On January 11, 1907, Wilm studied the effect of adding trace amounts of magnesium based on an Al-4%Cu alloy, found that aluminum alloys containing magnesium at 2% or less and copper at 5% or less, especially 4%Cu with 0.25 to 0.5%Mg, are effective, and applied for a patent (DRP 204,543, granted November 1908). The reason why the magnesium content was set at 2% or less was because it was already known and patented that a magnesium addition of 2% or more was necessary to increase the strength of aluminum, as typified by magnalium alloys. Subsequently, systematic experimentation followed, and Wilm was granted a patent DRP 244,554 for a "Heat Treatment Method for Aluminum Alloys Containing Magnesium" (filed March 20, 1909, granted March 9, 1912). The claims read, "A method of treating an aluminum alloy containing magnesium characterized by heating the aluminum alloy to 420°C or higher at the end of processing and, after any slight molding, leaving the aluminum alloy at room temperature." Wilm was granted four patents in the United States, including the two described above.[4] Figure 4.2 shows the effects of room temperature aging time and quenching temperature on the hardness of the Al-3.5%-Cu-0.5%Mg alloy that Wilm published in his paper.[5]

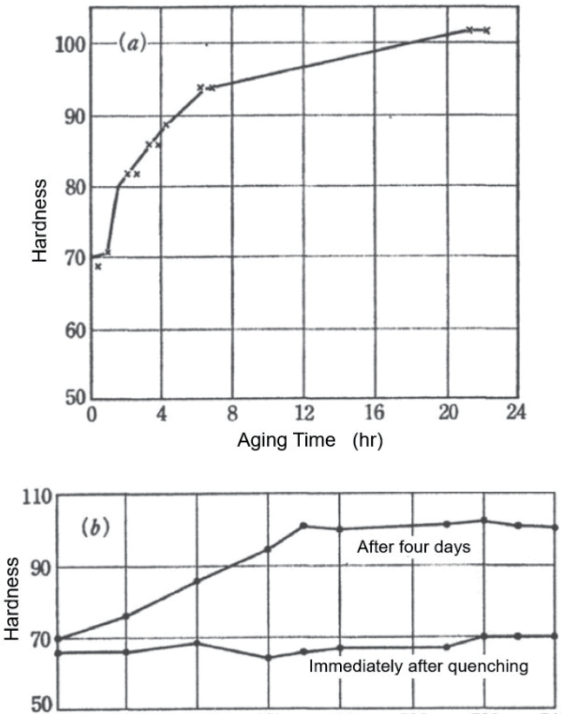


Figure 4.2 Effects of Room Temperature Aging Time and Quenching Temperature on Hardness of Al-3.5%Cu-0.5% Mg Alloy[5]

4.1.2 Industrialization of Duralumin

A factory trial of a Duralumin sheet at Dürener Metallwerke A.G. in Düren, a sister company of DWM in 1908, was conducted for the production of this material, but the laboratory was not interested in the invention. In 1909, the year Wilm applied for the patent, the director of the institute who had invited him was replaced, and Wilm's research was discontinued. In order to industrialize Duralumin on his own, Wilm negotiated with the institute to put the patent for Duralumin in his name and resigned from the institute. Fortunately, Dürener Metallwerke A.G. obtained the rights to use Wilm's patent and succeeded in industrialization with the cooperation of Dr. R. Beck, the company's technical director.[2, 6]

In 1909, Wilm and Dürener Metallwerke A.G. discussed a trade name for this new product. Wilm initially suggested Hartaluminium, adding the German word *Hart* for hard, but in consideration of the international market, they decided on Duralumin, using the French word *Dur* for hard. Duralumin is said to have come from the location name Düren or the company name Dürener Metallwerke A.G., which was named after the location, but most Germans today understand Duralumin to be Dur-Alumin and not Düralumin (Dürener-Alumin).[6] This was not the first time that Dur was used, but its use was also related to the fact that "DuranaMetalle" was already internationally recognized and used as a trademark for many of the alloys developed by Dürener Metallwerke A.G..[6]

In 1909, Vickers Company (later Vickers Sons & Maxim Ltd.) of England began building the highly rigid Royal Navy airship, the *Mayfly*. In 1910, Dürener produced 12.75 tons of Duralumin, of which 10 tons were supplied to Vickers. However, in September 1911, when the ship was being moved from the hangar for a test flight, it broke in half due to an operational error. This raised suspicion that the alloy was "Made in Germany" (Note 1) and, in 1911, Vickers obtained permission from Wilm to manufacture the alloy and began producing it itself.[6] Vickers had the right to manufacture in the U.K., France, Spain, Portugal, Italy, and the United States. As will be discussed later, the failure of the *Mayfly* also seems to have been due to the roll-forming technology of Duralumin in Germany.[7]

(Note 1) At that time, Germany's technology was the same as that of emergent developing countries and its economic development was tremendous. Although its production volume increased, the quality of its products was still considered inferior to that of the U.K.. In the U.K. at that time, "Made in Germany" was a synonym for shoddy imports in the form of inexpensive general-purpose products.[8] However, at the time, Germany was a complete world leader in both the high-tech electrical and chemical sectors, as well as in natural sciences such as physics and chemistry.

4.1.3 The Zeppelin Airship[9]

(1) Count Zeppelin

Duralumin was first used for airships. The famous Zeppelin airship was invented by Count Zeppelin (Ferdinand Adolf

Column: The Life of Wilm

Wilm was born on June 25, 1869 in Niederschellendorf near Haynau in Lower Silesia. His father owned a seigniory and his mother was the daughter of a great jeweler. After studying at *Königliche Gewerbeschule* (Royal Professional School) in Breslau (now Wroclaw, Poland) in 1886, he became a chemist auditor at the Technical University of Charlottenburg in Berlin, where he took theoretical and practical courses, especially with Professor Julius Weeren. He also learned metallurgy for the first time at the *Königliche Eisengießerei* (Royal Foundry). In addition, he participated in a three-month training course at the Mining Station of Kassel, where he became proficient in barium, strontium, and calcium separation methods. On November 1, 1893, he became an assistant at the University of Göttingen. The laboratory in which he was enrolled was where Wöhler (F.W. Wöhler, 1800-1882) had conducted research and taught for 50 years, and he continued in that vein. From March 1897, he worked at Th. Goldschmidt in Essen and, together with Hans Goldschmidt, worked on the separation of metals such as Cr, Mn, Co, Ni, and Ta from oxides using a thermite reaction (also called the aluminothermy method or the Goldschmidt method since it was invented by Goldschmidt) in which metal oxides are reduced with metal aluminum.

In the spring of 1901, Wilm left the Essen firm and moved to the Center for Scientific and Technical Research in Neubabelsberg, headed by Professor Stribeck. Beginning in 1902, Wilm began systematic research on aluminum alloys under the deep trust of Professor Stribeck. In 1906, he discovered and patented the hardening of an Al-Cu-Mn alloy by the addition of a trace amount of Mg and subsequent quenching. He studied alloy composition and heat treatment until 1909 when Professor Stribeck left the Center for Scientific and Technical Research to move to Krupp in Essen. Professor Stribeck's successor as director was a powder specialist and had no interest in high strength aluminum alloys, so Wilm himself became the patentee for the 1909 patent application as mentioned above and resigned from the institute.

The last years of Wilm's life were summarized in detail by Dr. M. H. Haas of *Aluminium Zentrale* in Germany around 1935 to 1940.* According to Dr. Haas, Wilm retired to his native mountain village in Silesia in 1919 after World War I with his wife and six children to devote himself to raising chickens. In poultry farming, he gained fame by improving egg-laying chickens, especially white leghorns, using the same methods he had developed for aluminum alloys. He later died on August 6, 1937, at the age of 68, according to the report.

*M. H. Haas. *Aluminium*, 18 (1936), 1936; 17 (1935), 502; 22 (1940), 497.

Heinrich August Graf von Zeppelin)[9] (Figure 4.3). The historical background of the times of Wilm and Zeppelin should first be discussed.[8]

Wilm was born in 1869 in the Kingdom of Prussia. In 1861, in Germany at that time, King Wilhelm I of Prussia ascended to the throne and, under his rule, Bismarck became Chancellor of the Kingdom of Prussia. Bismarck worked for German unification through his "blood and iron policy" and was called the Blood and Iron Chancellor. Bismarck eliminated the influence of neighboring Austria in the Austro-Prussian War, united the northern German states, and then united the southern German states, including the Kingdom of Bavaria, in the Franco-Prussian War to establish the German Empire in 1871. With the establishment of the German Empire, he became its first chancellor and, for about 20 years, under the Kaiser's deep confidence, worked to develop the empire and improve Germany's international standing. However, when the young Wilhelm II ascended to the throne in 1888, he was dissatisfied with Bismarck's policy of "protecting" the German Empire and retired Bismarck to begin a pro-regime rule. He advocated a "world policy" and expanded the military by increasing naval power and the like. As a result of switching from a "defensive" to an "offensive" policy, the 3B policy connecting Berlin, Byzantium, and Baghdad by the Baghdad Railway brought him into conflict with the U.K., France, and Russia, which triggered World War I. According to TAKENAKA Toru, "During this period of Imperial Germany, the size of the economy grew nearly four-fold, with industrial growth nearly six-fold. The country made a great leap forward from an agricultural country to Europe's foremost industrial power. Especially during the reign of Wilhelm II, the German economy was particularly strong."[8]

Zeppelin was born on July 8, 1838 in a noble family in Konstanz near the Bodensee (Lake Constance) in southern Germany. He entered the Military Academy in 1853 to become a soldier. After graduation, he went to the United States to observe the American Civil War as a military officer and rode in a tethered balloon for reconnaissance on the banks of the Mississippi River. Later, he participated in the Franco-Prussian War and began researching airships after learning that the French used manned balloons as a means of communication. He took a year off from the army to attend the University of Tübingen to study engines. While in the military, he studied airships and the airship he came up with was a huge airship that could accommodate 20 passengers and carry mail. In order to realize his vision, he proposed an airship structure to German Kaiser Wilhelm II in 1890, but was not understood, so retired from the army as a major general in 1890 to build an airship himself.[9]

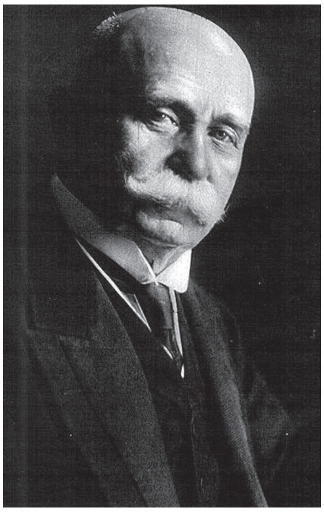


Figure 4.3 Count Zeppelin[9]

(2) Non-Rigid Airships[7, 10]

Before airships were invented, flying was done with hot air balloons that heated air to gain buoyancy. Later, when hydrogen was discovered, hydrogen balloons became the mainstream, but balloons had the disadvantage that their flight was dependent on the wind and they could not fly in the desired direction. Later, a propeller was attached to the gondola to make a balloon that could be steered by a hand crank. This led to the development of steerable airships with propellers and motors. Later, an airship powered by an electric motor with storage batteries was developed in France. In 1884, Charles Renard's "La France," a 50-meter-long, 8.5-meter-diameter airship with a 9-horsepower motor, reached a speed of 24 km/h and was a great success. However, the weight of the propulsion system was too great for practical use. In 1885, Karl Friedrich Benz and Gottlieb Wilhelm Daimler of Germany separately succeeded in developing a practical four-stroke gasoline engine, launching the beginning of the practical application of airships. However, previous airships were non-rigid airships filled with gas inside a flexible hull that did not leak gas. These airships could not be excessively large structurally due to the expansion and contraction in response to altitude and temperature, and could not withstand air currents in adverse weather conditions.

(3) Rigid Airships[7]

David Schwarz, a Hungarian-born Jew and lumber merchant, was contracted to build a rigid airship with a metal hull proposed by a Russian researcher in 1892 with the support of the Russian government. The metal was to be aluminum manufactured by Carl Berg, but unfortunately the metal hull broke during gas filling and the ship failed. Later, in 1894, he proposed this airship to Prussia. This time, the competition was with a train-type airship that connected Zeppelin's two airships, and Schwarz's design was adopted.[7, 10] As shown in Figure 4.4, Schwarz's airship had a cylinder shape 47.6 m in length and 12 m in diameter, with a cone on one side, and was filled with hydrogen gas, powered by a Daimler 12-hp engine, and equipped with four propellers turned by belts.[7] Schwarz died without completing the project. After his death, in November 1897, the airship made its first flight, but had trouble with its belt and crashed, resulting in failure of the second ship as well.

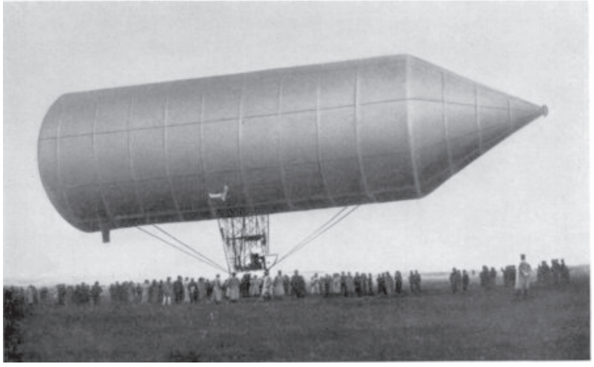


Figure 4.4 Schwarz's Airship[11]

In the competition with Schwarz, Zeppelin's idea was not adopted by the selection committee, but committee members were impressed by Zeppelin's ideas and offered constructive feedback. In a letter from the War Ministry summarizing its opinion, the War Ministry made the important suggestion that the structure should be cigar-shaped and covered with an outer skin, while the interior should be composed of regular polygonal ring-shaped ribs (frames), as devised by J.W. Schwedler, placed at regular intervals in the longitudinal direction and secured with wires. Zeppelin decided that this structure was likely to be adopted, designed a rigid airship, and applied for a patent in December 1897. He invested all his money and founded his own airship building company in 1898 in Manzell on Lake Constance, near his birthplace on the Swiss border.

Zeppelin's airship was not a conventional non-rigid airship filled with a gas envelope filled with hydrogen, but a rigid airship with a metal framework covered with an outer skin (linen or cotton cloth) and lined with several gas envelopes (Note 2) filled with hydrogen gas. The reasons were (1) as long as the hull was made of a metal framework, it would not deform even if the airship was large or the gas envelopes shrank slightly, and (2) as long as hydrogen gas was dispersed and filled in several gas envelopes, it would be safe even if a hole opened in one of them and gas leaked out. The hull frame was intended to be made of steel, but aluminum was used because of concerns that steel would be too heavy. Count Zeppelin adopted a zinc-aluminum alloy, which was considered a hard alloy at the time. A zinc-aluminum alloy is an alloy containing about 20% zinc.[7]

(Note 2) Gas envelopes for early airships had to be airtight as well as light, flexible, and resistant to moisture absorption. Generally, the base material was a fine cotton cloth with a thin layer of rubber applied to the inner surface, on top of which a layer or two of gold-beater's skin, made by cutting open and processing the cecum of a cow, was applied with a special adhesive, and then paint was applied on top to reduce gas leakage. The size of the cecum from one cow is 700x150 mm to 1000x250 mm, so the number of cow cecum needed for one large rigid ship, for example, the R101 (British rigid airship) with 16 gas envelopes, was about 150,000 cows worth. Gas leakage was said to be from 0.1 to 1.0 l/m^2 per 24 hours. Cotton cloth coated with rubber latex or gelatin latex was used on airships in the United States.[10]

In June 1900, the first Zeppelin rigid airship LZ1 (Note 3), 128 m in length and 11.65 m in diameter, was completed. Count Zeppelin continued to use this material until 1914, when he converted to Duralumin. At the time, Duralumin was 2.5 to 5 times stronger than aluminum of the same weight, but in 1910 it was difficult to manufacture the cross-sectional shape needed for airship girders, and Zeppelin initially refused to adopt it for this reason. Figure 4.5 shows the internal structure of the LZ1 Zeppelin airship and the LZ1 taking off over Lake Constance. The LZ1 was a regular 24-square cylindrical structure with fabric stretched over an aluminum framework that held 17 gas envelopes filled with hydrogen gas.[10, 12] For the next 40 years, Zeppelin airships followed this structural style.[10] Assembly took place in a floating hangar on Lake Constance near Friedrichshafen. Funds to purchase land was a problem, but this presented the advantage that the hangar could be rotated on the lake, making it less susceptible to crosswinds during loading and unloading. The LZ1 climbed 400 m and flew over Lake Constance for about 15 minutes before an anomaly unfortunately occurred, causing the hull to bend and the aircraft crashed. As a result of this failure, Count Zeppelin was even called "Count Madman," but he remained undeterred and built the LZ2 in 1905. At that time, the Kaiser was concerned that his country's navy was lagging behind the British navy, and decided to invest national funds in the hope of a Zeppelin airship, which could be called a flying battleship, and the LZ3 was built in 1906 and the LZ4 in 1908. With the success of these airships, Count Zeppelin became a national hero. In September 1908, he founded the airship-building company *Luftschiffbau Zeppelin GmbH* in Friedrichshafen, and the following year, 1909, he founded

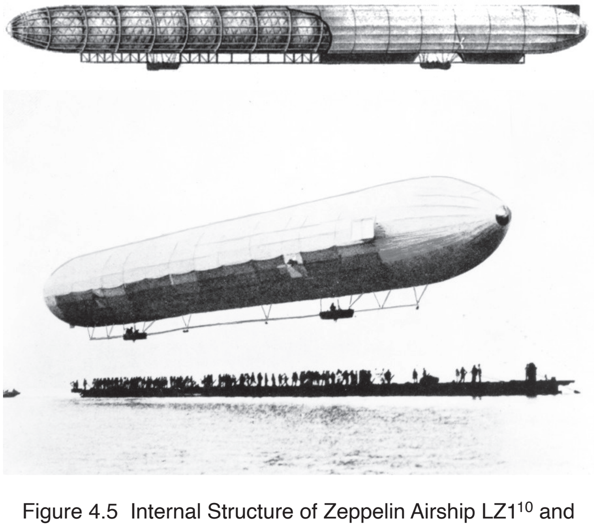


Figure 4.5 Internal Structure of Zeppelin Airship LZ1[10] and First Zeppelin Airship LZ1 Immediately Before its First Flight on Lake Constance[12]

Figure 4.6 Part of Skeleton of Zeppelin Airship on Display at Zeppelin Museum (Friedrichshafen) (Top Left), Its Roll-Forming Process (Top Right), and Its Roll and Rivet Joining Jig (Bottom) (photo by author)

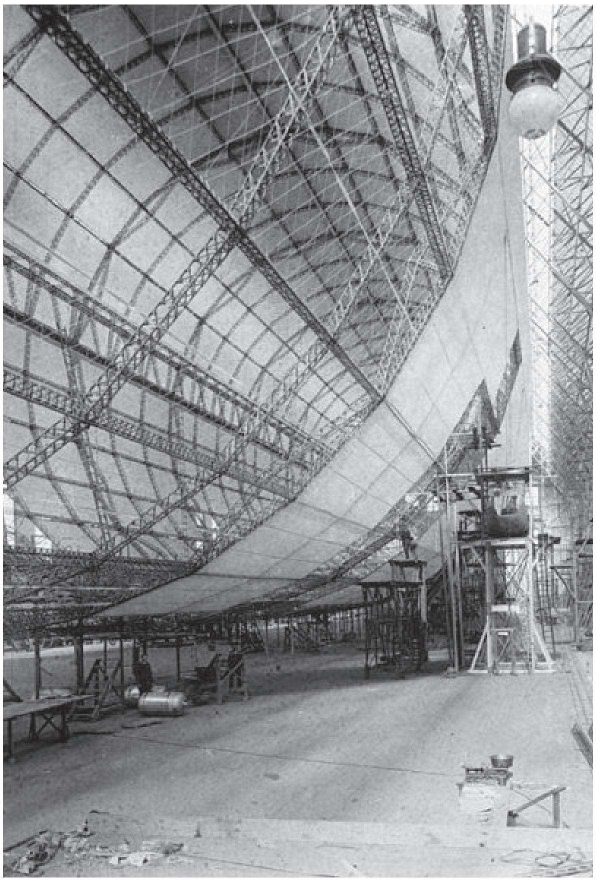


Figure 4.7 Skeletal Structure of the L127 Graf Zeppelin Airship[14]

Column: As Many As Four Zeppelin Museums in Germany!

When I (author) wanted to find out when Duralumin was first used for Zeppelin airships, I learned from KOMAE Hiromi's book, *"Pilgrimage of German Museum"* (Tokyo Shoseki, 2000), that there are four Zeppelin museums in Germany, and decided to visit them. When my wife and I went to Germany on vacation in October 2012, we were able to visit all of the museums except the one in the north due to time constraints. Fortunately, in June 2014, I attended the International Conference on Aluminum Alloys ICAA14 in Trondheim, Norway, to present a lecture, and on my way back, I had the opportunity to visit the remaining fourth museum in the north.

On October 9, 2012, we took the train to Friedrichshafen, located on the shores of Lake Constance on the border with Switzerland. Here lies the first Zeppelin museum I had wanted to visit. There was a monument at the entrance that resembled a Zeppelin airship. From the back, it was a children's slide. Once inside the museum, the remnants of the skeletal components (Figure 4.7) and the wreckage of the gondola and a propeller mounted with Maybach's engine were laid out on display. Deeper in the museum, there were exhibits of the skeletal fabrication technology of the time (Figure 4.7) and a full-scale section of an airship and its passenger cabin. It was evident that the skeleton was formed by roll-forming sheets and riveting the sheets together. The next morning on the 10th, in cloudy and sometimes drizzly weather, we took a bus from Friedrichshafen to Meersburg, which took about 30 minutes. Meersburg is a tourist destination, centered around an old castle by the lake. The second museum was on the other side of the old castle. However, this is a privately owned and operated museum with a personal collection of about 10,000 items, but few of them caught my interest. On the 12th, we took the train from Stuttgart to Frankfurt and went to the third museum. The third museum was located in Zeppelinheim near Frankfurt Airport. Frankfurt Airport is said to have been originally established when Zeppelin established DELAG in Frankfurt. A residential area for employees was built in the woods near the airport and named Zeppelinheim. The Zeppelin museum was located in a quiet residential area.

The museum is relatively cozy and, although there are exhibits, I thought there were many photographic descriptive presentations. Tubing was on display and, if they were seamless Duralumin tubes, the level of technology was so high that I felt the need to look again at the level of tube manufacturing technology at that time. Also on display were remnants of the *Hindenburg* (LZ129), which exploded in flames in 1937. The surface was black and the paint seemed to have been burned off by the fire. If the aircraft was painted, it was also interesting to see what kind of paint was applied and when.

The fourth and final museum, the *Nordholz Aeronauticum*, is located in Nordholz, about 80 km north of Bremen. It is about an hour away from Bremen by train. On June 21, 2014, after the international conference in Trondheim, I went to Germany, and the next day, on the 21st, I went to Nordholtz via Bremerhaven. A 15-minute walk from the station was the Naval Air Station, and the *Aeronauticum* museum was adjacent to the Naval Air Station. A statue of Count Zeppelin stood at the museum entrance. Inside, there were a number of various models and photographs on display, including a near full-scale model. Although more and more museums in Japan have been displaying the Zero fighter recently, there is little custom in Japan of preserving and displaying products and technologies from the past. In Germany, there are a great many museums dedicated to industrial products, including Zeppelin airships and various types of aircraft. Once again, I recognized that this is a country that values industrial technology.

(This column is reprinted from https://www.jilm.or.jp/page-essay066, Altopia, No. 1 (2015), 17-25.)

a) Museum in Friedrichshafen b) Museum in Zeppelinheim c) Museum in Nordholz

Figure Front Views of Zeppelin Museums in Various Locations (photos by author)

the world's first commercial airline specializing in passenger service, *Deutsche Luftschiffahrts-Aktiengesellschaft* (German Airship Travel Corporation) (DELAG), in Frankfurt.[10]

(Note 3) LZ is the aircraft serial number of Zeppelin (L: Luftshiff, Z: Zepplin). Apart from the LZ number, during World War I, the Army identified the aircraft by LZ (but using a number obtained by adding 30 to keep the production numbers secret) and the Navy by L. In contrast, the rival Schütte-Lanz airship was identified by SL. One-hundred-and-thirty Zeppelin airships (LZ1 to LZ130) were built between 1900 and 1940, and 22 Schütte-Lanz airships (SL1 to SL22) were built between 1909 and 1918.

By 1914, Germany had reached a level where parts could be manufactured with Duralumin, which proved to be superior to the magnesium alloy that had been considered as an alternative,[7] and thus the alloy was registered as a standard in 1914 for German Navy Zeppelin airships, and Duralumin was used starting from LZ26 in 1914, with 720 tons produced by 1916.[13] Figure 4.6 shows the airship skeleton on display at the Zeppelin Museum in Friedrichshafen and its roll-forming process.[7] The failure of the *Mayfly* also seems to have been in the Duralumin roll-forming technique. In the manufacture of the *Mayfly*, materials that had been processed into basic shapes in Germany were imported to the U.K., but it is said that 75% of these materials could not be used because they had not been roll-formed into the required shapes.[7] For Duralumin to be used in airships, roll-forming processing technology also had to advance.

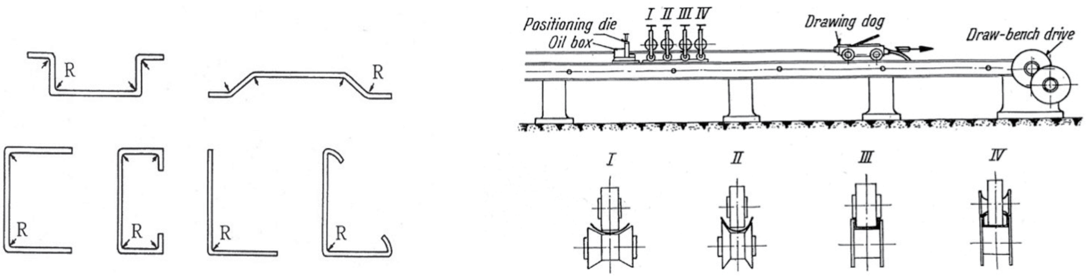
The internal structure of the airship is shown in Figure 4.7. This figure shows the hull skeleton of the Graf Zeppelin L127.[13] The complex framework made of Duralumin can be seen. Each ship used approximately nine tons, and between 1914 and 1918, 88 Zeppelin ships and 20 Schütte-Lanz ships were built. The Schütte-Lanz Airship Building Company built rigid ships with a framework of wood and veneer plywood adhered together, but they were used primarily by the army because of structural defects that made them vulnerable to water. After 1918, Duralumin replaced wood in Schütte-Lanz vessels for mainly the tubing.[10] Table 4.1 lists the specifications of typical airships from around the world and the materials used for their airframes.[7]

Table 4.1 Specifications of Typical Airships and Materials Used in Their Framework[7]

Airship	Serial Number / Name	Country	First Flight	Gas Capacity	Engine Manufacturer	Model	Quantity Mounted	Horsepower hp	Length m	Diameter m	Muximum Speed m/s	Material	Quantity Manufactured
Schwarz	No.2	Germany	3.11.97	3,700	Diaimler	P1896	1	12	47.5		7.5	Aluminium	1
Zeppelin	LZ1	Germany	2.7.00	11,300	Diaimler	N1899	2	28	128.0	11.7	7.8	Zn-Al Alloy	1
Zeppelin	LZ2	Germany	17.1.06	10,400	Diaimler	H4L	2	160	128.0	11.7	11.0	Zn-Al Alloy	2
Zeppelin	LZ4	Germany	20.6.08	15,000	Diaimler	J4	2	210	136.0	13.0	13.5	Zn-Al Alloy	2
Zeppelin	LZ6	Germany	25.8.09	15,000	Diaimler	J4L	2	230	136.0	13.0	13.5	Zn-Al Alloy	1
Zeppelin	LZ7, Deutchland	Germany	19.6.10	19,300	Diaimler	J4F	3	360	148.0	14.0	16.7	Zn-Al Alloy	2
Vickers	No.1	Germany	22.5.11	18,800	Wolseley		2	320	156.0	14.6	(18.8)	Duralumin	1
Zeppelin	LZ10, Schwaben	Germany	26.6.11	17,800	Maybach	A-Z	3	435	140.0	14.0	21.0	Zn-Al Alloy	3
Schütte-Lanz	S.L.1	Germany	17.10.11	20,500	Diaimler	J8L	2	480	131.0	18.4	19.7	Wood	1
Zeppelin	LZ11, Viktoria-Luise	Germany	14.2.12	18,700	Maybach	B-Y	3	450	148.0	14.0	21.0	Zn-Al Alloy	2
Zeppelin	LZ14 (L1)	Germany	7.10.12	22,470	Maybach	B-Y	3	540	158.0	14.9	21.2	Zn-Al Alloy	6
Zodiac	13 Spiess	France	4.13	12,800	Chenu		2	420	113.0	13.5	18.0	Wood	1
Zeppelin	LZ18 (L2)	Germany	9.9.13	27,000	Maybach	C-X	4	840	158.0	16.6	21.0	Zn-Al Alloy	1
Zeppelin	LZ21 (ZV1)	Germany	10.11.13	20,870	Maybach	C-X	3	540	148.0	14.9	20.5	Zn-Al Alloy	1
Zeppelin	LZ22 (ZV2)	Germany	8.1.14	22,140	Maybach	C-X	3	540	156.0	14.9	20.0	Zn-Al Alloy	2
Schütte-Lanz	S.L.2(S.L.2)	Germany	28.2.14	25,000	Maybach	C-X	4	720	144.0	18.2	24.5	Wood	1
Zeppelin	LZ24(L3)	Germany	11.5.14	22,470	Maybach	C-X	3	540	158.0	14.9	23.4	Zn-Al Alloy	12
Zeppelin	LZ26	Germany	14.12.14	25,000	Maybach	C-X	3	540	161.2	16.0	22.5	Duralumin	1
Schütte-Lanz	S.L.3	Germany	4.2.15	32,410	Maybach	C-X	4	840	153.1	19.7	23.5	Wood	3
Zeppelin	LZ36	Germany	8.3.15	24,900	Maybach	C-X	3	540	161.4	16.0	23.6	Duralumin	2
Zeppelin	LZ38	Germany	3.4.15	31,900	Maybach	C-X	4	720	163.5	18.7	26.7	Duralumin	22
Schütte-Lanz	S.L.6	Germany	19.9.15	35,130	Maybach	C-X	4	840	162.1	19.7	25.8	Wood	2
Zeppelin	LZ59	Germany	21.12.15	35,800	Maybach	H-S-Lu	4	960	178.5	18.7	26.5	Duralumin	12
Schütte-Lanz	S.L.8	Germany	30.3.16	35,130	Maybach	H-S-Lu	4	960	174.0	20.1	26.9	Wood	10/12
Zeppelin	LZ62	Germany	28.5.16	55,000	Maybach	H-S-Lu	6	1440	198.0	23.9	28.7	Duralumin	17
Vickers	No.9	UK	27.11.16	25,180	Maybach	C-X	4	600	161.5	16.2	20.1	Duralumin	1
Zeppelin	LZ91	Germany	22.2.17	55,500	Maybach	H-S-Lu	5	1200	196.5	23.9	27.7	Duralumin	2
Zeppelin	LZ93	Germany	1.4.17	55,800	Maybach	H-S-Lu	5	1200	196.5	23.9	28.9	Duralumin	2
Zeppelin	LZ59	Germany	22.5.17	55,800	Maybach	H-S-Lu	5	1200	196.5	23.9	29.9	Duralumin	5
Schütte-Lanz	S.L.8	Germany	30.3.16	35,130	Maybach	H-S-Lu	4	960	174.0	20.1	26.9	Wood	10/12
Zeppelin	LZ62	Germany	28.5.16	55,000	Maybach	H-S-Lu	6	1440	198.0	23.9	28.7	Duralumin	17
Vickers	No.9	UK	27.11.16	25,180	Maybach	C-X	4	600	161.5	16.2	20.1	Duralumin	1
Zeppelin	LZ91	Germany	22.2.17	55,500	Maybach	H-S-Lu	5	1200	196.5	23.9	27.7	Duralumin	2
Zeppelin	LZ93	Germany	1.4.17	55,800	Maybach	H-S-Lu	5	1200	196.5	23.9	28.9	Duralumin	2
Zeppelin	LZ59	Germany	22.5.17	55,800	Maybach	H-S-Lu	5	1200	196.5	23.9	29.9	Duralumin	5
Zeppelin	LZ100	Germany	8.8.17	56,000	Maybach	H-S-Lu	5	1200	196.5	23.9	29.9	Duralumin	10
Schütte-Lanz	S.L.20	Germany	10.9.17	56,000	Maybach	H-S-Lu	5	1200	198.3	22.9	28.5	Wood	3
Vickers	No.23	UK	19.9.17	28,250	Rolls-Royce	Eagle	4	1000	163.1	16.2	23.2	Duralumin	4
Zeppelin	LZ102	Germany	26.9.17	68,500	Maybach	H-S-Lu	5	1200	226.5	23.9	28.6	Duralumin	2
Admiralty	R27	UK	29.6.18	28,050	Rolls-Royce	Eagle	4	1200	164.3	16.2	24.6	Duralumin	2
Zeppelin	LZ112	Germany	1.7.18	62,200	Maybach	Mb Iva	7	1715	211.1	23.9	36.4	Duralumin	3
Admiralty	R31	UK	1.8.18	43,975	Rolls-Royce	Eagle	6	1800	187.3	20.1	31.8	Wood	2
Admiralty	R33	UK	6.3.19	55,460	Sunbeam	Maori IV	5	1250	196.0	24.0	26.8	Duralumin	2
Zeppelin	LZ120, Bodensee	Germany	20.8.19	20,000	Maybach	Mb Iva	4	980	120.8	18.7	36.8	Duralumin	2
Vickers	R80	UK	19.7.20	35,680	Maybach	Mb Iva	4	980	162.0	21.3	26.8	Duralumin	1
Admiralty	R36	UK	1.4.21	60,030	Sunbeam Maybach	Cossack Mb Iva	3 2	1540	205.0	24.0	29.1	Duralumin	1
RAW	R38	UK	23.6.21	77,600	Sunbeam	Cossack	6	2100	211.8	26.0	29.5	Duralumin	1
NAF	ZR-1, Shenandoah	USA	4.9.23	60,915	Packard	1A-1551	6	1800	207.3	24.0	28.0	Duralumin	1
Zeppelin	LZ126, Los Angels	Germany	27.8.24	70,000	Maybach	VL1	5	2000	200.0	31.9	32.7	Duralumin	1
Zeppelin	LZ127, Graf Zeppelin	Germany	18.9.28	75,000	Maybach	VL2	5	2650	236.6	30.5	35.6	Duralumin	1
Metalclad	ZMC-2	USA	19.8.29	5,720	Wright	J-5 Whirlwind	2	440	45.5	16.0	27.7	Duralumin and Alclad	1
RAW	R101	UK	14.10.29	141,540	Beardmore	Tornado III	5	2925	222.9	40.0	31.3	Duralumin and Steel	1
AGC	R100	UK	16.12.29	146,060	Rolls-Royce	Condor IIIB	6	4020	216.1	40.5	36.3	Duralumin	1
Goodyear-Zeppelin	ZRS4, Akron	USA	25.9.31	193,970	Maybach	VL2	8	4560	239.3	40.5	37.6	Duralumin	2
Zeppelin	LZ129, Hindenburg	Germany	4.3.36	200,000	Diaimler-Bentz	DB 602	4	4200	245.0	41.2	37.5	Duralumin	2

Column: Roll Forming Technology Supporting Airship Structure Construction

Generally, when bending a sheet into a specified cross-sectional shape, a groove is cut in the die (mold) in the specified cross-sectional shape and to the same thickness as the material, and the sheet is drawn into shape by being passed through the groove. If the shape is difficult to process in a single step, the shape is gradually approached in several steps. This sheet product is called a profile (left figure) and was applied to thin shapes difficult to extrude. To do this continuously, instead of a groove in a die, the shape is made between two rolls as shown in the figure on the right, and the material is processed into the desired shape by continuously passing it through a number of rolls. This is called a roll-forming process.



Profile and Profile Shapes (R ≤ 0.5 mm)

Roll-Forming Machine and Roll Shapes

Figure Profile Shapes (Left) and Roll-Forming Machine (Right)

Source: A. Zeerleder, *The Technology of Aluminium and its Light Alloys* (Nordemann Publishing Company, 1936), 31.

4.1.4 Zeppelin Airships and World War I

In World War I, Germany used airships to bomb the U.K. and France. London's first air raid was carried out by the Army's LZ38 late at night on May 31, 1915. The number of raids between 1915 and 1918 was three over Paris, but 51 over London.

The largest of the London air raids took place late on the evening of September 2, 1916. On that day, 16 Army and Navy airships simultaneously attacked London and the surrounding area, dropping more than 460 bombs. As the war dragged on, the British began firing back with anti-aircraft guns and fighter planes, and more and more airships were shot down. On September 23, 12 ships were dispatched. Among them, the Navy's L30, L31, L32, and L33, called Super Zeppelins (189 m in length and 24 m in maximum diameter), bombed London.[15] The L33, among others, found it impossible to return across the North Sea due to anti-aircraft fire and fighter attacks and made an emergency landing at Little Wigborough, Essex, on the 24th. The crew attempted to destroy the ship by fire, but only barely managed to burn part of it. Figure 4.8 shows the wreckage of the L33 airship that crash-landed in Essex and was destroyed by fire.

British engineers studied the skeleton and later used it as the basis for the construction of the British airships R33 and R34.[7, 15] The United States and Japan also acquired the wreckage of Zeppelin airships and began manufacture. Meanwhile, the performance of fighter planes was also improved to stop the bombing by these airships.

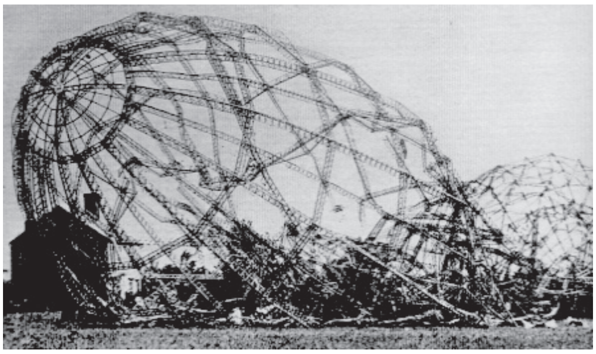


Figure 4.8 Wreckage of L33 (LZ76) Crash-Landed and Destroyed by Fire at Little Wigborough, Essex (from Imperial War Museum Photograph Archive Collection)[7, 15]

Figure 4.9 Junkers F.13, All-Metal Passenger Plane Using Corrugated Duralumin (©2006 Andi Szekeres)[16]

In Germany, Duralumin was used not only for airships but also for aircraft, with the German company Junkers using it for the first time in 1917 for its J4 single-engine biplane attack aircraft. In 1919, the company developed the F.13 (Figure 4.9),[16] an all-metal passenger plane made of corrugated Duralumin. It should be noted that Count Zeppelin died suddenly of pneumonia in March 1917. In peacetime, he would have been a national hero, and a grand funeral would have been held.[10]

4.1.5 Airships after World War I

After World War I, airships had the advantage of a long cruising range at high altitudes and the ability to carry heavy loads (effective load capacity of 30 tons for LZ127 and 88 tons for LZ129[10]) and served as a means of mail and passenger transport. In 1929, the 236.6 m long *Graf Zeppelin* (LZ127)[7] fulfilled Count Zeppelin's dream of sailing around the world. After departing Friedrichshafen and crossing Siberia, the ship made a stopover at the naval base in Kasumigaura, Japan, before heading to its next stopover in Los Angeles.

When Hitler came to power in 1933, he thought that airships would be very effective for foreign propaganda, so provided significant financial support and built the even larger *Hindenburg* (LZ129), which was completed in 1936. The ship was a modern facility, 245.0 m in length, 41.2 m in diameter, equipped with 16 gas envelopes and four 1,150-hp diesel engines manufactured by Daimler-Benz, had a hull that was regular 36-sided polygon in cross section and could accommodate 40 crew members and 50 passengers, boasted an interior equipped with guest rooms, a dining room, a lounge, a toilet, a shower room, and the like, and even featured an aluminum piano in the lounge.[7, 10, 17] The *Hindenburg* (Figure 4.10, top), decorated with the Olympic rings, contributed to Nazi national prestige, making an appearance at the Berlin Olympics held in the same year, but in 1937, just before landing at Lakehurst Naval Air Station in New Jersey, it exploded and burst into flames in what became known as "the Hindenburg disaster." (Figure 4.10, bottom). In 1997, Addison Bain, former manager of the hydrogen program at NASA's Kennedy Space Center, attributed the ignition to the iron oxide/aluminum mixed paint (the same ingredient as thermite) on the *Hindenburg's* hull, based on testimony at the time, video analysis, and analysis of the actual hull. His theory is that the static electricity accumulated during *Hindenburg's* flight did not escape sufficiently at the moment the landing ropes were lowered for landing due to a problem with the connection between the hull and the steel frame, resulting in a potential difference that caused a discharge near the front base of the starboard side tail fin, which ignited the hull and caused it to catch fire.[18] This theory is gaining strength today.

This explosion and the outbreak of World War II ended the era of airships. As aircraft speeds increased and surpassed those of airships, all airships were dismantled by the Nazis and converted to aircraft equipment.[10, 17]

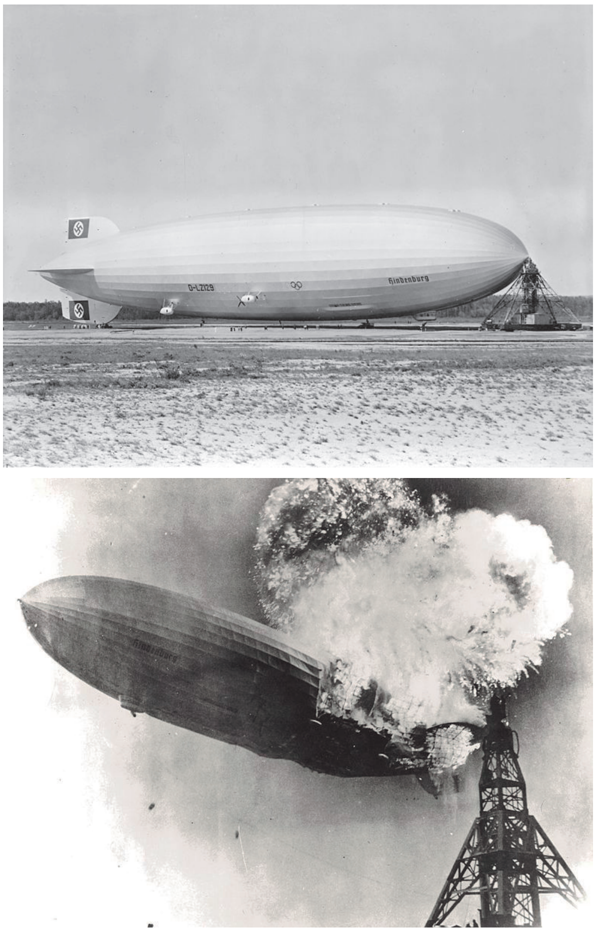


Figure. 4.10 The *Hindenburg* with Olympic Logo on Side of Fuselage and the Explosion Disaster[18]

4.1.6 British and French Responses to Duralumin

Wilm's research results were published as a paper in *Metallurgie* in 1911. The age-hardening curve published in that paper is shown in Figure 4.2 above. When Duralumin research was announced, Wilm's paper was presented in the same year by Le Chatelier in *Revue de Métallurgie*, a French journal of metallurgy, and an abstract of the paper was presented in the following year in the Journal of the Institute of Metals in the U.K.. Unfortunately, no research organization with the support of academia or industry was created in France. In this regard, Professor NISHIMURA Hideo of Kyoto University (1892-1978) wrote in his essay, "*History of Light Alloy (No.6)*" [Japanese: Keigoukin-shi] in *Age of Light Metals* [Keikinzoku Jidai], "Perhaps because Duralumin was born in Germany, there were not many academic publications with much to say on this subject in France until around 1920. The French are by nature ingenious and, although famous for many modern inventions and discoveries, do not like to follow up on what has already been studied in other countries."[19]

In the U.K., W. Rosenhain, head of the Department of Metallurgy of the National Physical Laboratory, and others reported in 1910 that an Al-3%Cu-1%Mn alloy exhibited excellent properties. The composition of Duralumin is close to this alloy, giving rise to the suspicion that the data in this report was utilized to create Duralumin and that Duralumin was not a German invention. In 1913, an article appeared suggesting that Duralumin was an invention of Vickers Company in the U.K., and Wilm immediately responded by writing an article entitled, "Improvement of aluminium and its alloys, and in particular Duralumin, for armaments."[6, 20] In the article, Wilm expressed his thoughts on his invention, including:

1) For the past decade, military authorities in our country have been trying to adopt aluminium because it is extremely light. The German Military Department, however, showed little interest in introducing aluminium. Although expectations often lead to disappointment, aluminium has never lost its luster in the military world, and new experiments are being made with tireless enthusiasm.
2) Improving small arms and increasing the rate of fire naturally raises the issue of reducing the weight of ammunition. Very importantly, the presence of Duralumin will be useful for our Prussian War Ministry.
3) Our military officials announced the conditions that aluminium should fulfill in its contribution to armaments, and our domestic industry started to solve the problem.
4) German arms and ammunition factories in Berlin and Karlsruhe worked primarily through the *Zentralstelle für wissenschaftlich-technische Untersuchungen* (Center for Scientific and Technical Research) in Neubabelsberg, near Berlin. In 1902, I took a formal position at this laboratory to study the improvement of mechanical properties as well as the improvement of corrosion resistance of aluminium in air.
5) Hence, the discovery of Duralumin was the result of many years of research done in Germany. It succeeded in 1906 by combining the addition of other metals to aluminum with a heat treatment that gave it the necessary strength and hardness to be usable as a shell casing.
6) In Germany, Duralumin has been manufactured in the Düren iron foundry for the past several years. The foundry has exclusive rights to manufacture and sell the product in Germany.

The controversy concerning the Anglo-German battle for the vanguard position of the Duralumin invention has continued since then. Note that, in the first edition of his book, "An introduction to the study of physical metallurgy" (D. Van Nostrand Co) published in 1914, Rosenhain himself describes, while citing Wilm's paper, a "strange phenomenon" in which the addition of 0.5% Mg to Al-Cu-Mn gradually increases its strength at room temperature, and so seems to have acknowledged Wilm's achievements.

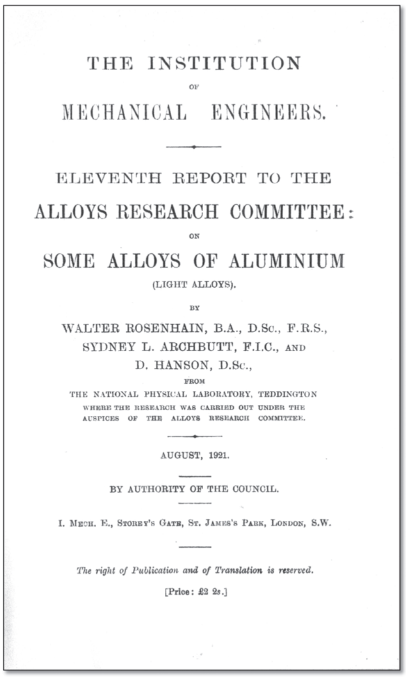
The problem is that Prussia, the key, was unaware of Wilm's outstanding research results, and the British were the first to notice his discoveries and inventions and order the materials. The reason for this was, as Wilm also stated in his rebuttal, that the Prussian War Ministry and War Minister, who prepared the human and material resources necessary for military operations, were often at odds with the General Staff Headquarters, which wanted to rapidly expand the army, and were indifferent to the introduction of aluminum. This seems to have been a problem closely related to the conservative and non-modern nature of the Prussian/German military.[21]

4.2 Development of Super Duralumin Part 1: Situation in the Europe and U.S. Countries

4.2.1 National Physical Laboratory (NPL) in the United Kingdom

Walter Rosenhain (1875-1934, Figure. 4.11[22]), who like Wilm was working on Al-Cu-Mn alloys, was born in Berlin in 1875 and emigrated to Australia at age five. After graduating from the University of Melbourne, he studied under Professor J.A. Ewing at the University of Cambridge. In 1906, he became the first head of the Metallurgy and Metallurgical Chemistry Department at NPL in Teddington, UK, a post he held until 1931, contributing significantly to the development of aluminum alloys. He is especially known as the inventor of the Y alloy, which is a heat-resistant alloy. He died in 1934 at the age of 58.[23, 24] The division he headed achieved significant results from 1910 to 1930 and had a major impact on subsequent research in aluminum alloys. Here, we will discuss three alloys that he reported in the August 1921 "Eleventh Report to the Alloys Research Committee on Some Alloys of Aluminium (Light Alloys)" (Figure 4.12) of the Institution of Mechanical Engineers of the United Kingdom and had a major influence on subsequent research.[25] This report summarized the results of NPL's research during and after World War I.

Figure 4.11 Rosenhain of the National Physical Laboratory (NPL), United Kingdom[22] (courtesy of NPL)



THE INSTITUTION
OF
MECHANICAL ENGINEERS.

ELEVENTH REPORT TO THE
ALLOYS RESEARCH COMMITTEE:
ON
SOME ALLOYS OF ALUMINIUM
(LIGHT ALLOYS).
BY
WALTER ROSENHAIN, B.A., D.Sc., F.R.S.,
SYDNEY L. ARCHBUTT, F.I.C., AND
D. HANSON, D.Sc.,
FROM
THE NATIONAL PHYSICAL LABORATORY, TEDDINGTON
WHERE THE RESEARCH WAS CARRIED OUT UNDER THE
AUSPICES OF THE ALLOYS RESEARCH COMMITTEE.

AUGUST, 1921.

BY AUTHORITY OF THE COUNCIL.

I. MECH. E., STOREY'S GATE, ST. JAMES'S PARK, LONDON, S.W.

The right of Publication and of Translation is reserved.
[Price: £2 2*s*.]

Figure 4.12 Front Cover of "Eleventh Report to the Alloys Research Committee on Some Alloys of Aluminium"[25]

(1) E Alloy

In Rosenhain's aforementioned publication "An introduction to the study of physical metallurgy" 1st edition, (D. Van Nostrand Co., 1914), there are only a few phase diagrams for Al-Cu and Al-Zn alloys, but the phase diagrams for Al-Zn alloys are quite detailed. This is due to the fact that the writing cites a 1911 publication by Rosenhain and S.L. Archbutt in J. Inst. Metals.[26, 27] Later, during and after World War I, Rosenhain focused his research on Al-Cu-Zn alloys with Mg and Mn additions, which he reported in his "Eleventh Report to the Alloys Research Committee on Some Alloys of Aluminium" described above.[25] The report revealed that the E alloy (Zinc Duralumin) with a composition of Al-20%Zn-2.5%Cu-0.5%Mg-0.5%Mn exhibits high strength. The relationship between alloy composition, manufacturing conditions, and strength based on the data in their report is shown in Table 4.2.[25] Figure 4.13 shows a perforated rolling mill (grooved rolling mill) used at the time for the hot rolling of extruded bars.[25] The E alloy hot-rolled on this perforated rolling mill exhibits a tensile strength of 629 MPa after quenching at 400°C and aging at room temperature for five days. This value is noted as being the highest strength in this report. Alcoa's R.S. Archer wrote in his book that 1 mm (18 gauge) sheets of this alloy had the potential to reach a tensile strength of 87 ksi (600 MPa) and an elongation of 10%, but the alloy of this system had serious weaknesses. First, Archer wrote, the alloy has a high specific gravity, is difficult to manufacture, easily corrodes, and is highly susceptible to intergranular cracking, that is, stress corrosion cracking, when stresses considerably smaller than its tensile strength are continually applied. However, he noted, stress corrosion cracking of this alloy was greatly improved by the addition of Mn.[28]

(2) Y Alloy

The Y alloy was also reported in the Eleventh Report. In the report, the high-temperature strengths of light alloys are summarized, and the Y alloy is included in the list.[25, 29] The term "Y alloy" is taken directly from the letter attached to the sample number and has no particular meaning. The composi-

Table 4.2 Strength Properties of Al-Zn Alloys
(from the Eleventh Report to the Alloys Research Committee on Some Alloys of Aluminium)[25]

Alloy	No.	Zn	Cu	Mg	Mn	Extruded Bar	Rolling	Aging Conditions	YS(MPa)	TS(MPa)	E(%)
Al-Zn-Cu based	W188	25	3			1.25″	Extruded as is		352	448	16.0
	W236	12	4			1.5″	Hot-rolled→0.875″ (*)		108	292	22.0
	W235	15	4			1.5″	Same as above		257	374	17.0
	W240	20	4			1.5″	Same as above		318	426	14.0
Al-Zn-Cu-Mg based	W191	15	3	0.25		1.25″	Extruded as is		329	432	17.0
	W193	13	2.5	0.5		1.25″	Same as above		263	395	19.0
	W191	15	3	0.25		1.25″	Same as above	Aged after quenching at 450°C	335	482	22.0
	W193	13	2.5	0.5		1.25″	Same as above	Aged after quenching at 450°C	286	442	22.0
Al-Zn-Mg based	W194	15		0.5		1.5″	Hot-rolled→0.875″ (*)		287	377	25.0
	W194	15		0.5		1.5″	Same as above	Aged after quenching at 500°C	215	377	28.0
Al-Zn-Cu-Mn based	W241	20	2.5		0.5	1.5″	Hot-rolled→0.875″ (*)		329	419	16.0
	W241	20	2.5		0.5	1.5″	Same as above	Aged after quenching at 350°C	210	426	21.0
Al-Zn-Cu-Mn-Mg based (E alloy)	W242	20	2.5	0.5	0.5	1.5″	Hot-rolled→0.875″ (*)		366	459	15.0
	W242	20	2.5	0.5	0.5	1.5″	Same as above	Aged 1.5 hours after quenching at 350°C	259	459	20.0
	W242	20	2.5	0.5	0.5	1.5″	Same as above	Aged 5 days after quenching at 350°C	508	584	12.0
	W242	20	2.5	0.5	0.5	1.5″	Same as above	Aged 5 days after quenching at 400°C	334	629	9.0

(*) Rod rolling mill (grooved rolling mill) was used for the hot rolling of extruded bars.

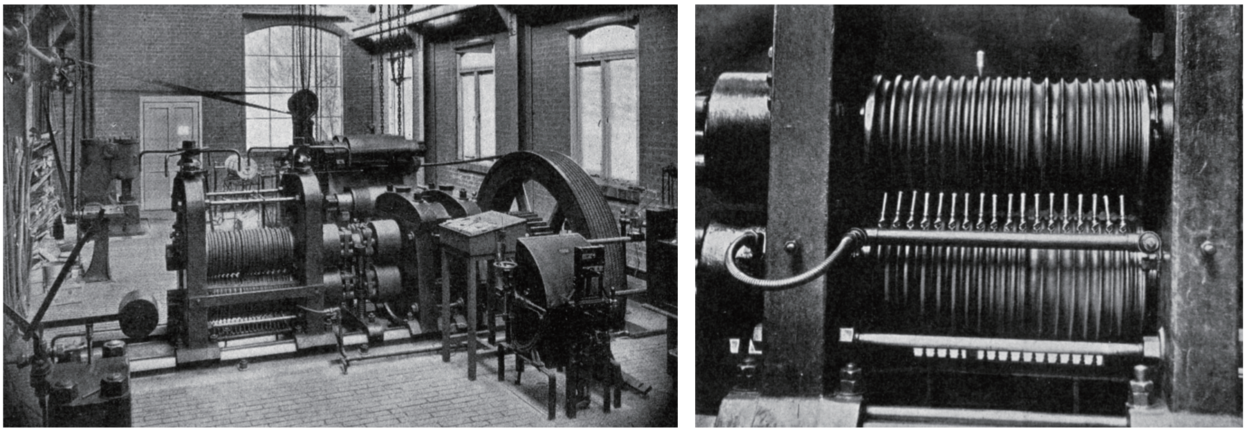


Figure 4.13 Rod Rolling Mill (Grooved Rolling Mill) Used at NPL; Preheating Rolls with Gas Burner (Right)[25]

tion of this alloy is Al-4%Cu-1.5%Mg-2%Ni. It is interesting to note that 1.5% magnesium is added to this alloy as with 24S, which will be discussed below.

The room temperature strength and elongation of material cast in a mold and quenched from 480°C and aged at room temperature for four days were 374 MPa and 24%, respectively, while 433 MPa and 15 to 18%, respectively for rolled material.[25] Alcoa also tested this alloy and found that the tensile strength and elongation were 427 MPa and 23%, respectively, after heating the forgings at 520°C for 24 hours and aging for one week, and 448 MPa and 18% , respectively, after aging at 150°C for 16 hours.[28] With the high-temperature strength of this series of alloys at 260 to 370°C being superior to that of Duralumin and 14S Super Duralumin (described later), Rolls-Royce in the U.K. put it into practical use for pistons as RR56 (Al-2%Cu-0.8%Mg-1.3%Ni-1.3%Fe-0.65%Si-0.08%-Ti-0.08%Ti). The machinability was excellent, but the forgeability was inferior, resulting in poor productivity.[28] Subsequently, High Duty Alloys, Ltd. manufactured forgings and plates as Super Duralumin.

(3) Al-Mg-Si Based Alloys

D. Hansen and Marie L.V. Gayler of NPL created a phase diagram of the Al-Mg_2Si quasi-binary system, showing that Mg_2Si is solid-soluble in aluminum, but the degree of solid solubility also decreases significantly from high to low temperatures, as reported in the Eleventh Report.[25, 30, 31] In 1922, Gayler clarified the phase diagram of a quasi-ternary alloy of Al-$CuAl_2$-Mg_2Si and thought that the precipitation hardening of both $CuAl_2$ and Mg_2Si contributed to the hardening of Duralumin.[32] Furthermore, in 1923, he studied the Al-Cu-Mg ternary alloy phase diagram and reported that $CuAl_2$, Al_6Mg_4Cu, and Al_3Mg_2 were in equilibrium with an aluminum solid solution.[33] Al_6Mg_4Cu had already been discovered by Z. Vogel in Germany in 1919,[34] but Gayler reconfirmed this discovery.[2]

Note that the research on the Al-Mg_2Si quasi-binary phase diagram and the aging of aluminum alloys containing Mg_2Si was conducted and published in the U.K., but it was the Swiss company Giulini that attempted to put the research to use in practical alloys, and in 1916 Giulini already obtained a patent (Swiss Patents No. 85606) for an alloy strengthened by precipitation by quenching and tempering under the name Aludur.[2]

Aludur 533: Al-1.3%Si-0.7%Mg-0.4%Fe

After sand casting heat treatment: Tensile strength 250 to 350 MPa, elongation 8 to 18%[36, 37]

Later, a patent was granted to AIAG of Switzerland for an alloy named Aldrey, an aluminum alloy with high electrical conductivity. Aldrey further improves in strength and exhibits high conductivity when tempered after quenching and wire drawing, and was therefore used for power transmission lines.[31]

Aldrey: Al-0.55%Si-0.43%Mg

After heat treatment: Tensile strength 300 to 340 MPa, yield strength 260 to 300 MPa, elongation 7 to 9%[36, 37]

4.2.2 Dürener Metallwerke A.G. and Goldschmidt A.G. in Germany

(1) Dürener Metallwerke A.G.'s Super Duralumin

K.L. Meissner, chief engineer at Dürener Metallwerke A.G. in Germany, also gave a presentation at the Institute of Metals in the U.K. in 1930, and published the papers "The Effect of Artificial Ageing upon the Resistance of Super-Duralumin to Corrosion by Sea-Water" and "The Artificial Ageing of Duralumin and Super-Duralumin" in British Journal of the Institute of Metals.[38, 39] This is the first time Super Duralumin appeared in a paper.[40, 41] Meissner's Super Duralumin is an alloy of 4% Cu, 0.5% Mg, 0.8% Si, 0.5% Mn, and the remainder Al, and contains a large amount of silicon compared with Duralumin. The tensile strength of a sheet of this alloy after quenching and tempering is close to 490 MPa. Meissner probably chose these compositions because, under the influence of Gaylor and others at NPL, he believed that the combination of $CuAl_2$ and Mg_2Si precipitation would result in age-hardening. Based on this basic research, Dürener Metallwerke A.G. developed Super Duralumin alloys called Super Duralumin 681ZB (Al-4.2%Cu-0.9%Mg-0.6%Mn-0.5%Si) and DM31 (Al-4.2%Cu-1.2%Mg-1.2%Mn-0.5%Si) having a strength improved by 10%.[42, 43] Professor Nishimura stated that if the goal had been to target an alloy that aged at room temperature, the research might have advanced in a different direction.[40]

(2) Sander's Alloy of Goldschmidt A.G.

W. Sander of the metallurgical laboratory of Th. Goldschmidt A.G. in Essen, Germany, jointly with Meissner, published phase diagrams and the mechanical properties of Al-Mg-Si-Zn alloys in 1923 and 1924.[44, 45] Although the state diagram of the Al-Zn-Mg alloys had already been published by G. Eger in 1913,[46, 47] Sander and Meissner reexamined this ternary state diagram and found that Al-$MgZn_2$ forms a pseudobinary alloy and the solubility decreases with temperature, changing from a maximum solid solubility of 28% at 475°C to 4 to 5% at room temperature. Sander and Meissner then made aluminum alloys containing 4 to 10% $MgZn_2$ and investigated their room temperature aging properties. Table 4.3 shows the room temperature aging properties of, among these alloys, the Al-8%Zn-1.5%Mg-0.2%Si alloy.[45, 48]

Table 4.3 Quenching Temperature and Room Temperature Aging Properties of Al-Zn-Mg Based Alloys[45, 48]

Component %				Quenching Temperature	As Quenched		After Aging 5 Days	
Al	Zn	Mg	Si	°C	Tensile Strength MPa	Elongation %	Tensile Strength MPa	Elongation %
90.3	8	1.5	0.2	150	234	4.2	234	4.2
				300	237	15.2	419	12.3
				450	216	18.1	413	13.4
				520	241	20.5	424	15.1

This alloy was later found to be even stronger with the addition of Mn and artificial aging, resulting in the development of Constructal 8 (Al-7%Zn-2.5%Mg-1%Mn-0.2%Si).[2] Its tensile properties include a tensile strength of 590 MPa and an elongation of 9 to 10%.[48, 49]

Professor Nishimura of Kyoto University wrote, "In 1927, as an experiment for his graduation thesis, NISHIHARA Kiyokado investigated the solid solubility of $MgZn_2$ in aluminum and also examined age hardening. When a depression was made in a hardened sample using a Brinell hardness tester, cracks appeared in the surrounding area immediately, in severe cases, or after a certain period of time, and so-called season cracking was observed, resulting in the conclusion that this alloy could not be used. The same phenomenon most likely was observed with Constructal 8 as well. Constructal 8 ended up not being used."[48]

4.2.3 U.S. Bureau of Standards

The U.S. government also supported the research and development of alloys and, in 1913, the U.S. Bureau of Standards organized a nonferrous metals research group headed by P.D. Merica and staffed by metallurgical experts. Merica had just received his degree from the University of Berlin.[6] He gave a presentation on Duralumin at a meeting of the American Institute of Mining and Metallurgy (AIME) in 1919, which was also published in the Transactions of AIME in 1921.[50, 51] The contents of the presentation are cited from Professor Nishimura's "*Essay on the History of Light Alloys (No. 3)*".[52] Merica et al. made 0.8-mm sheets from 16 samples containing 0.04 to 3.74% Cu and 0 to 3.5% Mg by casting, hot rolling, cold rolling, and annealing, which were then heat treated for tensile testing and hardness measurement. The sheets were quenched from 478 to 525°C and aged at 20°C and 100°C. The compositions of the alloy having the highest strength were Cu 3.18%, Mg 0.46%, Fe 0.34%, and Si 0.24%. The tensile strength was 340 to 350 MPa, lower than that of Duralumin, but this was thought to be due to the low Cu content and lack of Mn. Another alloy of 3.74% Cu, 1.08% Mg, 0.52% Fe, and 0.3% Si was quenched from 515°C and aged at 125°C for 14 days to obtain a tensile strength of 440 MPa and an elongation of 11%. These compositions were close to those of Super Duralumin that was subsequently developed, and materials beyond Duralumin were already being suggested.

4.3 Development of Super Duralumin Part 2: Alloy Development by Alcoa

4.3.1 Alcoa's Central Research Laboratories Established with Absorption of Lynite Laboratories

The U.S. Navy showed unusual interest in the development of German rigid airships at the outbreak of World War I, prompting Alcoa to develop and produce high strength materials. Prior to World War I, Alcoa focused on the research and development of primary aluminum production processes, so did not have the technology to develop or mass produce revolutionary fabricated products. In addition, Hall, one of the founders of Alcoa, had rejected the idea of creating a central research laboratories, and thus the experimental facilities necessary for materials research were either nonexistent or primitive, and there were no staff available to conduct experiments.[53]

After Hall's death in 1914, there was a need to develop new aluminum markets for the primary aluminum produced. This led to the decision to establish a central research laboratories that promoted a systematic research plan, and the Technical Department was established in 1919.[54] As a result, Alcoa acquired ACC's (Aluminum Casting Company's) Lynite Laboratories, which at the time had the finest nonferrous metal researchers and engineers in the United States. Zay Jeffries (see Figure 4.14 and Column),[55, 56] the director of Lynite Laboratories, believed that it was necessary to systematize and document the knowledge and know-how gained from research and to write down the metallurgical processes accurately so that engineers could carry out reproduction just by viewing the documentation.[54] In 1920, Lynite Laboratories was merged with Alcoa's Technical Department. In 1930, the Technical Department was integrated into ARL (Aluminum Research Laboratories, renamed Alcoa Research Laboratories in the 1950s), which was established in New Kensington.[54]

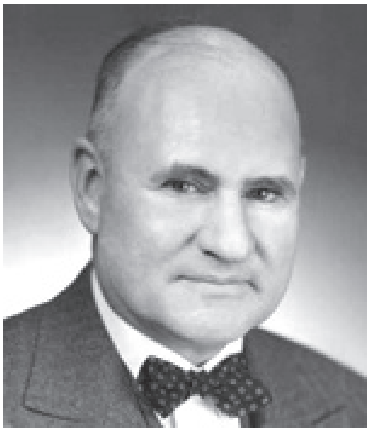


Figure 4.14 Z. Jeffries (1888-1965)[56]

4.3.2 Production of Duralumin Equivalent Alloy 17S

In 1916, Alcoa received a request by the U.S. Navy for an alloy of equal or higher strength than that used by Germany, and was conducting tests with Al-Zn alloy bars, which had been used in the early days of the Zeppelin airships. Around the same time, Commander Jerome Hunsaker of the Navy sent pieces of the framework of a Zeppelin airship that crashed in France to the National Bureau of Standards (NBS) and Alcoa. The pieces were sent to NBS because of the Navy's systematic collaboration on Duralumin. As a result of the examination, the material was found to be a thin sheet with Cu, Mg, and Mn additions.[54]

In 1917, the United States declared war on Germany and, because of the need to be able to produce high strength alloys domestically, the Navy provided Alcoa with Wilm's patents and technical information on how to manufacture high strength alloys. It also authorized the use of Wilm's patents related to Duralumin.[54] This use was limited to the war period, but according to R.E. Sander, Jr. of Alcoa, Alcoa obtained the right to use the patents even after World War I.[57]

Column: Zay Jeffries

Zay Jeffries (1888-1965) was born in South Dakota in 1888. After graduating in mechanical engineering from the South Dakota School of Mines in 1909, he was hired as a metallurgy instructor at the Case Institute of Technology in Cleveland (now Case Western Reserve University). He then became a consultant on new technologies in Cleveland and worked at GE's tungsten lamp operation and ACC in aluminum casting. He received his degree from Harvard University in 1918. He became a consultant to Alcoa in 1920 and developed Alcoa's aluminum alloy research in casting and forging in the 1920s. He later served on many government committees and became Vice President of GE in 1945. In Japan, his name is well known by the Jeffries Award of the Japan Institute of Metals. In 1951, the Japan Institute of Metals nominated him as an honorary member in recognition of his achievements and his efforts in promoting exchange between Japan and the United States. The institute, which received a $100 donation on that occasion, began to offer the Jeffries Award in 1954, using this donation as prize money to solicit prize-winning papers from up-and-coming researchers and engineers with a focus on scholarship. Today, with no medals left, the Jeffries Award is no longer awarded. (KIMRA Takashi. "*Remembering Dr. Jeffreys's Ambition*" *Bulletin of the Japan Institute of Metals*, 25 (1986): 782).

https://www.encyclopedia.com/science/dictionaries-thesauruses-pictures-and-press-releases/jeffries-zay

However, Alcoa had no knowledge of rolling, heat treatment, or sheet forming technology for high strength alloy materials at that time, so had difficulty in carrying out rolling that produced the prescribed flatness, smoothness, and uniform thickness, but the newly gained knowledge led to Alcoa's subsequent development. In such rolling technology, the United States was completely behind Germany. In addition, for material heat treatment and age hardening mechanisms, Alcoa received the support of NBS, including Merica. For Alcoa, to make it possible for the company to develop and manufacture high strength materials on its own in the future, the establishment of central research laboratories was an urgent issue.

Through trial and error, Alcoa was able to roll and produce the Duralumin equivalent alloy 17S (Cu 4.0%, Mg 0.5%, Mn 0.5%) having a tensile strength of 425 MPa, a yield strength of 275 MPa, and an elongation of 22%. Meanwhile, Alcoa was obligated to supply 17S rolled material for the *Shenandoah*, an airship to be built by the Navy. By the end of 1922, Alcoa could produce 25,000 tons of high strength alloy sheets yearly, and 17S (Note 4) became the mainstay.[53]

In the fall of 1923, the *Shenandoah* flew over the New Kensington plant in celebration of Alcoa. However, in 1925, the airship broke into three pieces and crashed in a storm, killing 14 people (Figure 4.15[58]). Upon receiving this information, Alcoa immediately went to the accident site to confirm whether the airship accident was caused by the metal, and checked the wreckage, confirming that all points of destruction were clean and free of corrosion. In response, the National Bureau of Standards and MIT professors raised suspicions of intergranular corrosion, and Alcoa's testing department developed high-performance testing equipment ahead of its peers to clear its name.[53, 54]

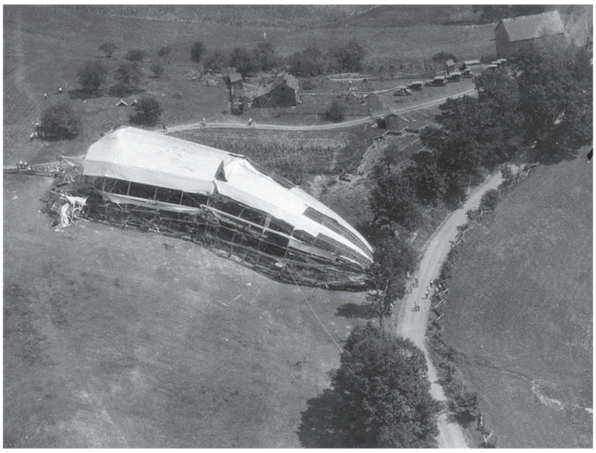


Figure 4.15 Wreckage of the *Shenandoah* Next to Wheat Field in Caldwell County, Ohio, on September 3, 1925[58] (of the 11 officers and 31 passengers on board, 14 were killed and two injured)

In 1927, a transatlantic crossing was made by C.A. Lindbergh's *Spirit of St. Louis* (Figure 4.16). The plane used Alcoa skin material and Alcoa castings for the engine. This marked the beginning of an era in which all-aluminum aircraft played a leading role, and Alcoa established a firm position as the main supplier of aircraft materials.[54]

To further improve corrosion resistance, a clad material was developed by Edgar H. Dix, Jr. of Alcoa, which consists of 17S sheet material with high-purity aluminum adhered to the surface at 2.2 to 10% of the sheet thickness. The material was put into practical use in 1928 and called Alclad.[28, 60] Figure 4.17 shows a cross section of the Alclad material developed by Dix et al.[28] It can be seen that a diffusion layer is formed and bonded between the pure aluminum of the skin material and the core material.

(Note 4) 17S, 14S, and 24S are Alcoa alloy names, which were standardized after the World War II and are now referred to as 2017, 2014, and 2024, respectively, in international standards.

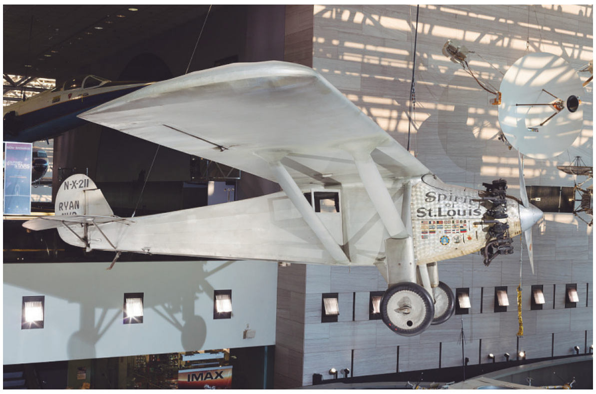


Figure 4.16 Lindbergh and the *Spirit of St. Louis* (Smithsonian National Air and Space Museum[59])

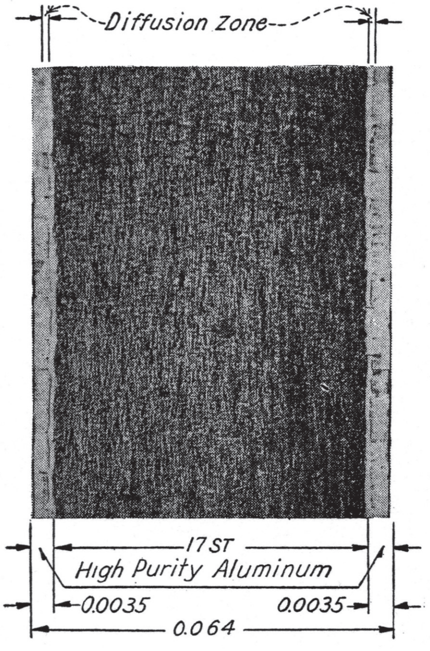


Figure 4.17 17S Clad Material (Alclad 17S)[28]

4.3.3 Alloy Development of Silicon-Containing Super Duralumin 14S

Alcoa's absorption of Lynite Laboratories gave birth to new alloys. The first achievement was the development of 25S, 51S, and 14S alloys by Archer and Jeffries from Lynite Laboratories. All of these alloys were developed between 1919 and 1920, with patent applications filed in December 1921 and patents granted in October 1923.[28]

25S is an Al-4.4%Cu-0.8%Si-0.75%Mn alloy and was produced as a forging alloy in 1921. Compared with Duralumin, it is superior in hot workability due to the absence of Mg. This is why it was used for aircraft propellers and connecting rods. Furthermore, a characteristic of this alloy was that, after quenching, it did not exhibit room temperature age hardening, but hardened by high temperature aging to obtain strength equivalent to that of Duralumin.[28] The propeller of the Zero fighter was also manufactured with this alloy. 51S is an Al-1.0%Si-0.6%Mg alloy with favorable hot and cold workability and can be forged, extruded, and formed into tubes, etc. The alloy was commercialized in 1921 and used for various applications. 25S and 51S are accompanied by intergranular precipitation after aging at high temperatures in thin sheets, so caution was required for use in severe corrosive environments.[28]

14S is an Al-4.4%Cu-0.4%Mg-0.9%Si-0.8%Mn alloy, which achieves higher strength than Duralumin with the addition of 0.5% or more of Si to Duralumin and aging at high temperature. In 1925, Archer and Jeffries submitted a paper to the American Institute of Mining Engineers (AIME) on the age-hardening of Si-added Duralumin. According to NISHIMURA Hideo, a professor at Kyoto University (1892-1978), the name Super Duralumin was first coined in 1927 at a meeting of the American Society of Mechanical Engineers (ASME) in Cleveland, when Jeffries produced a strong aluminum alloy with a tensile strength of 370 to 430 MPa and announced it as Super Duralumin.[40]

Alcoa commercialized 14S in 1928. With quenching and tempering, a tensile strength of 485 MPa and a yield strength of 415 MPa was achieved, but because of a low elongation of 13%, the material was used more in forgings than as sheets.[61] At that time, Super Duralumin with high Si content was called silicon-containing Super Duralumin.[2] Today, this alloy is rarely referred to as Super Duralumin, but rather “the other Super Duralumin.”

4.3.4 Alloy Development of 24S Super Duralumin Using High-Purity Primary Aluminum

In contrast to 14S, 24S (Cu 4.5%, Mg 1.5%, Mn 0.6%) was developed by Alcoa in 1931. The Mg content of Duralumin was increased to 1.5% and thus, while silicon-containing Super Duralumin requires artificial aging, 24S greatly exceeds the strength of Duralumin by room temperature aging alone. This was referred to as 24S Super Duralumin.[2] Today, the term “Super Duralumin” often refers to 24S.

Alloy 24-T3, as representative values, has a typical tensile strength of 485 MPa (49 kg/mm^2), a yield strength of 345 MPa (35 kg/mm^2), and an elongation of 18%, while 17S-T4 has a tensile strength of 430 MPa (44 kg/mm^2), a yield strength of 280 MPa (28 kg/mm^2), and an elongation of 22%, and thus boasts a 23% higher yield strength than 17S (Note 5). Alloys like 14S, which require high-temperature aging to gain strength, have the processing disadvantage that bending is done by room temperature aging, and then high-temperature aging is performed. Alloy 24S, however, has the great advantage that, like 17S, high strength can be obtained by room temperature aging and bending can be done in that state, so it quickly replaced 17S-T4. The cladding material Alclad 24S-T3 is still used as a material for aircraft fuselages, and the first such plane was the DC-3 (Figure 4.18).[62]

Figure 4.18 DC-3 Using Alcoa’s Alclad 24S-T3 for Fuselage Skin[62]

(Note 5) T4 refers to a temper obtained by quenching and then naturally aging, while T3 refers to a temper obtained by quenching and then cold-working, by several percent, a rolled or extruded material to flatten or straighten the material or minimize residual stress; yield strength increases due to the cold working.

While the DC-3 increased passenger capacity by 50% compared to the DC-2, its operating expenses increased by only about 3%. Prior to that time, air passenger transportation in the United States could not cover its necessary costs through passenger fare revenues alone, and managed to receive federal subsidies for mail transportation. However, the DC-3’s capacity allowed it to cover its costs with its own fare revenue alone. The advent of the “profitable airplane with passengers aboard,” which did not need to rely on postal subsidies, was a milestone in the development of air transportation. This is largely due to the development of the 24S alloy. D.D. Eisenhower, the commander-in-chief of the Allied forces in Europe in World War II and later President of the United States, stated that “the Dakota transport (name of the DC-3 military transport aircraft for the British), the Jeep, and the bazooka” contributed significantly to the Allied victory in World War II. Approximately 10,000 Dakotas and C-47 Skytrains (official name of the U.S. military transport aircraft) alone were produced by 1945.

4.3.5 Background of Development of 24S

Production from 17S and 14S to 24S only increased Mg by 1%, but manufacture was more difficult. Advances in melting, casting, and rolling technology were essential to the production of this alloy, according to J.A. Nock, Jr. of Alcoa.[63] Dix also noted that sheet production was very difficult, but rolling at high speeds became possible during World War II.[64] Extrudability was also very poor, but manufacture was being performed using 10 times the pre-World War II production equipment as well. In addition to these technological advances, I believe that Alcoa's invention of three-layer electrolysis in the mid-1920s made it possible to produce relatively pure 99.8% primary aluminum at a lower cost than the standard 99.5% primary aluminum of the time.[65]

(1) Impurities in Duralumin

Duralumin is analyzed by P.L. Teed in his book "Duralumin and Its Heat-Treatment" as Al: 93.94%, Cu: 4.20%, Mg: 0.56%, Mn: 0.69%, Fe: 0.40%, and Si: 0.21%. According to the composition standard for Duralumin in the U.K., the composition is Cu: 3.5 to 4.5%, Mg: 0.4 to 0.7%, Mn: 0.4 to 0.7%, Fe: 0.7% or less, Si: 0.7% or less, Ti: 0.3% or less, and Al: the remainder.[66] According to Japanese Army and Navy aviation material standards, the composition of high-strength aluminum alloy Type 1 (Duralumin equivalent) is Cu: 3.3 to 4.2%, Mg: 0.3 to 0.7%, Mn: 0.3 to 0.7%, Fe: 0.6% or less, and Si: 0.5% or less.[67] In any case, it is clear that the tolerance for impurities is large. The amount of impurities in Duralumin depends on the amount of impurities in the primary aluminum and primary magnesium. As discussed in Section 6.3, increases in iron and silicon decrease strength and elongation. Accordingly, a reduction in impurities was necessary to improve strength and elongation.

(2) Impurities in Primary Aluminum

The purity of primary aluminum depends on the method of smelting. Sainte-Claire Deville of France, the first person in the world to mass produce aluminum, used a sodium reduction method to produce aluminum, and the purity was about 97%.[68] Even with the development of electrolytic smelting using the Hall-Héroult process, it was not possible to achieve a purity of 99.7% or higher (99.85% is common today). Most of the impurities are attributed to the electrolytic bath, alumina, and anode carbon. According to C. Grard's book, "Aluminium and Its Alloys," the French ingot standard in 1921 stated:

Grade I: 99.5%, total of iron and silicon of 0.5% or less.
Grade II: 99.0%, total of iron and silicon of 1.0% or less.
Grade III: 98 to 99%, total of iron and silicon of 2% or less.

The impurities are (a) Fe, Si, (b) carbides, sulfides, Cu, Zn, Sn, Na, N, B, Ti, and (c) alumina, but the problem with alumina was that, when analyzed, it was combined with Al.[69] Standards in the U.S., U.K., and Germany are substantially similar, with slightly different provisions for impurity content.

(3) Progress in Refining Technology

The first high purification process using molten salt was carried out by W. Hoopes, an electrical engineer at Alcoa, in 1900.[68] Hoopes' proposal was to use a three-layered liquid refining bath, with molten aluminum floating as a cathode above a heavier electrolytic bath, and a heavier molten alloy placed as an anode below the electrolytic bath. Around 1919, Hoopes worked with Alcoa's research team to perfect an industrial production method. Figure 4.19 shows a three-layer electrorefining furnace.[70] The electrolytic bath consists of cryolite, aluminum fluoride, barium fluoride, sodium fluoride, and alumina. For pure aluminum to float in the electrolytic bath at 1000°C, 80% cryolite and 20% barium fluoride are required. The average purity thus obtained is 99.8% or higher. In fact, many of the metals were 99.90%, and several yielded 99.99% purity. Hoopes died in January 1924.

Many of the patents applied for by Hoopes were granted in 1925.[67] It is thought that the influence of impurities on the mechanical properties of Duralumin 17S became apparent at this time when high-purity primary aluminum became industrially available.

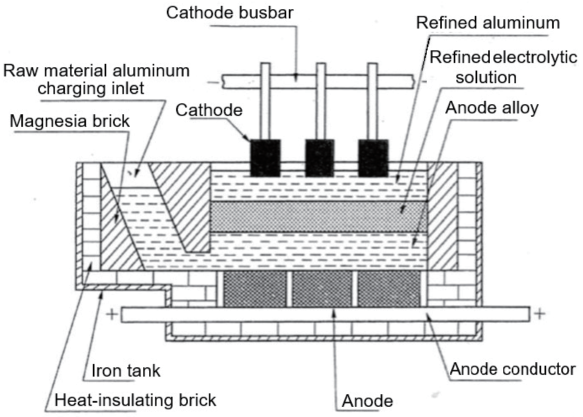


Figure 4.19 Structure of Three-Layer Electrorefining Furnace.[70]

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5 Production of Aluminum Materials in Japan

5.1 Start of Primary Aluminum Production in Japan[1-4]

In the year following Hall's and Héroult's invention of the electrolytic refining process for aluminum in 1886, a small amount of primary aluminum was imported to the Army Artillery Arsenal and apparently stored in a safe as a valuable item. It was not until 1894 that aluminum was used for military equipment. The Army decided to use aluminum for mess kits, canteens, and other portable military equipment, imported primary aluminum, and began production at the Tokyo and Osaka Artillery Arsenals. Sumitomo Copper Rolling Works was established in Ajigawa in 1897, and the following year received primary aluminum from the Army Artillery Arsenal and rolled aluminum for delivery.

At this time, aluminum was first called "*banso* (alum)," a name given by the Army. The name did not go over well, however, so a new name was invented, "*keigin* (light silver)," reflecting its silver-like aesthetic quality and lighter-than-silver weight.[5] In the 1890s, aluminum fixtures began to be manufactured in the private sector, and imported primary aluminum increased from 100 tons in 1900 to about 1,000 tons in 1912. The start of World War I interrupted the import of primary aluminum from Europe, but Northern Aluminum Company entered the Japanese market in the intervening years, bringing the Japanese market under Alcan's control. In 1920, the consumption of primary aluminum increased to 2,000 tons due to an increase in domestic demand as well as an increase in the export of goods to Southeast Asia, where imports from Europe had become difficult due to the world war.[6]

In July 1913, Sumitomo Copper Works (renamed from Copper Rolling Works to Copper Works in June of the same year) invited SUGIURA Shigezo, an engineer of the Ministry of Agriculture and Commerce who was engaged in the analysis and testing of metal products, to join its testing division. In 1916, Sugiura proposed that "unless we conduct our own research and development, we will always be subordinate to foreign countries," and that "if research is conducted exclusively at a factory, we can conduct factory-scale research that is not possible at government-run laboratories," and a Research Division was established. This was the first time that a research division was established in a factory in Japan.[2]

At the end of 1916, a part of the framework of the Zeppelin shown in Figure 5.1 was brought to Sumitomo Copper Works via the Imperial Japanese Naval Ship Administration Headquarters and the Chief Superintendent of the Osaka Navy, and Sugiura of the Research Division investigated this material the following year. Based on the results of the analysis and the literature in the Journal of the Institute of Metals (JIM) in the United Kingdom, he started trial production research at the plant, which was completed in 1919. The product was named "*Sumitomo Keigin* (Sumitomo Light Silver)," but with the phonetic guide above the Japanese characters indicating the pronunciation "Duralumin." The composition of this Duralumin is 4% Cu, 0.5% Mg, 1.0% Mn, and remainder Al. Although it is not clear how the Navy requested Sumitomo Copper Works to conduct this research, Sugiura stated at a roundtable discussion on light metal materials for aircraft after the war, "There were few research institutes on metals at that time, and Sumitomo Copper Works may have had an independent research department specializing in metals."[7]

Figure 5.1 Part of Framework from Zeppelin Airship Shot Down in the United Kingdom and Stored at UACJ

In 1921, Copper Works produced Duralumin industrially for the first time, and received an order from the Yokosuka Naval Arsenal for a total of about one ton of sheets, tubes, bars and rods as structural materials for lifting barges and other structures for the domestic production of SS non-rigid airships designed by the British Vickers Company. The Navy completed the SS No. 1 airship, replacing the wooden gondola of the airship ordered for manufacture by the British Vickers Company with Duralumin in 1921, but two months later it exploded during testing in a hangar. The airship was then produced domestically in 1922 based on blueprints and spare parts. This was called the SS No. 3 airship (Figure 5.2).[8, 9]

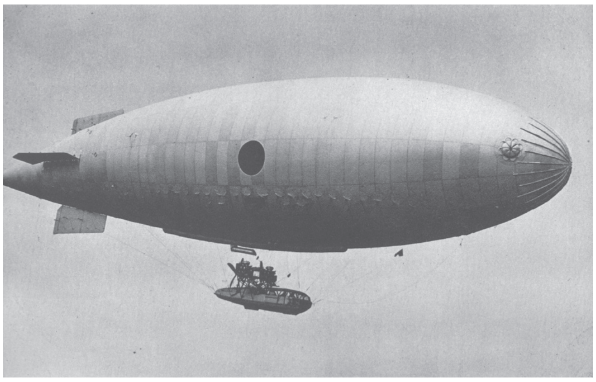


Figure 5.2 SS No. 3 Airship of Imperial Japanese Navy[9]

The airship was later completely refurbished, but exploded in mid-air in 1924, killing five people. This was 13 years before the *Hindenburg* explosion.

Duralumin manufacturing technology at that time was very rudimentary, so the Navy recommended T.W. Pagan to Sumitomo among the engineers invited to help build flying boats. He had studied under Rosenhain at the National Physical Laboratory (NPL) in the U.K. and had a grasp of British aluminum manufacturing technology. From January 1922, Pagan was employed by Sumitomo Copper Works as a contract consultant for eight months, providing guidance in the casting, rolling, extruding, and drawing departments, as well as in corrugated sheet and profile manufacturing methods. This brought about a change from the conventional ingot-making methods of the "flat flow method" (Figure 5.3) and "vertical flow method" to an inclined casting method (Figure 5.4).

The new method produced Duralumin ingots having a thickness of 57 mm (2.25 in) for sheets and a diameter of 89 mm (3.5 in) for rods. Under Pagan's guidance, the company also began to use niter furnaces for quenching.[1]

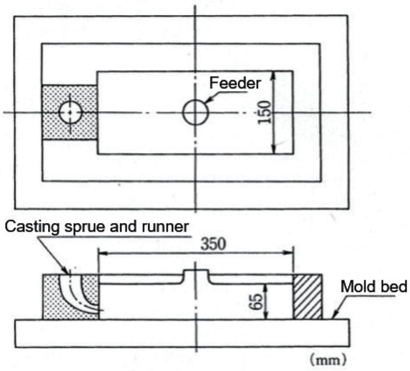


Figure 5.3 Flat Flow Method[1, 2]

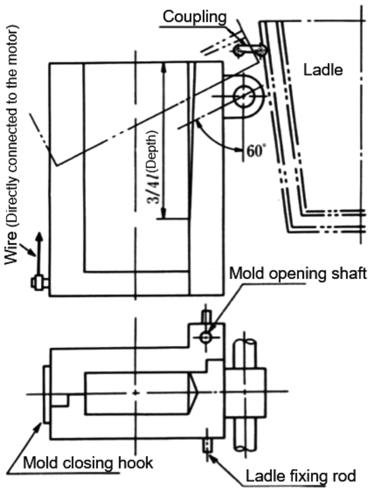


Figure 5.4 Inclined Casting Machines of Sumitomo Copper Works[1, 2]

In April of the same year, Duralumin manufactured by Copper Works was used for the first time in the fuselage structure of a Nakajima-style Breguet airplane (Nakajima B-6 biplane), which was named the "*Keigin* (Light Silver)" (Figure 5.5).[10-12] Duralumin was not fully adopted until after 1930, when the airframe became all-metal.

Figure 5.5 Nakajima Breguet Airplane (1922)[10]

5.2 Duralumin Manufacturing Technology Mastery Group[1-4]

In 1922, after World War I ended, Japan was to receive hundreds of airplanes from Germany as part of its reparations as a victorious nation, but it was recognized that acquiring airplanes would prove to be a temporary gain, and that learning the technology for manufacturing them, such as airframe design and light alloy manufacture, would be a grand plan for the long-term future of the nation. As a result, a Duralumin manufacturing technology mastery group was dispatched. In March 1922, the mastery group was organized under the leadership of Colonel ISHIKAWA Tokiji (see Figure 5.6, Column), with a few members from each of the Army and Navy and four engineers from Sumitomo Copper Works. The group departed on April 20, 1922, arrived in Düren in late July, practiced Duralumin manufacturing technology at Dürener Metallwerke A.G. until mid-September, and then visited factories in Germany and the U.K. before returning home on February 23 of the following year. At Dürener Metallwerke A.G., the group reportedly worked like the company's workers, compiled what they learned each week, checked it against the Duralumin manufacturing method learning manual provided by the company, and asked questions to ensure that they learned the essence of the technology. Duralumin was the result of the company's industrialization of Wilm's patents and, since the company had ceded its patents to Britain, the United States, France, and other countries at the time, it was requested that a paid contract be concluded in Sumitomo's name for the group's technical training. As a result, Army and Navy personnel were also formally trained as Sumitomo representatives. Note that, along with the Duralumin manufacturing technology mastery group, a metal airframe manufacturing technology mastery group also traveled to Germany. Regarding the Duralumin manufacturing technology mastery group, Dr. ISHIKAWA Tokiji, the leader of the group, authored an article titled, "*The Secret Story of Duralumin*" in the *Nihon Keizai Shimbun* newspaper dated March 16, 1958, after the war. In the article, he stated, "The victorious countries took the spoils from Germany on a first-come, first-served basis. The United States, for instance, was quick to secure two Zeppelins and dozens of airplanes. Japan got off to a slow start, and the amount of items received was not much." Dr. Ishikawa stated, "Actually, what we want in Japan is a Zeppelin airship. Even further, we seek the secrets of Duralumin, the material used in the Zeppelin. How do we produce this alloy? How do we spread it thin? How do we bend it? These are the secrets we seek." Dr. Ishikawa had a bitter experience when he studied at the University of Glasgow in the United Kingdom in 1915-1916, where he recovered pieces of Duralumin from a Zeppelin airship shot down at Dover and brought them back to Japan, but could not figure out how to make them. He was able to produce something that was close to the "real thing," but only with much lower performance as a metal. Because of these circumstances, he offered to get the materials to make two Zeppelins. As a result, a contract was finalized for Dürener Metallwerke A.G. to provide drawings and make tubes, sheets, and angles, and the group was sent to the local factory on a fact-finding mission. When the fabrication finally started, Dürener Metallwerke A.G. tried not to show the group the crucial points. In the factory, they were not allowed to get out notebooks and take notes; everything had to be learned by sight. In Japan, they were preparing to produce Duralumin on the same schedule as the factory, and were making the same products. What was learned at the factory was sent by secret telegram to Japan, where production was carried out based on that knowledge.

The group had done a lot of research in advance, but there were some things they did not understand. For example, a Duralumin sheet that was bumpy became flat overnight. When they questioned the chief engineer, he avoided pursuit of the matter by answering, "It extends at night," and so on. More details can be found in the article. There were many stories of hardship, which became the foundation for the subsequent development of manufacturing technology.

Note that, in 1921, Japan also received one Zeppelin airship L37 (LZ75) and one airship hangar as spoils of war, but the airship was left in the hangar for two years because they thought it was impossible to transport it to Japan and it deteriorated. The airship was dismantled onsite and the bow section, tail section, gondola, parts of the hull, air envelopes, instruments, radio, and engines (six) were brought back. On the other hand, the hangar was moved to Kasumigaura and was said to be large enough to hold two Tokyo Stations. This hangar was used by the Imperial Japanese Navy to store airplanes, but was temporarily used as a hangar for the Graf Zeppelin when this airship stopped in Japan in 1929.[8, 13]

Figure 5.6 Dr. ISHIKAWA Tokiji[14]

5.3 Establishment of Duralumin Manufacturing Technology at Sumitomo (Construction of New Sakurajima Plant)[1-4]

In 1923, plans were made to start a new manufacturing facility by combining Pagan's guidance with the technology brought by the Duralumin manufacturing technology mastery group. The manufacturing method was one of melting the ingredients in a pressurized-air tilt-pour furnace, casting 200 mm (8 in.) square ingots in an inclined casting machine, forging this ingot in a 1,000-ton vertical hydraulic machine, and attempting to strip-roll the ingot. However, a discussion of factory relocation ensued, deferring this plan until 1928 when relocation to the new Sakurajima plant was carried out.

Column: Dr. ISHIKAWA Tokiji

ISHIKAWA Tokiji was born in 1879 in Yanagawa, Kyushu. After graduating from Tokyo Imperial University, he worked at the Sasebo Naval Arsenal, during which time he studied in the U.K. In 1919, he was awarded the Imperial Academy Prize for his research on manganese bronze, the material used in marine propellers. Later, in 1930, he retired from the position of Lieutenant General of the Navy and served as the first president of the then Japan Foundry Association (now the Japan Foundry Engineering Society). He then became an advisor to Sumitomo Metal Industries, Ltd. In January 1937, Waseda University invited Dr. ISHIKAWA Tokiji to the university. He became a professor at Waseda University and established the Castings Research Laboratory, becoming its first director. Since casting technology forms the basis for making all metal products, he wanted the Castings Research Laboratory to contribute to the advancement of not only the metal industry in Japan, but also industry in general. Subsequently, he constructed an experimental building for forging, rolling, pressing, extrusion, and other plastic forming processes. In March 1946, the Director resigned. He passed away on June 23, 1964, at the age of 84.

(From the website of Kagami Memorial Research Institute for Materials Science and Technology)

During this period, Sumitomo Steel Tube & Copper Works, Ltd. was established in 1926 as a spin-off from Sumitomo Limited Partnership Company, and a partnership with Alcoa was formed in 1928. Alcoa had been seeking partnerships with Japanese manufacturing companies to expand primary aluminum sales channels and, in 1925, formed an alliance with Sumitomo Electric Wire and Cable Works. This relationship also led to Sumitomo Steel Tube & Copper Works forming a partnership with Alcoa to build a melting furnace and a rolling mill dedicated to aluminum sheets. Note that, in 1925, Alcoa changed the name of its Canadian subsidiary, Northern Aluminum Company, to Aluminum Company of Canada, Ltd. (Alcan) and, in May 1928, spun off the company as the Canadian company Aluminium Limited (Alcan), which was mainly engaged in overseas business. In 1930, Aluminium Sumitomo Limited (now Toyo Aluminium) was established as a joint venture with Aluminium Limited based on a sheet plant in Sakurajima and a foil plant in Yao.

With the relocation to Sakurajima, the company expanded its facilities and adopted new technologies for large forgings such as propeller blade materials and crankshafts, profiles made by the bending of thin sheets and die drawing, and casting, rolling, extrusion, and drawing. The profiles used for the frames of airships and other vessels at that time were made by bending Duralumin sheets and then drawing them several times with a die. When it came to mass production, the method was replaced by roll forming. Profiles from sheets were used because the minimum wall thickness for extruded profiles was limited to 3 mm. The profiles were about 0.4 to 0.6 mm in thickness and 4 to 5 m in length. Around 1939, the minimum extruded wall thickness was 1.2 mm. Thinner material was made by finishing the material by rolling and drawing.

5.3.1 Casting Technology

The new Sakurajima plant had four tilting furnaces and 48 crucible furnaces. Initially, an 80 kg square ingot and a 40 kg ingot with a diameter of 140 mm were cast by the inclined casting method, but, in 1931, 280 to 330 mm (11 to 13 in.) square ingots (110 to 120 kg) were cast for forging material, and 30 kg, 150 mm diameter ingots or 50 kg, 230 mm (9 in.) diameter ingots were cast for tubes, and the process moved successively to larger sizes. As shown in Figure 5.7, the molds were also improved from the Dürener Metallwerke A.G. method (left) of passing molten metal poured through the opening of the mold through a wire mesh and gradually introducing the molten metal into the mold from the bottom, to the method of providing a wire mesh opening on one side of the mold in advance (right). In both cases, wire mesh is used as a filter. As for the melting furnace, a 9-ton reverberatory furnace was adopted for the first time as a result of discussions with Aluminum Limited.

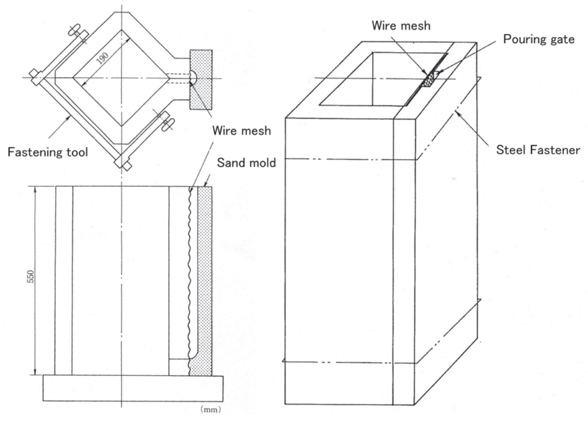


Figure 5.7 Molds of Dürener Metallwerke A.G. Method (Left) and Improved Method (Right)[1, 2]

As shown in Figure 5.8, four rows of inclined casting machines, 16 in total, were placed in front of the reverberatory furnace. Casting began at 8:30 in the morning and ended at 3:30 in the afternoon, the furnace was then cleaned, and 11 tons were melted at night - a one melting per day method. The mold is a book mold. The casting method is one of pouring molten metal from a reverberatory furnace into a ladle and starting casting into a mold inclined at a 60-degree angle, and then gradually rotating the mold until it becomes vertical and the casting is completed. At that time, the ingot dimensions for sheets were 110 x 280 x 610 mm (4.5 x 11 x 24 in.) (about 53 kg).

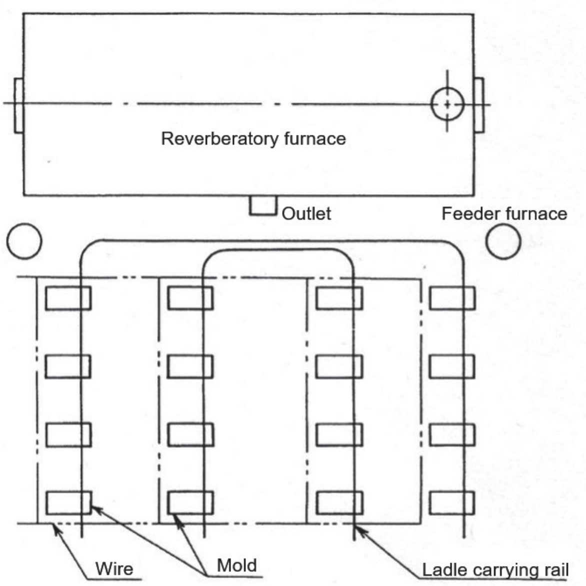


Figure 5.8 Arrangement of Reverberatory Furnace and Inclined Casting Machine[1, 2]

In 1928, the forging of propeller blade material began, creating the need for large castings. The propeller blade forging ingot was bucket-shaped, with an upper diameter of 330 mm, a lower diameter of 305 mm, a height of 483 mm, and a weight of 110 kg around 1931, which gradually increased to an upper diameter of 600 mm, a height of 800 mm, and weight of a 500 kg around 1942. The material was 25S (Al-4.5%Cu-0.8%Si-0.8%Mn).

From 1931 to 1940, the mold was heated with charcoal, poured from a reverberatory furnace, and placed in an empty tank. The lower part of the mold was cooled by spraying water from the surrounding area, and the water was successively transferred to the upper part of the mold for solidification. This was called the water-cooled casting method. The problem is that giant intermetallic compounds tend to form in the center of an ingot. To improve this, a heated water-cooled casting method (SKS-II method, SKS stands for *Sumitomo Kinzoku Shindosho*) was developed, as shown in Figure 5.9. An iron ladle filled with molten metal is gradually lowered into a wooden water tank to cool, and the cooling rate is controlled by a gas burner and water spray until the ladle enters the water tank.

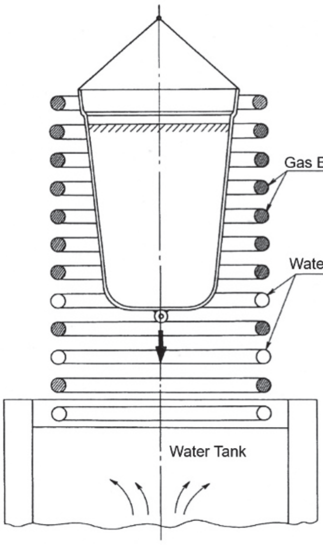


Figure 5.9 Heated and Water-Cooled Casting Method (SKS-II Type)[1, 2]

5.3.2 Rolling Technology

The main equipment of the sheet rolling plant included one three-high hot rolling mill, 10 large two-high rolling mills, 12 small two-high rolling mills, one sheet tension straightening machine, and 10 coal furnaces. The new equipment included a Krupp three-high hot rolling mill capable of rolling up to a width of 1,220 mm (4 ft.), a Robertson (United Kingdom) small-width rolling mill, and a coal furnace manufactured based on a patent purchased from Rockwell. The three-high hot rolling mill (Figure 3.10) features a higher efficiency than the two-high hot rolling mill because it does not require reverse roll rotation. All ingots were made by the inclined casting method, and the ingots used were from 60 kg to 80 kg around 1931 to 1932, then to 70 and 90 kg with round ingot ends, and finally to 120 kg around 1939.

In the case of Duralumin, the hot rolling process consists of homogenization at 500°C for 8 hours, rolling a 120-mm thick ingot to 75 mm at 440°C, followed by face cutting, reheating, and hot rolling to 6.4 mm, also at 440°C. This process is shown in Figure 5.10. What is unique here is the rolling method in which the ingot is first rolled to about two-thirds of its thickness, surface scraped to remove defects, reheated, and then normally hot rolled. The rolling before the normal rolling was called “pre-rolling.”[1]

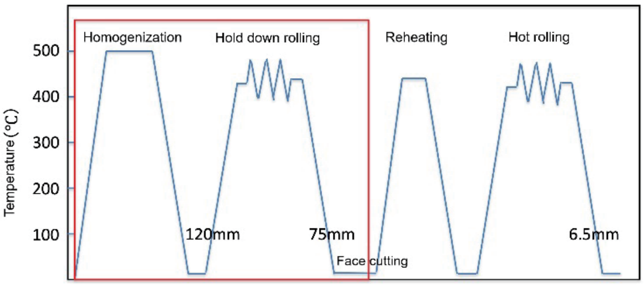


Figure 5.10 Pre-rolling Method (numbers in figure indicate plate thickness)[1, 2]

The concept of pre-rolling is the prototype of the concept of intermediate heat treatment proposed in the postwar development of high-toughness, high-strength alloys, and the challenge is how to break the cast structure by pre-rolling. Other companies used hot forging, called pre-forging, instead of pre-rolling. For clad material, both sides of the ingot were coated with a rolled skin material to a specified thickness, tightened with iron bands, and then crimped by hot rolling. Later, the clad material was hot rolled in the process described above with a skinned ingot after the skin material was welded on during casting.

For cold rolling, the standard dimensions for large sheets were the four types of 910 x 1,830 mm (3 x 6 ft), 1,220 x 2,440 mm (4 x 8 ft), 1,520 x 3,050 mm (5 x 10 ft), and 1,000 x 2,000 mm, and for small sheets were the two types of 400 x 1,200 mm and 500 x 1,200 mm. The minimum thickness was 0.5 mm for the large sheets and 0.3 mm for the small sheets. To roll the large sheets, a two-high rolling mill of 660 x 1,670 mm (26 x 66 in.) was used. 6.4 mm (0.25 in.) hot-rolled sheets were annealed and rolled and, after intermediate annealing, two sheets were joined and rolled down to 0.8 mm. 0.6 mm and 0.5 mm sheets were rolled in triplicate. After quenching, the process was mainly cold skin-pass finishing, with stretch straightening performed as needed. All sheets 1.0-mm to 1.5-mm thick were roll-straightened. For small sheet rolling, two Schmitz and one Farrel small strip mills were used. Some profiles were cut to 5,000-mm lengths and then stretch straightened, but some were shipped as coils.

Around 1935, Super Duralumin entered mass production as a material for airplane skin panels and the company became very busy. Therefore, a second plant of the Sheet Manufacturing Division, which specialized in large sheets, was built at Sakurajima Copper Works. This plant launched operations around 1938, and its main equipment consisted of 12 rolling mills. For the production of large sheets, the plant had one three-high rolling mill ((22, 30) x 66 in.) manufactured by Mesta of the United States as a hot rolling mill, one three-high rolling mill ((20, 30) x 66 in.) and four two-high rolling mills (28 x 60 in.) manufactured by United Engineering (U.E.) as cold rolling mills, two two-high rolling mills (28 x 61 in. and 28 x 66 in.) manufactured by Hitachi, Ltd., and one four-high strip rolling mill manufactured by U.E. Large sheets were manufactured using hot-rolled plates that were “pre-rolled” at the first plate manufacturing plant. The rolling process for large sheets was as follows:

Heating → hot rolling (0.25”) → annealing → bilateral cutting → layout cutting → cold rolling (three-high rolling mill, 3 mm) → layout cutting → annealing → scratch removal → cold rolling (1.5 mm) → annealing → double-sheet rolling → 0.8 mm → quenching → washing → skin pass (→ tempering)

The problems in hot rolling were, first, that edge cracking was common in pre-rolling, but sometimes surface cracking also occurred, in which case both sides were chamfered by 5 to 6 mm. Second, the three-high rolling mill involves a light pressure reduction process, which tends to cause crocodile cracking, and the upper skin material sometimes peels and flies off at the start of double-sheet rolling. Third, because the camber of hot-rolled sheets was uneven, it was necessary to adjust the amount of cooling water for each rolling.

5.3.3 Extrusion and Forging Technologies

For pipes, rods, and wires, one 1,000-ton horizontal hydraulic extrusion press manufactured by Krupp was installed and, around 1935, one 2,000-ton unit manufactured by Schloemann was installed. The former had no container heaters and was heated by wood. The ingots used were 140 mm (5.5 in.) in diameter. The latter was a double-acting type with a gas burner system container and the ingots used were 180 mm (7 in.). Two 600-ton vertical hydraulic extrusion presses from Hydraulik were installed and used to extrude small-diameter pipe stock. In addition, three three-high groove rollers and two two-high groove rollers were used for the hot rolling of rods and the hot mandrel rolling of tubes.

For extruded profiles, Sumitomo succeeded in producing Duralumin L-shaped profiles with 50-mm sides and a wall thickness of 3 mm or more using a 1,000-ton horizontal hydraulic extrusion press manufactured by Krupp around 1924, and it is said that the first practical application was usage for the small frame of a float for a watercraft of the Kawanishi Machinery Company. Even after the relocation to the new plant from Ajigawa to Sakurajima in 1928, there was only one unit and no demand for it. At that time, it seems that most of the shapes were made and finished by rolling and drawing. In 1935, a 2,000-ton horizontal hydraulic extrusion press (double-acting type) manufactured by Schlehmann was installed, and Sumitomo’s Super Duralumin SD (24S) was adopted in 1936 for use in the Type 96 fighter, an all-metal low-wing monoplane that ushered in a period of demand for military aircraft in its prime. For forging, a six-ton air hammer was installed for propeller blade material in 1930. Subsequently, three 1,000-ton vertical hydraulic machines, four screw presses, and two three-ton air hammers were installed.

5.4 Establishment of Nagoya Light Alloy Works[1-4]

In 1935, Sumitomo Steel Tube and Copper Works merged with Sumitomo Steel Works to form Sumitomo Metal Industries Company, Ltd. Aluminum alloy production for the year was 1,400 tons. In the latter half of the year, however, the need for a significant increase in air power due to the tense international situation demanded an increase in the production of aircraft materials. In February 1937, a plan was drawn up to expand the forging plant due to a sharp increase in demand for propellers. In addition, under three production increase plans by the Army and Navy, the Army set a target of 7,418 tons/year and the Navy set a target of 4,400 tons/year, and thus the second plant of the Sheet Manufacturing Division and a second plant of the Tube and Bar Division specializing in aircraft materials were constructed at Copper Works in Sakurajima Osaka, which launched operations between 1938 and 1939. At the end of 1938, the Naval Aviation Headquarters requested the production of 1,364 tons of aluminum alloy per month, three times more than the existing production increase plan, but Copper Works did not have room for the expansion, so a new plant site was considered. Taking into consideration the risks of air raids and natural disasters, the company looked for a site for the new plant in various locations, but eventually decided on Nagoya, the center of aircraft manufacturing.

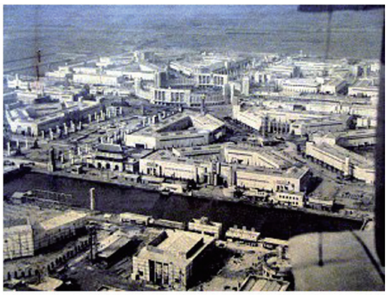
In early 1939, through the arrangement of AOKI Kamataro, president of Aichi Tokei Denki Co. Ltd., which was also involved in the aircraft business, a site was acquired on approximately 628,000 square meters of paddy fields in Chitose, Minato-ku, Nagoya City, including a 13,200 square meter exposition site as an annex to the plant. This area was the site of the Nagoya Pan-Pacific Peace Exposition (see Column) held in 1937 by Nagoya Mayor OIWA Isao to celebrate the 30th anniversary of the opening of Nagoya Port and to promote Nagoya as an international city. When the venue for the festival was originally chosen in 1935, the Atsutamae Shinden area in Minami-ku (now the Komei and Koraku area in Minato-ku, Nagoya City) was little more than a reed-lined rice field managed by the Kohoku Cultivated Land Consolidation Association. Oiwa had a plan to attract the automobile industry to Nagoya and make it “Chūkyō Detroit,” and the exposition was seemingly held as part of this plan to improve the transportation network and other infrastructure. The Nagoya Pan-Pacific Peace Exposition (Column) was held from March 15 to May 31, 1937, with 4.8 million visitors and 29 foreign countries participating.[15, 16]

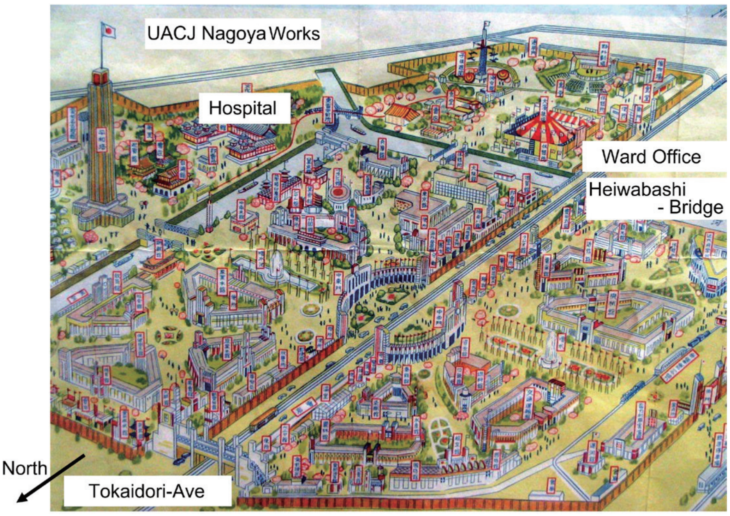
In July 1939, a temporary Nagoya Plant Construction Department was established with SUGIURA Shigezo as general manager to construct a comprehensive plant specializing in light alloys, including casting, sheet making, tubing, and forging (Figure 5-11). At the same time, with the promulgation of the National Mobilization Law, the copper works, light alloy-related plants and all propeller mills became jointly controlled by the Army and Navy, and superintendents were dis-

Column: Nagoya Pan-Pacific Peace Exposition

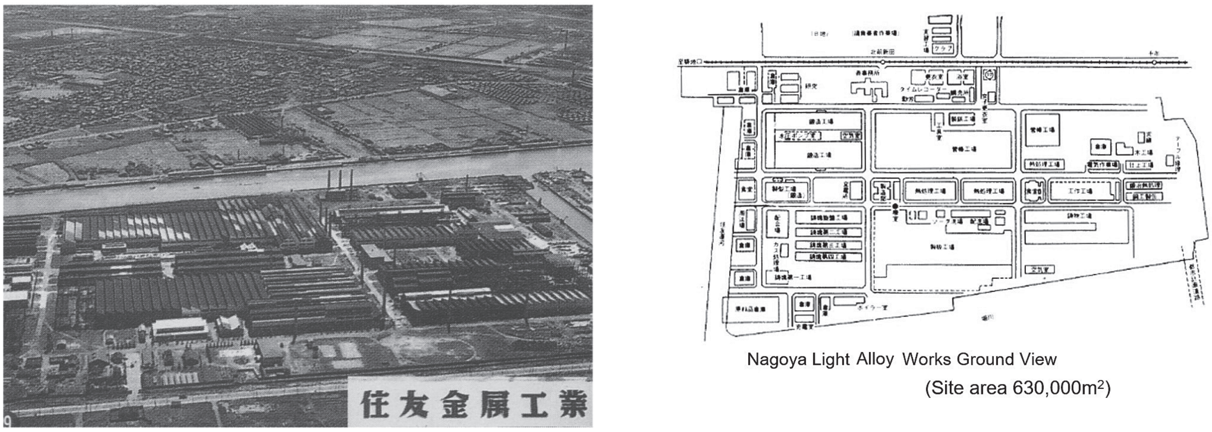
30th anniversary of the opening of the Port of Nagoya, appealing Nagoya as an international city
(Nagoya Mayor Isao Oiwa)

March 15 - May 31, 1937
4.8 million attendees
29 countries participated from overseas





Reference http://underzero.net/html/tz/tz_213_1.htm (2021.11.15), Nagoya Urban Institute, Newsletter Vol. 62 (December 2004), Nagoya Pan-Pacific Peace Exposition Guidebook (Nagoya Urban Institute, 2005).



Nagoya Light Alloy Works Ground View
(Site area 630,000m^2)

Figure 5.11 Outer Appearance and Plan View of Nagoya Light Alloy Works[2] patched to these plants to direct and supervise production and repair work by the Minister of the Army and Navy. In September 1941, Nagoya Light Alloy Works was established. SUGIURA Shigezo and MARUYAMA Masao were appointed as Director and Deputy Director, respectively, and Dr. Igarashi also became Research Director at this time. In February 1942, Nagoya Light Alloy Works also became a jointly controlled plant of the Army and Navy. The goal of this plant was a strip-type rolled sheet mill that would use large ingots cast by the continuous casting method, which was under development at Copper Works at the time.

In 1943, the plant was rapidly upgraded and became a comprehensive light alloy plant equipped with 30 reverberatory furnaces, Japan's first continuous casting facility, a reversible two-high hot rolling mill and four-high cold rolling mill, a 3,600-ton horizontal hydraulic extrusion press for producing large extruded shapes, a 4,000-ton vertical hydraulic machine for producing propeller blade materials, and a 35,000 kg-m air hammer. At its peak, the plant was capable of producing 4,000 tons per month. Note that, in 1943, Nagoya Light Alloy Works Narumi Branch, Toyohashi Copper Works, and Katada Copper Works were established and the casting business was transferred to them. Advances in casting, rolling, tube and rod, profile, and forging technologies will be presented below.

5.4.1 Casting Technology

With the development of sheet-making technology, the need for high-quality, large ingots had arisen for rolling by the strip method. In a foreign magazine published in the spring of 1936, there was an article of two or three lines, "From now on, we must turn to the continuous casting method," which attracted the attention of SATO Shinji. In 1937, he wrote, "The root of all things is talent. Even those without talent can reach a high skill level through hard work, but hard work alone does not make one a master... The continuous casting method is the only way to produce cast ingots with high quality, and submitted the report to MARUYAMA Itsuo, the head of the production department and, with his permission, began experiments. Later, Nagoya Light Alloy Works, which was under construction, was to be equipped with a strip-type rolling mill by United Engineering of the United States. This required large square ingots for sheet making, so it was essential to perfect large ingot continuous casting technology. In June 1941, KANOKOGI Tatsuro, who was in charge of this project, perfected a casting method, called the SKS-V method, of using copper molds, coating the inner surface of the molds with oil, devising a way to inject molten metal, and placing a dummy block on the bottom plate to manufacture an ingot 1,200 mm in length and approximately 400 kg in weight (Figure 5.12).

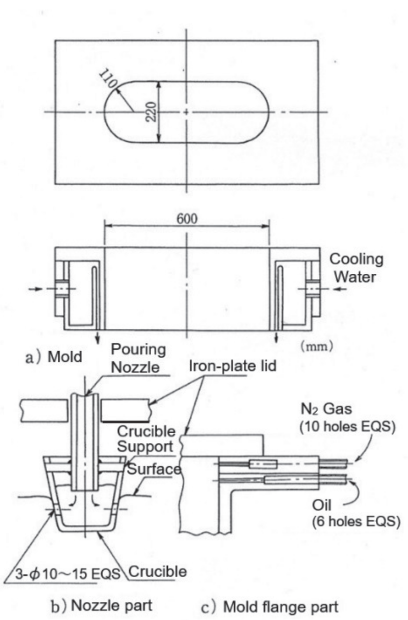


Figure 5.12 Mold and Nozzle Portions for Continuous Casting of Slabs for Sheets[1, 2]

In 1942, a 5-meter-deep pit was built in front of the reverberatory furnace, a lowering device with a dummy block was installed in the pit, a mold was installed, and molten metal was poured into the mold alternately with two ladles through a trough, forming slabs having a maximum weight of 1,400 kg, a thickness of 220 mm, widths of 600 and 800 mm, and a length of about 4,000 mm. With 400 kg and 600 kg ingots used for the actual rolling, three or two sheets were taken from a single slab. Initially, the plan was to manufacture the product by introducing technology from Vereinigte Leichtmetallwerke GmbH (VLW), but since Furukawa Electric had negotiated first, introduction of the technology was no longer possible (see Column). Therefore, referring to an article on the continuous casting method published in the German Aluminium magazine in 1937 and an Italian patent issued by VLW, Kanokogi experimented with the production of large ingots, established his own technology for molds, shapes, casting methods, cooling methods, crack prevention, and abnormal crystal grain and sweating prevention, obtained three patents, and launched mass production at Nagoya Light Alloy Works in 1942. The establishment of the continuous casting method contributed significantly to the improvement of productivity of strip-type rolling mills in a sheet plant. In this continuous casting method, only Duralumin and Super Duralumin were used. For Extra Super Duralumin (ESD), the Züblin method

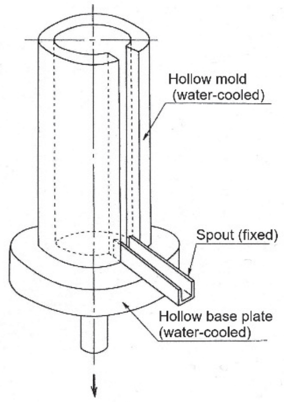


Figure 5.13 Züblin Casting Method for Circular Billets[1, 2]

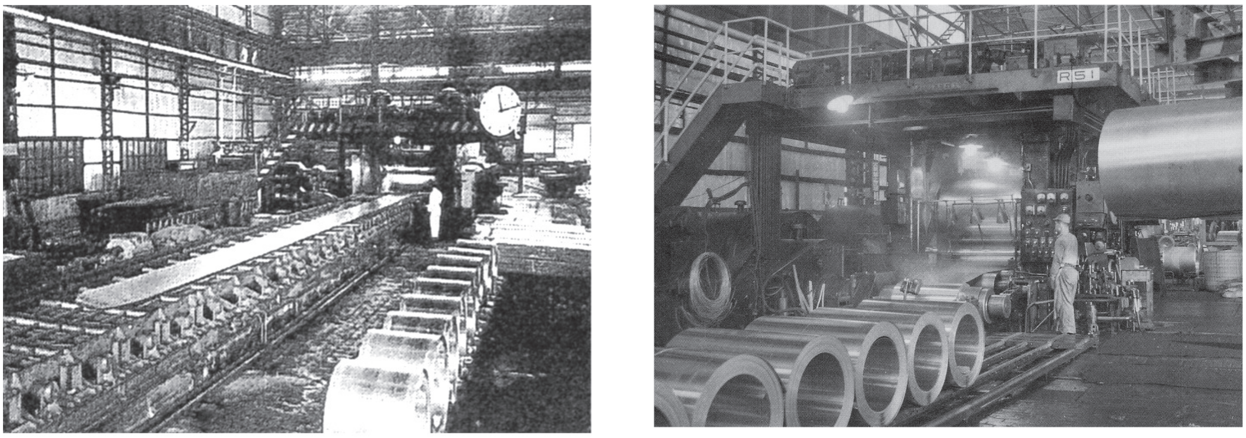


Figure 5.14 Sumitomo Rolling Mills (left: two-high hot rolling mill, right: two-tandem four-high cold rolling mill)[2]

(SKS-VI) was applied because of the problem of cracking when ESD was left as is after casting. In the Züblin method, one edge of the mold is left open, molten metal is poured into the mold by a horizontal trough through that opening, and the open edge portion is successively closed as the mold is lowered (Figure 5.13).

The ingot for ESD sheets by the Züblin method was about 120-mm thick x 400-mm wide x 600-mm long (approximately 80 kg).

5.4.2 Rolling Technology

In the hot rolling process at Nagoya Light Alloy Works, large cast ingots were rolled by the continuous casting method using the strip method, an extremely new method in the world at that time. In this method, slabs for 1000-mm wide plates were hot-rolled to a 6-mm thickness in a U.E. reversible two-high mill (Figure 5.14, top) and then coiled up. After annealing, the plates were subjected to cold rough rolling in three passes on a U.E. two-stand tandem four-high cold rolling mill (Figure 5.14, bottom), intermediate annealing, and then finish rolling in a single U.E. four-high cold rolling mill at a reduction ratio of 50% to obtain sheet thicknesses of 0.5 and 0.6 mm. The sheets rolled by the strip method were the three types of Duralumin (D2), Super Duralumin, and clad sheets thereof (SD, SDC), with thicknesses ranging from 0.4 to 1.2 mm and widths up to 1,250 mm. Extra Super Duralumins ESD and ESDC used conventional rolling methods.

The rolling process of Super Duralumin clad sheets (SDC) in reversible two-high hot rolling is as follows.

400 kg slab → pre-rolling (135 mm thick × 850 mm wide) → face cutting (10 mm on each side) → washing → skin sheet attachment → heating → hot rolling (6 mm thick × 1,100 mm wide) → bilateral cutting (1,050 mm wide)

Two two-high rolling mills (30 x 70 in.) manufactured by Hitachi, Ltd. were used for the hot rolling of ingots by the inclined casting method, and one three-high rolling mill ((31, 21) x 72 in.) manufactured by U.E. and seven two-high rolling mills ((32, 36) x (66 to 96) in.) manufactured by U.E. were used for cold rolling. For the cold rolling of small-width coils, there were two Schmitz (500 x 800 mm) and one Farrel (20 x 32 in.) two-high reversible rolling mills with a single coil weight of 50 to 60 kg. In addition, four Hitachi two-high rolling mills (36 x 130 in.) were installed for magnesium alloy rolling, and one Hitachi two-high rolling mill (36 x 130 in.) was installed for the hot rolling of naval brass plates for condenser tube.

A niter furnace was used for quenching. Large sheets were suspended, but small sheets were sometimes quenched as coils (final unit weight 40 to 50 kg), depending on dimensions.

The basis of strip method rolling technology practiced today began with small-width rolling, which, coupled with the development of the continuous casting method, was perfected by the Nagoya Light Alloy Works after 1942. In 1944, the second plant of the Sheet Manufacturing Division of Copper Works produced 500 to 600 tons of aluminum alloy per month, while the sheet manufacturing plant of Nagoya Light Alloy Works produced 2,000 tons per month at its peak (including 1,500 tons per month by the strip method).

5.4.3 Extrusion Technology

In 1941, eight horizontal hydraulic extrusion presses, one vertical hydraulic extrusion press and one vertical hydraulic machine, three rolling groove rolls for propeller wing material, 17 chain drawing machines, one 20-ton and one 300-ton stretch straightener, and a reeler straightener were installed as the main equipment for pipe and rod production. In all plants, the billets were 5”, 7”, 9”, and 10” in diameter, and were manufactured by the inclined casting method, with continuous casting also used in Nagoya. A niter furnace was used for quenching. The production volume was 300 tons/month of tubes and rods at both Copper Works (Sakurajima) and Nagoya.

Seven horizontal hydraulic extrusion presses were installed for the production of extruded shapes. Later, additional units were added, bringing the total to 11. ESD was produced in 2,000-ton class or larger extrusion presses, with a minimum wall thickness of 4 mm, but primarily 6 mm or thicker. Extrusion speeds were 2 to 2.5 m/min for SD and 1 to 1.5 m/min for ESD. Figure 5.15 shows a 3,600-ton horizontal hydraulic

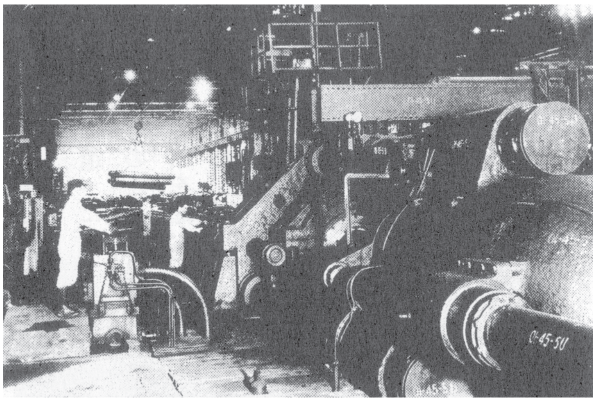


Figure 5.15 3600-Ton Horizontal Hydraulic Extrusion Press[2]

extrusion press installed at the Nagoya Light Alloy Works. This extrusion press was used for the extrusion of ESD large shapes.

The problems in extrusion shape production at that time included crystal grain coarsening at the tail of the extruded material, extrudability depended on shape and size, and emboly defects at the tail of the extruded material. Straightening methods for extruded shapes are stretch straightening, tapping straightening, press straightening, and torsional straightening with twisters. Correction, as with scratch removal, was a very labor-intensive and manpower-intensive process. The production was 700 tons/month at Sakurajima and Nagoya, respectively. In Nagoya, ESD production was 500 tons/month.

5.4.4 Forging Technology

Plants were built on the basis of larger equipment, the use of large crank presses, the use of forging rolls and upsetters, forging that leaves a black skin, and the establishment of a die-making plant. Two 4,000-ton vertical hydraulic machines, one 1,000-ton horizontal hydraulic machine (upsetter), one Beche 35,000 kg-m counter blow hammer, and one forging roll were installed. Four screw presses for pistons, one 1-ton air hammer, and one 3-ton air hammer were installed exclusively for small forgings. Later, two 1,500-ton crank presses made by National (USA) and three 700-ton and two 200-ton crank presses made in Japan were added. Figure 5.16 shows a forging die for an aircraft propeller stored at UACJ.

Figure 5.16 Forging Die for Aircraft Propeller Stored at UACJ

5.5 Introduction of Smelting Technology, Electric Power Business, and Aluminum Smelting[17]

5.5.1 Imported primary aluminum in Japan and Response by Sumitomo and Furukawa

As mentioned above, formation of the aluminum market in Japan began with military products. That is, in 1894, the Army decided to import aluminum primary aluminum to produce mess kits, canteens, and other portable military equipment at artillery arsenals in Tokyo and Osaka. Imported ingots were rolled at Sumitomo Copper Works, which opened in Ajigawa in 1897, and delivered to the arsenal as aluminum sheets. Later, aluminum fixtures were also manufactured in the private sector, and imported primary aluminum, which reached about 100 tons in 1900, increased to about 1,000 tons in 1912. The start of World War I interrupted primary aluminum imports from France, Switzerland, and the U.K., but Alcoa's subsidiary Northern Aluminum Company (Alcan's predecessor) entered Japan in the intervening years, and thereafter the aluminum market in Japan was under Alcan's control. By 1920, ingot consumption had grown to about 2,000 tons.[6]

Furukawa Electric also began wire manufacturing upon completion of Nikko Copper Works in 1908, and showed interest in aluminum wiring, sending TAKAHASHI Motoe to Europe in 1911 to investigate aluminum power transmission lines.

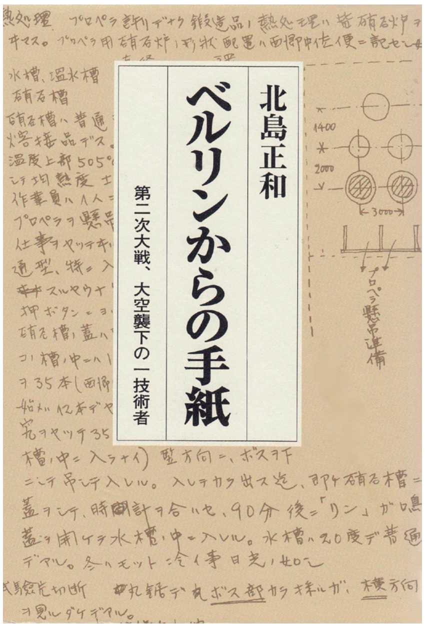
In 1919, Furukawa Partnership Corporation signed a contract with British Aluminium Ltd. for exclusive rights to sell aluminum wire bars and introduce the technology, and began manufacturing steel-core aluminum. In response, Sumitomo Electric Wire and Cable Works also began production in 1925 by introducing technology from Alcoa. While Sumitomo's raw materials came from Alcoa, Furukawa needed to obtain raw materials at a lower price due to competition. Furukawa was also inspired by Sumitomo's Duralumin production and sent TOBA Yasuyuki, an engineer, to the University of Tokyo's Institute of Aeronautics to conduct research. In 1926, the Army Aviation Headquarters received an order for Duralumin prototypes and, in 1928, the Army made a decision to designate Nikko Copper Works as a designated factory for the manufacture of Duralumin sheets.[18]

5.5.2 Development of Domestic Primary Aluminum

In 1916, Nippon Keigin built an electrolysis plant with an annual capacity of 200 tons in Nagoya, the first aluminum smelter in Japan. The plan called for the use of white clay from the Chita Peninsula as the raw material, treating the clay with caustic soda to produce alumina, and electrolyzing the alumina. However, the raw materials and the cost were not suitable, and the plant was closed after one year. The company's management was then entrusted to Fujita Gumi (Dowa Mining), and this new parent company continued research at the Nagoya Plant and built an electrolysis plant in Omachi, Nagano Prefecture in 1918. This plant was intended to ac-

Column: Furukawa Electric's Introduction of Technology from VLW - From *" Letter from Berlin"*

Furukawa Electric's Nikko and Osaka plants came under the control of the Army and Navy under the Industries Control Act of September 1937. In particular, Furukawa was required, at the request of the Army, to build a new plant for the mass production of aluminum alloys for aircraft. It was essential to introduce the latest foreign technology when building the new plant. In 1938, VLW approached Furukawa Electric about technical collaboration, the decision was made that VLW was superior in ingot manufacture technology and, in August 1939, Furukawa and VLW signed a contract to introduce technologies related to melting and casting, rolling, forging, extrusion, and research, and to dispatch engineers three times over a three-year period to learn these technologies. The three dispatched were MATSUO Toshihiko, KAWAMURA Tsukasa, and KITAJIMA Masamoto, who left for Germany via Siberia in May 1941. The group arrived in Berlin in June, but 12 days later Germany declared war on the Soviet Union. In July, the group arrived in Hanover, where they trained at VLW during a period of air raids and learned the VLW continuous water-cooled casting method and other technologies. They pulled out of Hanover in November, but the looming threat of war between Japan and the United States made it difficult for them to return home immediately. Purchased machinery and technical materials were transported to Japan by submarine. In September 1942, they were processed to return home, but were unable to obtain visas for travel through the Soviet Union, so were held over until the following year. In the spring of 1943, through technical documents and contacts with expatriates, Nikko built a continuous water-cooled casting facility. As a result, 24S was successfully made, but quality ESD products were not achieved. In October 1943, visas for transit through the Soviet Union were finally granted, but not to Kitajima due to the visa limitation of two persons per company. Kitajima, who was left alone, suffered a lung injury during an air raid in Berlin, and was forced by the army to enter a German army sanatorium for wounded soldiers. As the war situation worsened, he was moved to a tuberculosis sanatorium in Switzerland in January 1945, but died as a guest on September 18 at the age of 39. The book "*Letter from Berlin, One Engineer in the Air Raids of World War II*" written by KITAJIMA Masakazu, the eldest son of KITAJIMA Masamoto, was published by Chūō Kōron Jigyō Shuppan in 2005. (Figure: Kitajima's letter on the cover of the book)



北島正和

ベルリンからの手紙

第二次大戦、大空襲下の一技術者

From KITAJIMA Masakazu: "*Letter from Berlin, One Engineer in the Air Raids of World War II*" (Chūō Kōron Jigyō Shuppan, 2005).

commodate the development of a 30,000 kW power supply by Meiji Hydroelectric, a Fujita Gumi affiliate, but was set back by the recession following World War I.[6] In 1921, in response to the expansion of military demand, particularly for airplanes, the military promoted the commercialization of aluminum smelting by providing grants to encourage research in the munitions industry. With this government subsidy, industrialization tests were resumed at the Omachi Plant of Nippon Keigin, and research on alumina production was conducted at Tokyo Industrial Research Institute, a government agency.

(1) Smelting from Alum - Showa Denko and Sumitomo Chemical[6, 18-21]

After the withdrawal from the League of Nations in September 1931, there were concerns about imports of primary aluminum, spurring a rapid increase in momentum for the domestic production of primary aluminum using alunite from Korea and aluminous shale from Manchuria, which were under Japanese rule at the time. The patent for the alumina production method using alunite invented by ASADA Heizo of Asada Alum Works was granted in 1930. Asada built a test plant at Showa Fertilizer's Kawasaki plant in 1932 and conducted tests using alunite from Japan Iodine (subsequently Nippon Denko in 1934 and Showa Denko in 1939) and Korea.

The Asada process is an acid method of roasting alunite and adding sulfuric acid so that the solution becomes alunite sulfate (aluminum sulfate), leaving silicic acid and iron in the residue, which is separated and filtered to obtain crude alum. The crude alum is then further decomposed under pressure to obtain potassium sulfate and aluminum sulfate, which are extracted with water after roasting to obtain aluminum hydroxide. Later, however, the company adopted the patent of

Dr. TANAKA Hiroshi of Tokyo Industrial Research Institute instead of the Asada process,[6] and Nippon Denko constructed an alumina plant in Yokohama and an electrolysis plant in Omachi in 1934, successfully commercializing aluminum smelting.[22]

The Tanaka process involves roasting and decomposing alunite, treating the alunite with ammonia water to convert the sulfuric acid content into ammonium sulfate and the potassium content into potassium sulfate, and evaporating the extract to produce a potassium sulfate-ammonium sulfate mixture. The extracted residue is treated with caustic soda to form a sodium aluminate solution, which is decomposed with carbon dioxide to precipitate aluminum hydroxide, which is then calcined to make alumina. The mother liquor, a sodium carbonate solution, is causticized and circulated through the process. However, bauxite was later found to have a better recovery rate, so the switch was made to bauxite in 1937.

Asada gave up on Nippon Iodine and, in 1931, proposed commercialization to Sumitomo GSK, and an agreement was reached to carry out commercialization together with the transfer of Asada's mining rights of Okmaisan alunite in Korea (see Note). Sumitomo signed the contract with its eye on potassium sulfate, a raw material for fertilizer, which could also be extracted as a byproduct. In 1913, Sumitomo established a fertilizer plant in Niihama, which was directly managed by its head office. This plant became independent as Sumitomo Fertilizer Manufacturing Co., Ltd. in 1925 and changed its name to Sumitomo Chemical Co., Ltd. in 1934.

Sumitomo Chemical attempted to manufacture alumina using the Asada process, but the equipment was corroded by sulfuric acid and there were no suitable materials to make the equipment acid-resistant, so the company decided to manufacture alumina from alunite using the Sumitomo method it had developed and, in 1934, established Sumitomo Aluminium Smelting Co., Ltd. with an annual smelting capacity of 1,500 tons. The Sumitomo method is a method of treating alunite with acid and alkali. The method involves crushing, roasting, and further crushing alunite, and adding sulfuric acid to separate the alunite into crude alum and aluminum sulfate. The aluminum sulfate is then neutralized with ammonia to obtain aluminum hydroxide, which is dissolved in caustic soda to make sodium aluminate. When aluminum hydroxide is precipitated in the precipitation tank, silicic acid and iron remain in the residue. In this method, potassium sulfate and ammonium sulfate are obtained from the filtrate after neutralization with ammonia and filtration of aluminum hydroxide. In the end, the recovery of alumina from alum did not go well from both technical and cost standpoints, and such alumina could not be used for Duralumin due to its high impurity content, bringing Sumitomo Chemical to also make the switch to bauxite in 1938.

(Note) Composition of alunite from Okmaisan:[22] Al_2O_3: 24 to 33%, SiO_2: 14 to 15%, SO_2: 22 to 33%, Fe_2O_3: 0.5 to 15%, K_2O: 6 to 8%, H_2O: 9 to 10%

Column: Dr.TAKAMINE Jōkichi's Aluminum Smelting Business

In 1917, Dr. TAKAMINE Jōkichi (1854-1922), famous for his discovery of diastase, also thought that Takaoka, Takamine's birthplace, had long possessed copper manufacturing technology, and that this technology could be put to good use if an aluminum industry was started at this location (Toyama Prefecture), which has a nice port facing Toyama Bay. He established a joint venture company with Alcoa and Japan and made plans for aluminum smelting by introducing Alcoa technology. In 1917, he embarked on a survey of the Kurobe River, believing that the best way to start an aluminum industry, which requires large amounts of electricity, was to utilize the nearly inexhaustible water resource. In December 1919, Toyo Aluminum was established within the headquarters of Sankyo Co., Ltd., and the company took its first steps by launching Kurobe River power source development. In 1921, Toyo Aluminum established Kurobe Railway and began railroad construction. The company believed that if Unazuki could be used as a base for power supply development and simultaneously be developed as a hot spring resort, it would be possible to attract general customers and launch railroad business operations, power supply development, and regional development at the same time.

However, when Dr. Takamine passed away in July 1922 amid the economic depression after World War I, the power supply development business by Toyo Aluminum was scaled down, and Toyo Aluminum gave up its aluminum smelting business in the same year. SHIOBARA Matasaku, who had represented the company along with Dr. Takamine, transferred all shares of the company to Nippon Denryoku. YAMAOKA Juntarō of Nippon Denryoku was appointed president of Toyo Aluminum, and the electric power business was taken over by Nippon Denryoku (now Kansai Electric Power Company). In the aluminum smelting business realm, "Nippon Denko" first succeeded in production in 1934 through a company called "Nihon Iodine." In the aluminum manufacturing industry, Sankyo Aluminium Industry and Tateyama Aluminium Industry (now merged as Sankyo Tateyama, Inc.) were founded in 1960 by brothers TAKEHIRA Masataro and Eiji, with headquarters in Takaoka.
(http://www.npo-takamine.org/works/05.html)

Column: Alumina Manufacturing Process: Alkali Method and Acid Method

With alumina being an amphoteric compound, soluble in both alkali and acid, the alumina manufacturing process includes both alkali and acid methods. The alkali method treats the raw ore with alkali (caustic soda or sodium carbonate) to bind alumina to the sodium aluminate dissolved in water. This process separates impurities such as iron, silicon, and titanium as red mud, and separates aluminum hydroxide from sodium aluminate. In the alkali method, iron and titanium are relatively easy to separate, but silicon readily dissolves in alkali, so it is desirable to use raw ore with as little silicon as possible in the method. The alkali method is based on the Bayer method and is still widely utilized today. Austrian chemist K. J. Bayer found first that decomposition and precipitation occur spontaneously in a sodium aluminate solution and that this precipitation is enhanced by the addition of aluminum hydroxide, and second that alumina in bauxite dissolves in an alkaline solution using the mother liquor after decomposition of aluminate solution in an autoclave. These findings completed the Bayer process. The Bayer process is shown in the figure. The alkali method includes a dry method in addition to the wet method described above. In this method, raw ore is heated and dried in a rotary furnace together with an alkaline earth metal salt or alkali metal salt (carbonates such as sodium carbonate and calcium carbonate) or melted in an arc furnace to obtain solid aluminate. Aluminate is extracted by water or a soda solution to obtain a sodium aluminate solution, which is decomposed to obtain aluminum hydroxide.

In the acid method, on the other hand, the raw ore is treated with inorganic acids (sulfuric acid, hydrochloric acid, nitric acid) to produce aluminum sulfate or aluminum trichloride, which is then decomposed to obtain aluminum hydroxide. The acid method dissolves some iron and titanium oxides, but almost no silicon. Preferably, with iron removal from acid solutions being quite difficult, raw ore with low iron content is used. The equipment must also be acid-resistant. The figure on the right shows the Asada process, a type of acid method. (MORINAGA Takuichi: *Aluminum Smelting*, Nikkan Kogyo Shimbun, (1968).)

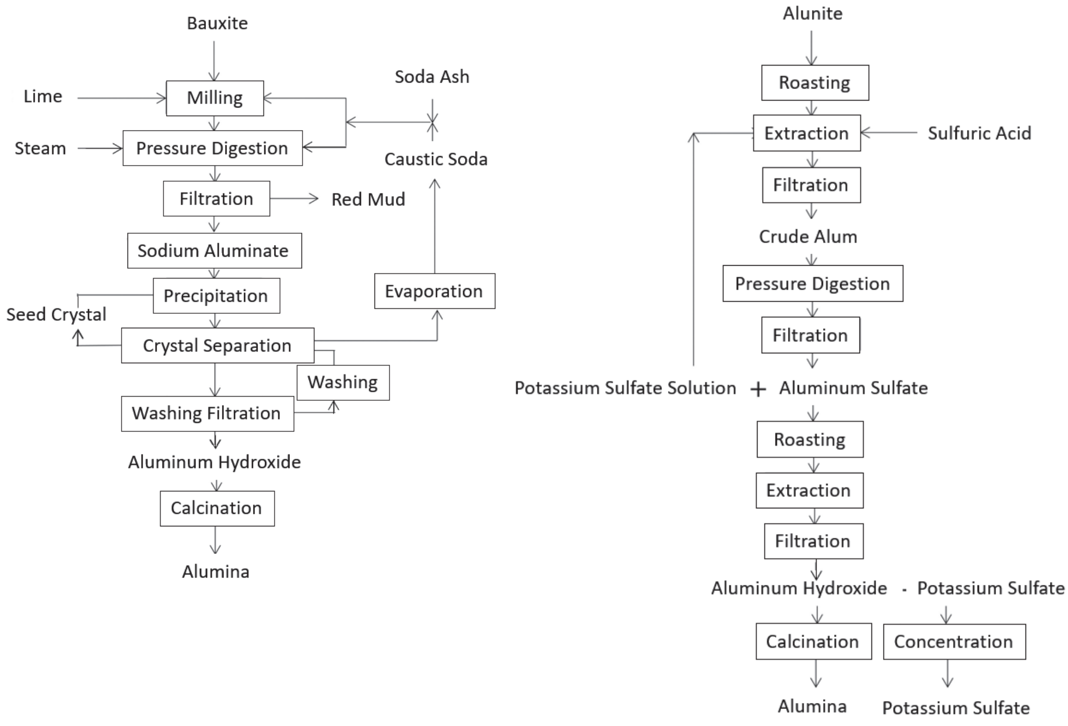


Figure Manufacturing Methods of Bayer Process (Left) and Asada Process (Right)

(2) Smelting from Aluminous Shale - Nichiman Aluminum and Manchuria Light Metals[23-26]

Aluminous shale was discovered in 1924 during a survey of refractory clay at the Yantai coal mine in Yantai (located between Anshan and Shenyang in northeastern China). The clay was found to contain an extremely high quantity of fine diaspore crystals, and was named " aluminous shale" by Dr. MURAKAMI Hanzō, the director of the Geological Survey of Japan at the time.[23] Because of the high alumina content of the aluminous shale, it was considered a national policy to use aluminous shale as a raw material for aluminum in the event the supply of bauxite was disrupted. Aluminous shale is a whitish brown rock, but contains more silica stone than bauxite, probably because it is less weathered than bauxite. Bauxite has a low silicic acid content of 5% or less, but aluminous shale has a silicic acid content of at least 10% and as much as 40%. The silicic acid content dissolves out even when treated with caustic soda, which increases the process of removing these impurities compared to the Bayer process of manufacturing from bauxite, making it a question of whether the process is profitable.

RIKEN developed a dry alumina manufacturing process using Manchurian aluminous shale. In 1933, Nichiman Aluminum Co., Ltd., a company that adopted this process, was established and built a plant in Higashi Iwase-cho, Toyama Prefecture. The plant began operations in 1935 with an annual production capacity of 3,000 tons. The method studied at RIKEN is called the "Suzuki dry process" by Dr. SUZUKI Yōsei. In this method, the aluminous shale is melted at high temperature together with coke in an electric furnace to reduce the silicic acid, iron oxide, and titanium oxide, the molten "silicon titanium iron" and "alumina" are separated by a difference in specific gravity, and impurities are removed through chlorine gas in the separated alumina.[19-21] Nichiman Aluminum was acquired by Showa Denko in 1943 and became the company's Toyama Plant.

Meanwhile, research and development for extracting alumina from aluminous shale[23] was also conducted at the South Manchuria Railway Central Research Institute and, based on their research it was determined that the manufacturing method differs for high-quality and low-quality ores of the aluminous shale, and that the alkali method and the dry method are better for high-quality ores (Al_2O_3: 50%, SiO_2: 20%, Fe_2O_3: 10%) because of the low silicic acid content, and the acid method is better for low-quality ores (Al_2O_3: 20 to 40%, SiO_2: 40%, Fe_2O_3: 3%) because of the high silicic acid content. Small-scale experiments had already been conducted at the South Manchuria Railway Central Research Institute to produce alumina with sulfuric acid from low-quality ore in large quantities. This is an application of the alumina production method from alunite and involves baking and dehydrating the aluminous shale, and then dissolving the aluminous shale in sulfuric acid to produce an aqueous solution of alunite sulfate. Subsequently ammonia is added to this to form ammonium alum crystals and, when ammonia is further acted upon, aluminum hydroxide is extracted as crystals. With this method of baking and dehydrating to produce alumina, alumina with high purity was readily obtained through electrolysis.

However, at the strong request of the Kwantung Army, the South Manchuria Railway Central Research Institute began working with RIKEN's Suzuki dry method. The rights to use the patent of the RIKEN method were obtained from Nichiman Aluminum, and an agreement was made to supply Nichiman Aluminum with aluminous shale. In 1934, a test plant was established in Fushun, near Mukden (now Shenyang). Power was supplied by the Fushun Coal Mine power plant. UCHINO Masao, an engineer at the South Manchuria Railway Central Research Institute, was troubled by difficulties in handling high-temperature chlorine gas, grinding molten alumina, and electrolyzing alumina. For the last problem of electrolyzing alumina, Uchino found that the reaction proceeded well when alumina produced by the acid method was added, and demonstrated that alumina could be produced from aluminous shale.[24] Uchino then toured a smelting plant in France and decided to perform smelting using the Søderberg method. Uchino and his staff completed the "Manchurian light metal process," established the Manchurian Light Metal Company in November 1936, and built a plant with an annual production capacity of 4,000 tons in Fushun, which began operations in 1938.

In the "Manchurian light metal process," the first stage is a process of producing aluminate lime (calcium aluminate) from ore, and involves baking aluminous shale and limestone in a roasting furnace to remove water and organic matter, melting the product in an arc furnace, and then adding coke and iron. Ferro silicon is then formed and precipitated in a reduction reaction. Aluminate lime is removed from the supernatant solution. The second stage is a process of producing purified alumina from the sulfate lime. Sodium carbonate is added to the sulfate lime in a dissolver to form sodium aluminate, which is filtered through a washing thickener and then desilicified. The supernatant liquid is guided through a purification tank to a precipitation tank, where carbon dioxide gas is blown in to precipitate aluminum hydroxide. After dehydration, roasting is performed in a rotary kiln to produce a fine alumina. The third stage is an electrolytic process of extracting metallic aluminum from the purified alumina. Manchuria Light Metal Company industrialized the process, and succeeded in smelting aluminum through this unique technique developed in Japan.[25-27]

5.5.3 Domestic Primary Aluminum Withdrawal and Smelting from Bintan Bauxite

In 1926, Furukawa formed the "Aluminum Industry Promotion Council" with six companies involved in the aluminum smelting industry (Mitsui Mining, Mitsubishi Mining, Sumitomo Mining, Fujita Mining, Furukawa Mining, and Taisei Kagaku) for the purpose of fostering the aluminum industry to secure primary aluminum. Although dissolved during the subsequent financial panic, the council was revived in 1930 as the "Aluminum Manufacturing Business Advisory Committee" and the "Three-Company Aluminium Council" (Furukawa Electric, Tokai Electrode, and Taisei Kagaku), organized by Furukawa Electric, took the lead in requesting government support for the aluminum business. In parallel with the committee, the Japan Aluminium Syndicate, led by the three companies, was established.

After returning from Europe and the United States, Furukawa's TAKAHASHI Motoe continued to investigate aluminum ores in Korea, China, and Southeast Asia, and identified prominent alunite deposits in China and Korea, but was convinced that bauxite was essential as a raw material for the economic production of alumina, as in Europe and the United States. Based on the results of surveys of the Johor area on the Malay peninsula and Batam and Bintan in the Rio archipelago, he submitted a mining application, but the mining rights were denied by the Dutch East Indies authorities since they were already held by Billiton and others. In 1928, Furukawa negotiated with Billiton for preferred status in development and, in 1934, a sole source sales contract for Japan was signed with the Japan Aluminium Syndicate. The Japan Aluminium Syndicate signed contracts with Taiwan Electric Power Company and others for power, established Nippon Aluminium in 1935 for the production of alumina by the Bayer process using the bauxite of Bintan, and built an alumina plant and electrolysis plant in Kaohsiung, Taiwan. Mitsui, Mitsubishi,

Table 5.1 Japanese Smelting Companies in Early Days of Aluminum Smelting Industry[28, 29]

Company	Sumitomo Aluminum	Nippon Denko	Nichiman Aluminum	Nippon Aluminium	Nippon Soda	Chosen Nitrogen	Manchuria Light Metal	Tohoku Shinko Aluminum
Capital	￥10M	￥50M	￥10M	￥10M	￥16M	￥8M	￥25M	￥10M
Establishment Date	Jun 1936	1938	Nov 1933	Jun 21 1935	—	—	Nov 10 1936	Nov 10 1936
Production Capacity	3000 t	7000 t	5000 t	6000 t	3000 t	4000 t	4000 t	Dec 23 1927
At the time of establishment	1500 t	5000 t	3000 t	6000 t	2000 t	4000 t	4000 t	4000 t
Subsequently	3000 t	10000 t	—	14000 t	6000 t	—	10000 t	
Start of Operation	1936	Jan 1934	Jan 1936	Nov 29 1936	May 1 1937	—	Jun 1938	
Alumina Production	Sumitomo Chemical	Yokohama Plant	Iwase Plant	Kaohsiung Plant	Takaoka Plant	Hungnam Plant	Fushun Plant	—
Plant Name	Shikama Chemical							—
Raw Ore	Alunite	Alunite	Aluminous Shale	Bauxite	Bauxite	Alunite	Aluminous Shale	—
Mine Location	Korea Yurisan	Korea Seishan	Manchuria Yantai	Dutch East Indies	Dutch East Indies	Korea Gasari	Manchuria Yantai	—
Alumina Manufacturing Method	Sumitomo Method Asada-Taniguchi Method	Okazawa-Tanaka Method	Suzuki-Tanaka Method	Bayer Method	Own Method	Soda Lime Method	Ammonium Sulfate Method	—
Electrolysis Factory	Niihama Plant	Oomachi Plant	Iwase Plant	Takao Plant	Takaoka Plant	Hungnam Plant	Fushun Plant	—
Electrode Manufacturing	Self Supply	Self Supply	Self Supply	Self Supply	Self Supply	Self Supply	Self Supply	—
Cryolite Supply	Purchased	Purchased	Purchased	Purchased/Self	Self Supply	Self Supply	Self Supply	—
Power Supply	Shikoku Chuo Electric Power	Private Generation Toshin Electric	Nihonkai Electric Power	Taiwan Electric Power	Nippon Electric Power	Private Electric Generation	Coal Mine Electric Power	—

Table 5.2 Prewar Primary Aluminum Production in Japan[28, 29]

(1) Aluminum production in Japan

(Unit: t)

Company		1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945 △
Nippon Keikinzoku	(Kanbara)	—	—	—	—	—	—	—	2,024	10,219	16,524	34,604	24,793	1,709
	(Niigata)	—	—	—	—	—	—	—	217	6,880	14,739	19,284	12,844	200
Nippon Soda		—	—	—	—	953	2,753	4,413	5,090	5,418	9,119	10,390	8,723	349
Showa Denko	(Kitakata)	—	—	—	—	—	—	—	—	—	—	166	5,061	765
	(Oomachi)	19	1,002	2,997	3,533	6,168	8,995	9,464	10,233	16,276	19,685	21,655	13,740	439
	(Toyama)∗	—	—	214	1,187	3,471	3,517	3,289	3,713	3,829	5,531	5,834	5,304	987
Sumitomo Alminuim		—	—	—	872	1,066	2,494	3,113	6,971	11,453	16,443	18,668	15,421	955
Tohoku Shinko Aluminum		—	—	—	—	—	—	1,379	2,372	2,008	3,170	3,456	2,368	0
Total		19	1,002	3,211	5,592	11,658	17,759	21,658	30,620	56,080	85,211	114,057	88,254	5,404

(Note) △ From April 1 to June 30

∗ From 1935 to 1942, Nichiman Aluminum was acquired by Showa Denko

(2) Aluminum Production in Korea and Taiwan

(Unit: t)

Company		1936	1937	1938	1939	1940	1941	1942	1943	1944	1945 △
Korea Light Metal ∗		—	—	—	—	—	582	2,266	3,579	2,838	382
Mitsui Light Metal ∗∗		—	—	—	—	—	—	—	5,690	6,009	328
Nippon Nitrogen		—	—	—	240	1,481	2,538	2,100	3,260	4,096	533
Total		—	—	—	240	1,481	3,120	4,366	12,529	12,943	1,243
Nippon Alminium	(Hualien Port)	—	—	—	—	—	329	1,415	3,813	1,638	0
	(Kaohsiung)	210	2,776	4,608	7,661	8,762	12,218	12,083	10,685	7,563	0
Total		210	2,776	4,608	7,661	8,762	12,547	13,498	14,498	9,201	0

(Note) △ From April 1 to June 30

∗ Between 1941 and 1943, Chosun Riken was known as Korea Light Metal

∗ ∗ In 1943 Toyo Light Metal became Mitsui Light Metal

Source: Takayuki Nakajima, Sumio Muratsu, *Aluminum Industry*

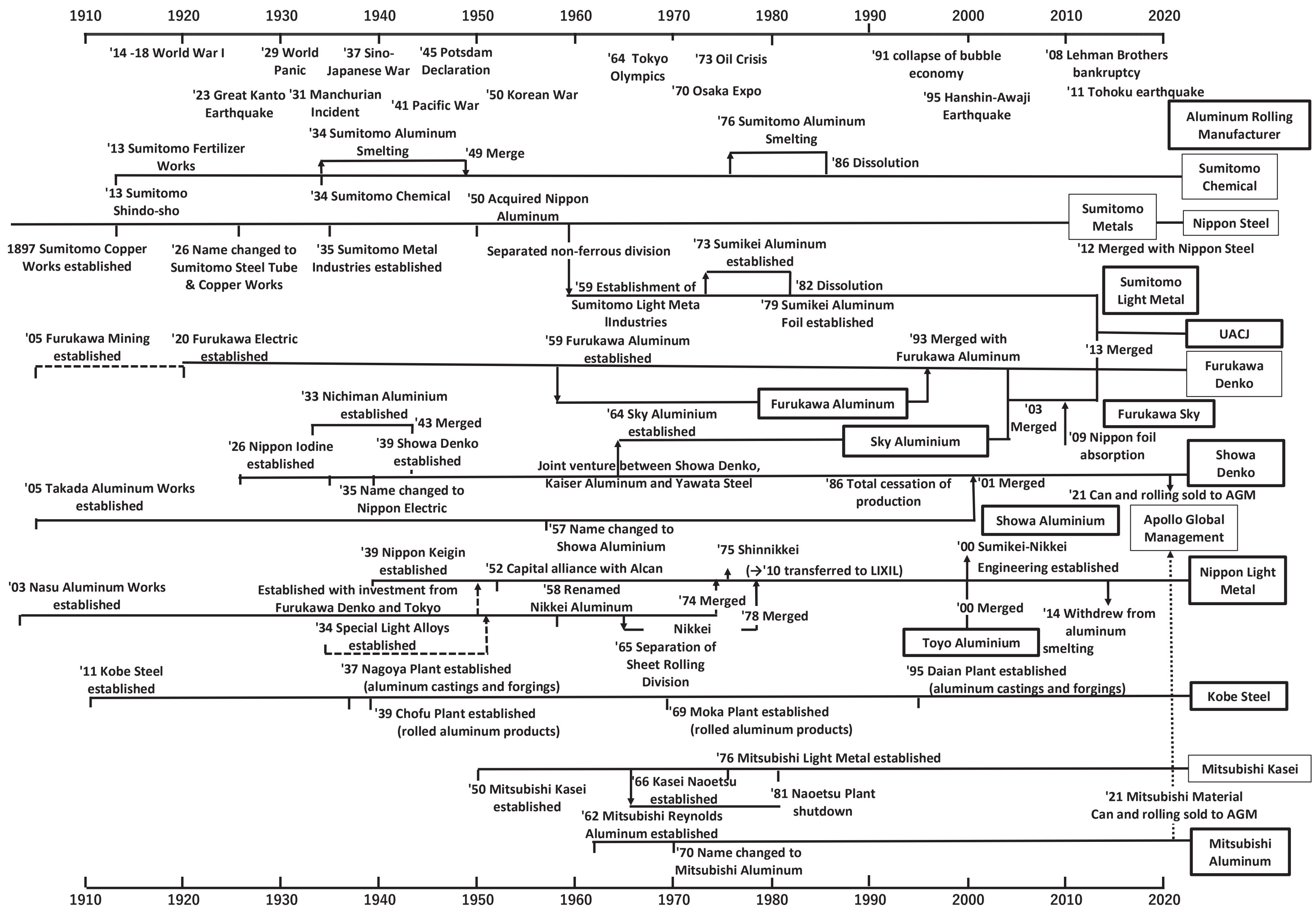


Figure 5.17 Development Flow of Aluminum Companies Involved in Smelting and Rolling in Japan^6 (author's additions to original figure after 1970)

Furukawa, Taiwan Electric Power and others invested in the new company. Production began at a scale of 6,000 tons per year. Meanwhile, Sumitomo established its own Sumitomo Aluminium Smelting in 1934. In 1938, a contract with Billiton was concluded through Nichiran Shoji, and Bintan bauxite (Al_2O_3: 55 to 56%, SiO_2: 3 to 4%, Fe_2O_3: 9 to 11%)[18] was sold to Nippon Soda and Sumitomo Aluminium Smelting in addition to Nippon Aluminium. With the advent of the Pacific War in 1941, Furukawa Mining Co. was commissioned by the military to operate the mine.

Established in 1935 as a joint venture by Mitsui, Mitsubishi, and Furukawa, Nippon Aluminium was the first company in Japan to use bauxite from Bintan as a raw material under the Bayer process. Nippon Denko and Sumitomo Chemical also switched to the cost-effective bauxite raw material around 1937. Two companies, Nippon Soda and Manchuria Light Metal, entered aluminum smelting in 1936, followed by Tohoku Shinko Aluminium in 1937. Chosen Nitrogen also had plans in the works, but the war ended before it reached the point of operation. Table 5.1 summarizes the situation of each company in the early days of the aluminum smelting industry.[28, 29]

Nippon Light Metal Co., Ltd. was established in 1939 as a joint venture between Furukawa Electric and Tokyo Dento, creating Japan's largest aluminum smelting company with an annual production capacity of 54,000 tons of primary aluminum. Japanese aluminum production from 1933 to 1945 is summarized in Table 5.2.[27, 28] By the end of the war, Japan's annual production of primary aluminum capacity had reached 130,000 tons in Japan and 54,000 tons outside Japan (Korea and Taiwan), ranking fourth in the world after the United States, Canada, and Germany.[6] Table 4 shows the aluminum demand by application during World War II. It is clear that the demand is extremely biased toward the military.

Figure 5.17 summarizes the prewar and postwar development of aluminum companies involved in smelting and rolling in Japan.

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6 Research and Development of Aluminum Alloys in Japan

This chapter presents the research conducted by Professor NISHIMURA Hideo of Kyoto University and Sumitomo Metal Industries. Dr. IGARASHI Isamu of Sumitomo Metal Industries was born in 1892, the same year as Nishimura, and is also a graduate of Kyoto University, but Nishimura graduated from the Faculty of Engineering while Igarashi graduated from the Faculty of Science.

6.1 Phase Diagram Research and S Phase Discovery by Prof. NISHIMURA Hideo, Kyoto University

6.1.1 Age-Precipitation Hardening Research

The first published study of Duralumin was published in September 1921 (Taisho 10) by Dr. KONNO Seibee, who was conducting research under Prof. HONDA Kōtaro.[1-3] In November, ŌTANI Buntarō of the Yokosuka Naval Air Technical

Table 6.1 History of Age-Precipitation Hardening Research (created by Nishimura and Obinata with additions made thereto)[4-7]

Year	Researcher	Main Research Topic	Literature
1906 - 1911	Wilm	Discovery of Duralumin age-hardening phenomenon	Metallurgie, 8 (1911), 225
1919	Merica, Waltenberg & Scott	Aging phenomenon of Duralumin caused by change in solid solubility of Al$_2$Cu relative to Al, and hardening caused by precipitation of Al$_2$Cu.	Sci. Pap. Bur. Stand., No. 347 (1919), AIME (1919), 913.
1921	Jeffries & Archer	Proposal of slip interference theory.	Chem. Met. Eng., 24 (1921), 1057.
1921	Rosenhain, Archbutt, Hanson & Gayler	Determined the Al-Al$_2$Cu-Mg$_2$Si pseudoternary phase diagram. Attributed age hardening of Duralumin to changes in solid solubility of Al$_2$Cu and Mg$_2$Si.	Eleventh Report of Alloy Research Committee, J. Inst. Mech. Eng. London, 26 (1921), 321. J. Inst. Metals, 29 (1923). 491.
1922	KONNO Seibee	Age hardening of Duralumin caused by special intermediate phase (β) before precipitation. X-rays indicated no change in crystal lattice.	The Science Reports of the Tōhoku Imperial University, 11 (1922), 269. Research on Metals [Kinzoku no Kenkyu] , 2 (1925), 13.
1925	SUGIURA Shigezō	Considered age hardening as change inside solid solution.	Duralumin Research and Hardening Effect of Single Solid Solution Alloy by Annealing and Low Temperature Softening
1928	GOTO Masaharu	Cause of hardening: Distortion in lattice by displacement of atoms that should produce compound.	Journal of the Aeronautical Research Institute, 39 (1927), 271. Alloy Theory (1929), 267.
1929	Gayler & Preston	Hardening by lattice distortion based on compound precipitation. Estimating lattice distortion by precision X-ray method.	J. Inst. Metals, 41 (1929), 191.
1930	HONDA Kotarō, KOGUBO Sadajirō	Age hardening of Duralumin caused by lattice distortion due to migration of solute atoms in supersaturated solid solution.	Research on Metals [Kinzoku no Kenkyu] 7 (1930), 343. The Science Reports of the Tōhoku Imperial University, 24 (1930), 365.
1926 - 1930	Schmid & Wassermann	Rejection of precipitation theory because no change observed radiographically during aging process.	Naturwiss. 14 (1926), 980. Metallwirtsch 7 (1928), 1329; 9 (1930), 421.
1930	Meissner	Research presentation on silicon-containing Super Duralumin.	J. Inst. Metals 44 (1930), 204.
1931	Hengstenberg & Wassermann	Measured width spread of reflection lines in Duralumin during aging. Presumed hardening to be the result of solute atoms assembling in part within supersaturated solid solution.	Z. Metallkunde 23 (1931), 114.
1935	Wassermann & J. Weert	Discovered appearance of intermediate phase (tetragonal) prior to precipitation of Al$_2$Cu during artificial aging of Al-Cu alloys.	Metallwirtsch 14 (1935), 605.
1936 - 1937	NISHIMURA Hideo	Determined the Al-Cu-Mg ternary phase diagram. Discovered age hardening of Duralumin mainly due to changes in solubility of S compounds in Al.	Journal of the Mining Institute of Japan 52 (1936), 381. Journal of the Japan Institute of Metals, 1 (1937), 8, 59, 262.
1936	Toba Yasuyuki	Presentation of effects of Si on the aging of Type 24S Super Duralumin.	Furukawa Electric (1936), No. B, 1.
1936	Fink & Smith	Observed interference lines of intermediate phase in Debye-Scherrer photographs, and designated this new phase as θ' in contrast to the θ phase of equilibrium phase Al$_2$Cu.	AIME, Met. Div., 122 (1936), 284.
1937	IGARASHI Isamu	Found strength distribution of Al-Cu-Mg alloys with different amounts of Cu and Mg.	Research Report of Sumitomo Metal Industries, Vol. 2, No. 10 (1937), 991.
1938	Preston	Found intermediate phase, which appears at 200°C, to have planar outline parallel to {001} plane of parent phase. Discovered aggregates of Al-Cu alloy solute atoms in early stage of aging by irradiating Al-Cu alloy single crystals with monochromatic X-rays.	G.D. Preston: Phil. Mag. 26 (1938), 855. Nature, 142 (1938), 570.
1938 - 1939	Guinier	Discovered aggregates of solute atoms in Al-Cu alloys in early aging stage using small-angle X-ray scattering technique. Found initial aging changes to be due to formation of GP zones and the weak hardening at high temperatures to be due to precipitation of intermediate phase.	Nature, 142 (1938), 569. J. Inst. Metals, 6 (1939), 177.

Arsenal gave a presentation at the Gakushi Kaikan using the term "light alloy." This was the first time the term was used.[3] This was about the same time that NPL reported E alloys, Y alloys, and Al-Mg-Si alloys at the Institution of Mechanical Engineers in August 1921. Sugiura of Sumitomo did not make an announcement regarding such research until 1925 due to confidentiality issues with the Navy. Table 6.1 shows a chronology of the history of the development of age-hardening research included in a paper by Prof. NISHIMURA Hideo and Prof. OBINATA Ichiji, with a few additions.[4-7] It is clear that many Japanese researchers were active in age-hardening research.

6.1.2 Phase Diagram Research and S Phase Discovery by Prof. NISHIMURA Hideo, Kyoto University

This section mainly introduces Nishimura's research on Al-Cu-Mg alloys at Kyoto University.

Nishimura of Kyoto University (Figure 6.1, left) stated that he started phase diagram research around 1925 to investigate alloys containing copper and magnesium, but his research was interrupted because magnesium was not yet available in Japan and obtaining pure material was difficult.[8] At that time, he wrote, "The cause of the aging of Duralumin

アルミニウム及其合金

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Figure 6.1 Prof. NISHIMURA Hideo of Kyoto University and His Book

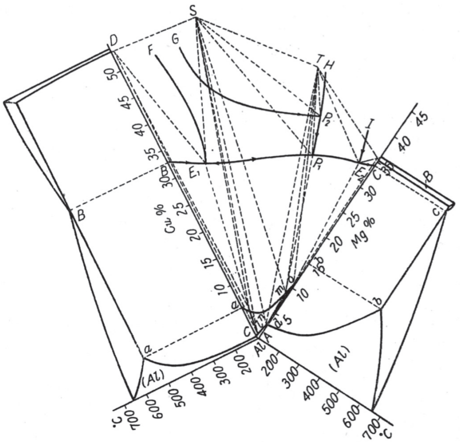


Figure 6.2 Phase Diagram of Al-Cu-Mg Alloys[11,14]

Column: Prof. NISHIMURA Hideo

NISHIMURA Hideo was born in Kyoto City in 1892. After graduating from the Department of Mining and Metallurgy at Kyoto Imperial University in July 1918 and working at the Mitsubishi Mining Research Institute, Nishimura returned to his alma mater after about two years, serving as a Lecturer and Assistant Professor before being promoted to Professor in 1930, and then held the positions of Director of the Engineering Research Institute and Dean of the Faculty of Engineering. He retired in 1955 and became a professor emeritus at Kyoto University. During this period, he taught courses and conducted research in metallurgy and metal processing. After retirement, he continued to nurture talent as Director of the Research Institute of Applied Sciences. Nishimura received the Gold Medal Award from the Japan Institute of Metals in 1962 and the Honda Memorial Prize in 1963, was elected a member of the Japan Academy in 1970, received the Order of the Rising Sun, Gold and Silver Star in 1968, and passed away in 1978 at the age of 86. According to Prof. MURAKAMI Yōtarō, "Nishimura often painted and drew calligraphy. Although he was usually too busy to spend time painting, he did so on occasional Sundays and during summer vacations when he had free time. He also liked to view art, so took his entire lab to exhibitions where he shared his insights with us. Even those of us with no knowledge at all enjoyed such opportunities." According to TANAKA Michio who worked at Furukawa Electric, "I visited the Professor's house one day while he was studying in Paris, and his room was filled with paintings, unlike the room of a metallurgical scholar." The fact that Tanaka would even bother to mention this reveals the extent to which Nishimura was also a cultured man with a deep knowledge of painting and calligraphy. Nishimura also included his own sketches in "*Essey: History of Light Alloys* [Zuihitsu: Keigokin-shi]" in "*Age of Light Metals* [Keikinzoku Jidai]." In his later years, he avoided the hustle and bustle of the city and visited "*Hekisui-kyo* (Deep Blue Clear Water House)", a residence he designed himself on Shōdo Island, where he wrote essays and other writings, and created calligraphy and paintings. Unfortunately, the huge volume of *Essays: History of Light Alloys* and other articles published in "*Age of Light Metals*," which are referred to in this article, were scheduled to be published in book form, but this was not realized due to the discontinuation of the publication of "*Age of Light Metals*." Such essays at a time when not only aluminum but metallography and metalworking were beginning to be established as disciplines are still valuable and informative. A move, spearheaded by the institute, to reprint the volume would be applauded.

(in Gayler's work at NPL) was thought to be related to the precipitation of the compounds Al_2Cu and Mg_2Si. The mechanism of hardening was believed to be that hardening occurs in the process of precipitating, these compounds by aging, which were solid-solved in aluminum. However, in fact, both aluminum-copper alloys containing only Al_2Cu and aluminum alloys containing only Mg_2Si do not age-harden much at room temperature after quenching. Alloys containing Mg_2Si, for example, do not exhibit any hardening at all. One cannot help but wonder why the hardening is so remarkable at room temperature when both compounds are included. Why, when it comes to ternary alloys of aluminum, magnesium, and copper, room temperature aging progresses as it does with Duralumin? There is no research to answer that question,"[9] and so he resumed his research on phase diagrams around 1934. He wrote, "As a result, we designated a ternary compound that should be in equilibrium with Al as an S compound, and proposed that its solid solubility is responsible for the aging of 24S."[10]

Nishimura published "*Aluminium-Corner of the Al-Cu-Mg System*"[11] in *Journal of the Japan Institute of Metals*, Vol. 1, No. 1 (1937), "*Age-hardening of Al-rich the Al-Cu-Mg Alloys*"[12] in No. 2 of the same volume, and "*An Investigation of Super-duralumin (I)*"[13] in No. 7 of the same volume in rapid succession. In 1941, he published "*Aluminum and Its Alloys*" (Figure 6.1, right),[14] which included the results of these studies. This book covers the topic starting with the basics in an easy-to-understand matter, from the history of aluminum to smelting, phase diagrams and the properties of various aluminum alloys, and processing from casting to treatment (surface treatment, welding). To pen such a topic so extensively on his own, one can infer that he had an extensive interest in aluminum. The breadth of this interest is reflected in his essay "*History of Light Alloys*" In his book, he devotes one section to "Duralumin and Super Duralumin." Figure 6.2 shows the ternary phase diagram of the Al-Cu-Mg system created based on his research. He conducted experiments with different Cu:Mg content ratios and found that the proportion of hardening by room temperature aging is high in alloys in regions where Al_2Cu and S compounds precipitate from an Al solid solution, that the proportion of room temperature age hardening is high in alloys having an Mg content of 0.5 to 1.0% given 4% Cu content as the standard, and that hardness reaches the highest value by age hardening in alloys having an Mg content of about 1.5 to 2.5%.[14] The discovery of the S phase and the elucidation of the age-precipitation hardening phenomenon in Al-Cu-Mg alloys are major achievements of Prof. Nishimura and demonstrate the high level of metallurgy in Japan. The Column highlights NISHIMURA Hideo as an artist in Kyoto, a different aspect of his character.[15]

6.2 Development of Super Duralumin by Sumitomo

6.2.1 Joint Research with Army and Navy

At Sumitomo Copper Works, Dr. MATSUDA Tsutomu succeeded SUGIURA Shigezō, who was the first in Japan to establish a research division at the plant, and conducted research on Duralumin, copper alloys, and other materials. Dr. Matsuda was followed by Dr. TANABE Tomojirō, and then by Dr. IGARASHI Isamu. At that time, Duralumin had a tensile strength of about 42 to 45 kg/mm^2 (410 to 440 MPa), and any alloy that exceeded this level of strength was called Super Duralumin, regardless of its alloy system. In Japan, around 1931 or 1932, as the performance of airplanes improved, the specific strengths of the materials needed to be improved.

In a business trip report on a trip to the Technical Department (Tachikawa) of the Army Aviation Headquarters in October 1933 (Matsuda, Research Report No. 2270, 10. 1933) and the research report, "*Two/Three Tests Leading to Super Duralumin Sample Submission*" (Igarashi and Nakata, Research Report No. 2363, 12. 1933), two types of "Super" Duralumin are described. Dr. Igarashi et al. reported in-house test results of an Al-4.2%Cu-0.70%Mg-0.65%Mn-0.65%Si-0.45%Fe alloy as Type 1 Super Duralumin and of an Al-6.0%Mg-4.0%Zn-0.45%Mn-0.15%Si-0.36%Fe alloy as Type 2 Super Duralumin. The former Type 1 Super Duralumin is silicon-containing Super Duralumin, and the latter Type 2 Super Duralumin is an Al-Mg-Zn alloy. The latter alloy was ordered by Commander Iokibe of the Naval Technical Research Institute ("*Report on Business Trip to Naval Technical Research Institute Regarding Production of Iokibe-type Super Duralumin*", Igarashi, Research Report No. 2167, 8.7.1933). Under Commander Iokibe was the engineer KITAHARA Gorō, who two years later would develop Extra Super Duralumin with Dr. IGARASHI Isamu.

6.2.2 Global Trend Survey

Dr. Tanabe and Dr. Matsuda made a series of trips to Europe and the United States from August 1933 to April 1934 and from October 1935 to April 1936, respectively, to conduct research on aluminum alloys and copper alloys for aircraft. This was probably due to the fact that, in the field of aluminum alloys, countries were fiercely competing to develop Super Duralumin for aircraft and alloys for pistons. According to a report by Dr. Tanabe, "*On Nonferrous Alloys for Aircraft in Europe and the United States*"[16], published in the Research Report of Sumitomo Metal Industries, the situation at that time was as follows: "As you know, every country in the world is experiencing a wave of nationalism, and factory tours are extremely difficult, especially when it comes to aircraft. In Germany, in particular, the Minister of Aviation, Göring, is extremely secretive, and even tours of aviation laboratories are not possible." Under these circumstances, Dr. Tanabe and Dr. Matsuda vigorously toured Europe and the United States.

As for light alloys in Germany, Dr. Tanabe wrote, "In Ger-

Table 6.2 List of Super Strong Wrought Aluminum Alloys of Europe and the United States[16]

		Cu	Ni	Mn	Mg	Fe	Si	Ti	Cr	Yield Strength MPa	Tensile Strength MPa	Elongation %
Germany	DM31-1 (*1)	3.5-4.5 3.66		0.9-1.5 1.17	0.9-1.5 1.38	0.29	0.2-0.9 0.65			310-390	450-510	16-10
	DM31-2 (*2)									390-410	490-510	12-10
Germany	681ZB-1 (*1)	4.2		0.6	0.9		0.5			270-330	410-450	18-12
	681ZB-2 (*2)									350-370	450-470	12-10
US	24ST (*1)	4.2		0.6	1.5					290	450	20
	24SRT (*2)									360	470	13
US	C17ST	4		0.5	0.5		1.25			340-380	430-480	14-8
France	Avial	1.5-3.5	0.5-1.5		0.25-1.0		0.5		0.5-1.0	290-370	430-530	20-10
UK	DTD252 Duralumin F	3.5-4.7		0.4-1.5	0.4-1.5	<0.7	0.7-1.5			340	<430	
UK	RR56	1.5-3.0 2	0.5-1.5 1.3		0.4-1.0 0.8	0.8-1.5 1.35	<1.0 0.6	<0.2 0.08		380-420	430-490	20-10

(*1): quenching and aging at RT(room temperature)
(*2): quenching, weak cold working and aging at RT

many, but not just Germany, Duralumin still holds the throne as a strong wrought aluminum alloy for aircraft. However, research to obtain tensile strengths of 45 kg/mm^2 (440 MPa) or higher and, if possible 50 kg/mm^2 (490 MPa) or higher, i.e., Super Duralumin, is flourishing."[16] Dürener Metallwerke developed a conventional Super Duralumin 681ZB (Al-4.2%-Cu-0.9%Mg-0.6%Mn-0.5%Si) and a Super Duralumin alloy called DM31 (Al-4.2%Cu-1.2%Mg-1.2%Mn-0.5%Si) having a strength improved by 10%. In the field of light alloys in the United States, the development by Alcoa is of particular interest. Tanabe reported, "The most notable alloys at the moment are 24ST and 24SRT. The composition is Al-4.2%Cu-1.5%Mg-0.6%Mn, and cladding materials of these are also available." In the United Kingdom, RR56 and RR59 piston materials were being investigated. Table 6.2 shows a list of super strong wrought alloys of Europe and the United States.[16]

6.2.3 US 24S Information and Examination

Around 1933, when information about the US 24S alloy came in, Sumitomo ordered 24SRT material made by Alcoa in September with a "warning" from the Naval Air Headquarters, obtained the material in December, and immediately conducted a validity test. The December report "*Test Results of '24SRT' Sheet Made in United States (First Report)*" (Matsuda, Research Report No. 2381, 12.1933) indicates the composition as Al-3.98%Cu-1.59%Mg-0.46%Mn-0.16%Si-0.22%Fe and states, "It should be noted that, compared to ordinary Duralumin, (1) the amount of Mg is very large, (2) the amount of Si is small, (3) the amount of Fe is small, (4) the compositions of each sheet are quite uniform, etc., and this increase in Mg in particular is because Mg increases tensile strength and yield point in the quenched state and increases elongation." The 24SRT material featured a higher Mg content and a lower Si content than those of the conventional Super Duralumin. The obtained material had a tensile strength of 48 kg/mm^2 (470 MPa), a yield strength of 40 kg/mm^2 (390 MPa), and an elongation of 16%, but it was noted that the repeated bending count was quite small. This was considered to be due to the increase in yield strength resulting from room temperature rolling after quenching.

6.2.4 Silicon-Containing Super Duralumin Alloy

Despite the examination of Alcoa's 24S, research reports from 1934 indicate that Sumitomo's research and development focused on silicon-containing Super Duralumin that was quenched and tempered in the same way as the German alloys 681ZB and DM31, designated the aforementioned Type 1 Super Duralumin as SD (Al-4.2%Cu-0.75%Mg-0.7%Mn-0.7%Si) and a laminated sheet coated with SA1 (Al-1.2%Mn-0.8%Cu) as SDC, and had just established these alloys in-house, engaging exclusively in the evaluation thereof. The time period of establishment is not clear, but the first time the name SDC was used in an internal research report was in a report dated September 8, 1934. On August 31, 1934, an SDC research meeting was held at the Naval Air Station to discuss a characteristics evaluation and shape-based strength test results of the silicon-containing Super Duralumin SDC and 45 kg/mm^2 (440 MPa) Duralumin sheets ("*SDC Research Meeting Summary*", Naval Air Armoury, August 31, 1934, Research Report No. 2731, 9.18.1934). A research report dated February 1935 (Matsuda, Research Report No. 2965, 2.1935) describes trends in SD and SDC standardization, "The standards for Super Duralumin and Super Duralumin cladding sheets were established and issued by the Navy and Army in succession, and the Army recently issued standards for tubes and rods. Standards for Super Duralumin cladding are also expected to be issued soon . . . The US standard for 24S series alloys is also included for reference, to the extent of our knowledge." Looking at the composition standards, the standards differ between the Navy and the Army, with the Navy being Cu: 3.5 to 4.5%, Mg: 0.4 to 1.0%, Mn: 0.4 to 1.0%, Si: 0.4 to 1.0%, and Fe: 0.6% or less, and the Army being Cu: 4.0 to 4.5%, Mg: 1.0% or less, Mn: 1.0% or less, Si: 1.0% or less, and Fe: 0.7% or less. The cladding alloy is the same for both the Navy and the Army: Mn: 1.0 to 2.0%, Mg: 0.4-1.0%, Cu: 0.25% or less, Si: 0.3% or less, and Fe: 0.6% or less. According to this report, the standard for 24S in the US is Cu: 3.6 to 4.7%, Mg: 1.25 to 1.75%, and Mn: 0.3 to 0.9%.

6.2.5 Change in Direction to 24S

However, internal company reports from about May 1935 began to report test results for T3 and T3C alloys. “The production of the new T3 formulation (with more Mg than conventional SD) and T3C sheets using this T3 began a few months ago, replacing the conventional SD and SDC sheets,” (“*T3 and T3C sheets (First Report)* “ (Higashio, Research Report No. 3200, 6.1935)). This is consistent with the chronology of Sumitomo Light Metal Industries. The composition of the T3 alloy extruded material was Al-4.14%Cu-1.36%Mg-0.68%Mn-0.14%Si-0.28%Fe (Taketomi, Research Report No. 3202, 6.1935), which is exactly the 24S alloy.

From this time on, Sumitomo made a major turn in the direction of Super Duralumin. Dr. TANABE Tomojirō, who was then Assistant Director of the Research Department under Dr. MATSUDA Tsutomu, summarized the situation in his research report “*Review of So-Called ‘Super Duralumin*’” (Research Report No. 3306, July 31, 1935) and described the future direction as follows:

“1) Super Duralumin can be broadly classified into the Al-Cu-Mg alloys, the Al-Zn alloys, and the Al-Mg alloys, but only the Al-Cu-Mg alloys is available for the industrial production of thin sheets.

2) Current SD alloys (author’s note: silicon-containing Super Duralumin) are quenched and tempered, but are nearly perfect. Further increases in Cu and Mg will sacrifice toughness, but result in higher strength.

3) The US 24S was developed in a country where high-purity primary aluminum, such as 99.8%, are quite freely available. If 24S is the way of the world, so be it, but I doubt that it will be adopted in Japan. Even in the US, 24S is too expensive. The US recently adopted 27S (Al-4.5%Cu-0.8%Mg-0.8%Si), which is exactly like the SD alloy, as a general material.

4) Having said this, we must express our profound respect for Alcoa’s efforts to raise the Mg content to 1.5%. Dürener Metallwerke also raised the Mg content of Duralumin from 0.2 to 0.7% to 0.2 to 2.0%. We must not be blind to the world at large. There is no doubt that, in the future, high-grade Super Duralumin will literally be Si-free and Fe-free, and Al-Cu-Mg alloys will dominate.

5) We, and Japan, should not be unnecessarily enamored with 24S now, but should refer to the examples of European countries and take our own position. One has to deeply wonder what will happen when imports of 99.8% ingots are discontinued.

6) Al-Zn, E alloys (developed by Rosenhain, Great Britain; Al-20%Zn-2.5%Cu-0.5%Mg-0.5%Mn), Scleron (Al-12%Zn-3%Cu-0.5%Mg-0.6%Mn-0 to 0.1%Li alloy), Constructal8 (Al-7%Zn-2.5%Mg-1%Mn-0.2%Si alloy),[17] etc., have already become relics of the past due to rolling difficulties, but shouldn’t we reaffirm our commitment to alloy development? I hope to somehow complete the Al-Zn-Li system discovered by Igarashi. Al-Mg systems are also a possibility as ingot purity increases, so we must not forget to pay attention.”

Immediately after this, “*Exploration of High Strength Light Alloys (No. 1)*” (Research Report No. 33326, 8.10.1935) was published on August 10, indicating IGARASHI Isamu’s intention to begin the research and development of Super Duralumin.

The background of the conversion from the 14S series Super Duralumin to 24S was the higher cost due to the need for tempering, and performance problems such as smaller elongation and inferior intergranular corrosion resistance compared to 24S-T3 due to the use of 14S with T6. However, Sumitomo could not easily proceed with the 24S series because, although it was a national policy at the time to use domestically produced aluminum, there was the problem that domestically produced primary aluminum smelted from aluminous shale in Manchuria, which was annexed by Japan at the time, and alunite from the Korean Peninsula contained many impurities.[18, 19] In 1935, Nippon Aluminium’s alumina electrolysis plant was established in Kaohsiung, Taiwan, and the problem of impurities was solved when bauxite from the Dutch island of Bintan became available. However, the Dutch embargo on bauxite in May 1940 is also said to have triggered the Japanese occupation of French Indochina and the subsequent entry into the war.[19, 20]

6.3 24S Research by Dr. IGARASHI Isamu

6.3.1 Research on 24S Super Duralumin

In 1937, Dr. Igarashi submitted the report “ *On Super Duralumin ‘SD’ and Super Dural Clad ‘SDC’*” in the Research Report of Sumitomo Metal Industries.[21] Internal research reports indicate that the research itself was conducted around 1935. It was just at the time when Sumitomo was steering the company toward 24S as Super Duralumin. He used 99.8% ingot, fixed the Mn content to 0.6% and varied the Cu content from 2.4 to 5% and the Mg content from 0.5 to 3.8%. The strength map after quenching from 505 to 515°C and aging

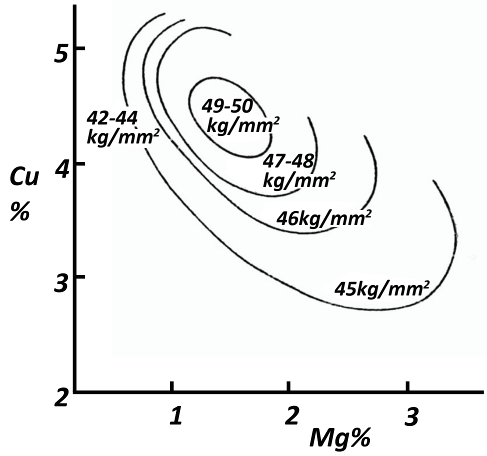


Figure 6.3 Effect of Copper and Magnesium Additions on Tensile Strength of Duralumin Alloys[14, 21, 22]

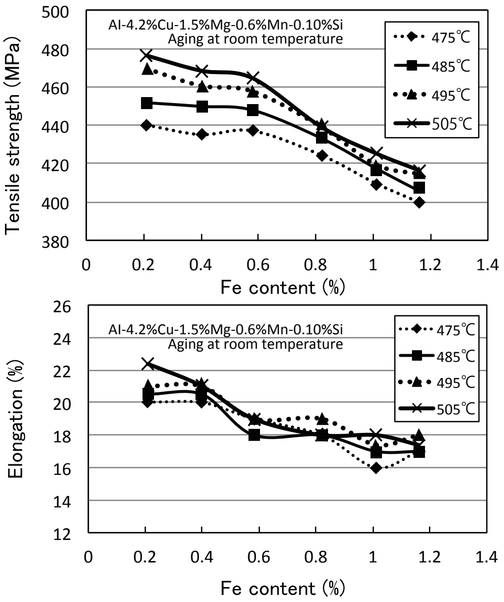


Figure 6.4 Effects of Fe Impurity Content on Tensile Properties of 24S Super Duralumin[23]

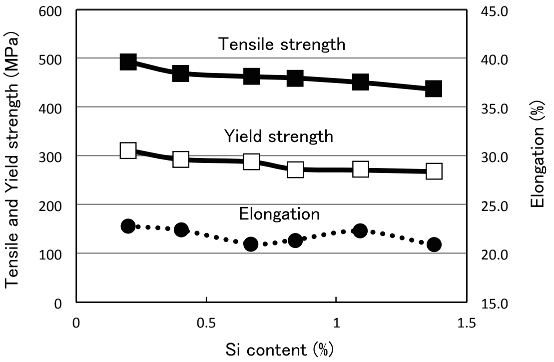


Figure 6.5 Effects of Si Impurity Content on Tensile Properties of Super Duralumin [14, 24]

for seven days is shown in Figure 6.3.[14, 21, 22] This map shows that a tensile strength of 50 kg/mm^2 can be obtained with 4.1 to 4.7% Cu and 1.2 to 1.8% Mg.

Unfortunately, however, the studies by Prof. Nishimura, Dr. Igarashi, and others all came after Alcoa's 24S was announced.

The effects of the Fe impurity were also revealed. NAKATA Hyōji, who was researching Super Duralumin under Dr. Tanabe, examined the effects of iron on 24S, saying, "As time progresses, the conservation of resources will be an increasingly important issue."[23] Figure 6.4 shows the tensile strength and elongation of materials made from 99.8% aluminum ingots with the iron content varying from 0.2 to 1.2% in 0.2% increments, rolled to 1-mm sheets, heated at 475 to 505°C for one hour, and aged at room temperature. It can be seen that both tensile strength and elongation decrease with an increase in iron. The increase in iron causes an increase in constituent particles and precipitates in the Al-Cu-Fe alloy, which leads to a decrease in copper concentration. These compounds do not decompose during solution treatment and remain, causing a decrease in elongation.

The effects of Si are shown in Figure 6.5.[24] Figure 6.5 is based on data by TOBA Yasuyuki of Furukawa Electric[14, 24] published in Nishimura's book, and shows tensile properties after seven days of quenching at 500°C for 30 minutes. The higher the Si content, the lower the tensile strength and elongation after aging at room temperature. When Si is high in Super Duralumin, the amount of Mg that forms S compounds to form Mg_2Si decreases, inhibiting age hardening. The S compound is expressed today as Al_2CuMg.

6.3.2 Development of Chromium-added 24S

Igarashi (Figure 6.6), upon joining the company, investigated the effects of 0 to 2.0% Mg addition to Silumin Al-Si, Al-Si-Zn, and Al-Si-Cu castings, to Sander alloys, and to Al-20%Zn-3%Cu materials of the E alloy. Subsequently, he conducted a series of studies on copper alloys as well as magnesium alloys for casting and wrought applications and the corrosion resistance of magnesium alloys. Internal research reports show that investigations were conducted on the mechanical properties and corrosion resistance of various aluminum alloys such as casting alloys for pistons such as Al-Cu-Mg-Ni-Fe Y alloys, Duralumin, Lautal Al-Cu-Si alloys, Aludur Al-Mg-Si alloys, Sander Al-Zn-Mg alloys, 3S, 4S, and SA3 Al-Mg-Mn alloys (Al-1.2%Mn-0.55%Mg), hydronalium Al-5-7%Mg alloys, and cladding materials. In his co-authored book "*Recent Advances in Light Metals and Alloys*" (Kōgyō Tosho K.K.) published in 1937, he incorporated some of the results of such research and wrote a chapter on "Corrosion Resistant Aluminum Alloys."[25] This research on a wide range of alloys during his first 10 years with the company is thought to have contributed greatly to the subsequent development of Extra Super Duralumin.

Figure 6.6 Dr. IGARASHI Isamu (1892-1986)

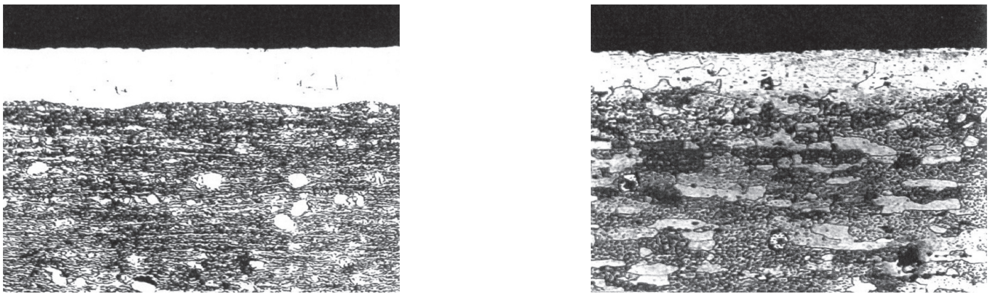
The addition of chromium, which was the decisive factor in the development of Extra Super Duralumin, had already been attempted in various alloys at Sumitomo. In the internal report dated October 12, 1926, " *On Al-Cu-Cr Alloys*", Dr. Tanabe reported that the addition of 0.5 to 1% chromium to

Al-4 to or 6%Cu resulted in no difference in strength when left quenched, but increased strength when tempered. Later, in October 1932, Dr. Matsuda, Dr. Tanabe's supervisor, also reported in Research Report No. 1842, "*Research on Special Duralumin (First Report)*", and in Research Report No. 1935, Second Report, in December 1932, that various trace elements were added at 1% or less and their strengths were compared, and that chromium increases strength to some extent up to 0.6%, but too much chromium is detrimental. Research Report No. 2019, Report No. 3, March 1933, examined corrosion resistance and stated that the addition of 0.91% chromium did not significantly improve the corrosion resistance of Duralumin, but there was little strength loss caused by corrosion.

Dr. Igarashi also reported in his July 1933 Research Report No. 2136 that he added copper, chromium, cobalt, vanadium, tungsten, and molybdenum to a 5.5% Mg alloy and compared strength and corrosion resistance, finding that the copper addition degraded corrosion resistance and the chromium addition was best.

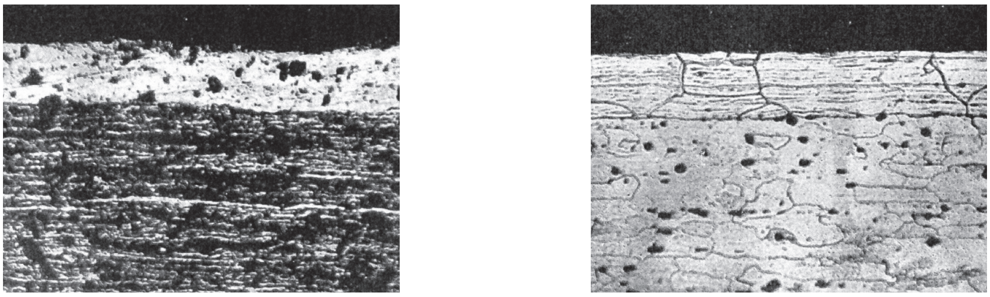
In his research report No.3455 "*New Clad Material for T3C Sheet*" of October 18, 1935, immediately after the development of Extra Super Duralumin was started, he reported that the copper of 24S in the core material diffuses into the cladding material (pure aluminum) during solution heat treatment, which inhibits corrosion resistance and reduces strength and elongation. He then developed a cladding material (Al-Cr alloy) with about 0.3% chromium added to prevent copper from diffusing into the cladding material. This was called "Cralclad."[22, 26] Sumitomo had already developed a cladding SA3 (Al-1.2%Mn-0.55%Mg alloy), which was stronger and more corrosion resistant than Alcoa's pure aluminum,[26] but the Cralclad resulted in less copper diffusion than this SA3. Figure 6.7 shows the cross-sectional microstructure of copper diffusing into cladding during solution annealing in quenching. The boundary between the cladding and core material was found to become indistinct after one hour of solution annealing with SA3, but was still clear after six hours of treatment in the Cralclad material, indicating that copper hardly diffused at all. The amount of copper diffusion into the cladding of the Cralclad material was about 1/20 to 1/5 that of the SDC material, depending on the thickness of the sheet.

In the Research Report No. 3480 "*Cr-Added Super Duralumin Sheet*" of November 5, 1935, HORI Sōji investigated the strength and corrosion resistance of an alloy of 24S Super Duralumin with 0.55% chromium, and concluded that the slightly poor results in corrosion resistance were probably due to the high content of Al-Cr compounds. Based on the results of these tests, in December 1935, a new SDC material was developed with 0.13% chromium added to 24S in the core material and 0.23% chromium added to the cladding.



a) SDC material as rolled

b) SDC material quenched and tempered 510°C/1 h WQ → 170°C/22h



c) 24S Cralclad material as rolled

d) 24S Cralclad material quenched 495℃ /6h WQ

Figure 6.7 Cross-sectional Microstructure of SDC Material (Cladding with SD and SA3)* 1 mm sheet as rolled and after quenching and tempering, and 1 mm sheet of 24S Cralclad material as rolled and after quenching
The boundary between the cladding and the core material is obscured by the copper diffusion layer formed by solution heat treatment in SCD, but is clear even after six hours of solution annealing in Cralclad material, indicating that copper hardly diffused at all.
*SD: Al-4.2%Cu-0.75%Mg-0.7%Mn-0.7%Si, SA3: Al-1.5%Mn-0.55%Mg
(From Higashio, research report, "*On Alclad and SA3-Clad (SDC) produced by US process*" (December 1934, No.2852))

Column: Dr. IGARASHI Isamu

The invention of Extra Super Duralumin was led by Isamu Igarashi. This Column reflects on Igarashi's personal history and research background.

Dr. IGARASHI Isamu (1892-1986) was born on January 15, 1892, the eldest son of three sons and four daughters of his father, Zenryu (11th head priest), and mother, Miki, at Higashi Kōmyōji Temple of the Otani sect of Shin Buddhism in Mizonoue, Tamana City. Higashi Kōmyōji Temple is currently headed by the 13th head priest, IGARASHI Kiyoshi, the eldest son of Igarashi's youngest brother Hideo (12th head priest) and a nephew of Isamu. After graduating from Hiroshima Higher Normal School in 1913, Igarashi taught at a junior high school in Taiwan, and then entered Kyoto Imperial University in 1919, and graduated from the Department of Physics, Faculty of Science in 1922. He joined Sumitomo Partnership Company, Ltd. at the age of 30 and worked at its copper works. From May of that same year to July of the following year, perhaps because the Sumitomo family supported HONDA Kotarō's invention of KS steel and the establishment of the institute, he studied at the Iron and Steel Research Institute of Tohoku Imperial University under the supervision of the Director, Honda. The Iron and Steel Research Institute was renamed the Research Institute for Iron, Steel and Other Metals, in 1922 in order to expand its research focus beyond iron and steel and include copper alloys and light alloys. In 1924, the monthly journal "*Research on Metals* [Kinzoku no Kenkyu]" was published, the first volume of which included Igarashi's paper "*On the Aging of Quenched Alloys*" and Matsuda's "*On the Transformation of Bronze, Aluminum Bronze, and Brass*". Many researchers were dispatched from Sumitomo Metal Industries. In 1935, Igarashi worked on the development of Extra Super Duralumin and filed a patent for the alloy in 1936. In 1939, he was awarded a doctorate in engineering from Osaka Imperial University for "*Research on Light Alloys as Aircraft Materials*". In 1941, he was appointed as Director of Research Department of Nagoya Works, and in 1943 became Director of Metal Research Laboratory and Director of Research Department of Copper Works at Sumitomo Metal Industries. The Metal Research Laboratory was established in 1943 to supervise the research and technology departments of Copper Works and Nagoya Light Alloy Works across the board. In 1945, he was appointed as Chief Engineer and Director of Engineering Department of Nagoya Works, and left the company in 1946. Dr. Igarashi was invited to Tohoku Imperial University as a lecturer, became a professor in the Faculty of Engineering the following year, a professor at the mining department of Akita University in 1951, and a professor at Iwate University in 1958, retired in 1962, and then served as a research advisor to Sumitomo Light Metal Industries, Ltd. During this period, he was awarded the Order of the Rising Sun, Gold Rays with Neck Ribbon in 1968 and the Honda Memorial Prize from the Honda Memorial Foundation in 1974. He spent the rest of his life in Shimazaki, Kumamoto City, where he passed away on March 7, 1986. He was 94 years old.

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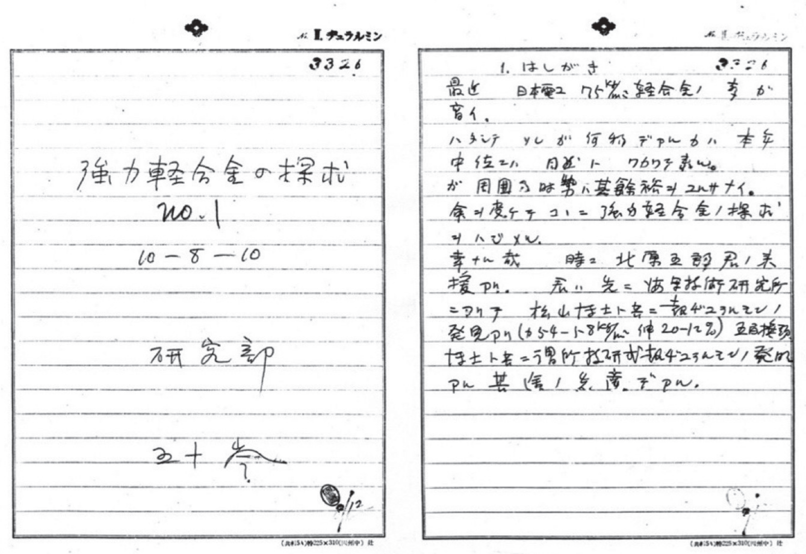
7 Development of Extra Super Duralumin

7.1 Research and Development Requested by Navy and R&D Initiated Declared by Dr. IGARASHI Isamu

In Sumitomo Metal Industries' internal Research Report No. 33326, dated August 10, 1935, Igarashi presented, "*Exploration of High Strength Light Alloys (No. 1)*", (Figure 7.1). This was the first report of the development of Extra Super Duralumin, and the same year that Sumitomo started 24S production. He was 43 years old, and his supervisor was Dr. Tanabe, who was three years younger than him. In the preface to the first section of the report, Igarashi states the following: "Recently, there has been a lot of buzz about Nippon Denko's 75 kg/mm^2 light alloy. What exactly this light alloy really is will naturally become clear around the middle of this year. But we don't have the luxury of waiting. Under orders, I began research on a high strength light alloy. Fortunately, Mr. KITAHARA Gorō (see Column) comes to our aid timely. Mr. Kitahara had previously discovered Super Duralumin (tensile strength: 54 to 58 kg/mm^2 (530 to 570 MPa), elongation: 20 to 12%) with Dr. Matsuyama at the Naval Technical Research Laboratory. Together with Dr. Iokibe, he invented the so-



No. I. ヂユラルミン

3326

強力軽合金の探求

No. 1

10－8－10

研究部

五十嵐

1. はしがき　3326

最近　日本電工 75瓩/mm² 軽合金ノ 事 ガ
喧イ。
ハタシテ ソレガ 何物デアルカハ 本年
中頃ニハ 自然ト ワカツテ来ル。
ガ 周囲ノ時勢ハ其余裕ヲ 許サナイ。
命ヲ受ケテ コヽニ 強力軽合金ノ探求
ヲハジメル。
幸ナル哉　時ニ 北原五郎君ノ来
援アリ。　君ハ 先ニ 海軍技術研究所
ニアリテ　松山博士ト共ニ 超ヂユラルミンノ
発見アリ（σ54－58kg/mm² 伸 20－12%）五百旗頭
博士ト共ニ 同所技研式超ヂユラルミンノ 発明
アル 其人ノ 名声デアル。

Figure 7.1 Cover and Overview of Research Report "*The Search for a High Strength Light Alloy (No.1)*" which Declared the Start of Research on Extra Super Duralumin

Column: KITAHARA Gorō

Mr. KITAHARA Gorō (1892-1971) joined the Naval Technical Research Institute after graduating from the Akita Mining College (predecessor of the Department of Mining Engineering, Akita University). After working for over 20 years, he joined Sumitomo Copper Works in 1935. With the birth of the Nagoya factory, he moved to Nagoya as the head of the research division, and in 1945 became the head of the research department at Shin-Fuso Metal Industries, Ltd. Dr. FUKAI Seikichi, a former Managing Director of Sumitomo Light Metal Industries, jointed Sumitomo Metal Industries at the same time and was 22 years younger, said, "I believe that ESD, the world-renowned high strength alloy that our company takes pride in for its invention and development, was only born because of the famous duo of Dr. Igarashi and Mr. Kitahara - or more precisely, because Dr. Igarashi had the strong support of Mr. Kitahara, who was like his right-hand man." Furthermore, "It is impossible for me, a junior, to describe Mr. Kitahara's personality, but he was an extremely kind and also impatient person. I often heard him say things like 'I'll just do the experiments first, thinking can come later. If I think too much or check reference materials, I'll start having doubts.' In other words, he 'worked quickly' and was skilled at experiments - someone who could carry out a wide range of experiments. I believe the combination of Dr. Igarashi coming up with ideas and Mr. Kitahara conducting experiments was truly an exquisite pairing." "For research and development, a lucid intellect and capable leadership are indispensable elements, but I also think speed is necessary. No matter how excellent an invention is, if others get ahead of you, its significance diminishes. The fact that a major undertaking like ESD was completed in an extremely short period of time may have been greatly due to Mr. Kitahara's 'swift hands.'" (FUKAI Seikichi, *Mourning the Passing of KITAHARA Gorō*.[1])

called Technical Research Laboratory-type Super Duralumin. He is a pioneer in this field."

The 75 kg/mm^2 (740 MPa) light alloy (Thom alloy) of Nippon Denko (later Showa Denko) was, in the words of NISHIMURA Hideo, a professor at Kyoto University, "much touted, and the news even reached overseas and was an issue in places like Germany. However, it could never be put to practical use because the problem of stress corrosion cracking was not resolved. Nevertheless, it is clear that the Thom alloy provided the impetus for the birth of ESD, so I would like to introduce here the aluminum alloy for which a patent application was filed on December 13, 1935, by MATSUNAGA Yōnosuke of Nippon Kako Co., Ltd. (Nippon Denko Group, currently Nippon Yakin Kogyo Co., Ltd.). This is an aluminum alloy containing 3 to 6% Mg, 6 to 14% Zn, 0.1 to 0.5% Fe, 0.1 to 0.7% Si, 0.1 to 1.5% Mn, 0.1 to 0.5% Ti, and 1 to 5% Ni and, when heat treated, has a tensile strength of 80 kg/mm^2 (780 MPa), However, it can be seen from the description that no attention was paid to season cracking, which is regrettable."[2]

Regarding the Thom alloy, the Navy was considerably concerned about it as well. After MATSUNAGA Yōnosuke gave a lecture at the Naval War College, ŌTANI Buntarō, who was then in charge of materials at the Naval Aviation Headquarters at the time, was summoned by his superiors who asked him what he was doing when there was such good material available.[3] In response, Ōtani said, "This is something that Sander had already announced 10 years earlier. We have already instructed Sumitomo to somehow solve the season cracking issue and put it into practical use." Ōtani later reminisced, "I don't know to what extent Sumitomo had progressed in their research before receiving these instructions. But I do remember issuing the research instructions. Earlier, the Army had adopted provisional specifications for this Thom alloy. As for the Navy, we decided not to adopt the Thom alloy unless the season cracking prevention issue was resolved, and waited for Sumitomo's research results. We frequently held consultation and research meetings with Mr. Kawamura from the Navy Aviation Arsenal to examine those results before adopting the alloy. When we did adopt it, we did so with truly solemn determination. However, at the time of adoption, we specifically adopted extruded shapes rather than sheets. I felt as if I had jumped from Kegon Falls. We then established standards and introduced ESD to the world for the first time."

According to YANAGIDA Kunio's "*Zero Fighter*" (Bunshun Bunko),[4] the person who ordered this development research was Lieutenant Colonel KAWAMURA Koui, an engineer in charge of materials research at the Naval Aviation Arsenal. In the book, he writes, "At that time, over 45 kg of Super Duralumin had already been developed, but in order to advance future fighter planes, we needed an alloy that was similarly lightweight, but even stronger - able to withstand a tensile strength of 50 to 60 kg per square millimeter. So, as the Navy Aviation Arsenal, we requested Sumitomo Metal to research and develop such a light alloy." Unfortunately, the official records relating to this seem to have been burned immediately after the war, as they cannot be found currently.

Column: Essay by Dr. IGARASHI Isamu, "*From a Corner of the Laboratory Room*"[5]

Dr. Igarashi's essay, "*From a Corner of the Laboratory Room*" in *Journal of The Japan Institute of Light Metals*, talks about the time when he started Extra Super Duralumin development. Here are some excerpts.

"I have been keenly reading the brilliant stories and valiant recollections of our esteemed seniors from the previous issues. However, this time I have been asked to write a retrospective on the light metals industry, but for someone like me who has spent a dreary life confined to a corner of the research lab, I can only offer rather dull memories compared to those vibrant tales. And yet, just as there are valleys beside mountains, if everything was a mountain, there would be no mountains at all. Allowing for some dreary recollections may serve to highlight the valiant stories.

Ever since graduating from school, I have been involved with light metals in a company research lab. It started with aluminum, which happened to coincide with the period of the rise of aluminum alloys in Japan, so while our accomplished seniors all took on aluminum, I could comfortably idle about.

Eventually, the era of handling magnesium arrived. I became tasked with assisting in that area. Since magnesium is difficult to handle, no one wanted to work on it. Being rather idle, I had no choice but to conduct various experiments."

"As our seniors each established their careers, an underling like me had no choice but to oversee all aspects of the research. It was around that time that Duralumin had matured as a material in the form of SD (author's note: Si added Super Duralumin) and SDC [author's note: a laminated sheet with SD cladding with SA3 (Al-1.2%Mn-0.55%Mg alloy) as the cladding material]. Just as we were breathing a sigh of relief, a new alloy called 'Thom alloy' was lavishly promoted. During World War I, the British had an 'E alloy,' and later the Germans had a 'Sander's alloy.' This wasn't a particularly special alloy, and suffered from season cracking, rendering it unusable - like a brilliant student who has excellent academic performance but cannot handle any load. Nevertheless, there was a clamorous demand in the world, so we reluctantly consulted on how we could make it usable."

7.2 Exploring Alloys with High Strength and Good Workability

7.2.1 Research on Various Alloys

Thus began the quest for light alloys based on the research of predecessors. The preliminary studies of alloy systems was first conducted from the perspectives of strength and workability based on data from Al-Zn-Cu E alloys, Al-Zn-Mg Sander's alloys, Al-Cu-Si Lautal alloys; Al-10%MgZn$_2$ Matsuyama alloys and Al-6%Mg-3.5%Zn Iokibe alloys from the Naval Technical Research Laboratory; and Al-8.5%Zn-1.5%Mg-1.5%Mn Matsuda alloys from Sumitomo Copper Works, and the like. This is probably due to the fact that the rolling process suffered greatly in the past. Interestingly, Al-Zn-Mg-Li was also considered. The E alloy was developed by Rosenhain et al. at the National Physical Laboratory in the United Kingdom, and its composition was Al-20%Zn-2.5%-Cu-0.5%Mg-0.5%Mn, containing up to 20% zinc, and was known as Zinc Duralumin. The rolled material had a tensile strength of 62.7 kg/mm^2 (615 MPa), a yield strength of 48.7 kg/mm^2 (478 MPa), and an elongation of 11% when a 1.04 mm sheet was quenched at 400ºC and aged (Research Report No. 3326, 8.10.1935).

However, alloys with high zinc content have a problem with season cracking (stress corrosion cracking) in which cracking occurs under prolonged loads even at stresses that are sufficiently small compared to the tensile strength. It was reported that the corrosive atmosphere promoted cracking, but the addition of Mn elongated the crystal grain size, reducing susceptibility to cracking. Table 7.1 lists research reports

Table 7.1 List of Research Reports Related to Extra Super Duralumin[6]

Report No.	Title	Date Created	Overview
No. 3326	*Exploration of Strong Light Alloys (No. 1)*	8.10.1935	Declared start of search
No. 3363	*Studies on Ultra-High Strength Light Alloys (Part 2)*	8.29.1935	Investigated effects of MgZn$_2$ on Lautal (Al-4%Cu-2%Si-0.5%Mg) alloys
No. 3379	*Exploration of High Strength Light Alloys (No. 3)*	9.1935	Investigated effects of composition on strength of E (Al-20%Zn-2.5%Cu-0.5%Mg-0.5%Mn) alloy systems
No. 3385	*Studies on Ultra-High Strength Light Alloys (Part 4)*	9.10.1935	Reported on age hardenability at room temperature and temper hardening of Al-(Al$_3$Zn$_6$Mg$_7$) and Al-(Al$_6$Mg$_4$Cu) alloys
No. 3427	*Exploration of High Strength Light Alloys (No. 5)*	10.1935	Evaluated performance of E alloy systems
No. 3479	*Studies on Ultra-High Strength Light Alloys (Part 6), Tensile Strength Tests of Several New Light Alloys*	11.5.1935	Tensile test of 1-mm sheet of Lautal + (Al$_3$Zn$_6$Mg$_7$) 8 to 10% additive material and Al + (Al$_3$Zn$_6$Mg$_7$) 10 to 14% additive material
No. 3538	*Studies on Ultra-High Strength Light Alloys (Part 7), Relationship between Heat Treatment and Mechanical Properties of Nos. 23 and 24 Alloys*	12.17.1935	Investigated optimal heat treatment conditions for alloys in previous report
No. 3586	*Studies on Ultra-High Strength Light Alloys (Part 8), On D (Duralumin)-S (Sander's Alloy)-E (E Alloy) Ternary Alloy*	2.4.1936	Research on "changing composition ratios of D (Al-4%Cu-1.5%Mg-0.5%Mn), S (Al-8%Zn-1.5%Mg-0.5%Mn), and E(Al-20%Zn-2.5%Cu-0.5%Mg-0.5%Mn) alloys and addressing the hypothetical question, "Are there any Al-Cu-Zn-Mg quaternary alloys that are quite excellent?"
No. 3719	*Studies on Ultra-High Strength Light Alloys (Part 9, Mechanical Properties of 60 kg Duralumin*	4.25.1936	Investigated mechanical properties of 1-mm sheet prototypes based on results of Part 8, assuming quaternary alloys Al-9.6%Zn-1.2%Mg(2.0%Cu(0.5%Mn, Al-10%Zn-1.3%Mg-2.5%Cu-0.5%Mn, and Al-6.5%Zn-3.0%Mg-0.5%Mn are excellent.
No. 3800	*Studies on Ultra-High Strength Light Alloys (Part 10), Mechanical Properties of 60 kg Duralumin Extruded Rods*	6.2.1936	Investigated the tensile strength of Al-10%Zn-1.5%Mg-2.5%Cu-0.5%Mn, Al-9.0%Zn-2.0%Mg-1.0%Cu-0.5%Mn alloy 30-mm diameter extruded rod prototypes. After quenching and tempering, the rods exhibited a yield strength of 60 kg/mm^2 or higher, tensile strength of 65 kg/mm^2 or higher, and elongation of 8% or higher. Of the extruded head portion and end portion, the end portion was harder and significantly stronger.
No. 3810	*Studies on Ultra-High Strength Light Alloys (Part 10, No. 2) Mechanical Properties of 60 kg Duralumin*	6.8.1936	Investigated the mechanical properties of rolled sheets and profiles. Sheet tensile strength 60 kg/mm^2, yield strength 50-52 kg/mm^2, elongation 10-15%; profiles equivalent to bars.
No. 3851	*Studies on Ultra-High Strength Light Alloys (Part 10, No.3) Influence of Other Elements on Properties of Ultra-High Strength Light Alloys*	6.26.1936	Added elements such as Ni, Fe, Cr, Ca, Ti, and V to Al-10%Zn-1.3%Mg-2.5%Cu-0.5%Mn alloys and Al-8%Zn-3%Mg-0.5%Mn alloys to investigate mechanical properties and seawater resistance. "The addition of Cr (in small amounts), Ca, V, and Ti has the effect of improving the corrosion resistance of the base alloy without decreasing its properties."
No. 3852	*Studies on Ultra-High Strength Light Alloys (Part 10, No.4) Workability of Super-Strength Light Alloys*	6.26.1936	Compared bendability of rolled materials of T415 (ESD: Al-10.1%Zn-1.61%Mg-2.3%Cu-0.52%Mn-0.28%Fe-0.18%Si), T418 (Thom alloy: Al-9.33%Zn-2.0%Mg-1.0%Cu-0.53%Mn-0.28%Fe-0.21%Si) by bending test.
No. 3854	*Studies on Ultra-High Strength Light Alloys (Part 10, No. 5) Mechanical Properties of Cladding Material of E.S.D. Alloy*	6.30.1936	Created prototype of E.S.D. alloy cladded with Cr-containing aluminum cladding. Good adhesion. Diffusibility due to heating becomes significant for longer periods of time, but need not be considered within the specified time.
No. 3859	*Studies on Ultra-High Strength Light Alloys (Part 10, No. 6) Thermal Treatment of E.S.D. Light Alloy*	7.4.1936	Determined optimum hardening temperature and tempering time.
No. 3865	*Studies on Ultra-High Strength Light Alloys (Part 10, No. 7) Seawater Resistance of E.S.D. Alloy*	7.6.1936	Tested materials by immersion in a corrosive solution, and subsequently evaluated by corrosion loss measurement and tensile strength measurement. The bare material did not have good resistance to seawater and grain boundary corrosion occurred. The Cr-containing cladding material improved markedly.
No. 3892	*Studies on Ultra-High Strength Light Alloys (Part 10, No. 8) Annealing Temperature of E.S.D. Alloy*	7.18.1936	Studied the optimum annealing temperature and time.

showing the history of alloy selection for the development of Extra Super Duralumin alloys.[6]

7.2.2 Selection of Candidate Materials for Extra Super Duralumin

Ultimately, the compositions studied were based on the Al-$MgZn_2$ Sander's alloy, Al-Cu-Mg Super Duralumin alloy, and Rosenhain's E alloy from the UK. The dissertation states, "The first one (S) is an aluminum alloy with Mg-Zn, the second one (D) with Cu-Mg, and the third one (E) with Cu-Zn-Mg as main compositions. Zn, Mg, and Cu form the most solid solutions with Al, with the exception of Ag, and their solubility also changes the most with temperature. Therefore, it can be imagined that the strongest and most heat-treatable practical alloy (the addition of precious metals like Ag is not interesting for industrial alloys) would come from this system. For aircraft structural materials, high strength is of course necessary, but the ability to fabricate thin sheets and extruded materials is an indispensable requirement to take advantage of the strength of the materials. So first, in the ternary systems of S, D, and E, an alloy search was conducted to find the alloy that is softest in the annealed state and strongest in the heat-treated state, and has the greatest workability and heat-treatment effect. "[7] And, thus the alloy search was performed. This is very important from an industrial perspective.

The respective alloy compositions are D: Al-4%Cu-1.5%Mg-0.5%Mn, S: Al-8%Zn-1.5%Mg-0.5%Mn, and E: Al-20%Zn-2.5%Cu-0.5%Mg-0.5%Mn. First, "Die cast ingots were cast over the entire D-S-E ternary system, held at 400°C, 450°C, and 500°C for 4 hours each and quenched, aged for 7 days, and then their Brinell hardness was measured. They were further tempered at 150°C for 24 hours and remeasured for hardness. Next, they were annealed at 300°C for 5 hours, furnace cooled (FC), and measured for hardness a third time." Detailed experimental data (hardness after aging and after furnace cooling) for different ratios of D, S, and E alloys are shown in Table 7.2.

Next, "the hardening ratio [Note: hardening ratio = (maximum hardness - annealed hardness) / annealed hardness] was obtained by comparing the hardness obtained by quenching followed by tempering with the annealed hardness as the basis." This is based on the belief that "a large hardening ratio indicates that the material is softer in the annealed state compared to its maximum hardness, and therefore should be easily deformable." As a result, No. 57 and No. 61 were hard and three alloys were selected with "their compositions being 8 to 10% zinc and around 2.5% copper."[8-10]

- Al-10%Zn-1.5%Mg-2.5%Cu-0.5%Mn-0.01%Ti (ESD No.1 alloy)
- Al-8%Zn-1.5%Mg-2%Cu-0.5%Mn-0.01%Ti (ESD No.2 alloy)
- Al-8%Zn-1.5%Mg-2.5%Cu-0.5%Mn-0.01%Ti

The properties of sheets, rods, extruded shapes, and tubes of these alloys were investigated, and the results were as follows: "The new high strength light alloy E.S.D has a yield strength of 36 to 65 kg/mm^2 (350 to 640 MPa), a tensile strength of 58 to 70 kg/mm^2 (570 to 690 MPa), an elongation of 8 to 20%, and a Brinnel hardness of 150 to 200. It has significantly superior mechanical properties compared to the aluminum alloys currently in use, and is considered to be an epoch-making new material for aircraft components. However, this alloy has a fatal flaw in that it cracks with time under certain special conditions. The German Sander's alloy and the British E alloy, despite their excellent mechanical properties, have not been put to practical use, mainly because of defects of this kind"[8] (from dissertation), and so the company began

Table 7.2 Relationship between Mixing Ratios of D, S and E Alloys and Strength and Hardenability (Workability).
(From Dr. Igarashi's dissertation)[8-10]

Alloy Number	D (%)	S (%)	E (%)	Zn (%)	Mg (%)	Cu (%)	Mn (%)	400°C/4h WQ		450°C/4h WQ		500°C/4h WQ		300°C/5h (FC)	Hardenability (%)
								RT/7days	150°C/24h	RT/7days	150°C/24h	RT/7days	150°C/24h		
39	80	20	0	1.6	1.5	3.2	0.5	94.2	93.0	116.0	109.0	107.0	113.0	52.8	120
40	60	40	0	3.2	1.5	2.4	0.5	96.8	99.2	110.0	106.2	96.4	105.0	63.0	75
41	40	60	0	4.8	1.5	1.6	0.5	102.0	132.4	109.0	131.2	95.0	126.4	56.2	136
42	20	80	0	6.4	1.5	0.8	0.5	114.0	140.0	101.0	137.4	95.0	147.2	62.6	136
43	80	0	20	4	1.3	3.7	0.5	105.8	104.0	121.0	118.0	108.0	120.0	59.8	102
44	60	0	40	8	1.1	3.4	0.5	120.0	138.8	130.0	153.2	107.4	145.8	83.6	74
45	40	0	60	12	0.9	3.1	0.5	130.0	154.6	140.2	161.2	120.0	147.2	83.0	94
46	20	0	80	16	0.7	2.8	0.5	153.0	156.4	143.0	153.2	114.0	131.2	95.4	64
47	0	80	20	10.4	1.3	0.5	0.5	116.0	147.2	125.2	158.0	110.0	156.0	76.4	107
48	0	60	40	12.8	1.1	1	0.5	134.8	162.7	140.2	161.2	127 6	158.0	63.6	89
49	0	40	60	15.2	0.9	1.5	0.5	134.8	158.0	140.0	151.6	130.0	144.4	94.8	67
50	0	20	80	17.6	0.7	2	0.5	147.2	161.2	141.6	159.6	118.0	138.8	95.4	69
51	80	10	10	2.8	1.4	3.45	0.5	102.0	97.6	113.0	116.0	108.0	113.0	57.4	102
52	10	80	10	8.4	1.4	0.65	0.5	119.0	151.6	110.0	147.2	109.0	159.6	73.0	116
53	10	10	80	16.8	0.7	2.4	0.5	153.0	165.8	150.0	153.2	119.0	131.2	97.6	116
54	60	20	20	5.6	1.3	2.9	0.5	109.0	119.0	115.0	130.0	117.0	132.4	77.6	74
55	20	60	20	8.8	1.3	1.3	0.5	117.0	150.0	122.0	154.8	109.0	153.2	67.6	129
56	20	20	60	13.6	0.9	2.3	0.5	145.8	161.2	144.4	164.2	127.6	145.8	86.6	137
57	40	30	30	8.4	1.2	2.35	0.5	126.4	156 4	125.2	161.2	109.0	123.0	65.0	148
58	30	40	30	9.2	1.2	1.95	0.5	124.0	154.8	128.8	169.4	120.0	159.6	73.6	129
59	30	30	40	10.4	1.1	2.2	0.5	131.2	156.4	115.0	150.0	115.0	145.8	74.0	112
60	20	40	40	11.2	1.1	1.8	0.5	127.6	153.2	131.2	161.2	103.0	140.2	75.6	113
61	40	20	40	9.6	1.1	2.6	0.5	122.0	150.0	130.0	167.6	118.0	151.6	67.6	148
62	40	40	20	7.2	1.3	2.1	0.5	113.0	115 0	116.0	162.7	116.0	148.6	71.2	128
63	100	0	0	0	1.5	4	0.5	94.2	93.6	113.0	105.0	113.0	117.0	53.6	118
64	0	100	0	8	1.5	0	0.5	108.2	136.0	112.0	143.0	111.0	148.6	73.8	101
65	0	0	100	20	0.5	2.5	0.5	158.0	161.0	145.8	144.4	124.0	124.0	89.8	79

to examine measures to prevent season cracks.

The first time the name E.S.D. alloy appears in a title of an internal research report is in Research Report No. 3854, " *Research on Super-High Strength Light Alloys (No. 10-5), Mechanical Properties of 'Cladding' Materials of E.S.D. Alloy*" (6.30.1936). This is probably due to the direction of alloy development being decided at this time. Each letter of E.S.D. is followed by a period in the expression at this time. There is no particular description in the research report as to the background behind the decision to use this name. According to FUKAI Seikichi, it was FURUTA Shunnosuke, Senior Managing Director of Sumitomo Metal Industries and Director of Copper Works, who coined the named ESD (Extra-Super-Duralumin) around May or June 1936, but the Sumitomo Light Metals chronology states, "In 1937, the alloy was named ESD after the initial letters of E alloy, S alloy and D alloy (Super Duralumin), which were the basis of research."[11]

7.2.3 Thom Alloy

Interestingly, according to research reports from Sumitomo Metal Industries in May, September, and November 1936, the company procured and conducted a performance verification study on Thom alloy sheets, rods, and forged round bars from Nippon Denkō, which were described as having caused "a great sensation in the aluminum light alloy world" with a claimed tensile strength of 75 kg/mm^2. This emphasizes just how big an impact this news had, as Prof. Nishimura mentioned earlier. In Research Report No. 3738, "*On Thom Alloy*" (5.5.1936), the procured Thom alloy sheet had a composition of Al-9.05%Zn-2.15%Mg-0.9%Cu-0.49%Mn-0.22%Fe-0.27%Si, a tensile strength of 61.7 kg/mm^2 (605 MPa), a yield strength of 43.2 kg/mm^2 (424 MPa), and an elongation of 13%. The report comments, "This alloy is very similar in composition and mechanical properties to '60-kg Duralumin'." This "60-kg Duralumin" is likely referring to ESD.

7.3 Establishment of Evaluation Method for Season Cracking (Stress Corrosion Cracking)

7.3.1 Detailed Observation of Occurrence of Season Cracking

Now, this was the period where the famous duo of Igarashi and Kitahara truly shined in tackling the issue of season cracking. It was the Research Report No. 3939, "*On the Cracking of the New E.S.D Alloy (First Report)*" dated August 20, 1936. The summary of this important research report is a bit long, but is quoted here. From the handwriting, the author seems to be Mr. Kitahara:

"We investigated the special phenomenon of cracking that occurs in the E.S.D. light alloy under residual internal stresses, and studied countermeasures to prevent this phenomenon.

(1) The following three methods were used as the cracking test methods.

1. Stamping method, 2. Cupping method,
3. Bending method

(2)

i) Regardless of whether copper is contained or not, alloys of this system have a tendency to naturally crack under residual internal stresses. Of course, there are differences in severity depending on the composition or condition, but they all eventually crack.

ii) Cracking is far more severe when the sample is subjected to impact forces rather than static external forces.

iii) The crack defects always follow along the grain boundaries. Even in intentionally fractured areas, the cracking tends to occur along the grain boundaries. This seems to be closely related to the grain size.

iv) For quenched and aged samples, no defects occurred from the stamping or cupping method within the test period, but cracking did occur from the bending method.

v) For the Al-Zn binary alloys, the alloys containing 20% Zn, the alloys quenched & aged, and the alloys annealed at 300°C cracked, but the alloys quenched & tempered and the alloys rolled did not crack. Of course, alloys with less than 20% Zn did not crack in any state (by bending method).

vi) Duralumin did not crack when riveted.

vii) It is reasonable to consider that this phenomenon is an inherent characteristic of this light alloy, similar to so-called "season cracking."

(3) The cracking phenomenon of this alloy can be improved by appropriately adjusting the quenching and tempering temperatures. For example, the E.S.D. alloy quenched at 430°C and tempered at 100°C does not crack from the stamping or cupping method. However, the bending method will eventually lead to cracking no matter how short or long the time, even for quenched and age-hardened samples. In other words, adjusting the quenching and tempering temperatures cannot completely prevent cracking.

(4) Based on the hypothesis that the cracking phenomenon of alloys is greatly influenced by the presence or absence of the γ phase (note: recently called the α phase in phase diagrams) in the Al-Zn alloys, tests were conducted on the following five alloys:

Al-8%Zn-1.5%Mg-2.5%Cu-0.5%Mn (failed to produce sheet),
Al-8%Zn-1.5%Mg-2%Cu-0.5%Mn,
Al-7.5%Zn-3%Mg-0.5%Mn,
Al-7.0%Zn-3%Mg-0.5%Mn,
Al-6.5%Zn-3%Mg-0.5%Mn

1) A small addition of copper seems to have a mitigating effect on cracking.

2) The three copper-free alloys showed significant cracking compared to the copper-containing ones.

3) Among these alloys, Al-8%Zn-1.5%Mg-2.5%Cu-0.5%Mn was the highest quality and least prone to cracking. The others cracked even in the quenched

and aged state, but this one did not, and its tensile strength was on par with E.S.D.

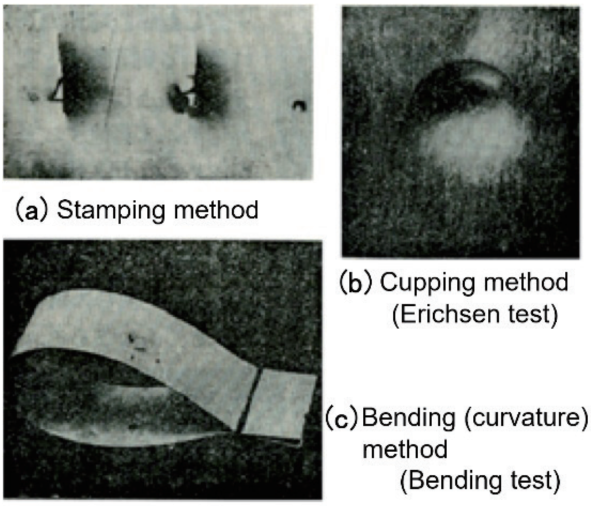
4) The effect of the tempering temperature on cracking of Al-8%Zn-1.5%Mg-2.5%Cu-0.5%Mn and E.S.D. alloys was worst at 125°C, and became better both above and below that temperature.

5) It was considered that the Al-8%Zn-1.5%Mg-2.5%Cu-0.5%Mn alloy could sufficiently withstand bending to the degree shown (figure omitted) for practical use.

(5) The addition of around 0.1% Ti in this alloy as well as Al-4%Zn-3%Mg-1-2%Cu-0.5%Mn alloys remarkably reduced cracking, allowing the alloys to pass the bending test without cracking even five days later. This may resolve the problem, though no premature conclusions should be made. The mechanical properties are comparable to those of E.S.D." This shows that the research team carefully observed the results of simple test methods for season cracking.

7.3.2 Evaluation Method for Season Cracking: Stress Load Method

Let's look at the experimental methods in more detail. The experimental methods were reported in Journal of the Japan Institute of Metals and in Research Reports of Sumitomo Metal Industries, which will be introduced here. Regarding the evaluation method for season cracking, the reports stated: "The phenomenon conventionally called season cracking is generally well-known as something specific to copper alloys, especially brass. There are many research papers on this topic, both domestically and internationally. However, for light alloys, while it has been said for quite some time that aluminum alloys containing a large amount of zinc tend to undergo season cracking, there are virtually no research papers on this topic, neither domestically nor internationally."[9-10] So they had to start by establishing the experimental and evaluation methods. Figure 7.2 shows the test methods.


(a) Stamping method

(b) Cupping method (Erichsen test)

(c) Bending (curvature) method (Bending test)

Figure 7.2 Various Evaluation Methods for Stress Corrosion Cracking[9, 10]

"(1) Stamping method

A 7-mm square English letter or number was stamped onto the sample surface with a chisel. As shown in the figure, cracks tended to occur at the protruding corners of the characters, in some cases just a few hours after stamping.

(2) Cupping method

Using an Erichsen tester, the maximum cup depth was taken as the Erichsen value. Cups of various depths were formed and left, with the deepest cups cracking in just over 10 hours. Shallower cups took several days, and even shallower ones did not crack after several months.

(3) Bending method (curvature method)

A 25-mm wide, 180-mm long sample strip was bent at both ends as shown in Figure 7.3, with the gap between the ends varied by binding with copper wire, and left at room temperature to observe cracking. The results showed that samples with zero gap, in other words completely touching, cracked in just tens of minutes. As the gap distance increased, the time until cracking became longer. Beyond a certain distance, almost no cracking occurred. In other words, the time until cracking increased or decreased proportionally to the bend radius at the apex of the bent sample strip. This indicates that cracking requires a certain minimum stress level."[9, 10]

In addition to these, tube flattening tests were conducted. It was reported that "season cracking is said to occur due to the tensile stress component of a complex stress state, and absolutely does not occur due to compressive stress. This is also evident from the fact that cracking in the above experiments was always limited to the tensile stressed side." Thus, tensile tests were also performed. "From the relationship curve between tensile stress and time until season cracking occurs, it becomes more difficult for season cracking to occur as the stress decreases. And, judging from the trend of the curve, it seems that cracking may not occur at all below around 15 kg/mm^2 stress," suggesting the existence of a threshold stress for season cracking to occur.

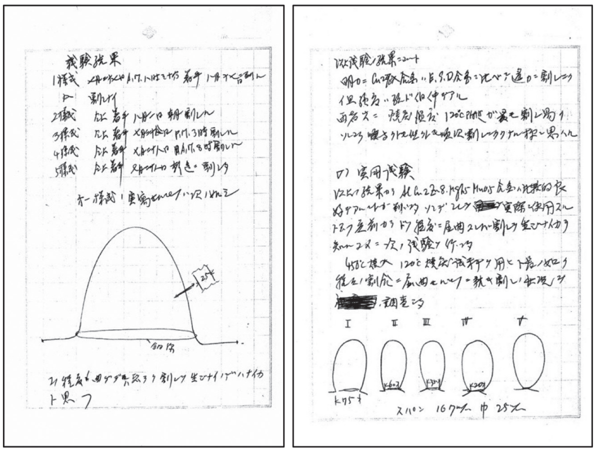


Figure 7.3 Evaluation of Stress Corrosion Cracking by Bending Test (Research Report No. 3939 dated 8.20.1936)

7.3.3 Corrosive Environment

"From the experimental facts that season cracking follows along grain boundaries and occurs even under stresses far lower than the alloy's tensile strength, stress alone cannot be considered a sufficient and satisfactory condition for season cracking. There is also no intrinsic evidence suggesting it is caused by internal changes in the metal. Therefore, it must be considered a combined effect of stress and external factors." With this, Igarashi and Kitahara examined the influence of the test environment. It was known that season cracking did not occur in pure air or with Ni plating for brass. To determine which element in air had the most influence, bending tests were conducted in air, dry air, oxygen, nitrogen, hydrogen, and vacuum environments. The results showed water vapor had the most severe effect, causing cracking about one-tenth as fast as in air. Notably, samples that cracked within around 30 minutes in air did not crack in a vacuum. Next, since cracking followed along grain boundaries, they considered that solutions causing intergranular corrosion would also promote cracking. Testing in various aqueous solutions revealed that salt water and hydrochloric acid solutions had a particularly strong effect. Furthermore, since cracks easily formed when applying stress during the soldering of brass or steel, immersion in molten low-melting point metal solutions (PbSn, BiCd) at 80°C caused cracking within 1 to 2 minutes. This was also considered a type of season cracking. By testing with cladding materials to eliminate external factors, they reported that no season cracking occurred.

7.3.4 Effect of Alloying Elements on Season Cracking

Following the first report compiled in August 1936, research on season cracking by bending tests was conducted using 0.5-mm thick sheets. Table 7.3 shows a list of the company's internal research reports regarding the effect of alloy elements on season cracking.[6] In the summary of Report 11 (No. 4144) from December of the same year, it states: "Now, assuming the chemical composition of the ultra-high strength light alloy (E.S.D.), it would be as follows: Al, R (remainder), Cu 2%, $MgZn_2$ 11-12%, Mn 0.5%, and Cr 0.3%., with the amounts of Cu, Cr, Mn additions requiring further study. The mechanical properties are tensile strength 55 kg/mm^2 (540 MPa), yield strength 45 kg/mm^2 (440 MPa), and elongation 8% or greater." Figure 7.4, published in the dissertation, shows the effect of added elements on season cracking.[8] It can be seen that the alloy with 0.17% added chromium did not exhibit season cracking within the experimental range.

The composition was largely fixed, and they were approaching the industrial trial production stage. According to Research Report No. 4241, "*E.S.D. Study on the ESD Light Alloy, On Several Properties of the ESD-No.2 Trial Product*" (2.22.1937), factory trials were conducted on E.S.D.-No.2 (Al-8%Zn-1.5%Mg-2%Cu-0.5%Mn) and E.S.D.-No.2+0.3%Cr. E.S.D.-No.2+0.3%Cr had a tensile strength of 58 to 60 kg/mm^2 (570 to 590 MPa), a yield strength of 48 to 52 kg/mm^2 (470 to 510 MPa), and an elongation of 10 to 16%, satisfying the specified standards (tensile strength 53 kg/mm^2 (520 MPa) or greater, yield strength 45 kg/mm^2 (440 MPa) or greater, and elongation 8% or greater). It passed the 180° bending test with a 3t radius and showed excellent fracture resistance, with no cracking even after two months. From this point on, 0.2 to

Table 7.3 Effect of Alloying Elements on Season Cracking[6]

Report No.	Title	Date Created	Description
No. 3939	*On the 'Cracking' of the New ESD Alloy (First Report)*	8.20.1936	Investigated the special phenomenon of cracking that occurs in the E.S.D. light alloy under residual internal stresses, and studied countermeasures to prevent this phenomenon.
No. 3988	*On the 'Cracking' of E.S.D. Alloy (Second Report)*	9.19.1936	Practicality in quenching and tempering study of low zinc E.S.D. (Al-4%Zn-3%Mg-1 or 2% Cu) alloy and E.S.D. No. 2 (Al-8%Zn-1.5%Mg-2%Cu-0.5%Mn) alloy.
No. 4017	*On the 'Cracking' of E.S.D. Alloy (Third Report)*	9.30.1936	Can withstand E.S.D. No. 2 use. Can be placed with Ti and Mo to prevent cracking.
No. 4030	*On the 'Cracking' of E.S.D. Alloy (Fourth Report)*	10.12.1936	Added Mn 1.2, 1.5%, developed crystal grain, inhibited fracture. Investigated Li-containing alloy as well.
No. 4047	*On the 'Cracking' of E.S.D. Alloy (Fifth Report)*	10.23.1936	E.S.D. No. 1 (Al-10%Zn-1.5%Mg-2.5%Cu); remarkable fracture resistance at Mn 1.2% or greater.
No. 4092	*On the 'Cracking' of E.S.D. Alloy (Sixth Report)*	11.18.1936	Added 0.5 to 1.67% Mo to E.S.D. No. 2. Addition of 1% or less Mo significantly reduces fracture resistance.
No. 4099	*On the 'Cracking' of E.S.D. Alloy (Seventh Report)*	11.27.1936	Added Mo, Cr, Co, Ti, Cu, Mg, and to E.S.D. No. 1 (Al-10%Zn-1.5%Mg-2.5%Cu-0.5%Mn). Co addition is superior in tensile strength, while Cr addition is superior in fracture resistance. Mo is not as good as No. 2. Mn 1.5% is too much.
No. 4112	*On the 'Cracking' of E.S.D. Alloy (Eighth Report)*	12.1.1936	Added Mn 0.5, Mo 0.3, Cr 0.3, Ti 0.1, and Mo 0.3, Cr 0.3, Ti 0.1 to E.S.D. No. 2 alloy. Good fracture resistance.
No. 4113	*On the 'Cracking' of E.S.D. Alloy (Ninth Report)*	12.2.1936	Investigated the effects of single and combined additions of Mn and Cr on the basis of E.S.D. No. 1 and E.S.D. No. 2. No. 2 series excellent.
No. 4121	*On the 'Cracking' of E.S.D. Alloy (Tenth Report)*	12.5.1936	Added Ni to E.S.D. No. 1 ZnCuMg base. Increased tensile strength, but no effect on fracture resistance.
No. 4144	*On the 'Cracking' of E.S.D. Alloy (Eleventh Report)*	12.21.1936	Added Ag, Ca, Si, and Sn to the E.S.D. No. 1 alloy, but the fracture resistance could not be improved.
No. 4244	*On the 'Cracking' of E.S.D. Alloy (Twelfth Report)*	2.24.1937	Effect of Cu, Zn, Cr, Bi and Sb on fracture resistance of E.S.D. No. 2 alloy. Little change within 0.1 to 0.35% Cr. Little Sb and Bi effect on fracture resistance.

0.3% Cr was added to the E.S.D.-No.2 alloy. It is considered that by around February, the E.S.D. alloy composition became Al-8%Zn-1.5%Mg-2%Cu-0.5%Mn-0.25%Cr.

The subsequent Research Report No. 4352, “*Ultra-High Strength Light Alloy E.S.D.-No.2, Properties of E.S.D.-No.2 Cladding Material*” (4.27.1937) investigated the properties of a cladding material using Al-2.5%Zn-0.5%Cr as the cladding. The tensile strength was 55 kg/mm^2 (540 MPa), the yield strength was 49 kg/mm^2 (480 MPa), and the elongation was 10%, comparable to the bare material, with good fracture resistance and corrosion resistance. It was mentioned that a patent application for this cladding material was underway as of May.

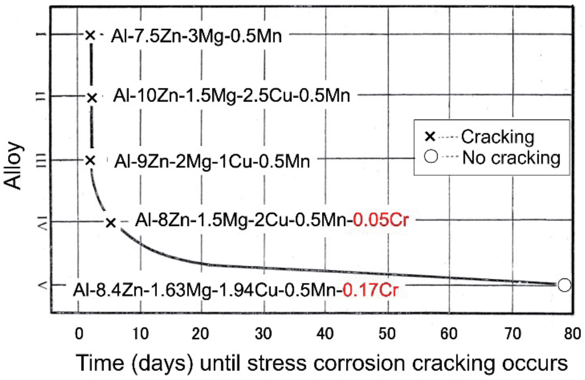


Figure 7.4 Effect of Chromium Addition on Season Cracking of Al-Zn-Mg Alloys[8]

7.4 Patent Applications and Academic Papers

7.4.1 Patents

The basic patent related to ESD was filed on June 9, 1936 under the title “*High Strength Light Alloy for Forging*” It was published on October 24, 1939 and established as Patent No. 135036 on February 28, 1940. The inventors were IGARASHI Isamu and KITAHARA Gorō, with Sumitomo Metal Industries as the patent holder. The first page of this patent is shown in Figure 7.5.

“Feature and Object of the Invention”

“The present invention relates to high strength wrought light alloys for forging characterized by containing 3 to 20% zinc, 1 to 10% magnesium, 1 to 3% copper, 0.1 to 2% ‘chromium,’ and either containing or not containing 0.1 to 2% manganese, with the remainder being aluminium. An object of the present invention is to obtain a high strength and season cracking-free wrought light alloy.” As shown in Table 7.4, there were five patents filed by Dr. Igarashi from 1935 to 1937 related to Al-Zn-Mg alloys, only two of which involved Cr. These patents, including related ones, are listed in the table in order of filing date.[6]

Note that, as for patents related to this ESD patent, applications were filed around 1938 in the United States, United Kingdom, Germany, France, and Italy. US Patent 2,166,495 (Application 6.20.1938, Patented 7.18.1939) specifies required compositions of 4 to 20% Zn, 1 to 2% Mg, 1 to 3% Cu, 0.1 to 1.5% Mn, 0.05 to 1.0% Cr, and 0.01 to 0.2% Ca, and for improving workability and properties, 0.01 to 0.2% Mo, 0.01 to 0.5% Ti, and up to 1% Fe and Si. It is unclear why the Mg range was narrowed and Ca was made a required composition in the US patent.

Interestingly, the application date of the ESD patent “High Strength Wrought Light Alloys “ was 6.9.1936. It is unknown to what extent they had grasped the season cracking mitigation effects of Cr by that point. There are no reports mentioning Cr-added alloys until Research Report No. 3851, “*Studies on Ultra-High Strength Light Alloy (Part 13), Effects of Other Elements on Properties of Ultra-High Strength Light Alloy*” (6.26.1936). Even that was not a test for season cracking. The first report believed to mention the effect of Cr addition on season cracking is Research Report No. 4099, “*On the ‘Cracking’ of E.S.D. Alloy (Seventh Report)*” (11.27.1936).

Of course, there can be a few months’ lag between experimental results and report writing even today, so the results

Table 7.4 Patents Related to Al-Zn-Mg Alloys[6]

Patent	Title	Inventor	Filed, Published, Granted	Details
114321	*High Strength Aluminium Alloy*	Igarashi Isamu	Filed 4.5.1935 Published 10.25.1935 Granted 2.4.1936	Zn 5 to 25%, Mg 5% or less, Li 3% or less
135036	*High Strength Wrought Light Alloy*	Igarashi, Kitahara	Filed 6.9.1936 Published 10.24.1939 Granted 2.28.1940	Zn 3 to 20%, Mg 1 to 20%, Cu 1 to 3%, Cr 0.1 to 2%, (Mn 0.1 to 2%) No season cracking
133183	*High Strength Light Alloy*	Igarashi, Kitahara	Filed 9.9.1936 Published 8.12.1939 Granted 11.13.1939	Zn 4 to 20%, Cu 1 to 3%, Mg 1 to 3%, Ti 0.01 to 0.5%, Mn 1.2 to 3%
145112	*Aluminium Alloy*	Igarashi, Kitahara, Ozaki	Filed 9.19.1936 Published 4.30.1941 Granted 8.22.1941	$CuAl_2$ 0.5 to 10%, Mg_2Si 0.5 to 5%, $MgZn_2$ 2 to 20%, Mn 1.2 to 2.0, Cr 0.1 to 0.5%, Ti 0.1 to 0.5, Mo 0.1 to 2% Prevention of crystal grain coarsening
133193	*High Strength Aluminium Alloy*	Igarashi, Kitahara	Filed 10.15.1936 Published 8.12.1939 Granted 11.13.1939	(Additional Invention of No. 114321) Zn 5 to 25%, Mg 1 to 5%, Li 3% or less, Cu 3% or less, supplement (Brinell hardness 150 or higher)
155806	*High Strength Aluminium Alloy Clad Sheet with Zinc*	Shoji	Filed 10.14.1939 Published 12.26.1942 Granted 4.2.1943	Clad sheet of Al alloy containing Zn at 0.5 to 1.5 and Mn at 0 to 2% as a coating material, corrosion resistance
161892	*High Strength Wrought Light Alloy*	Kitahara, Kodama	Filed 5.29.1942 Granted 2.19.1944	Zn 3 to 20%, Mg 1 to 10%, Cu 1 to 3%, Cr 0.1 to 2%, Bi 0.01 to 0.2%, (Mn 0.1 to 2%), object: free of season cracking

may have been obtained earlier. But it is considered that by around June when the ESD alloy was established, the results of simple season cracking evaluations were available, and the patent was filed based on those results.

1

特許第一三五〇三六號　（昭和十四年公告第五二七八號）

第百五十四類　一、合金

出願　昭和十一年六月　九日
公告　昭和十四年十月二十四日
特許　昭和十五年二月二十八日

大阪府中河內郡布施町永和一一六番地
發明者　五十嵐　勇
大阪府中河內郡小阪町上小阪八八〇番地
發明者　北原　五郎
大阪市此花區島屋町三十七番地
特許權者　住友金屬工業株式會社
代理人　辨理士　押田　翼
外二名

鍛錬用强力輕合金

發明ノ性質及目的ノ要領　本發明ハ亞鉛三乃至二〇%「マグネシウム」一乃至一〇%銅一乃至三%「クローム」〇・一乃至二%ヲ含ミ「マンガン」〇・一乃至二%ヲ含ミ又ハ含マス殘部「アルミニウム」ヨリ成ルコトヲ特徴トスル鍛錬用强力輕合金ニ係リ其ノ目的トスル處ハ强力ニシテ時期割性無キ鍛錬用輕合金ヲ得ントスルニアリ

圖面ノ略解　圖面ハ熱處理硬化比較線圖ナリ

發明ノ詳細ナル說明　亞鉛及「マグネシウム」ヲ適當量ニ含有スル「アルミニウム」輕合金ハ現今此種輕合金中ノ最モ强力ナル種類ニ屬シ更ニ銅ヲ添加シタルモノハ一層合金ノ性質ヲ改善スルコトハ一般ニ知ラレタル所ニシテ種々ノ成分範圍ヲ有スル强力ナル輕合金カ使用セラレツツアリ卽チ例ヘハE合金〔亞鉛二〇%「マグネシ

（昭和十五年四月十六日特許局發行）

明細

ウム」〇・五%銅二・五%「マンガン」〇・五%殘部「アルミニウム」〕「ザンダー」合金（Sander）〔亞鉛八%「マグネシウム」一・五%「マンガン」〇・五%殘部「アルミニウム」〕英國特許第一六二四六七號及同第二七二七〇六號合金〔$MgZn_2$ 二六%以下ヲ含ミ「ベリリウム」、珪素、銅及一%以下ノ「マンガン」、「ニツケル」、「チタニウム」、「タングステン」、「モリブデン」ヲ含ミ又ハ含マス殘部「アルミニウム」〕等ハ此種合金中ノ最モ優秀ナルモノニシテ機械的性質良好ナルモノナリ然レトモ又右系統ノ輕合金ハ何レモ或種ノ條件ノ下ニ於テ時期割レヲ生スル缺點アリ之カ爲此種輕合金ハ其ノ强度大ナルニ拘ラス實用上多大ノ支障アルモノナリ卽チ本發明者ノ實驗ニヨレハ前記E合金及「ザンダー」合金ノ厚〇・五粍ノ板ハ抗張力約六〇瓩／粍^{2}及五〇瓩／粍^{2}伸約一一%及一六%ナルモ何レモ一日以內ニ時期割レヲ生シ切斷スルニ至レリ

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本發明者ハ此種輕合金ノ時期割レ現象ノ防止ニツキ研究ノ結果適當量ノ「クローム」ヲ添加シテ合金ノ强度ヲ減退スルコトナク時期割現象ヲ全ク防止シ得ルコトヲ發見シ之ノ發見ニ基キテ本發明合金ノ成分ヲ決定シタルモノナリ

從來「アルミニウム」合金ニ「クローム」ヲ添加シタルモノハ若干存スレトモ何レモ單ニ耐蝕性又ハ機械的性質ノ向上ヲ目的トシテ「クローム」ヲ加ヘタルモノニシテ本發明合金ハ亞鉛―「マグネシウム」―銅系「アルミニウム」合金ノ時期割性ノ防止ヲ目的トスル點ニ於テ從來既知ノモノト相違ス

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Figure 7.5 Patent of Extra Super Duralumin[12]

7.4.2 Presentation of Papers and Awarding of Degrees

Regarding academic papers, Igarashi and Kitahara co-authored the report "*New Strong Light Alloy (1)*"[13] in the February 1937 issue of Research Report of Sumitomo Metal Industries. There was no "Part 3," and " *On Some New Strong Light Alloys (4),(5),(6)*"[14-16] followed from March to October 1938. "Part 2" came a bit later in May 1939 as " *On Some New Strong Light Alloys (2). Properties of ESD and Its Coated Material ESDC*"[17] Then, in September 1939, " *On Season Cracking of High Tensile Aluminum Alloys and Its Prevention*"[10] was reported. In Part 2, ESD (no longer with periods) was referred to as Extra-Super-Duralmin, and the compositions of the ESD cladding material ESDC (Extra-Super-Duralclad) were revealed, which may be why the publication of Part 2 was delayed.

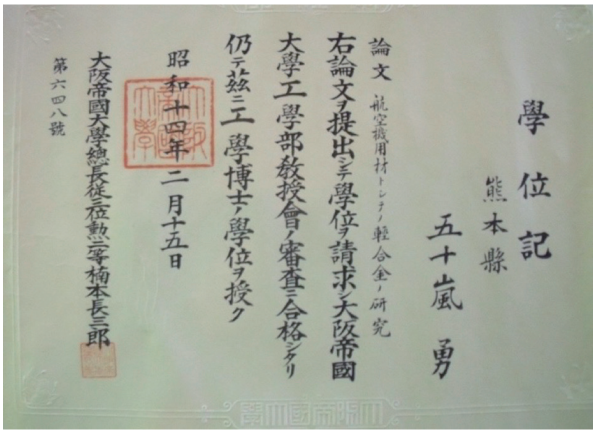
Reports with almost the same content as the Research Report of Sumitomo Metal Industries were also published in journals like "*Iron and Steel* [Tetsu to Hagane]"[18] and the Journal of the Japan Institute of Metals and Materials.[9] Furthermore, a paper by Igarashi and Kitahara titled, " *On Some Properties of Extra-Super-Duralumin"ESD" and Extra-Super-Duralclad "ESDC* "[19] was published in the September 1939 issue of the Journal of the Society of Aeronautical Science of Nippon. It can be seen that the composition of ESD was revealed around the same time as the publication of its basic Patent No. 135036. One wonders if the US military and Alcoa had read these papers.

Igarashi compiled the above research papers along with his previous publications on Duralumin, Super Duralumin, the corrosion-resistant Hydronalium alloys containing 4.5 to 8% Mg, the Al-Mn system alloys such as 3S and 4S, and Duralumin-based forged propellers, rivets, and corrosion protection of magnesium alloys. He submitted this as his doctoral dissertation (Figure 7.6) to the Faculty of Engineering at Osaka Imperial University in April 1939 and was awarded a Doctorate in Engineering.

Column: "If It's Going to Crack, Let It Really Crack!"[5]

Regarding season cracking, Dr. Igarashi spoke about it from a "reverse thinking" perspective:

"If it's going to crack, let it really crack! I tried to make alloys with the most severe cracking in order to grasp the root cause. I tested cracking in various gases, liquids, vacuums, etc. From the results, it became clear that localized corrosion at grain boundaries caused by moisture was a major factor behind this type of season cracking. So since you can't tell something that corrodes not to corrode, I decided, if it's going to corrode, let it really corrode. Rather than allowing just localized corrosion, I aimed to not be stingy and make it corrode across the entire surface. Increasing the Mn content deposited on the entire surface to 1.2% caused corrosion over the entire surface, eliminating season cracking. However, with large ingots, the Mn compounds became too big and unusable. So, I reduced the Mn and compensated with Cr. And that's how the Mn and Cr compositions in ESD were determined. As for the other compositions, I chose the most workable composition for mass production purposes. If mass production wasn't considered, a strength around 80 kg/mm^2 could have been achieved. That's how ESD was created. However, amateurs are quite intimidating, interrogating me with questions such as, 'Is it really completely free of season cracking?' From our perspective, even Duralumin can be made to undergo season cracking, so I can't definitively say that it will never crack. All I can say in response is that it's fine for practical use. The important thing is balancing the practical limits in the context of mass production and strength requirements. That's something I have to leave up to the judgment of others. And, by slightly tweaking the composition, alloys can be made to order."



學位記

熊本縣

五十嵐 勇

論文 航空機用材トシテノ軽合金ノ研究

右論文ヲ提出シテ學位ヲ請求シ大阪帝國

大學工學部教授會ノ審査ニ合格シタリ

仍テ茲ニ工學博士ノ學位ヲ授ク

昭和十四年二月十五日

大阪帝國大學總長従三位勲三等楠本長三郎

第六四八號

Figure 7.6 Dr. Igarashi's Doctoral Degree Certificate (Photographed with the kind permission of Mr. IGARASHI Kiyoshi)

7.5 Why Could ESD Be Developed So Quickly?

Dr. Terai Shirō, former Senior Managing Director and Director of the Technical Research Laboratories at Sumitomo Light Metal Industries, summarized the factors that enabled ESD's development into six points:[20]

(1) Concrete Needs

It was a semi-wartime period in 1935, and the military's demand for the development of superior fighter capabilities, especially high-strength aluminum alloys for advanced fighter aircraft structures that would achieve an edge over other nations, was pressing. The development of a new high-strength light alloy with a tensile strength of around 60 kg/mm^2 was requested by the Imperial Japanese Navy Aviation Bureau.

(2) Bold Conception

Due to the difficulty of resolving stress corrosion cracking, rather than opting for the lower-risk Al-Cu-Mg system alloys, they boldly strove to realize Al-Zn-Mg system alloys, which had superior strength potential. Recognizing that stress corrosion cracking in aluminum alloys occurs as localized cracking along grain boundaries, their brilliant idea was not a proactive approach of trying to put this alloy into practical use by preventing stress corrosion cracking, but rather a counterintuitive, reverse thinking approach of trying to prevent cracking by inducing overall corrosion.

(3) Appropriate Experimental Targets

They appropriately selected the D, S, and E series alloys as experimental targets. Based on their compositional ratios and strength maps, they chose suitable alloys and minor alloying elements that would cause uniform precipitation within the grains and overall corrosion.

(4) Systematic Experiments

Within a short period, they systematically conducted experiments on preventing stress corrosion cracking, examining factors like metallic structure, environment, stress, composition, and heat treatment. They concluded that minor Mn and Cr additions were effective, and acquired a patent for the alloy.

(5) Obsession with Creation

Dr. Igarashi often said, "There's no reason something achieved in the lab can't be done in the factory. If you tackle it with the determination to make it happen, nature will keep calling out, 'There's even this! And this!' You must have the ears to hear nature's calls."

(6) Excellent Collaborators

ESD likely would not have blossomed into an industrial product without the cooperation of factory production engineers. Dr. Igarashi reminisced that the dedicated support of Maruyama Itsuo, the production manager, greatly contributed to the production engineering at the time.

Column: "Observe Closely!" [22]

While Dr. Terai introduced the "reverse thinking" approach to addressing season cracking, Dr. SATO Shirō, another former company president and director of the Technical Research Laboratories, described it from the perspective of serendipity:

"Dr. Igarashi taught us researchers that the most important thing to keep in mind when conducting research is the importance of thorough observation of the subject. 'Observe closely! The reasoning (theory) can come later. If someone else provides the theory, that's fine too. But above all, observe closely.' Regarding stress corrosion cracking, Dr. Igarashi discovered, 'When observing the microstructure of stress corrosion cracks under an optical microscope, it was clear the cracks followed along the grain boundaries. Further, it was evident that precipitates were involved in stress corrosion cracking. So there was also the intention to thoroughly observe stress corrosion cracking. As a result of conducting stress corrosion cracking tests on sample alloys, unexpectedly, there was one alloy that showed significant improvement (suppression) of cracking. The additional element was Cr, which refined the microstructure and changed the precipitation mode from grain boundary precipitation to uniform precipitation within the grains,' which led to the invention of ESD. That is, he achieved the invention of ESD through this meticulous optical microscope observation and flexible insight – something well deserving to be called serendipity."

7.6 Dr. IGARASHI Isamu Analects

(1) Biography

First, Igarashi was born as the eldest son at Higashi Kōmyōji Temple (Note), which belongs to the Otani sect of Jōdo Shinshū Buddhism (head temple: Higashi Honganji). This seems to have greatly influenced his way of thinking and living.

> (Note: Higashi Kōmyōji means "East Bright Light Temple" of Higashi Honganji (Otani sect).) Near it is also Nishi Kōmyōji Temple. It was founded in Shōō 3 (1654) in what is now Tamana City, Mizonoue. Currently, the 13th resident priest is IGARASHI Kiyoshi, the eldest son of IGARASHI Isamu's younger brother Hideo. IGARASHI Isamu was the eldest of three sons and four daughters. With his first wife Iki, he had one son and three daughters. After his first wife passed away at age 33 in 1929, he took a second wife named Shizue. He spent his later years in Shimasaki, Kumamoto City. His eldest son, Tamotsu, became a lecturer in the Mining Department at Akita University and co-authored papers in *Journal of the Japan Institute of Light Metals* with Isamu around 1960, but passed away in 2003. For more details, refer to author's article, " *Visiting the Birthplace of Dr. IGARASHI Isamu, Inventor of Extra Super Duralumin*"[21]

Before entering Kyoto University, Igarashi graduated from Hiroshima Higher Normal School and taught at Yatsushiro Middle School and a middle school in Taiwan. He then entered the Department of Physics at the Faculty of Science, Kyoto University in 1919. It is unclear why he left teaching to study physics, or if he had intended to research metals from the beginning. However, as he stated in his opening message[22] for the 15th anniversary edition of the Sumitomo Light Metal Technical Reports in 1975, he seemed to have a desire to grasp the "laws of great nature." At that time, physics was undergoing major changes with the publication of Einstein's theories of relativity and the light quantum hypothesis and the establishment of quantum mechanics from quantum theory. It was a turbulent era when values regarding nature were also transforming. In Japan, this was when NAGAOKA Hantarō and HONDA Kōtarō were active. Seven years later, YUKAWA Hideki and TOMONAGA Shinichirō, who would go on to win the Nobel Prize, entered the Department of Physics. The "laws of great nature" that Dr. Igarashi sought seem to resonate with the ancient Greek philosopher Heraclitus' view that all things are in flux, as well as Buddhism's "laws of cause and effect." In the opening message of the Sumitomo Light Metal Technical Reports, he wrote:

"All things flow eternally with time, never ceasing. Humans create pauses and punctuations in this flow. In the old days, when a boy turned 15, there was a celebration for coming-of-age. He was recognized as a full-fledged man. Today, there are coming-of-age ceremonies. This is also a punctuation. Once a punctuation is made, you must start anew from that point. Go forth independently - you never know what will happen, whether a snake will appear, a snake charmer, or the God of Fortune will come rolling out.

The world is changing at an astonishing pace. If you try to keep up with the changes, you'll never catch up. Fifteen years of experience and achievements are a great treasure. Various keys are contained within. The keys are small. But pushing those small keys can open big doors.

Apples and persimmons will fall when ripe. That is only natural. Every small, ordinary thing follows the laws of great nature. We must cultivate the eyes to see the laws of great nature within these small happenings. Every tree and blade of grass manifests the laws of great nature.

When a boy turns 15, he is overflowing with youthful vigor. It would be fitting to let out a masculine roar of 'Everyone, follow me!' Napoleon fought alongside the French people at Waterloo and was drenched in defeat. But the French people still remain today.

Let us rise up based on achievements, not theories. Let out a virile roar. And let us all applaud and celebrate it."[22]

(2) Research Method

In a dialogue with the former executive director Dr. FUKAI Seikichi, who was directly mentored by Dr. Igarashi, Dr. Igarashi states the following:[24]

"This time, I completely changed my way of thinking and studied how cracking occurs. After various research, I made something that cracks very easily. Normally, stress corrosion cracking occurs between one month and two years, but I was able to make something that cracked in five to 10 minutes after bending. The cracking occurs along the grain boundaries. Since corrosion happens here leading to cracking, I thought that if I let it corrode in acid or alkali, it would become even more prone to cracking. But contrary to expectations of more cracking, it didn't crack at all. This clearly shows how foolish human thinking can be. Something I was convinced would definitely crack, didn't crack.

So I investigated the cause, and found that it also cracked in air, so I tried various factors like oxygen and nitrogen, and found the most influential factor was water vapor. Next, we had to examine whether the metal itself cracks. So I tested it in a vacuum. What normally cracks in four to five minutes didn't crack even after one day, two days. That made it clear - it cracks in the presence of water vapor. It's known that pure aluminum doesn't crack. So when immersed in acid or alkali, the entire surface corrodes, preventing cracking. This is where the problem gets resolved.

In the end, I made the entire surface corrode at the same rate as the grain boundaries. To make the whole surface corrode evenly, I created fine precipitates all over. This syncs the corrosion of the entire surface with that of the grain boundaries. Doing this prevents cracking. After all, it takes years for a millimeter to corrode, so the aircraft itself will degrade before the metal corrodes. That's the end of the research. After that, it's just a matter of experimenting with what percentage of this, what percentage of that. From there, I could simply follow the American way."

Mr. OKUDA Akira , who graduated in 1953, recounted his memories of Dr. Igarashi in the 75th anniversary memorial book of the Tohoku University Department of Metallurgy (2000, p. 124) as follows: "'Facts, facts are important!' 'Don't give various theories. You may have questions, but don't give incomprehensible theories trying to explain why. Just say, 'if you do this, it turns out like this.' This was the instruction from the professor the day before my graduation thesis presentation. I also received the same advice on the day of my academic conference presentation that spring. This is so typical of Professor Igarashi." In his writing, " *Extra Super Duralumin and IGARASHI Isamu*"[25] Former Iwate University Professor Iijima Yoshiaki added that Dr. Igarashi was an extremely humble person, "Unfortunately, I never got to hear his personal account of his experience with Extra Super Duralumin. Even if I had asked, he might have just smiled while puffing on his cigarette dampened by saliva. I have never heard him boast."

Similarly, Dr. Igarashi went so far as to say, "All things must be pursued thoroughly. If you pursue thoroughly, you can discover new facts. Truth is not theory, but the result of experimentation" (from the eulogy by Mr. Fukai Seikichi to Dr. Igarashi)

About the time when he returned as an adviser to Sumitomo Light Metal Industries, Mr. TAKASHIMA Akira, who was then in the Aluminum Alloy Division of Technical Research Laboratories, recounted the following:

"I thought he spent his daily routine meticulously reviewing research reports in the adviser's room, but one day he asked me to come see him. Having never directly spoken to the professor before, I stood rigidly in front of him, wondering if I was about to be scolded. He said, 'I've read many reports, but yours is the most interesting.' I couldn't rudely ask what part was interesting, so I just said, 'Oh. ' Next, he said, 'Recent academic journals aren't very interesting. Too much sophistry. The previous ones (perhaps referring to those of the Research Society of Light Metals, predecessor to the Japan Institute of Light Metals) were more interesting.'"

"I think the professor wanted to convey his philosophy of 'Theorizing should be a discussion of results; closely observe phenomena and processes, and immediately try what you think.' Conversations with the professor were like Zen dialogues." (Journal of The Japan Institute of Light Metals, 60 (2010), 475.)

(3) The state of Research in the Company

In conversations between Dr. Igarashi and Dr. Fukai,[24]

1) How to do research in a company

"First and foremost, an engineer must master the technology of the company they work for, whether it's Sumitomo Light Metal Industries or another company. Just because you graduated from school or were excellent at another company doesn't mean you can act arrogantly. And it's not enough to just superficially nod along saying, 'ah, I see' and let it pass through your mind. That may work for lectures at school, but you can't actually make products that way. So first, master the technology of the company. This is the most important thing. Next, after working for at least four to five years, you need to firmly grasp all the various issues that arise associated with that technology itself - like cracking here, breaking there, this happening over there. Only then can you be said to have truly mastered the technology. It's at this point that you can finally be considered a prospective engineer. Once you reach this stage, you can then explore how to apply that technology in new markets when opportunities arise, like the collaborative construction research meetings I mentioned earlier."

2) Basic Research

"As you go about mastering the technology, areas you don't understand will arise. Basic research then becomes necessary to clarify those areas. So even basic research is always related to the company. And by pursuing that basic research thoroughly, unexpected results can emerge. This is true creativity, and the source of new ideas and new products.

There is no creativity in simply using something that already exists elsewhere, or doing the same as others. It's a problem if you overlook doubts and take things for granted. You have to thoroughly pursue the questions of 'why?' and 'why is it this way?' Whether it's possible or not is unknown, but you must pursue it thoroughly no matter what. Only from that can something new be born."

3) Development of Human Resources

"That differs from person to person. These days there's a lot of talk about developing people, but the recent educational approach of trying to cultivate broad common knowledge is fine on one level, but it's no good when you hit a wall. They don't know how to pursue something thoroughly. You may produce plenty of American-style technicians that way, but you won't produce people with the thorough knowledge to break through the walls they encounter. So how should we educate them? Thinking that talent can be created through education is a mistake itself, it's a fundamental problem. (laughs)" "That aspect is extremely difficult. In general, if we consider having an American-style research institute and developing people to work there, that's possible. But whether those people can break through the walls they encounter, I think it's mistaken to hope for that." "What's important is the theme, who selects that theme - in the end, the person assigned that theme is just being told to run like a horse pulling a carriage. The one setting the theme is the chief engineer."

His reference to the "American-style" seems to be made with awareness that, for the development of Extra Super Duralumin, the seven to eight person research team at Sumitomo was working on the same thing that 600 people were researching at the Naval Technical Research Laboratory and Alcoa.

(4) From His Book

Dr. Igarashi authored one book during his lifetime, shown in Figure 7.7 - *Introduction to Aluminum Technology*[26] published by Tekko Shinbunsha. Even today, it serves as a perfectly viable introductory book, covering the necessary minimum of topics. He concisely writes things that one would not understand without actual experience, making the reader pause and take notice frequently. In the preface of this book, he discusses his motivation for writing it:

"All things are in constant flux, never staying still even for a moment. Regarding aluminum as well, a mountain of new wide-ranging achievements is being accumulated. Based on these accumulating new achievements, new theories are being constructed to replace the old ones. Day by day, month by month, and at a rapid pace.

In household kitchens after the war, black iron was replaced by white aluminum. What I thought was a gold cap on a fountain pen turned out to be aluminum. I was surprised to hear that even the gold and silver threads in an obi sash were aluminum. The exterior walls of buildings became aluminum curtain walls. Plans are underway for the 250 km/h Shinkansen bullet trains to be made entirely of aluminum. At this time, I thought I should write about what aluminum is. Leaving the difficult theories and precise numerical values to the experts, here I aim to cover the common knowledge about aluminum. And with that common knowledge, information centers can provide the latest data as needed. Just a bit of leisure reading for the layman, common knowledge that anyone can understand. And this is just the common knowledge of today - new facts will continually advance, overturning this common knowledge."

Figure 7.7 Dr. Igarashi's Book, *Introduction to Aluminum Technology*

In the afterword, he writes about the mindset with which one should read the book. It conveys Dr. Igarashi's thoughts on science and technology:

"I have written about the common knowledge of aluminum so that newcomers entering the field of aluminum can understand what aluminum is. I have simplified theoretical matters as much as possible. And I have limited the detailed practical data to just two or three examples needed for application. This is neither science nor technology, but common knowledge.

There are calls for promoting science and technology. Science can only develop freely when unbridled under unconstrained thinking. The first obstacle it faces is bureaucratization, and the second is popularization. Technology is based on science, but it becomes bureaucratized once a project is assigned, and the produced results become popularized, amplifying the effect. In this chaotic situation where different boats float along together, embedding some phantom-like "common knowledge" is likely to draw criticism from all sides. However, I hope you'll read through the book without complaint. You should be able to breeze through "How Aluminum is Made." If you find any part of "Properties of Aluminum" a bit complicated, feel free to skip over it. "Aluminum Alloys" covers the essentials of the alloys themselves. For "Fabrication of Aluminum," focus only on the path relevant to you. That way, it should only take a few hours. Complete novices should understand the gist of it. Experts are bound to notice questionable points. I hope you'll scrutinize those points closely. Lurking there are major openings awaiting new leaps forward. There lies development, progress, and a constant flux that knows no pause."

Regarding the postwar period, Dr. FUKAI Seikichi wrote the following about Dr. Igarashi's circumstances in the "News of Honorable Members" section of Journal of the Japan Institute of Metals and Materials:[27]

"After retiring from Fuso Metal Industries, Ltd. (Sumitomo Metal Industries changed its name for several years under the directive of occupying forces) at the mandatory retirement age toward the end of 1947, just after the end of the war, Dr. Igarashi served as a professor at the School of Engineering of Tohoku University, the Faculty of Mining of Akita University, and the Faculty of Engineering of Iwate University, fostering numerous talented individuals." "Although nominally an advisor on research and technology in general, his belief seemed to be that young people were the key to reviving defeated Japan, and his mission was to guide and nurture those youths. He was especially entrusted with mentoring the young technical staff, but just as when he was actively employed, Dr. Igarashi disliked so-called instructions and guidance, and maintained his usual relaxed demeanor, truly exhibiting the air of a true adult. His character of being tolerant of others while extremely strict with himself has not changed from the past. He diligently works from 9am to 4pm. Being proficient in foreign languages, Dr. Igarashi thoroughly reads literature, books, and internal research reports from both domestic and overseas sources. He meticulously notes the key points and analyzes and organizes them in his own way. So even when I casually visit his room for idle chatter, I often feel a sharp

1. Mastering everything about your company’s history, people, technologies, etc., is most important. It takes four to five years. Lectures from school alone are not enough.
2. Both theory and experimentation must progress day by day for industry to advance. It’s problematic to consider an immature theory as absolute truth.
3. Facts are important! Don’t give all sorts of theories. Progress and development only occur when facts contradict your expected results.
4. When you have doubts, you must thoroughly investigate by repeatedly asking “why?” and “why is it this way?”
5. The theme is important, but who decides the theme?

Figure 7.8 Dr. Igarashi Analects[28]

flash of inspiration that makes me pause in surprise. When my own literature research falls short, I make use of Dr. Igarashi’s without him showing any unpleasant reaction. What seems to be of greatest concern to Dr. Igarashi, who was blessed to have lived in the esteemed Meiji era, is Japan’s future - how Japan as a cultural nation can squarely take on the world’s great powers. The promotion of science and technology as well as human resource development are not matters of quantity but quality. He seems to think that steps forward are made by achieving coordination between high-quality components.”

(5) Igarashi Analects

Dr. NAGATA Kōji, former vice president and head of the Technical Research Laboratories, selected some of Dr. Igarashi’s words and introduced them as Igarashi Analects (Figure.7.8).[28]

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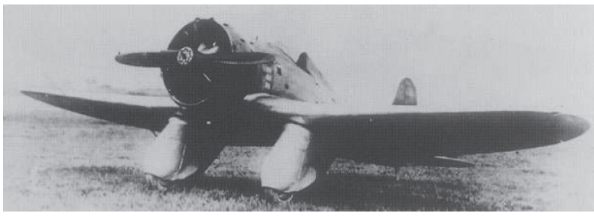
8 Dr. HORIKOSHI Jirō and His Carrier-Based Fighters

The aircraft depicted in MIYAZAKI Hayao’s anime film “The Wind Rises”[1] were not the famous Zero Fighter, but rather the preceding aircraft that led up to it - the Prototype 7 Carrier-Based Fighter (Figure 8.1a)[2], with “Prototype 7” indicating it was ordered by the Navy as a prototype in the 7th year of the Showa Era (1932), and the Prototype 9 Single-Seat Fighter (Figure 8.1b).[2] The success of the Prototype 9 Single-Seat Fighter led to the Type 96 Carrier-Based Fighter (Figure 8.1c)[2] [with “Type 96” denoting its adoption by the Navy in 1936 (the 2596th year of the Imperial Era)], followed by the Prototype 12 Carrier-Based Fighter, and eventually culminating in the Type Zero Carrier-Based Fighter [adopted in 1940 (the 2600th year of the Imperial Era; known as the “Zero” by the last digit of that year)].



a) Prototype 7 Carrier-Based Fighter

b) Prototype 9 Single-Seat Fighter

c) Type 96 Carrier-Based Fighter

Figure 8.1 Fighters Designed by Dr. HORIKOSHI Jirō[2]

8.1 Prototype 7 Carrier-Based Fighter and Use of Duralumin

The Prototype 7 Carrier-Based Fighter ordered for production in 1932 (7th year of the Showa Era) was the first monoplane fighter with a metal structure designed by Dr. HORIKOSHI Jirō (see Figure 8.2) as the chief designer at Mitsubishi (company name changed from Mitsubishi Internal Combustion Engine Mfg. Co., Ltd. in 1920 to Mitsubishi Internal Combustion Engines in 1921, Mitsubishi Aircraft Corporation in 1928, and finally Mitsubishi Heavy Industries, Ltd. in 1934; referred to as Mitsubishi hereafter). Although an advanced low-wing monoplane, the wing was not fully metal but rather was of mixed construction consisting of a metal frame covered with fabric.[3] At that time, large extruded profiles of Duralumin were still not readily available, so the wing spars were riveted together with thin sheets of Duralumin, rather than using the weight-advantageous extruded profile of Duralumin, to provide sufficient strength for the cantilever wing design, resulting in excessive thickness.[4, 5] The old-style landing gear legs supporting the large-diameter main wheels and the spats covering them also stood out for their high aerodynamic drag. Horikoshi self-deprecatingly referred to this prototype as a “clumsy duck” or an “ugly duckling,” [3-5] saying, “the fuselage was ungainly and the overall design lacked harmony no matter how charitably you looked at it.”[4] With its thick wings, bulky fuselage, and thick landing gear legs - all aerodynamically unfavorable features - it failed to achieve the 350 km/h target speed and also suffered a crash, making it a failed project.

Figure 8.2 Dr. HORIKOSHI Jirō (1947 photograph)
(Courtesy of SUZUKI Kazuyoshi, National Museum of Nature and Science)

8.2 Prototype 9 Single-Seat Fighter and Type 96 Carrier-Based Fighter and Use of Super Duralumin

8.2.1 Prototype 9 Single-Seat Fighter and Type 96 Carrier-Based Fighter

Since both Mitsubishi and Nakajima (Nakajima Aircraft Company) failed with their Prototype 7 Carrier-Based Fighters, new prototypes were ordered again in 1934 (9th year of Showa Era), which became the Prototype 9 Single-Seat Fighter. Learning from the bitter failure of the Prototype 7 Carrier-Based Fighter, Horikoshi incorporated the latest technol-

Column: Dr. HORIKOSHI Jirō

Dr. HORIKOSHI Jirō was born on June 22, 1903 in Fujioka City, Gunma Prefecture. He entered the Aeronautical Engineering Department of the Faculty of Engineering at Tokyo Imperial University in 1924. He graduated in 1927 as one of nine students in the 5th class of the Aeronautical Engineering Department and joined Mitsubishi Internal Combustion Engine Mfg. Co., Ltd. the same year. From 1929 to 1930, he inspected aircraft technologies in Europe and the United States at companies like Junkers in Germany and Curtiss in the US. In 1932, he was appointed as the chief designer for the Prototype 7 Carrier-Based Fighter. Although the Prototype 7 Carrier-Based Fighter ended in failure, its bold challenge represented a technical leap for the struggling Mitsubishi, and in 1934 he was again appointed chief designer for the Prototype 9 Single-Seat Fighter. The Type 96 Carrier-Based Fighter that was formally adopted became a masterpiece exceeding the Navy's expectations with its high performance. In 1937, he became chief designer for the Prototype 12 Carrier-Based Fighter, and developed the Type Zero Carrier-Based Fighter. Later, he served as chief designer for the Prototype 14 interceptor Fighter (*Raiden*) in 1940 and the Prototype 17 Carrier-Based Fighter (*Reppū*) in 1942. He fell ill in December 1944 and rested for about six months. He then became an executive advisor at Mitsubishi Heavy Industries in 1945. He retired as a managing director at the new Mitsubishi Heavy Industries in 1963. From 1964 to 1965, he served as lecturer at the University of Tokyo's Institute of Space and Aeronautical Science. He was awarded a Doctorate of Engineering from the University of Tokyo in 1965. From 1965 to 1969, he served as a professor at the National Defense Academy. From 1972 to 1973, he was a professor at Nihon University's College of Science and Technology. He was awarded the Order of the Rising Sun, Gold Rays with Neck Ribbon in 1973. He passed away on January 11, 1982, at the age of 78.

ogies available at that time into this Prototype 9 Single-Seat Fighter.[3-6] The thick metal-framed, fabric-covered wings were replaced with thin all-metal wings with extruded main spars. The bulky landing gear was slimmed down using smaller wheel diameters on a single strut configuration. The wings adopted a reverse-gull shape and the landing gear was shortened to reduce weight.

Down to the smallest details, streamlining was pursued, and for the first time flush rivets were used to reduce surface air drag. The engine was the lightweight, high-power Nakajima Kotobuki 5, giving a maximum speed of 450 km/h.[3-6] This Prototype 9 Single-Seat Fighter was officially adopted in November 1936 as the Type 96 Carrier-Based Fighter. However, the Type 96 Carrier-Based Fighter and the Prototype 9 Single-Seat Fighter were not exactly the same - the reverse-gull wing was changed to an elliptical wing as the gull shape could cause instability during carrier landings. The fuselage was also redesigned to be thicker as the slender original shape made it difficult to accommodate radio equipment. The landing gear was also made more robust to match the thicker fuselage.[4, 6] The performance of the Type 96 Carrier-Based Fighter was highly praised as "having caught up to or even surpassing global standards."[4] The success of this Type 96 Carrier-Based Fighter paved the way for development of the next Prototype 12 Carrier-Based Fighter (the Zero prototype).

8.2.2 Super Duralumin Used in Prototype 9 Single-Seat Fighter

In the anime mentioned above, an L-shaped extruded profile appears, and Miyazaki has a character say "It's so light, extruded Duralumin is such a luxury..." (Figure 8.3).[1] Regarding the extruded profile used for the wing spars of this Prototype 9 Single-Seat Fighter, Horikoshi writes, "The wings could be made thin because the skin was Duralumin, and thick extruded sections could be used for the spar flanges."[3, 6] However, he does not clearly specify what alloy these thick extruded sections were made of.

Figure 8.3 Extruded Profile of Duralumin in the Anime, "The Wind Rises"[1]

However, when describing the adoption of Extra Super Duralumin (ESD) for the Prototype 12 Carrier-Based Fighter, Horikoshi wrote, "Even if ESD material was only used for the upper and lower spar caps and web sheets, it allowed a weight reduction of 300 kg (likely a mistake for 30 kg) in the Prototype 12 Carrier-Based Fighter compared to the conventional SD material."[7] This suggests that the material used for the Prototype 9 Single-Seat Fighter was SD, or Super Duralumin.

In the book *Zero Fighter* (Bunshun Bunko) by YANAGIDA Kunio, he writes the following as Horikoshi's words: "Unlike the Prototype 7, extruded profiles for the spar flanges had become available, and a new stronger Duralumin alloy had also been developed, so this time I think we can make thin all-metal wings. Since this is an important matter, I plan to go to Sumitomo Metal myself to investigate"[8] (p. 164), indicating he actually did travel to Sumitomo Metal in Osaka. "The new Duralumin that Horikoshi is going to use for the Prototype 9 Single-Seat Fighter is a strong light alloy that can withstand a tensile stress of up to 45 kg/mm^2 called '45-kilo Super Duralumin' or 'SDH'"[8] (p. 166). (Author's note: SDH refers to SD that was quenched and then aged at room temperature.) If this account is correct, then the extruded section appearing in that anime would not be Duralumin, but rather Super Duralumin, more commonly known as the 24S (2024) alloy.

However, the problem is not that simple. According to the 1989 edition (p. 60) of the company history of Sumitomo Light Metal Industries (which was spun off from Sumitomo Metal's aluminum and copper divisions in 1959), it states: "Matsuda (author's note: the research department head and assistant factory manager) resumed research into industrializing the 24S alloy series, and succeeded around April 1935. These alloys later came to be called 'Super Duralumin.'"[9] Information regarding the Prototype 9 project was communicated via the Navy Aviation Headquarters in early February 1934, and the basic design was completed in late March.[7] The first prototype plane was completed in January 1935,[5] just 10 months after the design started. If this first prototype used the 24S Super Duralumin alloy, then at the very least, the factory trial production and manufacturing technology must have been completed six months to a year prior, as it could not have been applied to an actual aircraft otherwise. Additionally, being a military aircraft for the Navy, the Navy's material specifications would also have been required.

Based on Sumitomo's internal research reports from 1934, the company was researching and developing a quenched and tempered silicon-containing Super Duralumin alloy similar to Germany's 681ZB and DM31 alloys. Specifically, they had just formulated the SD (Al-4.2%Cu-0.75%Mg-0.7%Mn-0.7%Si) and SA1 (Al-1.2%Mn-0.8%Cu) coated cladding, called SDC, and were primarily evaluating these alloys. Therefore, the extruded shapes used in the wing spar of the Prototype 9 Single-Seat Fighter produced in 1934 were likely the silicon-containing SD (Al-4.2%Cu-0.75%Mg-0.7%Mn-0.7%Si) Super Duralumin mentioned above. However, looking at the internal research reports from around May 1935, test results for the T3 and T3C alloys (T3, T3C were Sumitomo's alloy designations) started to be reported. The compositions of the T3 extruded material were Al-4.14%Cu-1.36%Mg-0.68%Mn-0.14%Si-0.28%Fe, which is exactly the 24S alloy. Around this time, Sumitomo made a major shift in their approach to Super Duralumin. The 24S type Super Duralumin T3 became known as SD, and its clad version T3C became known as SDC. The SDC skin material was the SA3 alloy (Al-1.5%Mn-0.55%Mg), providing higher strength than Alcoa's 24SC clad product.[10, 11] In 1935, a 2,000 ton horizontal hydraulic extrusion press (double-action type) made by Schleomann was installed, allowing SD shapes to be mass produced. Sumitomo's Super Duralumin SD (24S) was adopted for the Type 96 Carrier-Based Fighter, the all-metal low-wing monoplane established in 1936, meeting the demand for the heyday of military aircraft.[12, 13]

8.3 Prototype 12 Carrier-Based Fighter, Zero Carrier-Based Fighter, and Use of Extra Super Duralumin

8.3.1 Prototype 12 Carrier-Based Fighter

On October 6, 1937, Dr. HORIKOSHI Jirō at Mitsubishi Heavy Industries' Nagoya Aircraft Works received a document typed in a mix of Japanese kana and kanji from his section manager. It was " Prototype 12 Carrier-Based Fighter Project Requirements." " Prototype 12" refers to the order for a prototype issued in the 12th year of the Showa Era (1937), and a carrier-based fighter means a fighter aircraft that takes off and lands on aircraft carriers. Horikoshi stated, "These requirements demanded things that were unthinkable in the aviation world of that time. If such a fighter could truly be realized, it would certainly become a fighter that far surpassed the world's level."[3] The contents of the requirements are shown in Table 8.1.[3] This Prototype 12 Carrier-Based Fighter was

Table 8.1 Prototype 12 Carrier-Based Fighter Project Requirement[3]

Item	Description
Mission	Must possess superior air combat performance compared to enemy fighters as an escort fighter. Must be able to engage and shoot down enemy attack aircraft as an interceptor fighter.
Dimensions	The total width, that is, length from wingtip to wingtip, must be within 12 meters.
Maximum speed	500 km/h at an altitude of 4,000 m
Climb	Must be able to climb to an altitude of 3,000 m within 3 minutes and 30 seconds
Endurance	Must be able to fly for 1.2 to 1.5 hours at an altitude of 3,000 m at full power with just internal fuel tanks. Must fly for the same 1.5 to 2.0 hours with auxiliary drop tanks installed in an overload state. Must have a range of 6 to 8 hours under normal cruising speed.
Takeoff run	Must have a takeoff run of 70 m or less with a 12 m/s headwind (or approximately 2.5 times that distance with no wind) in order to allow takeoff from an aircraft carrier.
Maneuverability	Not inferior to Type 96 Carrier-Based Fighter Model 21.
Armament	Two 20-mm cannons and two 7.7-mm machine guns.
Radio	Installation of standard radio equipment as well as a radio direction finder that can accurately determine the return direction by radio waves.
Engine	Use Mitsubishi Zuisei 13 (maximum 875 hp at 3,600 m altitude) or Mitsubishi Kinsei 46 (maximum 1,070 hp at 4,200 m altitude).

the name for the prototype stage of what would later reign as the "Zero Fighter," the master of the skies in the first half of the Pacific War.

The reason for this demand was that, at the time, during the Second Sino-Japanese War, the Japanese Navy's newest and most advanced attack aircraft, which had been deployed without fighter escort and were almost naked, were unexpectedly dropped by the enemy fighters that intercepted them. This led to a demand for a fighter that could carry 20-mm cannons to take down large aircraft, while also being able to escort attack planes long distances to and from enemy territory, and moreover, possess the air combat capability to defeat any enemy fighters lying in wait there.[3]

At the time, Mitsubishi's chief designer HORIKOSHI Jirō had organized the challenges in designing this aircraft into four main points. First was deciding on the engine. Second was selecting the propeller. Third was weight reduction measures. Fourth was the aerodynamic design - minimizing the aircraft's air resistance while simultaneously achieving ideal stability and maneuverability. For the first point, they decided to use Mitsubishi's lightweight Zuisei engine (later switching to the more powerful Nakajima Sakae 12 engine from the 3rd prototype onward). For the second point, they opted to use a new constant-speed propeller design. Note that, regarding this propeller, Sumitomo Metal was involved from the forging of the Duralumin blades to the manufacture of the propeller. For the fourth point, they examined the fuselage shape, wing cross-section and area, wingtip shape, tail size and shape, etc., to determine the optimal form. Retractable landing gear and flush rivets were adopted to reduce air resistance.

The greatest challenge was the third point of weight reduction measures. For this, they had to review the uniform safety factors and, in order to reduce weight down to the gram level, they practiced "defleshing" - removing material from areas not related to structural strength. The choice of materials also greatly impacted weight reduction.

In particular, for the wing spars, the most important part of the internal structure, they wanted to use the lightest and strongest material possible. For the previous Type 96 Carrier-Based Fighter, a 45-kg/mm^2 Super Duralumin (SDH) had been developed and its extruded shapes were manufactured. But since the new aircraft would be even larger, an increase in wing weight was unavoidable. The Super Duralumin used for the Type 96 Carrier-Based Fighter thin spars greatly contributed to weight reduction, but for the Prototype 12 Carrier-Based Fighter, the extruded material would have to be made thicker, resulting in increased weight. And if the spars became thicker, the wing itself would also have to be made thicker, exacerbating the problem further.

8.3.2 Encounter with Extra Super Duralumin

While Horikoshi was considering whether there was something better than the conventional Duralumin that had been further improved, or some other superior lightweight metal, the following encounter with Sumitomo's ESD occurred.

"One day, Mr. Kimura, the engineer in charge of purchasing materials for the company, casually came to Mr. Horikoshi's desk and said, 'Mr. Horikoshi, it seems Sumitomo has developed an extremely strong new alloy.' According to the story, they had slightly changed the composition of conventional Duralumin, developed a high-strength material, and were at the stage of trial production. I was greatly interested in this information. So, I inquired with Sumitomo Metal, and the person in charge said they would directly explain it to me and show me the actual material. I immediately flew to Sumitomo's factory in Osaka, and Dr. Igarashi and Engineer Kozeki explained to me, 'Sumitomo can guarantee with responsibility that the material has a strength of 60 kg/mm^2. It has not yet been adopted in the Navy's material standards, but the issue of season cracking has been technically resolved for extruded materials.'[6,14] While listening to the explanation and seeing the actual material, I determined that it could definitely be used. I carefully listened to the points that needed to be noted when using this new material. For the time being, assuming I would only use the extruded material for the wing spars, I roughly calculated the weight, and found that it would be 30 kg lighter. So, the company petitioned Aviation Headquarters for use of the material. It turned out that Aviation Headquarters had already noticed this metal and was one step away from approval. The Navy side was rather pleased with the request and allowed the use of this new material."[3, 6, 8, 14]

The fact that this ESD was limited to extruded materials is also described in the meeting records of Engineer Sone in "*The Truth of Mitsubishi Navy Fighter Design (Engineer SONE Yoshitoshi's Confidential Report)*" by SUGITA Chikayoshi published recently.[15] Engineer Sone was the engineer who assisted Engineer Horikoshi and later became the president of Mitsubishi Motors after the war. The document is a record of when Mitsubishi visited Sumitomo Metal on July 16, 1938 to inquire if the joint fittings for the left and right wings could be formed from forged ESD. Sumitomo stated, "Simple shapes of ESD can be forged, but there is a risk of cracking, so due caution is required. If it is an extruded profile, strength is the greatest advantage, and there is no concern of cracking, etc. The method of machining after extrusion and then finishing by bending is considered the safest." Here, "cracking" is considered to be season cracking (stress corrosion cracking). This is because, in the case of forging, the recrystallized structure formed by quenching leads to a decrease in strength and increased susceptibility to season cracking.

Figure 8.4 shows a drawing of the Zero's wing and a spar cross section.[16, 17] The "front and rear spar flanges" refer to the two wing spars that incorporated Extra Super Duralumin. As shown on the right of the figure, they are composed of upper and lower flanges and a vertical wall web, with T-shaped ESD-extruded profile used for the flanges. For the web, it is said that ESDC, which was an ESD sheet cladded with an Al-Zn-Cr alloy as a countermeasure against season cracking, was used, but in reality this ESDC was not used much and the 24S clad material SDC was used instead. This is considered

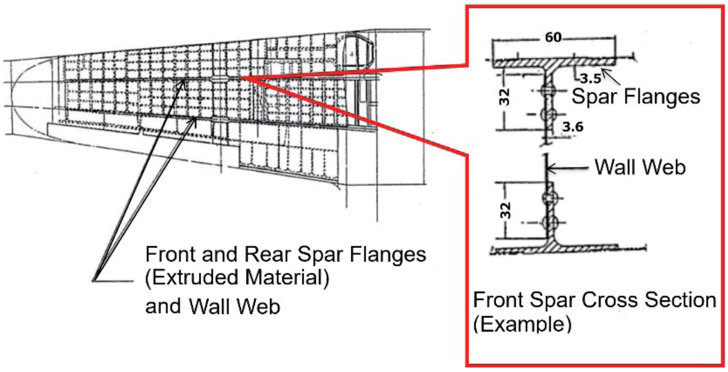


Figure 8.4 Zero Wing and Cross-Sectional View of Front Spar[16, 17]

to be because DC casting of ESD was difficult and had poor productivity.[18]

8.3.3 Prototype 12 Carrier-Based Fighter

According to Dr. Horikoshi's words, "after starting an adventurous method of washing away the monotonous safety factor regulations and establishing a design policy on new rationality, we studied and adopted every means until reaching the adoption of Extra Super Duralumin, an epochal incident in the history of Japanese aircraft."[3] The first prototype was completed in March 1939. The prototype was disassembled into several sections and packaged. A little after 7pm on March 23rd, it was loaded onto two ox-carts and departed from the factory in Ōe-cho, Minato-ku, on the southern outskirts of Nagoya City. Passing through Nagoya City at night and going through Komaki and Inuyama, it took an entire day to arrive at a Mitsubishi hangar in a corner of Kakamigahara Airfield in Gifu Prefecture, about 48 km away. The first flight was on April 1st, yielding mostly satisfactory results, but problems were also revealed. Afterwards, it made groundbreaking progress in maneuverability and responsiveness, especially through a review of the design requirements. Just as they were about to deploy the Prototype 12 Carrier-Based Fighters to the front line by the end of April 1940, on March 11th, they received notification that the Prototype 12 second prototype had disintegrated in mid-air in Yokosuka, killing the pilot, and urgently needed to identify the cause. On March 16th, a review meeting was held in which YAMANA Masao, the chief aircraft strength researcher at the Air Technical Arsenal, Aircraft Division, stated that there were suspect issues regarding the fatigue strength of the wing spars made of the Extra Super Duralumin newly adopted for the Prototype 12 Carrier-Based Fighter. He said there was a risk that the flush rivets used to affix the outer skin could come off when an extremely strong force causes wrinkles on the outer skin. He mentioned they were still experimenting to determine whether the wing broke from a simple impact or whether the wing broke midflight from season cracking of the ESD or cracks due to metal fatigue.[8]

On March 18th, at the Air Technical Arsenal accident investigation committee meeting, observation of the fractured surface of the broken wing spar confirmed that the feared season cracking phenomenon of Extra Super Duralumin had indeed not occurred. Furthermore, fatigue testing also showed that no fatigue fracture that could have led to the mid-air disintegration had occurred. However, it became clear that the machined portion of the spar had a stepped sharp corner, causing the service life to be considerably shorter than expected. The flat-head rivets were also found to be unrelated to this accident. While strong suspicion was initially cast on the newly adopted Extra Super Duralumin, ESD was "cleared" of the charges, but the reduction in notch fatigue strength led to subsequent changes in the corner shapes.[8]

The conclusion on the cause of this accident was that repeated lateral oscillation vibrations of the elevator mass balance gradually caused a fatigue fracture in the arm of the mass balance, leading to a mass imbalance. This then caused flutter in the tail section, resulting in the mid-air disintegration. As shown in Figure 8.5, the mass balance is a kind of weight attached to prevent flutter in the rudder.[3, 19] It was unnecessary for low-speed aircraft, but became necessary at higher speeds where airflow could cause vibration of the rudder, so it began being installed around the Type 96 Carrier-Based Fighter. Flutter refers to a phenomenon in which, at higher speeds, components like the wing, tail, ailerons, elevators, or rudder experience oscillations like a flag flapping in the wind.[3, 7] This flutter issue is also mentioned in the business trip records of Engineer Sone in the aforementioned book by Sugita.[15] The recently published "The Vibration of Zero Fighter" by ANDŌ Takayuki also provides a detailed materials science perspective.[20] Colonel KAWAMURA Koui of the Air Technical Arsenal also stated, "The fractured surface of the wing looked like a piece of wood that had snapped, so we investigated quite thoroughly into whether the cause of the crash was season cracking of ESD."[21]

Despite this fatality, Horikoshi continued modifying the Prototype 12 Carrier-Based Fighter. In July 1940, before official adoption but with its long-range flight capability, more than 10 Prototype 12 Carrier-Based Fighters were sent to mainland China by the Navy for combat testing and onsite modifications. By late July, the Prototype 12 was officially adopted as the first Type Zero Carrier-Based Fighter. In September's invasion of Chongqing, 13 Zeros achieved a major victory, shooting down an entire formation of 27 Chinese Air

Force planes. Table 8.2 shows a performance comparison between the Type 96 Carrier-Based Fighter and the Type Zero Carrier-Based Fighter.[22]

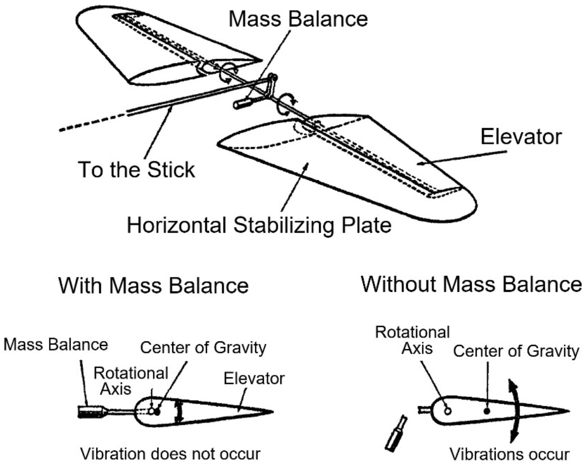


Figure 8.5 Mass Balance of Elevator and Vibration with Mass Balance Loss[19, 20]

8.4 Type Zero Carrier-Based Fighter

At the end of July 1940, the Prototype 12 Carrier-Based Fighter was officially adopted by the Navy and, since that year was the 2600th year of the Japanese imperial calendar, it was named the first “Zero Fighter Carrier-Based Fighter,” taking the last digit “0” of the calendar year. “Zero Fighter” is actually an abbreviation for “Type Zero Carrier-Based Fighter.” The nicknames “Zero” and “Zeke” were attributed by foreign pilots, and became postwar nicknames based on its reputation abroad, but both *Reisen* and *Zero-sen* were also used.[23]

As of the summer of 1942, the model designation used the first number to indicate airframe changes and the second number for engine changes. So, Model 21 (Figure 8.6[24]) meant it was the second airframe fitted with the first engine model.[23] The Navy Aviation Headquarters, impressed by the Zero’s outstanding performance due to its remarkable exploits over the continent, decided to have Nakajima Aircraft also produce the Zero. This was because the newly established and state-of-the-art Nakajima Koizumi Factory had set up an American-style automation production line, giving it a high level of mass production capabilities with respect to Mitsubishi’s production capabilities.[23] In such a case, “Rather than issues of manufacturing rights or patents as with private companies, the Navy would pay an appropriate amount of compensation to the company in charge of development, and provide all technical documents and technical assistance to the companies designated by the Navy to take over manufacturing.”[3] From No. 67 onward, the left and right wingtips were made foldable for easier handling on carriers, changing the model to the Model 21 Zero Fighter. After that, the folding wingtip mechanism was eliminated, and it was fitted with the Nakajima-built “Sakae 21” engine with a two-speed supercharger that could switch to a higher rpm at super high altitudes, becoming the Model 32 Zero.

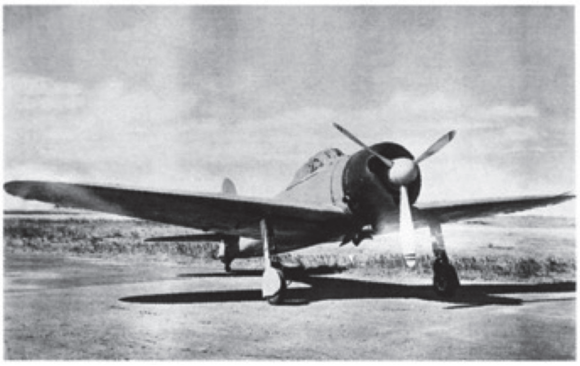


Figure 8.6 Type Zero Carrier-Based Fighter Model 21 (A6M2b) [24]
Courtesy of Mr. Nohara Shigeru

8.5 Dr.HORIKOSHI Jirō and the Zero Fighter

The Zero fighter was also an aircraft that greatly matched the military’s requirements, achieving remarkable results in the early stages of the war, and it acquired a legendary reputation that lasts to this day. However, it is necessary to also look at its negative aspects. Perhaps due to the military’s thinking at the time, bullet-proofing was not considered in the early stages, resulting in “the loss of hundreds of excellent pilots who had been trained since before the war.”[3] While it cannot be denied that the lack of bullet-proofing allowed for thorough weight reduction, even Dr. Horikoshi said, “The initial planning requirements for the Zero Fighter did not mention bullet-proofing in a single line.”[3] Furthermore, in response to the Japanese military’s poor technological policy that “led to a situation where they had to rely on the Zero Fighter from beginning to end,” the US Navy concentrated its technological development capabilities to wrest air superiority from the

Table 8.2 Performance Comparison Between Type 96 Carrier-Based Fighter and Type Zero Carrier-Based Fighter[22]

	Fourth Type 96 Carrier-Based Fighter	Type Zero Carrier-Based Fighter Model 21
Max. speed	432 km/h (altitude: 3,160 m)	533 km/h (altitude: 4,550 m)
Climb	3,000 m/3 min. 35 sec.	6,000 m/7 min. 27 sec.
Range	1,120 to 1,652 km	2,222 to (increased tank use) 3,502 km
Armament	7.7-mm machine gun x 2, 30-kg bomb x 2	20-mm machine gun x 2, 7.7-mm machine gun x 2 60-kg bomb x 2 or 30-kg bomb x 3
Wing loading	106.6 kg/m^2	107 kg/m^2
Wing spar material	Super Duralumin (45 kg/mm^2)	Extra Super Duralumin (60 kg/mm^2)
Engine	“Kotobuki” 680 horsepower (3,000 m)	“Sakae 12” 950 horsepower (4,200 m)

Zero Fighter, developing the new F6F fighter with an engine nearly twice as powerful as the Zero's. Dr.Horikoshi recounts, "Showered with a rain of bullets" from the overwhelmingly superior F6F in both quality and quantity, "the Zeros we had painstakingly built were scattered one after another into the deep blue seas of the distant south,"[3] expressing a sentiment like that of helplessly losing one's own child. When he learned that the Zero was being used as a plane for the kamikaze units, he said, "Why did the Zero Fighter have to be used in this way?" and, "Even if it was for the sake of the war, if we had truly done what should have been done, perhaps we would not have had to resort to such extreme measures as the kamikaze units."[3]

8.6 Comparison of Japanese and US Airpower in World War II

While World War I demonstrated that aircraft were far more important for conducting warfare, a comparison of the number of military aircraft produced in 1939, when war broke out in Europe, shows that the United States produced only 2,141 aircraft, far fewer than Japan's 4,467 and Germany's 8,295. Germany's offensive attack in the spring of 1940 revealed the superiority of the German Air Force, prompting

Table 8.3 Comparison of Military Aircraft Production (Numbers) in World War II Between Japan and the US by Military Aircraft Category[28]

	Japan		US	
Fighter	Type 96 Carrier-based Fighter	980	F4F Wildcat	8,061
	Type 97 Fighter	3,396	P-39 Airacobra	9,558
	Type Zero Carrier-based Fighter	10,425	P-40 Warhawk	16,802
	Type 1 Fighter 'Hayabusa'	5,751	P-38 Lightning	9,924
	Type 2 Fighter 'Shoki'	1,225	F4U Corsair	12,571
	Type 2 Land-based Reconnaissance Aircraft	470	P-51 Mustang	15,586
	Type 3 Fighter 'Hien'	2,783	P-47 Thunderbolt	15,634
	Type 4 Fighter 'Hayate'	3,488	F6F Hellcat	5,200
	Interceptor Fighter 'Raiden'	470	P-61 Black Widow	740
	Interceptor Fighter 'Shiden'/'Shiden Kai'	1,413	P-63 Kingcobra	3,305
	Type 5 Fighter	396		
	Local Defense Fighter 'Gekko'	470		
	Subtotal	3,1267	Subtotal	97,381
Single-engine Attack Bomber	Type 96 Carrier-based Attack Bomber	205	SB2C Helldiver	7,140
	Type 96 Carrier Dive-Bomber	428	SBD Dauntless	5,936
	Type 97 Carrier-based Attack Bomber	1,149	TBD Devastator	250
	Type 97 Light Bomber	686	TBF Avenger	9,837
	Type 98 Light Bomber	854	A-31/35 Vengeance	1,931
	Type 99 Carrier-based Bomber	1,492		
	Type 99 Dive Bomber	1,472		
	Carrier-based Bomber 'Suisei'	2,157		
	Carrier-based Attack Bomber 'Tenzan'	1,266		
	Carrier-based Attack Bomber 'Ryusei'	117		
	Subtotal	9,826	Subtotal	25,094
Twin-engine Attack Bomber	Type 96 Land-based Attack Bomber	1,048	A-20 Havoc	7,385
	Type 97 Heavy Bomber	2,064	167F Maryland	290
	Type 1 Land-based Attack Bomber	2,416	B-25 Mitchell	10,000
	Type 99 Twin-engine Light Bomber	1,977	B-26 Marauder	5,157
	Type 100 Heavy Bomber 'Donryu'	819	Baltimore	1,575
	Type 2 Fighter 'Toryu'	1,691	A-26 Invader	2,466
	Type 4 Heavy Bomber 'Hiryu'	698		
	Land-based Bomber 'Ginga'	1,002		
	Subtotal	11,715	Subtotal	26,873
Four-engine Flying Boat, Bomber	Type 97 Flying Boat	217	B-17 Flying Fortress	12,731
	Type 2 Flying Boat	167	B-24 Liberator	19,203
			B-29 Superfortress	3,970
	Subtotal	384	Subtotal	35,904
Transport plane	Type 0 Transport plane	487	C-47 Skytrain	10,048
	Type 97 Transport plane	351	C-45 Expeditor	4,500
	Type 100 Transport plane	507	C-56 Lodestar	625
	Type 1 Cargo Transport plane	121	C-46 Commando	3,140
			C-54 Skymaster	1,164
	Subtotal	1,466	Subtotal	19,477
Total	Japan total	54,658	US total	204,729

President Roosevelt to announce the production of 50,000 aircraft per year. To promote production, W.S. Knudsen, president of the automaker GM, was appointed to the National Defense Advisory Commission and given responsibility for production.[25]

This plan required enormous production facilities, but the aircraft companies lacked sufficient funds, so a system was created to establish the Defense Plant Corporation (DPC) as a subsidiary of the Reconstruction Finance Corporation (RFC). Under this system, the military built its own factory facilities and had aircraft companies operate them, resolving the funding issue for the time being. The construction of new factories and the rapid increase in aircraft production occurred after the Pearl Harbor attack in 1941. The president set production targets of 60,000 aircraft in 1942 and 125,000 in 1943. Initially, it was thought that utilizing the mass production system of automakers would enable the production of large quantities of aircraft in a short period, but it became clear that the number of parts differs greatly between aircraft and automobiles, and aircraft undergo constant design changes, making it difficult to directly apply the traditional automaker system. Subsequently, significant increases in production capacity were achieved through the development of a linear production organization, subcontracting most of the assembly, worker training, and decentralization of authority. This technological progress owed much to the partnership with Ford Motor Company, which sought to introduce mass production methods to aircraft production. In fact, in the production of the B-24 bomber, it is said that while other aircraft manufacturers had a production capacity of one aircraft per day, Ford produced one B-24 per hour using a 24-hour system.[26] Automakers were mainly engaged in the manufacture of aircraft parts and engines. Figure 8.7 shows the trends in aircraft production numbers of the participating countries during World War II.[27] In a comparison of 1944, the United States had about four times the production of Japan. Table 8.3 breaks down the comparison between Japan and the United States by military aircraft category.[28] For single-engine small aircraft, the United States had about three times the production capacity of Japan, while for transport and large (four-engine) bombers, Japan had overwhelmingly fewer, which well illustrates the state of the war as seen from the perspective number of aircraft produced.

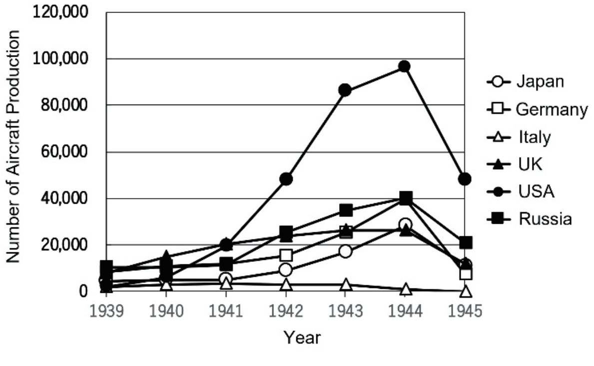


Figure 8.7 Aircraft Production Numbers of Participating Countries during World War II[27]

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9 Alcoa's 7075 Development and Japan's Alloy Development after ESD

9.1 Alcoa's 7075 Development

9.1.1 Recovery of Undamaged Zero Fighter by US Navy

During the Aleutian operation, which took place simultaneously with the Battle of Midway in June 1942, the Americans acquired an almost undamaged Zero fighter (Type 0 Carrier-Based Fighter Model 21) that had made an emergency landing on Akutan Island after being hit by anti-aircraft fire and leaking engine oil. This allowed them to successfully identify the weaknesses of the Zero fighter.[1] Figure 9.1 shows the Zero that made the emergency landing and its recovery operation.[2, 3] Even prior to this, "America had been trying to unravel the secrets of the Zero, known as the mystery plane, since the Pearl Harbor attack, even by piecing together fragments of fallen Zeros."[4] "Several aircraft shot down during the Pearl Harbor attack were also recovered. First, an analysis was carried out. Detailed data was collected on the aircraft's structure and materials. What surprised the US military was the high strength of the ESD used in the wings. This became one of the factors that awakened the US Army, Navy, and aviation industry officials who had assumed that Japan's aircraft development technology was 'several years behind the West.'"[5] The US military promptly had Alcoa produce an alloy equivalent to this alloy. This led to the birth of 7075, a representative aluminum alloy used for aircraft in the post-war period. However, Alcoa still has not officially admitted that the alloy was developed based on Japan's ESD. This is one reason why prominent U.S. professor ignored Japan's ESD when talking about the history of aluminum alloy development for aircraft at an international conference.

9.1.2 Dr. IGARASHI Isamu and GHQ

Dr. HATA Eiichi, who was the Managing Director and Research Director of Sumitomo Light Metal Industries, wrote the following in the Sumitomo Light Metal Technical Reports: "After the war, an American military officer appeared at the Nagoya factory with the aim of meeting the inventor of 75S. Dr. Igarashi had already left for Tohoku University. We had heard rumors that America had created 75S after discovering that ESD was used in the captured Zero fighter, but it was at that time that I first learned that the US military officially recognized Dr. Igarashi as the inventor of 75S."[6] This is valuable testimony supporting the fact that the US military analyzed the materials of the downed Zero fighter and developed 75S based on such analysis.

ŌHIRA Gorō, Professor Emeritus at Tohoku University, stated the following in the 75th anniversary commemorative journal of the Department of Metallurgy at Tohoku University (2000, p.112): "One day after Professor Igarashi's arrival, a senior engineer from the US Naval Research Laboratory and someone from the Alcoa Research Laboratory suddenly visited. They had questions about ESD, and when they inquired at Sumitomo Metal in Nagoya, they were told he was here, so they came all the way to Sendai. They then asked the professor to come to America immediately. The professor's only response was, 'What good can come from someone from a defeated country going to the victorious country? I refuse.' As a result, two to three engineers visited without fail one to two times a month, sometimes three times. I think this continued for about two years. The professor, knowing his own work well, said that they would probably come to ask about this next, and I was impressed that it generally turned out as he predicted. The research conducted at Sumitomo by seven to eight people was conducted at the Naval Research Laboratory and Alcoa by 600 people."[7]

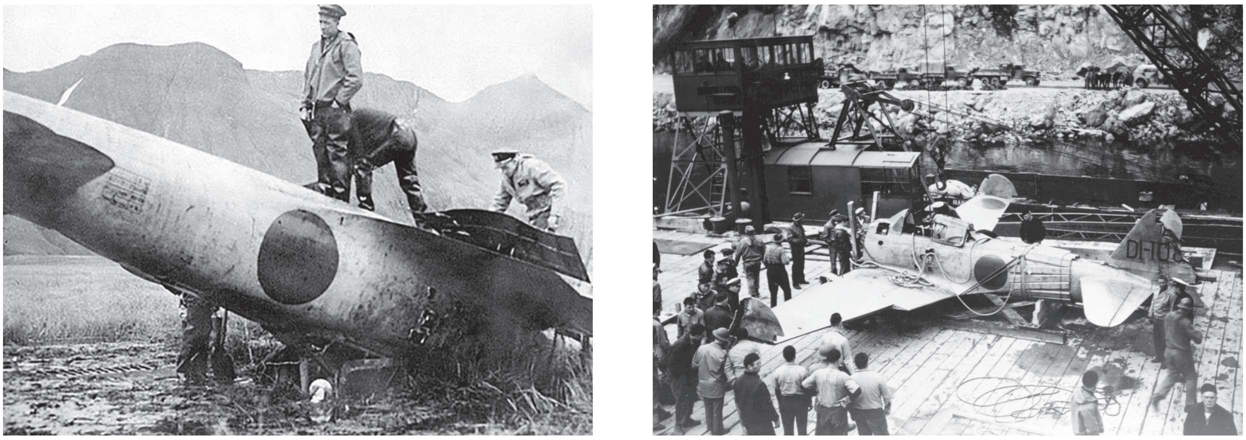
a) Zero Fighter after Emergency Landing b) Zero Fighter Recovery Operation

Figure 9.1 Crash-Landed and Overturned Zero Fighter[2] on Akutan Island in the Aleutian Islands and Its Recovery Operation[3]

Dr. TANABE Tomojirō, who was Dr. Igarashi’s superior and also served as Research Director, stated: “At the end of the war, we learned that a huge forged product of a certain important part of an American aircraft was an Al-Zn-Mg-Cu alloy, but it had less Zn and more Mg than ESD, and probably did not contain Cr. In retrospect, this was probably 75S or an early version of it. After the defeat, we learned what 75S was from an Alcan catalog, and learned further details from the Materials & Methods magazine (June, 1949). Reynolds’ R303 is probably of the same type. It’s entirely the same system, with similar performance, and it’s pleasing that the skin of the clad material has settled in the same place. We prevented season cracking by adding chromium, and it’s probably the same with 75S.”[8]

9.1.3 Sumitomo’s ESD and Alcoa’s 75S

Table 9.1 shows a comparison of the compositions of Sumitomo’s ESD and Alcoa’s 75S alloy, along with the current AA international standards.[8-10] Although Mn is now treated as an impurity element, at that time, it was considered an essential composition in both ESD and 75S. In Alcoa’s patents, the alloy with a Cr addition, which is most important for stress corrosion cracking resistance, appears in US Patent 2,240,940.[11] Its claims are as follows:

1) Zn 4-6%, Mg 0.75-2.5%, Cu 0.1-2%, and Mn 0.1-1% with at least one or more additions of Ti 0.02-0.25%, B 0.005-0.1%, Zr 0.01-0.15%, Mo 0.02-0.25%, W 0.02-0.2%, Co 0.02-0.2%, Cr 0.05-0.5%, V 0.02-0.2%
2) Zn 4-6%, Mg 0.75-2.5%, Cu 0.1-2%, Mn 0.1-1%, Cr 0.05-0.5%, Ti 0.02-0.25%
3) Zn 4-6%, Mg 0.75-2.5%, Cu 0.1-2%, Mn 0.1-1%, Ti 0.02-0.25%

The second claim corresponds roughly to the 7075 alloy, but there were no examples of alloys with Cr added. Incidentally, Sumitomo’s JP Patent 135036[12] specifies 3 to 20% Zn, 1 to 10% Mg, 1 to 3% Cu, 0.1 to 2% Cr, and 0.1 to 2% Mn or without the Mn addition. This corresponds to US Patent 2,166,495[13], which specifies 4 to 20% Zn, 1 to 2% Mg, 1 to 3% Cu, 0.1 to 1.5% Mn, 0.05 to 1.0% Cr, 0.01 to 0.2% Ca as essential compositions, and includes 0.01 to 0.2% Mo, 0.01 to 0.5% Ti, and 1% or less of Fe and Si to improve workability and characteristics. It is unclear why the US patent narrowed the claimed range for Mg and made Ca an essential component.

Comparing the Zn and Mg compositions of Alcoa’s 75S with Sumitomo’s ESD in Table 9.1, it is understood that the Zn content is substantially below the lower limit of ESD, while the Mg content is above the upper limit, deviating from ESD’s composition. Is this coincidental or intentional? While Alcoa was also investigating the strength properties of Al-Zn-Mg-Cu alloys during the same period, suggesting a possibility of coincidence, I believe it is more likely that Alcoa examined Japanese literature on the new alloy when determining the composition of 75S. In a paper published by Alcoa researcher Dix in 1949,[14] a table comparing 75S includes the composition of ESD, citing a paper by Igarashi and Kitahara titled “*On Extra Super Duralumin ESD and ESDC*”[15] published in the September 1939 issue of Journal of the Society of Aeronautical Science of Nippon. This paper fully describes the composition, mechanical properties, and stress corrosion cracking characteristics of ESD and its cladding material ESDC. Similar content is also written in a Research Reports of Sumitomo Metal Industries.[16] This was at the stage when the US patent was registered. It is clear that if Alcoa had carefully followed Japanese literature, they could have created something equivalent to ESD. However, Alcoa announced the development of 75S in 1943. No Al-Zn-Mg-Cu alloy with chromium addition can be found prior to this. Most likely Alcoa had not examined Japanese literature until the Zero fighter was captured in 1942 and brought to the attention of the US military.

9.1.4 Evaluation of 75S by Dr. TANABE Tomojirō, Sumitomo Metals

Dr. TANABE Tomojirō stated, “It’s difficult to compare the merits of both in detail now, but it’s undeniable that 75S’s 5.5% Zn is advantageous over ESD’s 8% Zn in various aspects. The extruded profiles mainly used in our country were specified to have a tensile strength of 58 kg/mm^2 (570 MPa) or greater, but 75S’s 54 kg/mm^2 (530 MPa) should be sufficient for practical use. Here we see our country’s tendency to unnecessarily seek high strength. For reference, Table 9.2 shows the performance of Alcoa’s 75S. While cladding materials were hardly used in our country, I believe they must be used considerably in the US, and I’d like to know the actual situation. Also, while 0.3-mm sheets are specified in the US, we stopped at 0.5 mm. Although there are differences in composition and manufacturing methods, they seem to have the advantage.”[8]

Table 9.1 Comparison of Composition limits Between Sumitomo ESD and Alcoa 75S (mass%)[8-10]

	Zn	Mg	Cu	Mn	Cr	Fe	Si	Ti
Sumitomo ESD	6.0-9.0	1.2-1.8	1.5-2.5	0.3-1.0	0.1-0.4	0.6	0.6	
Sumitomo ESD cladding alloy	0.5-3.0	—	0.2	—	0.1-0.4	0.5	0.5	
Alcoa 75S	5.1-6.1	2.1-2.9	1.2-2.0	0.1-0.30	0.15-0.40	0.7	0.5	0.2
Alcoa 75S cladding alloy	0.75-1.25	0.10	0.10	0.10	—	—	—	—
AA7075	5.1-6.1	2.1-2.9	1.2-2.0	0.30	0.18-0.28	0.50	0.40	
AA7072 cladding alloy	0.8-1.3	0.10	0.10	0.10		0.70		

Table 9.2 Technical Data of Alcoa 75S Alloy (Materials and Methods, June 1949)[8]

(1) Compositions %

	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Other Materials	Total of Other Materials
Core Alloy	5.1～6.1	2.1～2.9	1.2～2.0	0.15～0.40	0.1～0.40	<0.7	<0.5	<0.2	<0.05	<0.15
Cladding Alloy	0.75～1.25	0.10	<0.10	—	<0.10	—	<0.7	—	<0.05	<0.15

(2) Mechanical Properties

Process	Thickness mm	Tensile Strength kg/mm^2	Yield Strength (0.25%) kg/mm2	Elongation (50mm) %
75S (Bare Alloy)				
Annealling	0.279～12.7	<28.2	—	>10
Quenching and Tempering	0.406～0.991	>53.5	>45.5	>7
	1.016～12.68	>54.0	>46.5	>8
	12.72～25.4	>54.0	>46.5	>6
	25.42～50.8	>54.0	>46.5	>4
75SC (Clad Alloy)				
Annealling	～12.7	<25.3	—	>10
Quenching and Tempering	～0.991	>49.0	>42.0	>7
	1.016～12.68	>50.5	>43.5	>8
	12.72～25.4	>54.0	>46.5	>6
	25.42～50.8	>54.0	>46.5	>4

(3) Physical Properties

		Annealing		Quenching and Tempering	
		Bare Alloy	Clad Alloy	Bare Alloy	Clad Alloy
Shear Drag	kg/mm^2	—	—	26.0	—
Rockwell Hardness		H86～H96	H86～H96	B85～B95	B80～B90
Elastic Modulus	kg/mm^2	—	—	7300	
Rigidity Modulus	kg/mm^2	—	—	2700	
Poisson's Ratio				0.33	
Specific Gravity				2.8	
Thermal Conductivity	100°C C.G.S			0.101	
Expansion Coefficient	20～100°C			0.0000129	
	20～178°C			0.0000135	
	20～300°C			0.0000144	
Electrical Conductivity (Ratio to Copper) %				30	

(4) Heat Treatment Process

Process	Temperature, °C	Processing Time, hours	Material Symbol	Remarks
Annealing	410	2～3	75S-O	If necessary to leave for a longer period times, heat at 240°C for another 6 hours
Quenching	470	—	75S-W	Sheets can also be quenched at slightly higher temperatures
Tempering	120	22～26	75S-T6	For sheets, two-stage heat treatment (4 to 6 hours at 100°C and another 8 to 10 hours at 157°C) is possible (U.S. Patent 1858092)

The composition of ESD still presents many challenges in productivity, such as ingot cracking during casting and extrudability issues. It is impressive that they could produce this much with the technology of that time. The US significantly reduced the Zn content compared to ESD, perhaps prioritizing productivity, such as castability, rolling workability, and extrudability, or perhaps considering stress corrosion cracking. Regarding thin sheet rolling, although the rolling mills were imported from the US, the rolling technology of the US was even more advanced, indicating that Japan's production technology was considerably behind. One can well understand the situation where they had to determine the composition while meeting the unreasonable high-strength demands from the Air Technical Arsenal. Without these demands, they probably would not have been able to create materials that are now world-renowned. This principle of how challenging requirements, though difficult to meet, often drive innovation and result in breakthrough technologies remains unchanged throughout time.

Dr. Tanabe continued, "In Japan, where the aircraft industry is currently prohibited, there may not be a way to utilize this excellent alloy. However, I'd like to rejoice with Dr. Igarashi and former colleagues for leaving a small footprint in the history of this field. Although ESD is not entirely new, being born from a systematic exploration of the E-S-D system by re-examining the achievements of predecessors like the German Sander's alloy and the British E alloy, I'd like to note that, at the very least, the addition of chromium to improve season cracking resistance was an unprecedented achievement by Igarashi and Kitahara."[8] In the post-war development of high-strength aluminum alloys for aircraft, development is progressing in the direction of high Zn content, similar to the composition of ESD.

9.1.5 Alcoa's Response to ESD

E.H. Dix, who had been researching stress corrosion cracking since 1930 and played a central role in Alcoa's material development, stated, "Alcoa 75S, after many years of research, was put into commercial production for alclad sheet and extrusions in1943 and later for nonclad sheet, wire, rod and bar, and forgings."[17]

Similarly, J.A. Nock, Jr. of Alcoa, who was also an inventor on US Patent 2,240,940 and involved in the development of 7075, is introduced as follows in M.B.W. Graham's book, "R&D for Industry, A Century of Technical Innovation at Alcoa,"[18] "Ultimately, Joseph Nock, working with small DC ingots cast on the premises at Alcoa Research Laboratories, solved the problem empirically, demonstrating that small amounts of chromium added to Al-Zn-Mg-Cu composition yielded resistance to SCC that had long been sought." Nock himself stated, "This alloy is the culmination of a number of years intensive work."[19] He later reiterated this in a 1949 ASM monograph: "Years of extensive laboratory investigation, including painstaking studies of susceptibility to stress corrosion cracking, finally terminated in the selection of the alloy composition designated 75S,"[20] stating that the composition of 75S was determined as a result of their research.

H.Y. Hunsicker, who was the leader of Alcoa's physical metallurgy division, also stated, "Continuing alloy development efforts led to the discovery that the addition of a small amount of chromium greatly reduced the sensitivity to stress corrosion."[21]

J.T. Staley, who played a central role in Alcoa's aircraft material development from the 1960s to 1980s, reported in 1989 regarding Al-Zn-Mg-Cu alloys that Alcoa developed 7076 (Al-7.5Zn-1.6Mg-0.7Cu-0.6Mn) in 1940 as a forging alloy used for propeller blades. By 1938, Alcoa had solved the stress corrosion cracking problem in sheets in the lab, so X74S (Al-5.2Zn-2.1Mg-1.5Cu-0.4Mn) was used for parts of the wing. However, field tests revealed that this alloy sheet became sensitive to stress corrosion cracking when aged material was processed and used. Therefore, they investigated the effects of trace additions of high melting point elements and found that alloys containing 0.2 to 0.35% chromium were resistant to stress corrosion cracking. They developed the well-known 7075-T6 in 1943, which had slightly improved strength and good resistance to stress corrosion cracking.[22]

Staley then stated, "Interestingly, chemical analysis of sheet from a downed Japanese Zero fighter aircraft disclosed that the composition was almost the same as that of 7075." Staley reported that this new alloy was immediately reflected in airframe design, and 7075-T6 sheet was used for upper wing skins and stringers in late models of the B-29 Superfortress.[22] This is probably the first time an Alcoa researcher wrote about the Zero fighter, but the statement by no means acknowledges the precedence of Japan's ESD. It is understandable that inventions often reach similar conclusions around the same time when similar research is being conducted, as seen with the inventions of Hall and Héroult. However, the reality is that there is very little published data on how Alcoa developed 7075 through their research.

Perhaps because successive Alcoa material researchers have deliberately avoided mentioning Japan's ESD, at the first keynote lecture of the International Conference on Aluminum Alloys (ICAA11) held in Aachen, Germany in 2008, Professor E.A. Starke, Jr. of the University of Virginia gave a talk on "Precipitation Hardening: From Alfred Wilm to the Present," discussing the history of Al-Zn-Mg-Cu development. Japanese participants, including Professor Satō from Tokyo Institute of Technology and myself, were surprised that ESD was completely absent from the figures in his PowerPoint presentation. This was despite the fact that his book distributed at the same time stated, "The early alloys were susceptible to stress-corrosion cracking but later examination of small additions, of first Mn and then Cr, proved that alloys containing 0.2 to 0.35% Cr had high resistance to stress-corrosion. In 1940 Sumitomo developed an Al-Zn-Mg alloy for the Mitsubishi A6M2 (Zero) airframe. The chemical composition of the Sumitomo alloy was very similar to the Al-Zn-Mg alloy 7075 developed by Alcoa and introduced in 1943."[23] Even here, the precedence of Sumitomo's invention is not directly addressed.

However, Q.R. Skrabec, who specializes in technological history, wrote in his recent book, "Aluminum in America," "Most of the Japanese aircraft incorporated a top-secret equivalent of 75S (7075) aluminum alloy developed by Sumitomo Metal Industries in 1936, ahead of ALCOA's research. ALCOA was probably aided by the capture of a Japanese Zero early in the war."[24] He clearly states that Sumitomo's ESD was developed before Alcoa's. It seems that the US is gradually changing its perspective on this matter.

9.2 Alloy Development after Extra Super Duralumin: Other Extra Super Duralumin

9.2.1 HD and ND Alloys Through Military-Government-Academia Collaboration

(1) HD Alloy

Regarding HD alloy and ND alloy mentioned in the next section, Professor Nishimura wrote in detail in his "Essays: History of Light Alloys" (Part 34, 35, 38), reintroduced here. [25-27]

In late November 1941, a preparatory meeting for a special committee of the Japan Society for the Promotion of Science was held at the Josuikaikan Hall in Tokyo, with Professor HONDA Kōtarō and others as the organizers, sponsored by the Army to conduct comprehensive research on aircraft. The 3rd subcommittee was planned as a research group on high-strength light alloys, with Professor Honda as the chairman and including Professor OBINATA Ichiji from Tohoku University, Professor ISHIKAWA Tokiji from Waseda University, and Professor NISHIMURA Hideo from Kyoto University on the university side, and Sumitomo Metal, Furukawa Electric, and Kobe Steel on the manufacturer side. As it was organized by the Army, there was no cooperation from the Navy. The first meeting was held in April 1942, during the first air raid. Professor Nishimura stated, "We were to determine the research policy, and as there was no particular plan, I proposed creating an alloy that could substitute for Super Duralumin without using copper. Although the amount of copper used in light alloys is not that large, our country's copper resources are not necessarily abundant, and if we could save even a little, it would be useful for the current situation."[25] As a result, they decided to work on Al-Zn-Mg alloys. They examined whether it was possible to create a material with strength equivalent to Super Duralumin that would show age hardening at room temperature after quenching. They started by setting composition targets and having the three companies produce prototypes for examination.

A sheet produced by Sumitomo Metal with a target of 6% Zn, 2% Mg, 0.8% Mn, and 0.25% Cr exhibited a tensile strength of 45 kg/mm^2 (440 MPa) and an elongation of 18%, meeting the specifications for Super Duralumin (tensile strength of 43 kg/mm^2 (420 MPa) or greater, elongation of 14% or greater). However, the annealed material exceeded specifications, causing workability issues. “We considered ending the research and moving in a different direction, but decided to try making forged materials and extruded profiles since the research was already started, and made a prototype of such a forging.”[26] The results of the extruded material (Al-6%Zn-2%Mg-0.75%Mn-0.35%Cr) produced by Furukawa Electric were very good, with a tensile strength of 50 to 54 kg/mm^2 (490-530 MPa) and an elongation of 12 to 15%, fully satisfying the specifications for Super Duralumin SD. Professor Nishimura noted at the time, “We learned that extrusion was easy and could be done several times faster without issue. This was an unexpected discovery. At the time, the production of extruded profiles was a bottleneck in aircraft manufacturing. Since it was difficult to quickly manufacture extrusion machines, if there was a material with good extrudability, it would increase production capacity, making it a noteworthy discovery.”[26] Kobe Steel also experimented with extrudability, achieving speeds about twice that of Super Duralumin. It was decided to call this alloy HD, proposed by the Army. This took the initial H from Dr. Honda, who was the committee chairman. Thus, the HD (Honda’s Duralumin) alloy was born. The chemical composition is shown in Table 9.3.[28] After the war, this alloy developed greatly as a ternary alloy, being applied to Shinkansen cars and motorcycles, among other things.

(2) ND Alloy

As the war approached its end, primary aluminum became scarce, and the rate of using scrap from dismantled aircraft and other recycled materials (recycled ingots) increased. This led to an increase in impurities such as Fe, Si, and Zn, making it difficult to produce high-quality Super Duralumin SD, which was essential for aircraft. Therefore, the allowable range for these impurities was expanded, and there was a demand for the development of materials with mechanical properties comparable to SD. ND was an alloy developed jointly by the military, government, and private sector to meet this need.[27]

ND stands for Nippon Duralumin. Its composition is shown in Table 9.3. The mechanical properties after quenching and room temperature aging are a tensile strength of 44 kg/mm^2 (430 MPa) or greater, a yield strength of 32 kg/mm^2 (310 MPa) or greater, and an elongation of 10% or greater. Professor Nishimura stated that, in retrospect, “It was merely a slightly modified version of what was already being used by Alcoa as 14S, and became 25S with added magnesium. The material called ND was created out of unavoidable circumstances for light alloys and cannot be called an advanced material.” However, he noted that the ND research provided academic questions, as “it remained unclear why even with 0.8% silicon content, the mechanical properties of the quenched and aged material did not deteriorate like SD, and why iron did not inhibit aging.” Therefore, he concluded that it was not a futile research effort.[27]

9.2.2 ESD Extrudability Improvement and Al-Zn-Mg-Cu NSD

At Sumitomo, the extrusion speed of Extra Super Duralumin ESD was 1 to 1.5 m/min, about half compared to the extrusion speed of Super Duralumin at 2 to 2.5 m/min. Therefore, increasing the productivity of ESD became an urgent matter. NSD was developed in 1943 with the idea of “something with a higher extrusion speed, even if the strength is slightly lower than ESD.”[28, 29] The N in NSD comes from Nagoya. When the copper content of ESD was reduced from 2% to 1.1% and the Mg content was slightly increased, a speed of 3 m/min was achieved, but there was an issue of not reaching the desired strength. It was found that this was due to an increase in the impurity silicon content, and the material was put into practical use by increasing the zinc content. Table 9.4 shows the composition of NSD compared to ESD.[29] NSD was established as the Aircraft Material Specifications 7222 (Chi 263) in 1944.

9.2.3 Other Extra Super Duralumin

According to Professor KŌDA Shigeyasu, “Around the same time, the so-called Kōken Extra Super Duralumin was invented by Professor ISHIDA Tōshirō and others at the

Table 9.3 Chemical Compositions of HD (Honda’s Duralumin) and ND (Nippon Duralumin) (mass%)[28]

	Zn	Mg	Cu	Mn	Cr	Fe	Si	Al
HD	5-5.8	1.5-1.8	<0.8	0.3-0.8	0.1-0.4	<0.6	<0.5	Remainder
ND	<1.0	0.6-1.2	4.0-4.8	0.6-1.0	—	<0.8	0.3-1.0	Remainder

Table 9.4 Chemical Compositions of NSD and Extra Super Duralumin ESD (mass%)[29]

	Zn	Mg	Cu	Mn	Cr	Fe	Si	Al
Specification*1)	7.0-9.0	1.2-1.8	0.8-1.7	0.3-1.0	0.1-0.4	<0.6	<0.6	Remainder
NSD	8.5	1.6	1.1	0.45	0.2	(<0.6)	(<0.45)	88.15
ESD	8	1.5	2	0.45	0.2	(<0.6)	(<0.5)	87.8

*1) Army and Navy Aircraft Material Specifications 7222, Chi 263

Aeronautical Research Institute of the University of Tokyo, and SSD Extra Super Duralumin was invented at Furukawa Electric Industry Co., Ltd. The former prevented stress corrosion sensitivity by adding Sn, while the latter did so by adding Zr. However, perhaps because they were not as effective as ESD, they were not put into practical use."[30]

Professor Ishida's patent was filed about two years later than Igarashi's. The composition was 6.0 to 10.0% Zn, 1.0 to 3.0% Mg, 1.5 to 4.5% Cu, 0.5 to 1.5% Mn, 0.1 to 1.0% Sn, 0.8% or less Si, and 0.8% or less Fe.[31] Furukawa Electric's patent composition was 4 to 10% Zn, 0.5 to 3% Mg, 0.5 to 4% Cu, 0.1 to 1.5% Mn, 0.4 to 1% Si, and 0.05 to 1% Zr.[32] In particular, the patent states that season cracking was prevented by the action of silicon and zirconium. Recent aluminum alloys for aircraft have shifted from a chromium addition to a zirconium addition for reasons such as quench sensitivity, and this patent could be said to be the forerunner of this trend. Regarding this, Dr. KOYAMA Katsumi of Furukawa Sky (now UACJ) wrote, 'Perhaps because sufficient microstructural control was not possible at the time, it did not lead to practical application."[33]

After the Pacific War, the production of aircraft materials became urgent, and requests came from the Army and Navy Air Headquarters to transfer the implementation rights of the ESD patent to Kobe Steel, Ltd. and Furukawa Electric Industry Co., Ltd., which Sumitomo granted. In 1943, Kobe Steel, Ltd. requested technical guidance from Sumitomo regarding aluminum alloys, including everything from melting, casting, equipment, drawings, and factory training to patents, which Sumitomo agreed to, and the technical guidance was carried out at the Nagoya Light Alloy Works.[28]

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10 Development of Aircraft Materials after World War II

10.1 Postwar Conditions

With the defeat in the war, aluminum smelting, being a military industry, was terminated by order of the Allied forces. This forced the industry to struggle, converting smelting facilities to the production of potash fertilizer and calcium cyanamide. On the other hand, manufacturing companies experienced an unusual boom as the demand for household items, which had been suppressed during the war, became apparent. Many manufacturing companies resumed production of household utensils, such as pots and kettles, using aluminum alloy scraps from dismantled aircraft as raw materials. However, these products were of poor quality, made from Duralumin alloy scraps with poor corrosion resistance, giving the incorrect impression that aluminum utensils were prone to corrosion, which had a significant negative impact on subsequent product development.[1]

The relationship between post-war reconstruction and Duralumin can also be seen at Tokyo Station.[2, 3] The Marunouchi station building of Tokyo Station lost its north and south domes, roof, and interior to fire damage in 1945. After the war, the three-story station building was rebuilt as a two-story structure. In the recent “preservation and restoration work” led by Kajima Construction, not only was the exterior faithfully reproduced to its original appearance, but also a new underground structure was built under the steel-framed brick construction to pass it on to the future. To make it resistant to massive earthquakes, the building was constructed using “seismic isolation methods.” Figures 10.1 and 10.2 show Tokyo Station and its ceiling dome before and after restoration. The inner surface of the station building ceiling restored after the war (Figure 10.1) used 0.8-mm thick aircraft Duralumin sheets and galvanized iron sheets joined with aluminum rivets and painted, as shown in Figure 10.3. The compositional analysis of this sheets shows Al-4.2%Cu-0.43%Mg-0.79%Si-0.74%Fe-0.80%Zn, indicating very high levels of impurities such as iron and zinc. This Duralumin sheet was manufactured during the war, and it corroborates that towards the end of the war, a substantial amount of scrap was being used.

Figure 10.1 Tokyo Station and Its Ceiling Dome Before Restoration

Figure 10.2 Tokyo Station and Its Ceiling Dome After Restoration
(Left: National Museum of Nature and Science, Courtesy of Murotani Chikayoshi; Right: Same as left, courtesy of Kamei Osamu)

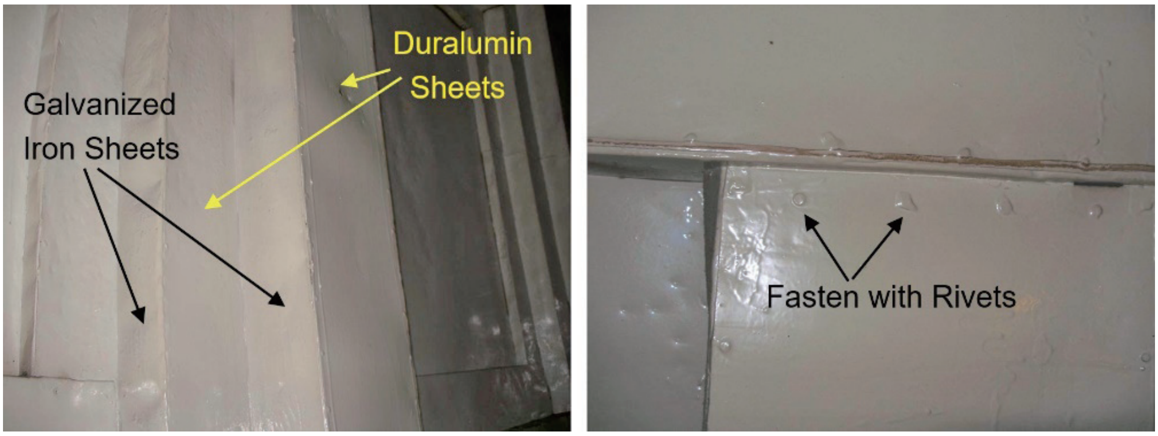


Figure 10.3 Ceiling Dome Before Restoration Galvanized sheets, Duralumin sheets, Rivets

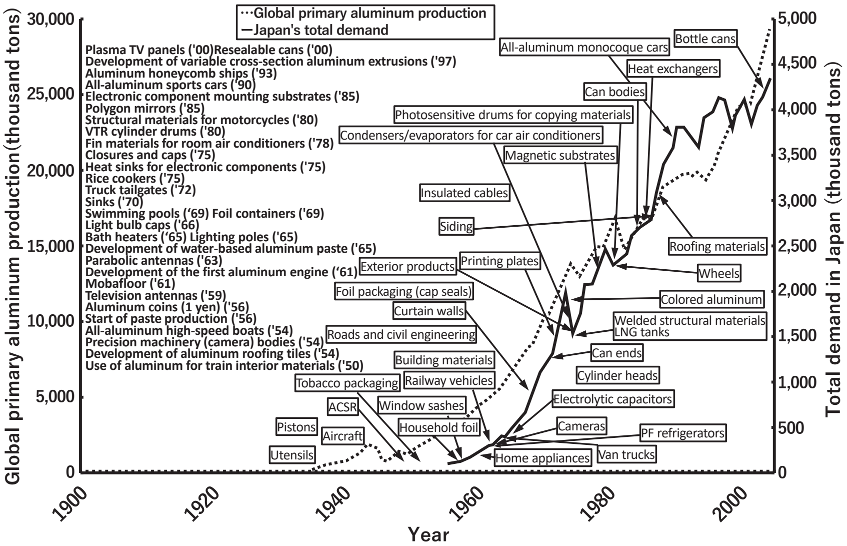


Figure 10.4 Global Primary Aluminum Production and Total Demand in Japan (Japan Aluminum Association)[4]

Demand for aluminum was dominated by aircraft applications during World War II, but diminished significantly after the war. As shown in Figure 10.4, demand for aluminum first grew rapidly for household utensils and commodities, followed by new demand in the automobile, vehicle, machinery, and other sectors. Subsequently, the general civilian demand market expanded rapidly in the building sector, including sashes, doors, and curtain walls; transportation, including automobiles, trucks, trailers, railway vehicles, and ships; electrical communication equipment, including televisions and electric washing machines; electric power transmission lines; and packaging containers.[4]

10.2 Flow of Postwar Structural Materials Development, from Aircraft to Railway Vehicles, Automobiles, and Motorcycles

After World War II, GHQ issued an aviation ban, prohibiting the research, development, and manufacturing of aircraft. As a result, many researchers and engineers who had been involved in aviation during the war shifted to the development of railway vehicles, automobiles, and motorcycles. The HD alloy (Honda Duralumin, Al-5.4%Zn-2.0%Mg-0.55%Mn-0.25%Cr), an Al-Zn-Mg alloy derived from the Extra Super Duralumin developed during the war by removing Cu, was significantly developed in postwar Japan as a ternary alloy for non-aviation applications such as railway vehicles, automobiles, and motorcycles. Japanese materials researchers were also heavily involved in the development of ternary alloys in the postwar period.

10.2.1 Railway Vehicles

Aluminum alloys were first used in Japanese railway vehicles immediately after World War II in 1945, when Duralumin from aircraft was repurposed due to material shortages. However, these were modified due to severe corrosion issues. The full-scale adoption of aluminum alloys in railway vehicles began with the debut of the Sanyo Electric Railway 2000 series train in 1962.

In the first generation, represented by the Sanyo Electric Railway 2000 series, the use of aluminum initially started with replacing the outer panels of steel bodies. Later, as the 6061 alloy used for the underframe had poor weldability, the body was welded in blocks, with these blocks coupled to each other using rivets. In Japan, before World War II, riveted joints were predominantly used due to the immaturity of welding technology. After the war, as a result of the development of high-purity gas production in the United States during World War II, argon arc welding methods were researched, leading to the development of tungsten inert gas (TIG) and metal inert gas (MIG) welding technology. This made it possible to weld Al-Zn-Mg alloys.[5]

Around 1961 in Europe, Al-Zn-Mg alloys such as AlZnMg1, AlZnMg2, and Uni-dur gained attention for their significant strength recovery at room temperature after welding. These alloys began to be utilized in large structures like vehicles and bridges. Shortly after, alloys like Alcan 7004 and Alcoa 7005 emerged.[6] These Western alloys, like Japan's HD alloy, were characterized by the addition of Mn and Cr. However, excessive Cr addition risked formation of large Cr compounds during casting, potentially reducing product toughness. To address this, Dr. BABA Yoshio and colleagues at Sumitomo Light Metal Industries reduced the Cr content by adding trace amounts of Zr, suppressing the formation of large Cr compounds.[7, 8] They discovered that Zr addition also improved stress corrosion cracking resistance and weld cracking, leading to a patent application in late 1961. When this alloy was prototyped in the factory, it showed high quench sensitivity. Slow cooling after extrusion made it difficult to achieve high strength after high-temperature aging.[9] Dr. Baba and his colleagues found that Zn and Mg, which contribute to age hardening, precipitated at Cr compound interfaces during cooling, causing strength reduction. They developed a new Cr-free alloy and filed a patent in February 1965.[10] Its characteristics included "3 to 8% Zn, 0.5 to 3% Mg, 0.05 to 0.3% Zr, 0.1 to 0.5% Mn, and heat treatment of ingots at 400°C or higher to bring out Zr's effect." It should be noted that this alloy also showed reduced weld cracking sensitivity. Subsequently, Western Al-Zn-Mg alloys also began incorporating 0.1 to 0.2% Zr as an essential composition.[7, 8] This development, like that of Extra Super Duralumin, demonstrates the foresight of Japanese researchers.

This alloy achieved high strength even with air cooling after extrusion, with minimal cooling-induced strain, leading to good productivity. As a result, various domestic companies developed it and, in 1970, JIS A7N01 was established (internationally registered in 2005, called AA7204, with a representative composition of Al-4.5%Zn-1.5%Mg-0.45%Mn-0.15%Zr). Dr. Baba and his colleagues further discovered that adding about 0.15% Cu was effective in suppressing stress corrosion cracking in the thickness direction.[11, 12] The second generation of vehicles (structure shown in Figure 10.5(a), Kyoto Subway 10 Series shown in Figure 10.6(a)) featured all-welded aluminum alloy bodies using 7N01 alloy for the frame, outer panels, and underframe. Extensive use of extruded profiles in the frame and underframe reduced the weight to less than half compared to conventional steel bodies.[13]

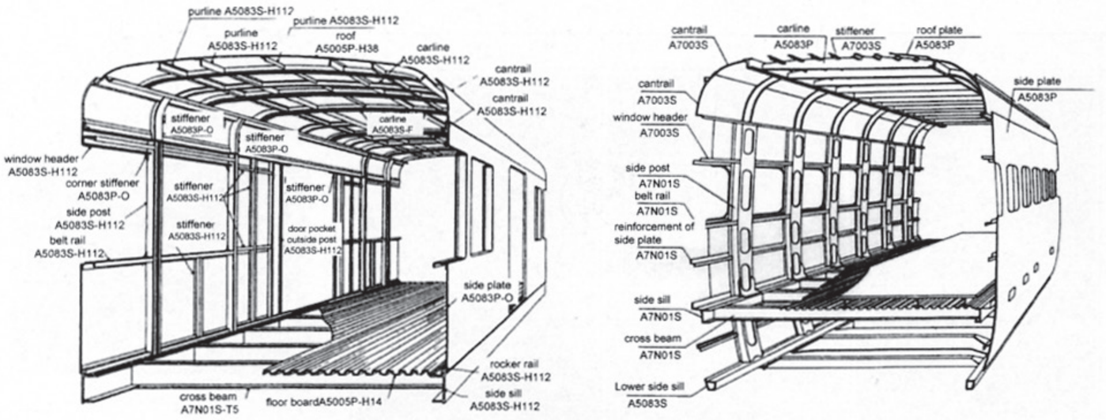
In 1967, Dr. Baba and his colleagues developed an alloy with reduced Mg and increased Zn content from those of A7N01 for improved extrudability, later internationally registered with the Aluminum Association (AA) as alloy 7003 (representative composition: Al-6%Zn-0.75%Mg-0.15%Zr).[15-17] This alloy enabled the production of wide, large-scale profiles. In 1969, the manufacturing companies of wrought aluminum alloys jointly established Keikinzoku Oshidashi Kaihatsu (KOK) in Yokkaichi City, installing Japan's largest 9,500-ton extrusion press. This allowed extrusion of profiles up to 520 mm wide, and 7003 alloy wide, large-scale profiles were adopted for the frames of Shinkansen. This led to the so-called 2.5 generation vehicle structure shown in Figure 10.5(b) and the 200 Series Shinkansen shown in Figure 10.6(b). Subsequently, it was extensively used in floor panels and side structures. As shown in Figure 10.7, the 7003 alloy was widely utilized not only in railway vehicles but also as strength members in containers, vans, and trailers. It could also be hollow-extruded for use in motorcycle and bicycle rims, car bumpers, and more.

Due to the high initial costs of aluminum alloy vehicles as compared with steel vehicles, there was a demand for alloys with superior extrudability, weldability, and corrosion resistance. In Europe, the Al-Mg-Si alloy 6005A was developed and used in vehicles. This alloy contained 0.12 to 0.5% Mn+Cr, but depending on the addition amount and extrusion conditions, could develop coarse grains. The ratio of Mg to Si could also affect toughness, and welding could easily cause micro-fissures and other cracks. Companies optimized the composition and, in 1980, these efforts were consolidated into the JIS 6N01 alloy.[18] This alloy allowed for the manufacture of thin-walled, hollow extruded profiles, enabling the entire structure to be composed of extruded profiles. This led to the third generation of vehicle structures (Figure 10.5(c)) and the 300 Series Shinkansen (Figure 10.6(c)). The 7N01 alloy was still used for parts requiring high strength, such as bolsters and crossbeams in the underframe. Entering the 1990s, the mainstream shifted to what was called the next-generation vehicle structure: a double-skin type structure using hollow truss cross-section extruded profiles. Even the bolsters and crossbeams were replaced with 6N01 alloy (Figure 10.5(d) and 700 Series Shinkansen, Figure 10.6(d)). New technologies such as brazed honeycomb panels[19] and friction stir welding (FSW) also came into use.[20]

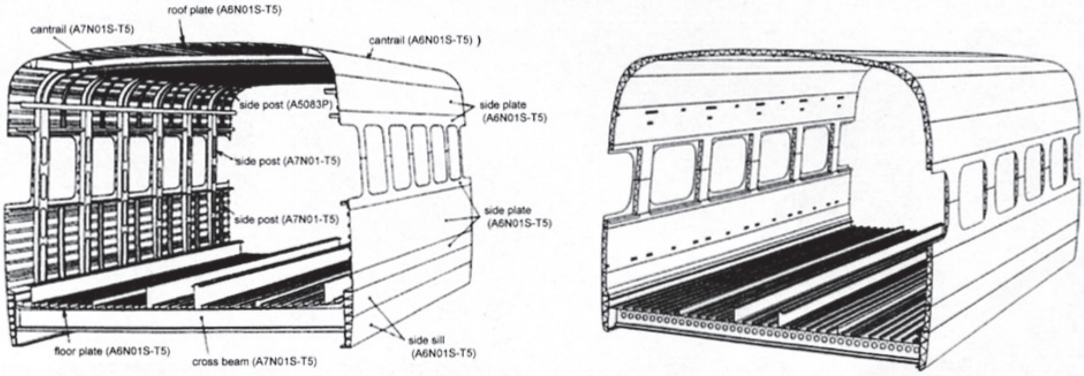
10.2.2 Motorcycles and Sports Equipment

Motorcycles are the form of transportation that incorporate the second highest use of aluminum in their construction after aircraft. For off-road racers, aluminum materials reportedly account for about 30% of their weight. There has been a high demand for lightweight, high-performance motorcycles, making adoption of aluminum parts proactive from early on. Parts that form the exterior of the engine, such as cylinder heads and cases, have been designed incorporating aluminum alloys from the start.

Around 1980, the demand for weight reduction and improved design in sport vehicles increased, leading to an in-



(a) Kyoto subway 10series (generation 2)　　(b) JR East 200series (generation 2.5)



(c) JR Central & West 300series (generation 3)　　(d) JR Central & West 700series (next generation)

Figure 10.5 Changes in Aluminum Railway Vehicle Structures[13]

(a) 2nd Generation (Kyoto Subway 10 Series)　　(b) 2.5 Generation (Shinkansen 200 Series)

(c) 3rd Generation (Shinkansen 300 Series)　　(d) Next Generation (Shinkansen 700 Series)

Figure 10.6 Representative Examples of Aluminum Vehicles[14]

Marine Containers Trailer Railway Vehicle

Rims Housing Tennis Rackets

Figure 10.7 Application Examples of 7003 Alloy[16]

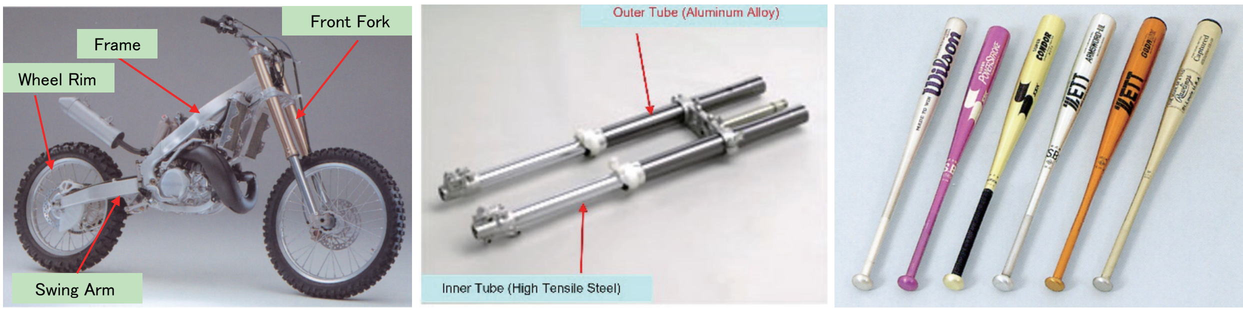
creased use of aluminum in wheels, frames, swing arms, radiators, and other parts. Wheels were among the earliest parts to adopt aluminum, with Al-Zn-Mg alloy 7003 being used for the rims of spoke wheels. This is due to its high strength and favorable weldability. Typically, the material is softened (O material), bent, flash-butt welded, and then subjected to bulging for spoke holes before quenching. Recently, Al-Zn-Mg-Cu alloys with higher copper content have also been used. Figure 10.8(a) shows the areas of a motorcycle where high-strength 7000 series extruded materials are used.[18]

Controlling the microstructure of extruded materials was also an important issue, as grain coarsening during solution heat treatment affects the appearance quality after subsequent surface polishing and anodizing. Generally, high-strength alloy extrusions have a fibrous structure due to the addition of small amounts of Mn, Cr, Zr, and other elements for strength, toughness, and stress corrosion cracking resistance. However, the extruded surface layer tends to recrystallize due to shearing by the die. The recrystallized structure thickens during solution heat treatment and, if recrystallized structures

Column: Dr. BABA Yoshio

Dr. BABA Yoshio
(1935-2012)

Dr. BABA Yoshio was born in 1935. He graduated from the Department of Metallurgy, Faculty of Engineering, Kyoto University in 1958. He came from the research lab of Prof. MURAKAMI Yōtaro, who had succeeded Prof. NISHIMURA Hideo in running the lab. Baba joined Sumitomo Metal Industries with the desire to engage in titanium research and development. The following year after joining, when Sumitomo Light Metal became independent, he became part of the first generation of employees and started working on aluminum alloy research and development. In 1969, he was awarded a Ph.D. in Engineering from Kyoto University. In 1972, he became a senior researcher at Sumitomo Light Metal Industries, Ltd. When I (author) joined the company (in 1975), Dr. Baba was a senior researcher. I was given research themes on stress corrosion cracking in welded parts of Al-Zn-Mg ternary alloys, which later evolved into studying the effects of Zr addition on the mechanical properties and stress corrosion cracking of Al-Zn-Mg-(Cu) alloys. In 1985, he became a director of the company. From 1992, he concurrently served as a visiting professor at Toyohashi University of Technology for three years. In 1999, he retired from his position as senior managing director and became an advisor to the company. His awards include the 9th Oyamada Memorial Award for “Research and Development of New Al-Zn-Mg Ternary Alloys” in 1974, 36th Japan Institute of Metals and Materials Achievement Award (Metallic Materials Division) in 1978, National Invention Award for “Manufacturing Method of High-Strength Al-Zn-Mg Alloy for Welded Structures with Excellent Quench Sensitivity” in 1980, 9th Chunichi Industrial Technology Award for “Development of High-Strength Aluminum Alloy Sheets for Aircraft Tapered Stringers and Their Fabrication Technology” in 1996, and 3rd Japan Institute of Light Metals Award in 2000. Dr. Baba sadly passed away at the age of 77 in 2012.



(a) Railway vehicle alloys applied to motorcycles

(b) Aircraft alloys applied to outer tube of front forks

(c) Aircraft alloys applied to hardball baseball bats

Figure 10.8 Application of Railway Vehicle and Aircraft Alloys to Motorcycles and Sports Equipment (from UACJ catalog)

and fibrous structures coexist after polishing and anodizing, an unevenness in luster occurs, requiring control for making the structures be either one or the other for the sake of appearance. 7N01 and 7003 extruded materials are used for the main pipe areas of the frame and the arm area of the swing arm, which are joined by welding with cast or forged parts of the head pipe and bracket area. For some press forming, 5083 alloy sheet material with favorable weldability was adopted.

The front forks serve as a suspension connecting the body to the front tire, and aid in steering, cushioning, and suspension. The forks consist of a double tube to absorb shock, with high-tensile steel used for the inner tube and aluminum alloy cast material for the outer tube. Around 1990, for off-road racers like motocross where large impact forces are applied during jump landings, high-strength, high-toughness alloys were needed instead of cast materials, drawing attention to Al-Zn-Mg-Cu alloys used in aircraft. Among these, Zr-added alloys can suppress surface grain coarsening after indirect extrusion and are less sensitive to quenching, allowing the use of vertical quenching furnaces with polyalkylene glycol instead of water cooling, reducing non-uniform residual stress. Currently, the aluminum alloy material having the highest strength and toughness is being practically used for the outer tubes of the front forks (Figure 10.8(b)).[21] This can be regarded as an example of how the tradition of material development for prewar aircraft is still alive in motorcycle material development. It should be noted that tube manufacturing technology is also applied to high school hardball baseball bats. More than half of the hardball baseball bats used in the spring and summer high school baseball tournaments at Koshien Stadium are made from high-strength Al-Zn-Mg-Cu alloy extrusions manufactured by UACJ. Examples of aluminum baseball bats are shown in Figure 10.8(c).

10.3 Trends in Commercial Aircraft Development and Materials Development in the Postwar World

10.3.1 Trends in Commercial Aircraft Development Worldwide

After World War II, transport aircraft shifted from military use to commercial airlines. Until then, airliners had flown at low altitudes without the need for oxygen masks, but the practical application of pressurized cabins that could provide a comfortable environment even at high altitudes made it possible to fly at high altitudes at high speeds with little air turbulence. This new era began in 1945 with the Lockheed L-049 operating between Washington DC and Paris, followed by the Douglas DC-6 in 1947, which could carry 50 to 100 passengers. The 1950s saw the introduction of jet airliners capable of nearly doubling the speed of propeller-driven aircraft, and in 1957 the revolutionary Boeing 707, a four-engine jet airliner with a cruise speed of 973 km/h, 140 to 200 passenger capacity, twice the speed and twice the payload of conventional four-engine propeller-driven aircraft, took its maiden flight. Douglas followed suit in 1958 with its first flight of the DC-8, a four-engine jet airliner.

The 1960s ushered in the era of mass air travel. Boeing introduced the Boeing 727, a full-fledged three-engine jet airliner with a cruise speed of 964 km/h and a maximum capacity of 189 passengers for short and medium routes, followed in 1967 by the Boeing 737, a twin-engine small regional jet in the 100-120 passenger class. The Boeing 737 was later expanded to compete with Airbus' A320 and increased to 200 passengers, making it a best-selling aircraft. In 1969, the Boeing 747 Jumbo Jet, a four-engine jet with a cruise speed of 910 km/h and a capacity of 350-594 passengers, was introduced for long routes. The 747 was the first wide-body aircraft with two aisles in the cabin and was equipped with state-of-the-art equipment such as an inertial guidance system. In 1970, two notable wide-body aircraft were introduced. The first was the American Douglas DC-10 (later succeeded by the MD-11), a three-engine wide-body aircraft with a cruising speed of 876 km/h and a passenger capacity of 206 to 380. It featured two engines on the wings and one engine mounted on the vertical stabilizer. The second was the Lockheed L-1011 TriStar, also a three-engine wide-body aircraft, designed under similar conditions as the DC-10 around the same time. The L-1011 had a cruising speed of Mach 0.85 and could accommodate 255 to 326 passengers.

In 1972, the Airbus A300 made its maiden flight. This twin-engine wide-body aircraft was designed with a cruising speed of 875 km/h and a passenger capacity of 200 to 300, specifically intended to carry 300 passengers within European routes. Later, in 1987, Airbus introduced the A320 series, a high-tech passenger aircraft incorporating cutting-edge technology in a smaller narrow-body design. The A320 series had a cruising speed of 840 km/h and could accommodate 107 to 220 passengers. The tremendous success of this A320 series played a crucial role in Airbus's growth, elevating the company to become one of the two major passenger aircraft manufacturers alongside Boeing.

From 1980 onwards, Boeing engaged in international collaborative development and manufacturing efforts with Japan and Italy. This partnership led to the first flight of the Boeing 767, a medium-sized aircraft for medium-range routes, in 1982. In 1994, the large Boeing 777 for long-distance routes made its maiden flight. Then in 2009, the Boeing 787, a medium-sized twin-engine aircraft designed for medium to long-range flights, took to the skies for the first time. The 787's airframe marked a significant shift in materials used, with approximately 50% of its structure composed of carbon fiber composite materials instead of the traditional aluminum alloys, reducing weight. Meanwhile, Airbus developed the twin-engine A330 for medium-range routes and the four-engine A340 for long-range flights, both of which entered service in the early 1990s. In 1989, Airbus began work on a large aircraft capable of competing with the Boeing 747. This project evolved into the A380, with development officially starting in 2000. The A380 made its first flight in 2005 and was delivered to airlines in 2007. It has a seating capacity of 525 passengers in a three-class configuration and up to 853 passengers in a single-class layout. In its standard three-class configuration (First, Business, and Economy), the A380 offers approximately 1.3 times the seating capacity of the Boeing 747-400. Furthermore, Airbus set out to develop a new generation of medium-sized twin-engine aircraft with the goal of developing an aircraft with 787-equivalent or better performance at less cost and with greater ease. This led to the A350. However, in 2006, the design was revised, resulting in the development of the A350XWB. The A350XWB made its maiden flight in 2013. Similar to the 787, the A350XWB's airframe incorporates 53% carbon fiber composite materials. During this period, Lockheed withdrew from the commercial aircraft market, and McDonnell Douglas was absorbed by Boeing. As a result, the medium and large aircraft market is now dominated by two major players: Boeing and Airbus.

10.3.2 Global Trends in Aircraft Materials Development [22]

Table 10.1 shows the history of aluminum alloy development for aircraft and its relationship with the aircraft to which it was first applied.[23] This data partially supplements Warren's data. The 7075 alloy developed by Alcoa based on the Extra Super Duralumin ESD alloy was used in the B-29D (B-50) that played an active role in the Korean War. The 7150 and 7055 alloys in this table are improvements on 7075, with changes in the amounts of Zn, Mg, and Cu compositions and reduced impurities to enhance strength and toughness. Similar to the Al-Zn-Mg series alloys, they replaced the trace element Cr with Zr, improving quench sensitivity and stress corrosion cracking resistance. While these alloy developments are the result of Alcoa's post-war research and development, it could be said that they are fundamentally based on ESD. Regarding the 2000 series alloys, there are 2324 and 2524, which are high-purity versions of 2024 designed to improve ductility, toughness, and fatigue crack propagation characteristics, but their basic compositions remain unchanged from 2024.

Table 10.1 Aircraft and New Alloys Used Therein [23]*

Maiden Flight	Aircraft	Alloy & Tempering
1903	Wright Brothers	Al-Cu casting
1919	Junkers F13	2017-T4
1935	DC-3	2024-T3
1939	Zero Fighter	ESD-T6
1945	B-29D (B-50)	7075-T6
1957	Boeing 707	7178-T651
1970	DC-10	7075-T7351
1970	L-1011	7075-T7651
1981	Boeing 757, 767	2324-T39, 7150-T651
1994	Boeing 777	7055-T7751, 2524-T3
2003	Boeing 777-300ER	2324-T39 Type II (2624-T39)

*Some additions to Warren's data

Figure 10.9 shows the relationship between yield strength and fracture toughness.[23] Generally, there is an inverse relationship where increasing yield strength decreases fracture toughness. However, after the war, this inverse relationship trended upward. This is due to improvements in material toughness through impurity control and microstructure control via thermo-mechanical treatment. Figure 10.10 illustrates the typical alloys used in various parts of the Boeing 777.[24] Figure 10.11 shows the flow of aerospace alloy development in Europe and America.[25] Table 10.2 lists the aerospace alloys registered with the Aluminum Association (AA).[26] A notable characteristic is the use of high-purity base metals to improve fracture toughness and fatigue crack growth rates. For 7000 series alloys, many are now alloys with about 7 to 10% zinc

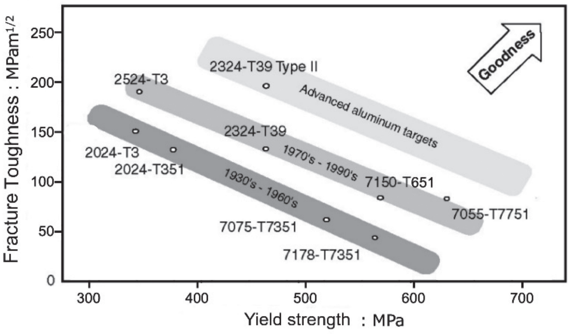


Figure 10.9 Trends in Development of High-Strength, High-Toughness Aluminum Alloys for Aircraft Applications[23]

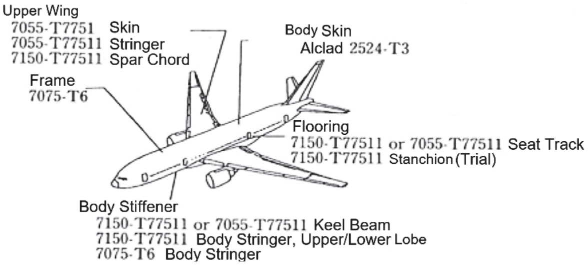


Figure 10.10 Aircraft Aluminum Alloy Used in Boeing 777[24]

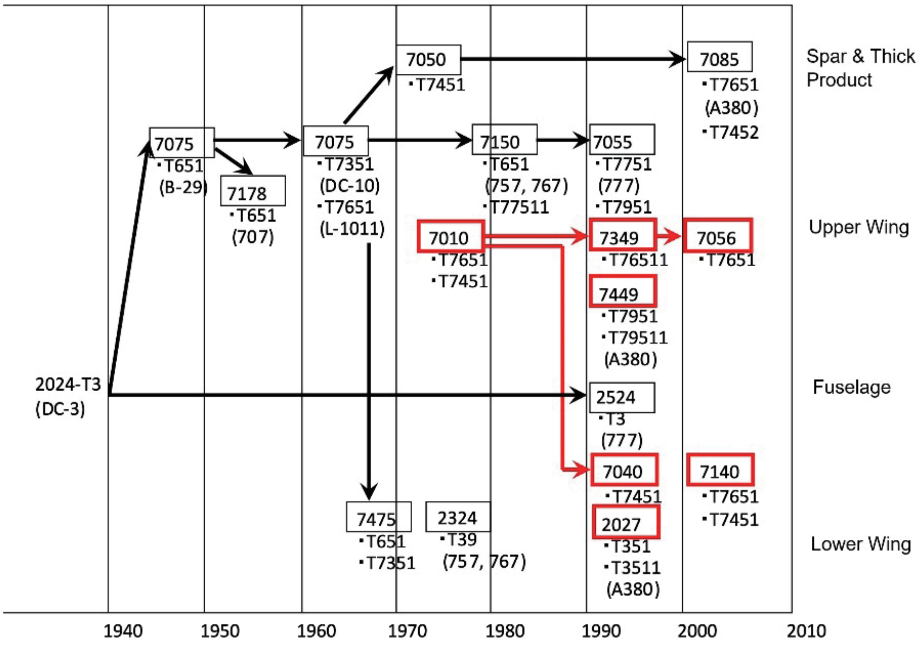


Figure 10.11 Relationship between Parts of Aircraft and Aluminum Alloys Developed [Black Frame: Alcoa, Red and Bold Frame: Alcan (now Constellium)] Added to J.D. Bryant, Alcoa Aluminum: Rolled Product, March 18, 2015[25]

Table 10.2 Compositions of Aircraft Aluminum Alloys Registered with AA (mass%) [26]

No.	Date	By	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ti	
2013	2003	JAPAN	0.6–1.0	0.40	1.5–2.0	0.25	0.8–1.2	0.04–0.35	0.25		0.15	
2014	1954	USA	0.50–1.2	0.7	3.9–5.0	0.40–1.2	0.20–0.8	0.10	0.25	0.20 Zr+Ti	0.15	
2017	1954	USA	0.20–0.8	0.70	3.5–4.5	0.40–1.0	0.40–0.8	0.10	0.25		0.15	
2024	1954	USA	0.50	0.50	3.8–4.9	0.30–0.9	1.2–1.8	0.10	0.25	0.20 Zr+Ti	0.15	
2124	1970	USA	0.20	0.30	3.8–4.9	0.30–0.9	1.2–1.8	0.10	0.25	0.20 Zr+Ti	0.15	
2424	1994	USA	0.10	0.12	3.8–4.4	0.30–0.6	1.2–1.6		0.20		0.10	
2524	1995	USA	0.06	0.12	4.0–4.5	0.45–0.7	1.2–1.6	0.05	0.15		0.10	
2624	2009	USA	0.08	0.08	3.8–4.3	0.45–0.7	1.2–1.6	0.05	0.15		0.10	
2025	1954	USA	0.50–1.2	1.0	3.9–5.0	0.40–1.2	0.05	0.10	0.25		0.15	
2026	1996	USA	0.05	0.07	3.6–4.3	0.30–0.8	1.0–1.6		0.10	0.05–0.25	0.06	
2027	2001	FRANCE	0.12	0.15	3.9–4.9	0.50–1.2	1.0–1.5		0.20	0.05–0.15	0.08	
2056	2003	FRANCE	0.10	0.12	3.3–4.3	0.10–0.50	0.6–1.4		0.40–0.8			
2219	1954	USA	0.20	0.30	5.8–6.8	0.20–0.40	0.02		0.10	0.10–0.25	0.02–0.10	0.05–0.15 V
2519	1985	USA	0.25	0.30	5.3–6.4	0.10–0.50	0.05–0.40		0.10	0.10–0.25	0.02–0.10	0.05–0.15 V
2618	1954	USA	0.10–0.25	0.9–1.3	1.9–2.7		1.3–1.8		0.10		0.04–0.10	0.9–1.2 Ni
7010	1975	UK	0.12	0.15	1.5–2.0	0.10	2.1–2.6	0.05	5.7–6.7	0.10–0.16	0.06	
7136	2004	USA	0.12	0.15	1.9–2.5	0.05	1.8–2.5	0.05	8.4–9.4	0.10–0.20	0.10	
7037	2006	GERMANY	0.10	0.10	0.6–1.1	0.50	1.3–2.1	0.04	7.8–9.0	0.06–0.25	0.10	
7040	1996	FRANCE	0.10	0.13	1.5–2.3	0.04	1.7–2.4	0.04	5.7–6.7	0.05–0.12	0.06	
7140	2005	FRANCE	0.10	0.13	1.3–2.3	0.04	1.5–2.4	0.04	6.2–7.0	0.05–0.12	0.06	
7049	1968	USA	0.25	0.35	1.2–1.9	0.20	2.0–2.9	0.10–0.22	7.2–8.2		0.10	
7149	1975	USA	0.15	0.20	1.2–1.9	0.20	2.0–2.9	0.10–0.22	7.2–8.2		0.10	
7249	1982	USA	0.10	0.12	1.3–1.9	0.10	2.0–2.4	0.12–0.18	7.5–8.2		0.06	
7349	1994	FRANCE	0.12	0.15	1.4–2.1	0.20	1.8–2.7	0.10–0.22	7.5–8.7	0.25 Zr+Ti		
7449	1994	FRANCE	0.12	0.15	1.4–2.1	0.20	1.8–2.7		7.5–8.7	0.25 Zr+Ti		
7050	1971	USA	0.12	0.15	2.0–2.6	0.10	1.9–2.6	0.04	5.7–6.7	0.08–0.15	0.06	
7150	1978	USA	0.12	0.15	1.9–2.5	0.10	2.0–2.7	0.04	5.9–6.9	0.08–0.15	0.06	
7055	1991	USA	0.10	0.15	2.0–2.6	0.05	1.8–2.3	0.04	7.6–8.4	0.08–0.25	0.06	
7255	2009	USA	0.06	0.09	2.0–2.6	0.05	1.8–2.3	0.04	7.6–8.4	0.08–0.15	0.06	
7056	2004	FRANCE	0.10	0.12	1.2–1.9	0.20	1.5–2.3		8.5–9.7	0.05–0.15	0.08	
7068	1996	USA	0.12	0.15	1.6–2.4	0.10	2.2–3.0	0.05	7.3–8.3	0.05–0.15	0.10	
7075	1954	USA	0.40	0.50	1.2–2.0	0.30	2.1–2.9	0.18–0.28	5.1–6.1	0.25 Zr+Ti	0.20	
7175	1957	USA	0.15	0.20	1.2–2.0	0.10	2.1–2.9	0.18–0.28	5.1–6.1		0.10	
7475	1969	USA	0.10	0.12	1.2–1.9	0.06	1.9–2.6	0.18–0.25	5.2–6.2		0.06	
7085	2002	USA	0.06	0.08	1.3–2.0	0.04	1.2–1.8	0.04	7.0–8.0	0.08–0.15	0.06	
ESD	1936	JAPAN			1.5–2.5	0.3–1.0	1.2–1.8	0.1–0.4	6.0–9.0			

added. The Extra Super Duralumin ESD, invented in pre-war Japan and used in the Zero fighter, contained 6 to 9% zinc. So, it could be said that the world finally reached the level of Extra Super Duralumin.

10.4 Aircraft Industry and Aircraft Materials R&D in Postwar Japan

The domestic aviation industry in Japan was revived by the special demands of the Korean War. As a result, in 1956, the Ministry of International Trade and Industry formulated a plan for domestic civilian aircraft production. In 1959, the public-private joint venture Nihon Aircraft Manufacturing Corporation (NAMC) was established, and the twin-engine turboprop passenger aircraft YS-11 (Figure 10.12) was developed. This YS-11 struggled significantly with overseas sales, and the project's financial situation deteriorated, leading to YS-11 termination in 1971 after producing a total of 182 aircraft. The YS-11 was used not only by domestic and international commercial airlines but also by military forces like the Japan Air Self-Defense Force, as well as government agencies such as the Japan Coast Guard and the Ministry of Land, Infrastructure, Transport and Tourism. Subsequently, the Japanese aviation industry grew by producing parts for Boeing's 767, 777, and 787 aircraft.

Figure 10.12 YS-11, First Domestic Commercial Aircraft after the War (Courtesy of Aoki Masaru)

Unfortunately, the current aviation industry in Japan is significantly smaller in scale compared to those in Europe and the United States. Its main role is subcontracting manufacturing for Boeing aircraft. Similarly, the Japanese aluminum industry produces far less aviation material compared to can and automotive materials. This makes it difficult to invest in production facilities, resulting in higher production costs. As a result, much of the aircraft aluminum alloys is imported cheaply from overseas, with domestic products accounting for only about 10 to 20% of the market. Research on aircraft aluminum alloys in Japan is primarily focused on obtaining material certification from Boeing, rather than developing new materials. For Japanese aluminum material researchers, it is unfortunate that the aircraft material market is too small compared to can and automotive materials, limiting practical research. In terms of high-strength alloy development and manufacturing technology, Japan has fallen significantly behind Europe and the United States. Without a market, neither research and development nor manufacturing technology can thrive. It is crucial to revitalize the aircraft industry.

Regarding Japanese aircraft development, apart from the Honda Jet produced overseas, Kawasaki Heavy Industries developed the P-1 anti-submarine patrol aircraft and C-2 transport aircraft (Figure 10.13) for the Ministry of Defense, albeit in small quantities. There is also the Mitsubishi MRJ (currently known as SpaceJet, shown in Figure 10.14), a domestic regional jet currently under development, though it is currently on hold due to the COVID-19 pandemic. There are no other aircraft currently planned beyond these.

Before World War II, Japan was a major aviation power and actively engaged in materials development. This accumulated knowledge contributed to the post-war development of

a) P-1

b) C-2

Figure 10.13 Anti-Submarine Patrol Aircraft[27] and C-2 Transport Aircraft[28]

Figure 10.14 SpaceJet of Mitsubishi Aircraft (Provided by Mitsubishi Aircraft Corporation)

Japan's aluminum industry. Unfortunately, the post-war aviation industry in Japan was small in scale, forcing a reliance on cheaper imported materials. Instead, Japan significantly expanded demand in other sectors such as railway vehicles, automobiles, motorcycles, building materials, sashes, beverage cans, air conditioners, printing sheets, and foils. By developing and providing finely-tuned aluminum materials to meet user requirements, Japan has created world-class aluminum products in collaboration with users, thus expanding demand in the global market.

In post-war Japan's aircraft material development, one notable achievement was the development of tapered rolled stringer materials (Figure 10.15), which foreign competitors could not produce. These were installed in aircraft like the Boeing 767.[29-32] Furthermore, Japan developed the 2013 alloy, which allows for hollow extrusion similar to railway vehicle materials and offers strength comparable to 2024. This alloy was registered with the AA international alloy registry and included in the Metallic Materials Properties Development and Standardization (MMPDS), an essential metal material data collection for aerospace equipment development and manufacturing.[33] For the industry, the ability to manufacture materials requiring advanced technology, such as aircraft materials, serves as a testament to a company's technological credibility.

Figure 10.15 Boeing 767 Fuselage with Tapered Rolled Stringers[31, 32]

10.5 Future Prospects for Aircraft Materials

Concerned about falling behind in the high-strength aluminum alloy development race with Europe, America, and China, a national project titled "Development of Innovative Aluminum Alloys with High Strength and High Toughness" was launched in 2013 to compete with the specific strength of Al-Li alloys from Europe and America. This project, in collaboration with Professor KANETAKE Naoyuki of Nagoya University and others, aimed to develop a high-toughness, high-specific strength alloy that would maintain the toughness of conventional 7000 series alloys while increasing tensile strength by 25% to over 700 MPa, as shown in Figure 10.16.[34] If successful, this would be the world's first development of an Extra-ESD. Those familiar with the history of Extra Super Duralumin believe this goal is achievable. However, as evident from Figure 10.9, the challenge is that as strength increases, toughness and ductility decrease. The cause of this issue is believed to lie in the casting microstructure shown in Figure 10.17(a). High-concentration segregation of alloying elements and compounds remain at the grain boundaries, persisting even after rolling and heat treatment (Figure 10.17(b)).[35, 36]

To solve this issue, the solution is to add massive strain to the casting microstructure, thereby destroying the grain boundaries through shear. Based on fundamental research, Professor Kanetake and his team discovered that warm compression torsion processing is effective. As one means for making this process continuous for industrialization, there is a hot torsion processing device called CREO, invented by Professor NAKAMURA Katsuaki of the Kyushu Institute of Technology and CEO of Rinascimetalli (http://rinascimetalli.co.jp/12.html). Figure 10.18 shows the principle diagram of this device.[34] This is a technology unique to Japan. It is believed that new alloys can be developed in conjunction with such innovative technologies.[37]

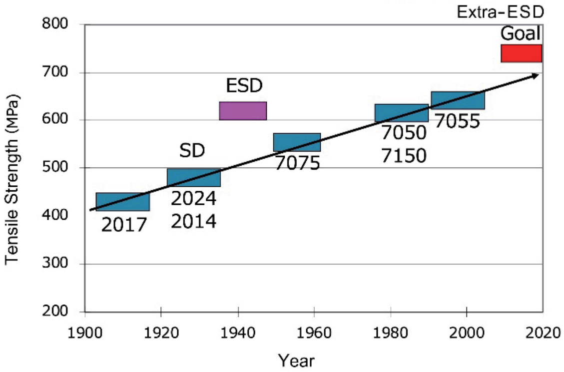
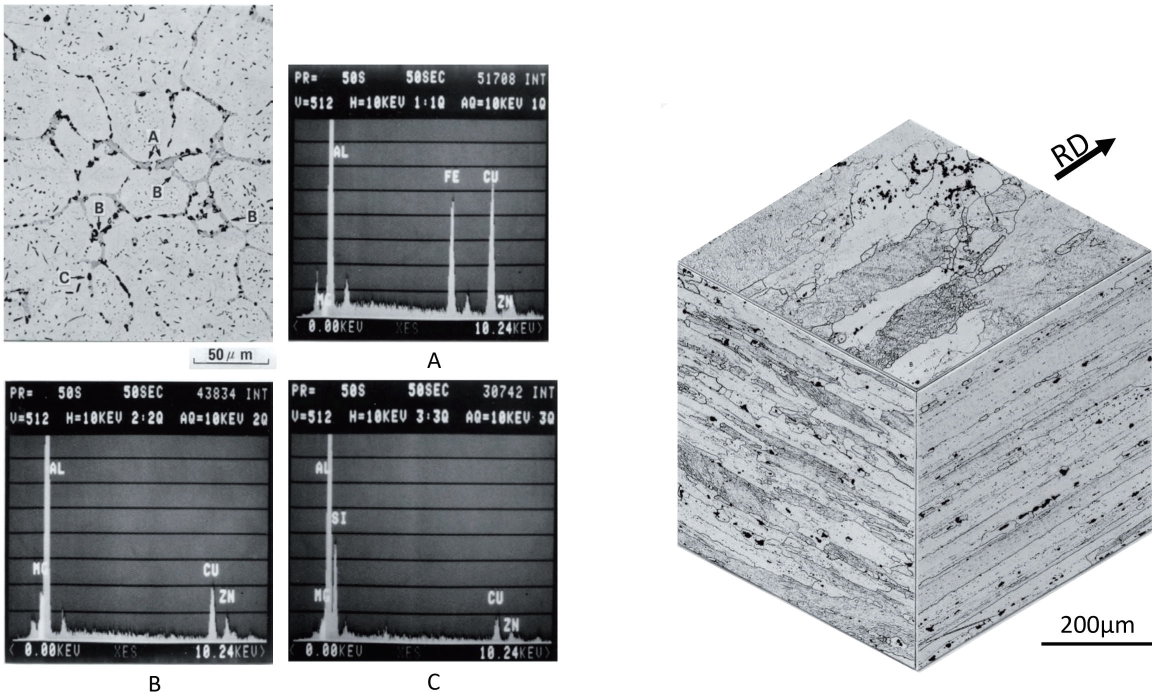


Figure 10.16 History and Future Goals of High-Strength Aluminum Alloy Development



(a) Compounds Formed During Casting

(b) Dispersion of Compounds after Hot Rolling

Figure 10.17 Compounds Formed During Casting of 7150 Alloy (a) and Dispersion of Compounds at the Grain Boundaries after Rolling (b)[36]

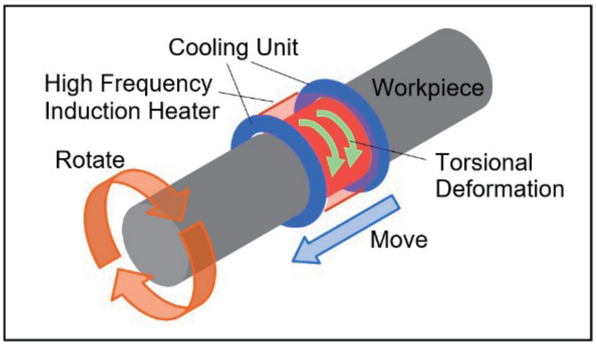


Figure 10.18 Principle Diagram of CREO Hot Torsion Processing Equipment[34, 37]

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11 Conclusion

For the past decade, I have been researching the history of Extra Super Duralumin developed by my predecessors. The catalyst for this was a lecture by a renowned American professor at the International Conference on Aluminum Alloys (ICAA11) held in Aachen in 2008. The lecture was a keynote on the history of age hardening in aluminum materials. I attended expecting to hear about Extra Super Duralumin, but to my surprise, the slides on the development of aluminum alloys for aircraft using age hardening completely ignored Japan's Extra Super Duralumin. Of course, the professor was not entirely unaware – his abstract mentioned that Sumitomo had an alloy similar to Alcoa's 7075, which was used in the Zero fighter. However, it became clear that while Extra Super Duralumin is well-known among Japanese aluminum material researchers, it is either ignored or largely unknown overseas. As I have pointed out in the main text, I believe this relates to the pride of Alcoa's researchers. As someone who has researched aircraft materials for many years, as a way to pay tribute to the research of my predecessors, I want to continue disseminating the history of Extra Super Duralumin to the international community.

For those of us who joined Sumitomo Light Metals (now UACJ), Extra Super Duralumin is like an identity, something our seniors taught us about upon joining the company. However, the extent of our detailed knowledge was questionable. Fortunately, Sumitomo Light Metals' library systematically preserved handwritten research reports along with academic journals and books from around the world dating back to pre-war times. In addition to these materials, Dr. TAKEUCHI Katsuji compiled a detailed book about the manufacturing technology situation at the time. Unfortunately, as he was not a materials engineer, the book lacks details about alloy development. So, following in the footsteps of our seniors, I delved deep into the library, copying and reading old handwritten reports. Besides these reports, Sumitomo Metals also published a research journal called "Research Reports of Sumitomo Metal Industries" for external distribution. Systematically deciphering these reports helped solve the mystery of how development could be achieved in such a short time.

In any case, I want to express gratitude to the researchers of that time and the seniors who guided the research. They naturally built a system where research results, even if incomplete, were always recorded, important findings were patented, results were later submitted as papers to company magazines or academic societies, and researchers who needed degrees would obtain degrees. This system is still worth learning from today and is important for passing on technology to future generations.

We can summarize the answers to the questions posed in the "Introduction" of this report as follows:

Firstly, aluminum became affordable because the Hall-Héroult process succeeded in mass production by utilizing hydroelectric power. The use of hydroelectric power, a clean energy source, for aluminum smelting is particularly significant in light of current environmental concerns. Moreover, the advancement of manufacturing technologies such as casting and rolling, as well as processing technology such as roll forming, were essential for producing hard Duralumin and enabling its use in airships and aircraft.

Secondly, the reason Alcoa was able to develop Super Duralumin 24S, while the UK, Germany, and Japan could not, lies in Alcoa's high-purity aluminum technology. Impurity elements like iron and silicon in Duralumin cause a decrease in strength and ductility, hindering the enhancement of its strength. Alcoa had perfected the three-layer electrolysis method by the mid-1920s, enabling mass production of high-purity ingots, which led to the development of 24S. The issue of impurities is deeply related to the choice of raw materials. Using bauxite allowed for a reduction in impurities compared to other ores. The war made it clear how crucial it was to secure bauxite resources for material development. This was a problem that could only be addressed by those involved in smelting research from an early stage.

Thirdly, the reason Extra Super Duralumin could be developed in a short period is believed to be related to the fact that senior researchers, including Igarashi, had already conducted research on chromium addition before the development of Extra Super Duralumin. Igarashi had also confirmed the effectiveness of chromium addition in improving the corrosion resistance of 24S cladding materials. It seems that the research progressed with a sense that it would also be effective against stress corrosion cracking, based on this broad knowledge and experience. Without this background, it would not have been a problem that could have yielded results within a year. Of course, his research methods also played a role.

Lastly, regarding the future prospects of aircraft material development, unfortunately, there are currently no plans for independent aircraft development in Japan other than Mitsubishi's MRJ (renamed SpaceJet), which has been frozen due to the COVID-19 pandemic. However, there is still a good possibility of recovery and revival in the future. Aircraft represent a culmination of cutting-edge technologies, and aircraft materials are no exception. It can be said that without aiming for aerospace, there will be no new development for Japan. Research on aircraft materials requires government support. While research topics have been identified for this purpose, securing and nurturing talent capable of carrying out this research has become of utmost importance, including for companies.

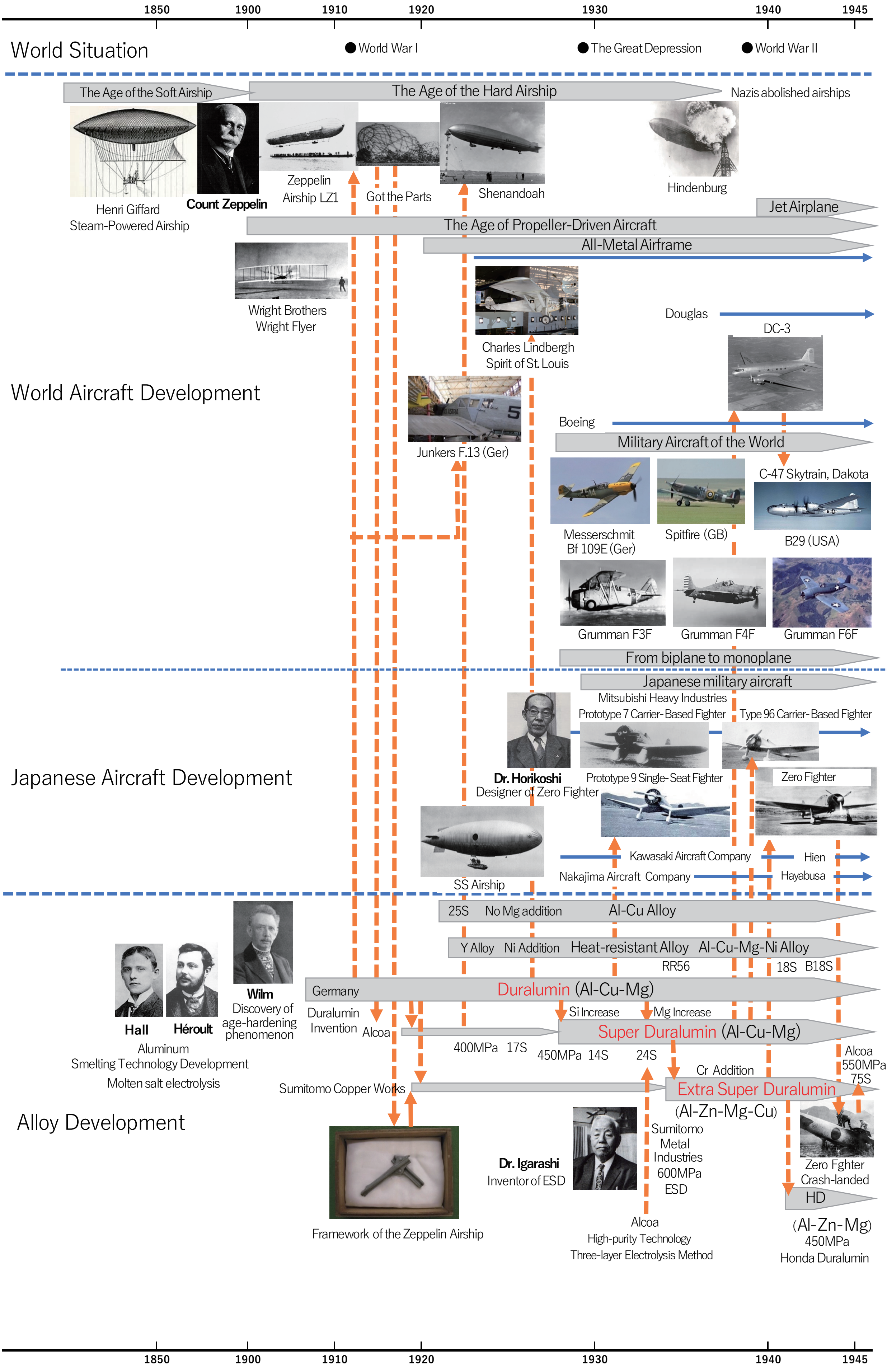
Acknowledgments:

I would like to express my deep gratitude to Mr. SHIBUE

Kazuhisa, former Director of the UACJ R&D Center, for recommending me for this project. I would also like to extend my sincere gratitude to Mr. HIRANO Seiichi, Director, and Dr. KOJIMA Yōichi, Assistant Director, for their willingness to store important scientific and technological materials related to Extra Super Duralumin.

For the history of manufacturing technology, I referred to "*Technology Milestones*" by Dr. TAKEUCHI Katsuji, former technical research officer at Sumitomo Light Metals Technical Research Laboratories. For the pre-war history of light alloys, I consulted valuable technical materials such as "Essays: History of Light Alloys" and "Continued: History of Light Alloys" by Prof. NISHIMURA Hideo, compiled by Dr. Takeuchi. For these valuable resources, I once again express my sincerest gratitude.

Systematic and Technical Flowchart of the Development of Aluminum Alloys for Aircraft



1850 1900 1910 1920 1930 1940 1945

World Situation

● World War I ● The Great Depression ● World War II

The Age of the Soft Airship

The Age of the Hard Airship

Nazis abolished airships

Henri Giffard
Steam-Powered Airship

Count Zeppelin

Zeppelin
Airship LZ1

Got the Parts

Shenandoah

Hindenburg

Jet Airplane

The Age of Propeller-Driven Aircraft

All-Metal Airframe

Wright Brothers
Wright Flyer

Charles Lindbergh
Spirit of St. Louis

Douglas

DC-3

World Aircraft Development

Junkers F.13 (Ger)

Boeing

Military Aircraft of the World

C-47 Skytrain, Dakota

Messerschmit
Bf 109E (Ger)

Spitfire (GB)

B29 (USA)

Grumman F3F

Grumman F4F

Grumman F6F

From biplane to monoplane

Japanese military aircraft

Mitsubishi Heavy Industries

Prototype 7 Carrier-Based Fighter

Type 96 Carrier-Based Fighter

Japanese Aircraft Development

Dr. Horikoshi
Designer of Zero Fighter

Prototype 9 Single-Seat Fighter

Zero Fighter

SS Airship

Kawasaki Aircraft Company

Hien

Nakajima Aircraft Company

Hayabusa

25S No Mg addition Al-Cu Alloy

Y Alloy Ni Addition Heat-resistant Alloy Al-Cu-Mg-Ni Alloy

RR56 18S B18S

Hall **Héroult**
Aluminum
Smelting Technology Development
Molten salt electrolysis

Wilm
Discovery of
age-hardening
phenomenon

Germany Duralumin (Al-Cu-Mg)

Duralumin
Invention

Alcoa

Si Increase

Mg Increase

400MPa 17S

Super Duralumin (Al-Cu-Mg)

450MPa 14S

24S

Cr Addition

Alcoa
550MPa
75S

Sumitomo Copper Works

Extra Super Duralumin
(Al-Zn-Mg-Cu)

Alloy Development

Dr. Igarashi
Inventor of ESD

Sumitomo
Metal
Industries
600MPa
ESD

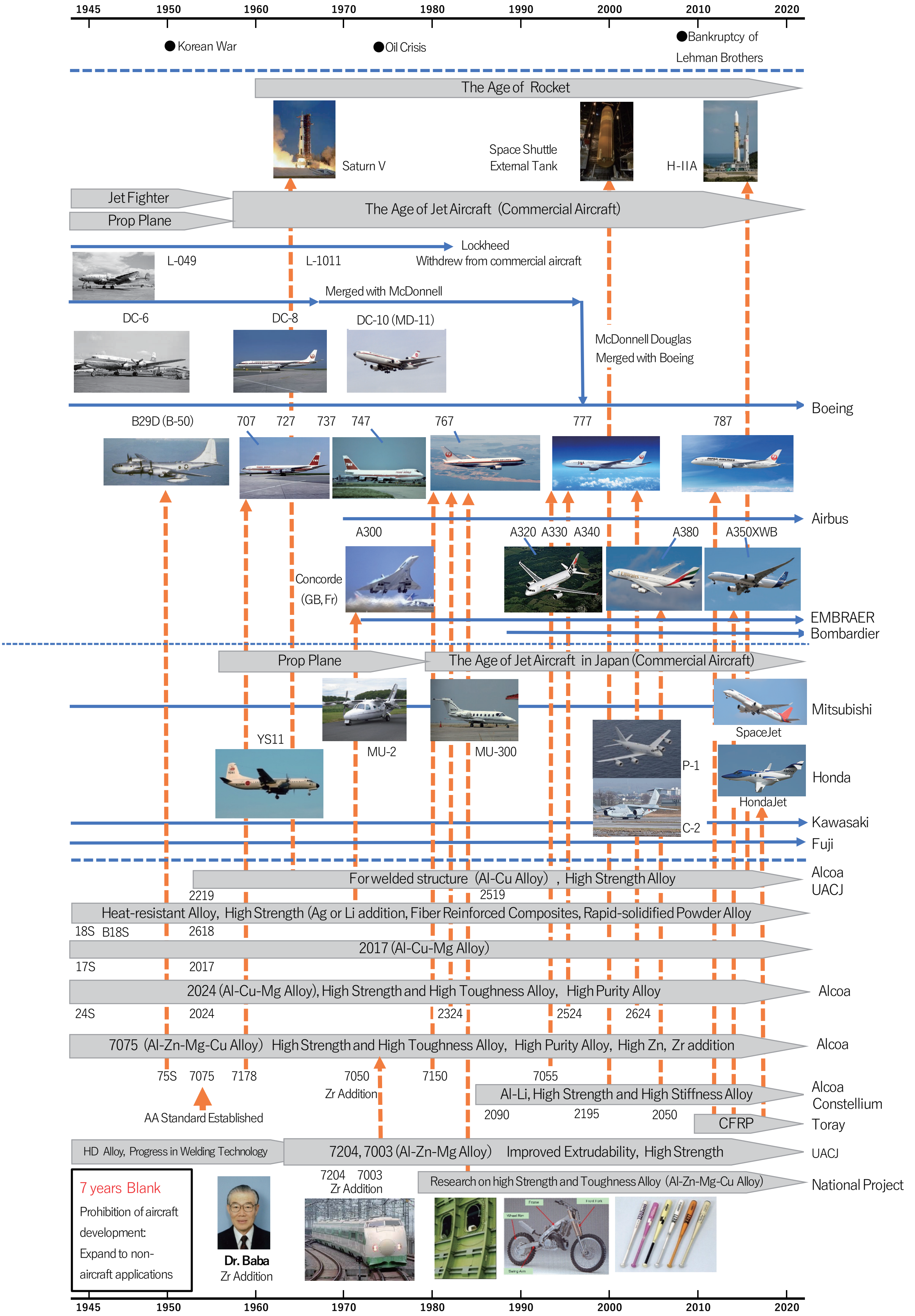
Zero Fghter
Crash-landed

HD
(Al-Zn-Mg)
450MPa
Honda Duralumin

Framework of the Zeppelin Airship

Alcoa
High-purity Technology
Three-layer Electrolysis Method

1850 1900 1910 1920 1930 1940 1945


1945
1950
1960
1970
1980
1990
2000
2010
2020
Korean War
Oil Crisis
Bankruptcy of Lehman Brothers
The Age of Rocket
Saturn V
Space Shuttle External Tank
H-IIA
Jet Fighter
Prop Plane
The Age of Jet Aircraft (Commercial Aircraft)
L-049
L-1011
Lockheed Withdrew from commercial aircraft
Merged with McDonnell
DC-6
DC-8
DC-10 (MD-11)
McDonnell Douglas Merged with Boeing
Boeing
B29D (B-50)
707
727
737
747
767
777
787
Airbus
A300
A320
A330
A340
A380
A350XWB
Concorde (GB, Fr)
EMBRAER
Bombardier
Prop Plane
The Age of Jet Aircraft in Japan (Commercial Aircraft)
Mitsubishi
SpaceJet
YS11
MU-2
MU-300
P-1
C-2
Honda
HondaJet
Kawasaki
Fuji
For welded structure (Al-Cu Alloy), High Strength Alloy
Alcoa UACJ
2219
2519
Heat-resistant Alloy, High Strength (Ag or Li addition, Fiber Reinforced Composites, Rapid-solidified Powder Alloy
18S B18S
2618
2017 (Al-Cu-Mg Alloy)
17S
2017
2024 (Al-Cu-Mg Alloy), High Strength and High Toughness Alloy, High Purity Alloy
Alcoa
24S
2024
2324
2524
2624
7075 (Al-Zn-Mg-Cu Alloy) High Strength and High Toughness Alloy, High Purity Alloy, High Zn, Zr addition
Alcoa
75S
7075
7178
7050 Zr Addition
7150
7055
Al-Li, High Strength and High Stiffness Alloy
Alcoa Constellium
2090
2195
2050
CFRP
Toray
AA Standard Established
HD Alloy, Progress in Welding Technology
7204, 7003 (Al-Zn-Mg Alloy) Improved Extrudability, High Strength
UACJ
7204 7003 Zr Addition
Research on high Strength and Toughness Alloy (Al-Zn-Mg-Cu Alloy)
National Project
7 years Blank
Prohibition of aircraft development:
Expand to non-aircraft applications
Dr. Baba
Zr Addition
1945
1950
1960
1970
1980
1990
2000
2010
2020

Systematic Survey on the Development of Aluminum Alloys for Aircraft Materials on the History of Industrial Technology, Location Verification

Number	Name	Fabrication Year	Manufacturer	Location		Reason for Selection
1	Part of framework from Zeppelin airship	1910’s	Zeppelin Airship	UACJ, R&D Division	Chitose 3-1-12, Minato-ku, Nagoya, Aichi, Japan	Framework material for Zeppelin airships made of Duralumin, which was brought back to Japan by the Navy from a crashed airship in the United Kingdom, and which Sumitomo was asked to investigate. It is a valuable historical heritage that has been preserved after surviving the ravages of the last war.
2	Forging die for the propeller of the Zero fighter	1940~1945	Sumitomo Metal Industries, Ltd.	UACJ, Nagoya Works, courtyard	Chitose 3-1-12, Minato-ku, Nagoya, Aichi, Japan	A forging die for a propeller made of Duralumin for the Zero fighter. Today, there are very few remaining examples of aluminum manufacturing technology from that era, but this die is a valuable historical legacy that clearly shows the manufacture of fighter propellers, as evidenced by its shape.
3	Sumitomo’s internal research reports for the development of Extra Super Duralumin	1920-1945	Sumitomo Copper Works, Sumitomo Metal Industries, Ltd.	UACJ, R&D Division	Chitose 3-1-12, Minato-ku, Nagoya, Aichi, Japan	Handwritten research report of the period from Duralumin to Extra Super Duralumin. In this research report, the process of developing Extra Super Duralumin with the world’s highest strength and the results of the experiments are recorded. This is a first-class document and a valuable historical heritage. Extra Super Duralumin was developed based on the data described here.
4	The main wing of Zero fighter (Type 52) salvaged from the sea	Investigation around September 1995	1940’s	UACJ, R&D Division	Chitose 3-1-12, Minato-ku, Nagoya, Aichi, Japan	Although there are no remaining pieces of Extra Super Duralumin from that time, we were able to clarify the composition and performance of the material used in the Zero fighter by examining main wing of the Zero fighter that were salvaged from the sea. It was confirmed that Extra Super Duralumin used for the wing spar was Al-8.0%Zn-1.4%Cu-1.6%Mg-0.35%Mn-0.16%Cr, with tensile strength of 670 MPa, yield strength of 591 MPa, and elongation of 12%, equivalent to the highest strength aluminum alloy used today. Stress corrosion cracking resistance was also comparable. The results of the study are reported in the UACJ research report.