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TEXTE

Introduction

1 To support the various physical loads the aircraft undergoes during its lifetime, such as forces acting and generating a set of constraints on the structure, the materials constituting the aircraft structure must withstand high stresses and be as light as possible.[1] The only suitable material available when the first heavier-than-air flight appeared was wood.[2] For over a century, from Louis XVI to the beginning of the 20th century, France was at the leading edge of the technology regarding air forces.[3] The most important pioneers of the second half of the 19th century were mainly Europeans, namely Otto Lilienthal,[4] Clément Ader,[5] the French-born American civil engineer Octave Chanute.[6] However, based on Lilienthal's work the first motorized flight was unequivocally achieved in the United States.[7]

2 Meanwhile, aluminum, a metal presenting lightweight properties, was discovered at the end of the 19th century, and quickly used, even before the first motorized flight. However, because of its bad mechan-

ical properties the metal was not used as a structural material until Alfred Wilm discovered Duralumin, an aluminum alloy. The alloy quickly became the material of aircraft construction all over the world. The term Duralumin was often used as a general term, but it will be seen hereafter that the alloy is named differently according to the supplier, and depending on the country.

3 This paper will address the evolution of Duralumin alloys in aeronautics in the United States and Western European countries, namely France, Britain and Germany, from the early ages of aviation to the end of 1945. The role of different entities in the development of both aluminum and aircraft industries will be discussed using a multidimensional approach. In order to assess this topic, the research is based on a panel of serious primary and secondary sources:

- The Institute for the History of Aluminum (IHA, Paris);
- The Departmental Archives of the Haute Garonne (Toulouse);
- The Institute of Transportation and Technology Communications (ITTC, Toulouse);
- The National Air & Space Museum archives (Washington DC, USA);
- German aircraft constructors' technical files;
- Photographs from the American National Archives;
- Digitised newspaper articles from Flight magazine;
- National Advisory Committee for Aeronautics (NACA) and British Intelligence Objectives Sub-Committee (BIOS [8]) reports;
- Archive.org website;
- Aluminum Company of America's (ALCOA) publications;
- Metallurgical database: Metallurgical research and technology review.

4 The article will address the following research questions: Which nation was at the forefront of the technology? What were the policies regarding the use of aluminum? What were the main components of the wood to all-metal aircraft transition? What were the axes along which aluminum alloys in aircraft construction have evolved? What were the innovations seen during this period?

5 These questions will be answered to, in five different sections of the article. The three first parts give a chronology of the development of aluminum alloys and their use in the aircraft industries of these nations. It addresses more precisely the use of aluminum in a wooden era, and the discovery of the Duralumin. It also deals with the im-

provements seen in the interwar period, and the attempt in establishing a standardization of the alloys. The final section tackles the developments and confusions caused by the Second World War along with the return to wood. In the second part, the discussion revolves around the synergy observed between industrialists, scientists and governments throughout this period regardless of the war or peace time.

1. During the wooden era between the birth of aviation to WWI, the slow appearance of aluminum in aircraft construction was first observed in engines and slowly moved to the structural parts of aircraft.

1. 1. The reluctant aluminum use in aircraft construction during a wooden era

6 The first aircraft used wood and fabric as construction materials, the only material light yet strong enough that would allow a flight. The birth of aviation is a wooden era, despite the more or less successful attempts of some pioneers to use metal in airplane construction. As mentioned before, aluminum was used even before the first motorized flight. In 1862, a helicopter prototype was equipped with an aluminum boiler. Then, in 1896, the work of the German David Schwartz allowed the manufacture of a dirigible balloon made of aluminum sheets. Few years later, the first "reliable" dirigible balloons in aluminum carcasses appeared. [9] These airships were designed and created by Lord von Zeppelin and Carl Berg under the trademark Zeppelin. Later, in 1903, the Wright brothers took off with the first motorized aircraft at Kitty Hawk. [10] In this aircraft, engine parts were made of aluminum, and the crankcase [11] was made of an aluminum alloy containing 8 wt% of copper.

7 During the Great War, the use of aluminum castings quickly developed in aircraft engines. For instance, Hispano Suiza, the engine equipping the *Société de Production des Aéroplanes Deperdussin* (SPAD)[12] of Georges Guynemer, had an aluminum engine block and a crankcase made in aluminum alloy.[13] In Britain aero-engines designers saw the great potential aluminum alloys had, which resulted in the introduction of the RR series, manufactured by Rolls Royce.[14] Therefore, in the early years of aviation, aluminum was mainly used in the form of molded aircraft engine casings, and crankcases.

1. 2. The appearance of a light weight, yet strong alloy: Duralumin

8 The density of aluminum is much lower than that of iron.[15] The light density of this metal is a very attractive property for both military and civil industries for weaponry and transportation. Although the metal was lightweight, the low mechanical properties of this metal made its use for certain applications impossible. In the past, alloying metals had proved to enhance their mechanical properties (e.g. steel). Hence, alloying aluminum seemed necessary. Alfred Wilm, a German metallurgist discovered the Duralumin, a high-strength aluminum alloy. It is one of the most pivotal innovation in both aviation and the metal-making world. This aluminum alloy is heat-treated at a temperature between 450°C to 500°C. It contains 3 to 5 wt% of copper, 0.5 to 0.8 wt% of manganese and 0.5 wt% of magnesium.[16] The alloy is quenched and stored at room temperature. Its physical properties[17] compare very favorably with those of steel, with the difference that it is one third of its weight. Therefore, Wilm's Duralumin was a lightweight and strong alloy, both properties sought after in aircraft construction.[18]

1. 3. The all-metal aircraft, a visionary concept

9 On the eve of WWI, Duralumin had just been patented and aircraft manufacturers were still reluctant to use metal as an airplane framework. The development of all metal aircraft was only possible because of key visionary personalities. In Germany, the first all-metal aircraft

was developed by an aircraft manufacturer named Hugo Junkers. Junkers had tried, on several occasions, to assemble an all-metal aircraft, *i.e.* the J-I.[19] It was equipped with a steel coating (l'Aérophile: 1st-15 Mars 1921), and tested in 1915. Although it did not receive the expected success, it opened the way to the all-metal-aircraft-construction. Junkers later replaced steel by Duralumin; and by 1917, the German army was equipped with Junkers J-4[20] aircraft to fight in the Great War.[21] The Breguet XIV[22] is known to be one of the first aircraft to use Duralumin, in France. Breguet XIV was specially designed for long-distance and high-altitude reconnaissance and bombing missions. Thanks to its powerful weaponry, it was able to safely locate targets, take photographs and bombard. The brilliant services rendered by this aircraft during WWI in 1917 and 1918 contributed to its remarkable success. It included Duralumin spars, a frame and a section made of Duralumin, and was produced in 12.000 copies.[23] Another French aircraft, that contained tubes in Duralumin is the Salmson 2A2. This airplane was developed in response to a 1916 army requirement. It was used for recognition missions. It was very useful to spot the strategic areas and bomb the enemy. Salmson 2A2 was a state-of-the-art aircraft as it benefited from the innovations of the Great War.[24] This two-seater biplane was produced in over 3.000 copies.

1. 4. Was Duralumin really surpassing wood?

10 Although some airplane designers experimented with the use of metal in aircraft construction, wood was still predominant during WWI thanks to its numerous advantages, which matched the requirements for the flight. The properties of wood consisted of high strength-to-weight ratio, easy workability, unalterable properties[25] and the ease of construction and repair. During the Great War, the large quantities of aircraft production and shortages in the supplies of good quality wood resulted in the realization that wood was no longer the appropriate material. WWI revealed the limitations of wooden aviation. In a 1919's report titled "Duralumin wing section on aeroplanes",[26] a comparison between the characteristics of wood and several metal is given such as steel and Duralumin. Apart from the

light weight and greater strength, the advantages of metal over wood listed in the report are various. Metal, in general, is more resistant to fire and less subject to moisture absorption, which gives it a good stability. It also allows the manufacturing of larger airplanes. Thus, once large-scale production of Duralumin was achieved, its use allowed aircraft mass-production, another aspect that favored metal over wood. Therefore, wood as a primary structural material lived its heydays from the beginning of human flight until WWI. It was mainly in Germany that important measures, in favor of the all-metal airplanes, were taken during the First World War. A period during which, increasing demands for strength, stability and security resulted in the progressive shift from wood to Duralumin.

2. The interwar period and the structural revolution: Duralumin taking over and becoming the indispensable material for aircraft construction

2. 1. The progressive shift from the archaic wooden biplane to the modern all-metal monoplane aircraft with some exceptions: the British conservatism

11 The late 1920s and 1930s marked the transition from the “archaic” wooden biplane to the “new and progressive” all-metal monoplane. By 1935, the wood and fabric construction ceased to predominate, and aluminum became the metal of modern aviation. This period was marked by the emergence of civil aviation, which stimulated the material change. Different approaches and policies regarding all-metal-aircraft were taken.

2. 1. 1. The use of Duralumin in aircraft construction followed different approaches: The German special case and their fear of shortages, the British scepticism and rejection of the alloy, the French confusion, and the American civil aviation acting as a catalyst in favor of the material change

12 All-metal-aircraft-production was not adopted by the entire community, as there were various issues at stake. In this paper, the American, the British, the French and the German approaches will be discussed. These four nations had the most significant aviation at the time.

13 In the early days of the 20th century, Germany focused on the research and development of light alloys and weight reduction. Indeed, in 1909, Griesheim-Elektron presented a new metal called Elektron to the international exposition. It is an alloy containing 90% of magnesium, plus aluminum, silicon, zinc and manganese additives. Elektron presented workability issues, and water vulnerability, therefore, it was not tremendously used when it first appeared. However, it made its breakthrough in the 1920s and was used in bombs, engines and even in rivets.[27] Although Elektron is not an aluminum alloy, it helps to understand German's approach towards light metals and could explain that the all-metal aircraft was born in Germany. This "German alloy" aroused great enthusiasm in Germany, largely because it was indigenous. Elektron was used more in Germany than elsewhere until 1945. After WWI, the Versailles Treaty involved significant restrictions in the motorization of German military aircraft.[28] To overcome these limitations, Germany focused on the development of new materials. Accordingly, the Versailles Treaty both inhibited and stimulated the development in the German aircraft industry. It definitely played as an accelerator in the development of new materials for aircraft construction. Germany had a technical advance thanks to its experience with Zeppelins. These airships were the first to use Duralumin as the main construction material for their framework.[29] Occasionally, a zinc Duralumin developed by the Carl Berg company was also used. It contained: 9%Zn, 0.6%Cu, 0.7% Mg.[30] This zinc alloy

was a primitive form of the Al-Zn-Mg alloys which will be developed in part 2.2.1. Because of its lack of elasticity and its brittleness, zinc Duralumin was abandoned. Zeppelin is probably one of the “founding fathers”, in terms of German aeronautical technology; many aircraft designers and inventors such as Dornier, Rohrbach, were working on the Zeppelins and gained significant knowledge in aerodynamics before specializing in airplanes.[31] German officials were favourably considering the use of Duralumin in aircraft. Several German aircraft manufacturers successfully designed numerous aircraft using this alloy. However, the copper shortages that marked WWI in Germany (due to the British blockade) were omnipresent in everybody’s minds. This entailed the autarkic side of the various German political regimes, which led to the relaunch of the research on Al-Zn-Mg alloys. In fact, Germany had to import almost all metals but Zinc.[32] Therefore, the Reich put considerable efforts in the substitution of metals such as copper, in an attempt to be more independent regarding the import of metals and raw materials. These efforts led to the development of various alloys. As the inventors of Duralumin, Germans certainly used this alloy as the new material for aircraft construction, but kept on looking for a substitute, and the main incentive was to reduce the copper in case of shortage.

14 Since aluminum ores were not abundant in Britain, it imported most of its aluminum from Canada (ALTED) and the US (ALCOA) (fig. 1).

Fig. 1. British War Production 1939-1945.

	Bauxite Imports	Aluminium Imports	Domestic Al. Production Primary	Secondary	Total Imports	Primary Al. Available	Imports to Primary Ratio	Total Al. Available	Imports to Total Ratio
1939	302.1	57.7	25.0	?	359.8	82.7	4.4	82.7 + ?	< 4.4
1940	112.4	66.1	19.0	37.9	178.5	85.1	2.1	123.0	1.5
1941	87.2	132.7	22.7	53.2	219.9	155.4	1.4	208.6	1.1
1942	47.8	131.6	46.8	78.8	179.4	178.4	1.0	257.2	0.7
1943	241.8	213.0	55.7	93.5	454.8	268.7	1.7	362.2	1.3
1944	172.1	149.7	35.5	104.5	321.8	185.2	1.7	289.7	1.1
1945	162.6	21.1	31.9	81.0	183.7	53.0	3.5	134.0	1.4

Note: “Bauxite Imports” are from Central Statistical Office, *Digest of the War*, 168 (Table 148) and “Aluminium Imports” are from Central Statistical Office, *Digest of the War*, 169 (Table 149). “Total Imports” is the sum of these two. “Domestic Al. Production” is from Central Statistical Office, *Digest of the War*, 110 (Table 96). “Primary Al. Available” is the sum of “Aluminium Imports” and primary “Domestic Al. Production.” “Imports to Primary Ratio” is “Total Imports” divided by “Primary Al. Available.” “Total Al. Available” is the sum of “Primary Al. Available” and secondary “Domestic Al. Production.” “Imports to Total Ratio” is “Total Imports” divided by “Total Al. Available.”

“The British War production 1939-1945: A record”, *The Times*, Printing House Square, 1945, p. 135-136.

15 Britain was quite sceptical regarding the use of Duralumin as the construction material for its fleet due to a particular spectacular event. The British company James Booth Cy acquired from the German Dürener Metallwerke company the license to produce Duralumin in Europe in 1910. James Booth Cy used all the available alloy to produce the Mayfly airship. Unfortunately, the dirigible broke during a trial and the incident was known as the Mayfly fiasco.[33] The German Duralumin was considered unreliable, and British disposed of the Duralumin patent. Even if British officials first forbade the use of this light alloy in aircraft construction,[34] equivalent alloys were investigated and tests using various aircraft parts made of British Duralumin were nonetheless held.[35] For instance, right after the spruce shortage during WWI, Vickers was in charge of developing a metal wing section for the British Air Ministry. The metallic wing had to be interchangeable with a wooden one. The report concludes by the statement that for airships and large airplanes Duralumin was a necessity, but when it comes to small machines, the costs were too high for a machine with such a short lifespan. It was not until the late 1920s that British officials conceded to equip the Royal Air Force (RAF) with “all-metal-airplanes”. Indeed, in a 1928 correspondence between the American embassy and London,[36] regarding the metal construction of aircraft for the RAF, the British secretary of State for Air declared that:

> It is expected that at least nineteen of all metal machines will be in service before the end of 1928 and that the whole Air Force will be equipped within 5 years. The all-metal-machine is not, however, being introduced as a safety measure, but to facilitate the standardization of aircraft and to simplify their production, maintenance and repair.[37]

16 This declaration reveals that although British officials were not enthusiastic about the Duralumin, its use became unavoidable for the sake of reproducibility and standardization. It is important to specify that the use of “all-metal-airplane” term is not strictly accurate, since structural pieces such as fuselage skeletons, spars and wing frames were indeed metallic, but wood and fabric were still used for the covering of fuselage skeletons. Therefore, British aviation was composed of a mix of wood and metal.

17 At the end of WWI, France was at the leading edge of technology regarding aviation. It was also known to be the country where Aluminum[38] was discovered and the land of Bauxite ore.[39] Thus, when Britain rejected the German alloy, France did not share Britain's view and quickly bought the patent in 1911, as it presented a huge economic interest.[40] The company "*Électro-Métallurgie*" based in Dives, which later became "*La société du Duralumin*", acquired the license to produce Duralumin, and would later be in charge of the production of Duralumin pieces that would be used in aircraft construction during the Great War. At the beginning, French aircraft manufacturers were still sceptical but it quickly changed. In this context, the first innovations appeared, for example the metallic hull developed by Dewoitine and Béchereau, well-illustrated by the Dewoitine D1.[41] By the mid-1920s numerous aircraft designers and firms broadly used the metal. Duralumin was no longer just a structural material, it was now also used for fuselage skin and hulls. During the interwar period, the ambient pacifism and the Great Depression led to a lack of funding for aviation. This explains that innovations in aircraft were not seen before the late preparation for WWII and the design of the Dewoitine D.520 at the end of the 1930s.[42] Metallic construction had only imposed itself in the field of military aviation, with some exceptions like the archaic Morane Saulnier MS.406 with its cloth-lined rear. The MS.406 was quite progressive in its appearance, but its structure was not yet self-supporting. This aircraft is emblematic of the French aircraft construction of the interwar period. French civil aviation, on the other hand, was still mainly composed of wooden aircraft such as Potez 56, Potez 62 and Caudron Goéland. Consequently, although France was in favor of the use of Duralumin in aircraft construction, by the end of the interwar period, French aviation, both military and civil, was still composed of wooden aircraft.

18 When it comes to the United States, when they entered the Great War, their aviation was lacking as illustrated by F. D. Roosevelt's 1917 quote: "This country, which gave birth to aviation has so far lagged behind that now, three years after the Great War began and six months after we were dragged into it, we still have not a single machine competent to fight the war machines of our enemies."[43] Yet, the United States quickly, caught up. Within few months, within few months, America had almost surpassed the European lead in aero-

nautical technology. Just like European nations, it took several years for aircraft metal construction to establish in the United States. Even though no striking superiority of metal over wood was observed, NACA declared the contrary in its 1920 Annual report.[44] The same year, one of the first all-metal-aircraft was brought to the US by John M. Larsen.[45] Larsen bought a Junkers patent and produced his aircraft under the name Junkers Larsen JM-6.[46] After a successful demonstration, US Postal service purchased 8 planes, but they soon proved to be inadequate and presented numerous issues such as a lack of stability and their lifespan did not exceed 6 years as it presented tremendous corrosion issues.[47] Americans started to design their own all-metal-aircraft quite late. In fact, there was no American all-metal-airplane until the mid-twenties. In 1926, the trimotor commercial airplane 4-AT[48] was built by Henry Ford, which had the particularity of being all-metal construction.[49] At the beginning of the 1930s, the United States set the tone in the field of aeronautical technology with the development of fast metallic transport aircraft. Civil aviation was therefore one of the main factors to the wood to metal transition in the American aircraft construction.

2. 1. 2. The American tedious journey to obtain the German Duralumin pushed them to successfully develop their own version of Duralumin, the 17S

19 Obtaining the new alloy was not an easy thing. Nations which had bought the patent quickly started to manufacture the new metal; but for those without the license, it was more tedious. Americans did not have the German patent, yet the US Navy was keenly interested in the development of a hard alloy for rigid airships, a field in which Germany had advanced technology, especially with their Zeppelin. Therefore, the US government put pressure on ALCOA to double its efforts to make Duralumin. For years, ALCOA tried to develop a substitute to Duralumin by analyzing samples at the National Bureau of Standards in Washington D.C. When WWI arrived and once the patent was obtained, it proved to be vague and ALCOA's metallurgists were frustrated by their inability to understand the basic properties of high strength alloys for large-scale fabrication.[50] In the 1920s

ALCOA put an effort to catch up the Europeans advance in the heat-treatable aluminum alloys industry by launching a research program and hiring numerous scientists, and engineers. In 1922 ALCOA finally developed its own version of Duralumin and marketed it under the trade mark 17S. It was the beginning of a long journey filled with innovations for ALCOA.[51]

20 It is not until 1922, that ALCOA in its research

2. 1. 3. Understanding the age hardening, an international concern

21 Wilm empirically showed that aluminum alloys harden after natural aging (few days at room temperature). But Wilm himself did not really understand the phenomenon behind his discovery. The American metallurgist Paul Merica and his colleagues of the Scientific Bureau of Standards, *i.e.* R. G. Waltenberg, H. Scott and J. R. Freeman were the first to explain the remarkable hardening that happens after the quench and natural aging. They investigated the influence of heat treatment and chemical composition of aluminum alloys on hardness.[52] They concluded that copper has a decreasing solubility in the aluminum phase in the solid solution with decreasing temperature. They also concluded that the hardening is due to the formation of Al_2Cu, a highly dispersed precipitate. Because of the technical limitations no direct evidence of the presence of fine precipitates was found. Particles responsible for the hardening were far too small to be observed with an optical microscope. However, numerous optical micrographs of the alloy microstructure revealed the presence of various phases and constituents such as Al_2Cu, Al_3Fe, Mg_2Si. Later, the phenomenon was referred to as structural hardening by precipitation or age hardening.[53] In 1937, Guinier and Preston simultaneously made another major contribution to the understanding of age hardening thanks to Small-Angle-X-Ray Scattering technique.[54] It is based on the difference of X-ray scattering factors. Although Guinier and Preston were not able to directly observe the precipitates, they indirectly proved their presence. Precipitates responsible for the hardening are now known as Guinier-Preston zones.[55] Other techniques such as Scanning Electron Microscopy and Transmission Electron Microscopy that are now largely used for characterization of

these materials were first developed during that time. Indeed, the BIOS-1671 final report titled *Electron Microscopy in Germany* stated that Electron microscopy was used on a large scale during the war in Germany, the United States and later, in Britain. The use of electron microscopy yielded no new fundamental knowledge at the time. Because of various shortages and war issues, efforts were not put in this technique but in more urgent needs.[56] However, it is not before the 1950s that these techniques were extensively used.

3. The late standardization and the evolution of aluminum alloys, towards greater properties

3. 1. The late standardization and the confusion it caused internationally and within each nation

22 In 1925 National Advisory Committee for Aeronautics technical memorandum (NACA) listed and described a number of alloys similar to Duralumin that were patented in France, Britain and the United States.[57] Similar alloys were named differently depending on the nation, and even amongst one nation. An alloy could have several designations: the military and the commercial designations. Besides, depending on the manufacturing company, several commercial designations could be found for one single alloy. This resulted in a certain confusion.

23 During the XIIth "salon de l'aéronautique", held in Paris in 1930,[58] various high-strength light alloys were presented. They were distinguished by slight differences in composition or heat treatments, but they were generally of a type close to that of the original Duralumin; for instance, Alugir, Avial and Duralumin in France. In England, the RR alloys were presented, and in Germany alloys such as Duralumin DM31, Ulminium, or Bondur 17/11 were showcased. All these alloys had comparable properties. In Germany, in a technical report giving instructions to subcontractors regarding materials, Dornier declared that "there is no practical difference between the materials of the dif-

ferent suppliers". Indeed, Duralumin manufactured by Dürener Metallwerke, Bondur made by V.L.M., and Ulminium are all similar alloys. [59]

24 With the industrial massive production of aluminum alloys, standardization became necessary. In industry, standardization gives the production its chances of spreading. It also ensures the consumer a certain constant quality. Besides, standardization is a fundamental element in the expansion of international trade, as it is dependent on the harmonization of national standards. Needless to say that in this particular period of History, with the uprising tensions, no international harmonization was established. In fact, international standardization only appeared well after the Second World War. Hence, each nation had its own system of designation. [60] Until WWII, almost all aluminum alloys were still referred to by the name given by the manufacturers or producers, giving no clues, as to the elemental composition of the material, its properties or its thermo-mechanical treatments.

25 It is therefore important to distinguish the two existing types of alloys, the cast and wrought aluminum. The cast aluminum is an aluminum that is melted in a furnace and poured into a mold whereas for the wrought aluminum, the metal is worked in the solid form with the help of specific tools. In this section, the focus is made on wrought alloys.

26 In Germany, prior to 1935, no standardization existed. In 1935, the first industrial standardization appeared for aluminum alloys with the *Deutsch Institüt for Normung* DIN 1712 specification. The DIN 1713 quickly replaced it. [61] The DIN 1713 did not include all the existing alloys and would later be replaced by the DIN 1725. [62] In this standardization, different process stages are denoted by a four-digit number, giving information related to the chemical composition and manufacturing process. 3115, 3116 and 3125 are few alloys used in aircraft construction. The use of this military designation in the industry was probably not done immediately. By 1939 it widespread. In 1952, some changes were added leading to new standardization, *i.e.* DIN 1748. [63]

27 Aluminum alloys were produced by different companies in Britain. British Aluminium Company (BACo), created in 1894, was the only British producer of raw aluminum. [64] James Booth Company Ltd, in

which BACo had considerable holdings was another producer of aluminum alloys. Imperial Chemical Industries Metals (ICI Metals) and Reynolds Rolling Mills Ltd were other companies that produced aluminum products along other metals. In 1939, Reynolds ceased bicycle tube production and switched to the production of fighter plane tubing for the Spitfire, the most emblematic British WWII fighter designed by Reginald Mitchell.[65] The same year, it became a supplier of the aircraft industry. Yet, the main aluminum alloys manufacturer for military uses was High Duty Alloys, which used its own designation gathered in the Hiduminium technical data book.[66] Rolls Royce Ltd developed new alloys, later manufactured by High Duty Alloys, *i.e.* Hiduminium R.R. alloys. Hiduminium is the contraction of HIgh DUty AluMINIUM. They are often referred to as RR followed by two figures.

28 In France the first aluminum alloy was known as Avial or Duralumin, and the chemical composition depended on the manufacturing company. During the French occupation by the Nazi, the French government made an effort to stop the German attempt to impose their own standardization.[67] Therefore, a French agency, l'*Association Française de Normalisation*[68] (AFNOR) set up the standardization of aluminum alloys which led to an alphanumerical standardization in 1943. French aluminum alloys were designated by means of letters and figures, indicating the base metal, the element of majority additive, the purity and the mechanical and thermal treatments. In table 1, some abbreviation used for the designation of French alloys are listed.

Table 1. Example of abbreviated symbols representing the elements present in French alloys.

Letter	Element	Letter	Element
A	Aluminum	**Pb**	Lead
C	Chromium	**S**	Silicon
U	Copper	**T**	Titanium
G	Magnesium	**W**	Tungsten
M	Manganese	**Z**	Zinc
N	Nickel	**Zr**	Zirconium

29 For example, the chemical composition of French alloys such as A-U4G, A-U4G1 and A-Z8UG are detailed hereafter.

- A-U4G: Alloy which the base metal is aluminum and containing 4 weight percent (wt%) of copper and less than 1 wt% of magnesium (in this case 0.7 wt%).
- A-U4G1: Alloy which the base metal is aluminum and containing 4 wt% copper and more than 1 wt% of magnesium (approximately 1.5 wt%).
- A-Z8GU: Alloy which the base metal is aluminum and containing 8 wt% of zinc, 1.75 to 3 wt% of magnesium and 1 to 2 wt% of copper.

30 When it comes to Americans, up until WWII, ALCOA was the only aluminum manufacturer of the country. During WWII other companies started to produce aluminum alloys and used their own designations. Even then, the most common designation was ALCOA's. Until 1947, for their wrought alloys, Americans used a designation using of 1, 2 or 3 numbers followed by the letter "S", which indicated that the alloys were used in the wrought condition. The letters designating the thermal treatments of the alloys were separated from the symbol of the alloy by a dash [69] (table 2). summarizes the different thermal treatments that an alloy could undergo.

Table 2. Abbreviated symbols representing thermal treatments applied to American alloys.

Letter	Element
F	Annealed temper
O	Chromium
T	Heat-treated (solution treatment+ natural aging)
W	Heat-treated (solution treatment+ artificial aging)
H	Hard temper
R	Strain hardening

31 For example: 17S-T means alloy n°17 in the wrought (S) condition with a temper designated as "T". The chemical compositions and thermal treatments of different alloys are explained:

- 17S: Aluminum alloy, composed of 4 wt% of copper, 0.5 wt% manganese and 0.5 wt% magnesium.

24S-RT: Aluminum alloy, with 4 wt% of copper, 0.5 wt% manganese and 1.5 wt% magnesium. The heat treatment in this case consisted in strain hardening which resulted in the increase of mechanical properties.

32 Sometimes, the number is preceded by a letter. In this case, it means that the chemical composition of the original alloy was modified.

- A17S: Aluminum alloy, containing 2.5 wt% of copper and 0.5 wt% magnesium.

33 This designation quickly proved to be obsolete since it no longer allowed responding to the constant progress in metallurgy.

34 The corrosion resistance amelioration evolved from the use of varnishes and paint to oxidizing and to Alclad

35 Without the work on corrosion protective processes or anti-corrosion products the implementation of metals in aircraft industry would have been very difficult and even impossible. Indeed, although aluminum is corrosion resistant, because of the addition of alloying elements (*i.e.* copper, magnesium), aluminum alloys, are more prone to corrosion. Before solving this issue, their use in many applications was limited. The investigations held on the corrosion protection of aluminum alloys were pivotal and served as the backbone of the wood to all-metal-airplane transition.

36 Investigations on the corrosion protective products started early in the 1900s in the form of alkaline carbonate-chromate solutions, which consisted in the immersion of the metal in a dichromate bath. The process can take up to several hours and allows the surface of the metal to be converted into a surface that accepts more easily a corrosion resistant coating. Conversion coatings were up to 600µm thick and were often used to enhance paint adhesion, in which cases, the paint was to be applied quickly after being formed.[70] The first attempts mainly revolved around inorganic coatings. The protection given by these paints, varnishes or other coatings was however not sufficient. Indeed, these products were easily scratched leaving the bare metal unprotected and more prone to corrosion.[71] During WWI, durability and lifespan of aircraft were of much less importance than rapidity and ease of production. In the interwar period, the controlling factors in the material choice were now dependent on the commercial flight requirements, thus, longevity of aircraft was a priority. Corrosion has indeed been the concern of the early manufac-

turers as it was linked to the success of metal application in aircraft and airship construction. In its pure state, aluminum is corrosion resistant. This property is linked to the formation of a thin oxide film when exposed to atmospheric environment. This layer passivates the surface of the metal. However, the alloy used in aircraft construction contains additions of other elements such as copper, magnesium and silicon. These additions increase corrosion sensitivity, especially when subjected to severe environmental conditions. Corrosion can therefore certainly be detrimental to aircraft by causing loss of ductility resulting in the loss of strength. Corrosion can appear in various forms depending on the environment in which the material evolves and the fabrication process of the alloy. It can be in the form of pitting, intergranular or galvanic corrosion.

37 A NACA statement in its 1927 report revealed that Duralumin was not widely used in aviation because of corrosion issues. "It is worthy of note, however, that under normal atmospheric conditions, unprotected strong aluminum alloys are giving very satisfactory service [...] In aircraft however, where so much depend upon the absolute reliability of every unit, it is essential that the structural parts have a maximum of resistance to deterioration under service conditions."[72] The use of Duralumin in airplanes was greatly retarded on this account. Therefore, in the 1920s, several committees were mandated to investigate this subject by testing methods for protecting the metal. It was also known that cadmium, aluminum, zinc and magnesium could provide Duralumin with a certain protection against electrolytic corrosion by transferring the attack primarily to themselves.[73] The objection against the use of Duralumin in aircraft construction was progressively abandoned. In the mid-twenties, one of the first solutions investigated was anodizing, *i.e.* covering the metal with a thin layer of oxide by using an electric current. It is an electrolytic passivation leading to the formation of a protective film composed of hydrated oxides. With this process, the thickness of the natural oxidation layer is increased. This method consists of the immersion of a sheet of aluminum or Duralumin in a chromic acid bath. It was investigated in Britain and was known as the Bengough process. The process was patented by Guy Dunstan Bengough and John Mc Arthur Stuart. In Germany the term referring to the anodic electrolytic process is eloxal.[74] Anodizing was largely used in the industrial world, yet it

presented some limitations, as it was neither cost effective nor easy to apply on large metal pieces. The corrosion resistance processes then focused on the protection of aero-engine parts. In Germany, the protection of pistons was investigated by Dr. Sterner-Rainer, a German metallurgist working for Karl Schmidt's firm in Neckarsulm near Neilbronn. Dr Sterner-Rainer was a specialist of light metals and alloys and his work focused on the study of corrosion. Other techniques such as lead or tin coatings were used.[75]

38 The anodization technique was used in the American emblematic Boeing 247 airliner, in the form of anodized 17-ST sheets. The first major civil airplane to use anodized aluminum[76] is another example of the influence of civil aviation on the development of new materials for the American aircraft industry.

39 The improvements made by the oxidizing were far from being sufficient. Hence, for four years, under the supervision of E. H. Dix, assistant director of research, ALCOA's researchers were actively researching solutions for the corrosion issue in its Research and Technical Departments, in fact it appeared that intergranular corrosion could have radical consequences on the loss of ductility and strength. What led to the most striking improvement for the aircraft industry, the Alclad was the idea that "A product combining the corrosion resistance of pure metal at the surface and the strong alloy underneath would seem to be ideal to meet the service conditions imposed by aircraft."[77] Alclad represents Alcoa's first major innovation in aeronautics in 1927. This process consists of coating a 17S (or Duralumin) metal sheet on each side by hot rolling a thin corrosion resistant layer of pure aluminum.[78] In general, a cladding of 5 to 10% of the total thickness of the metal sheet is sufficient. This innovation, the Alclad 17-ST was implemented in the DC-2 in 1934.[79]

40 A similar process called Vedal, later appeared in France.[80] In Germany, the equivalent corrosion protective product is known under the designation 3116, which is a Dural 3115 sheet coated with an aluminum-manganese-silicon alloy. This is different from the French and American practices.[81] The cladding can also be done with a layer of aluminum-silicon-magnesium alloy depending on these nations. Similar procedures also exist for different alloys, for instance in France Zicral is coated with a thin layer of aluminum-zinc alloy.[82]

3. 2. The mechanical improvements of aluminum alloys started with nickel additions for high tensile strengths and went from the Duralumin to the Super Duralumin, leading to the Extra Super Duralumin

3. 2. 1. Nickel additions for high strength materials

41 Nickel additions in aluminum alloys seemed to have been a British specialty. Indeed, the "Y" alloy is one of the first light alloys developed by the British after they handed over the Duralumin license.[83] Rosenhain along with Archbutt and Hanson, from the National Physical Laboratory conceived the "Y" alloy, containing 4% copper, 2% nickel and 1.5% magnesium. This alloy is the result of a research on the influence of iron and nickel on cast alloys for use at high temperatures. Only nickel showed interesting characteristics, especially when added along with magnesium which would allow the reduction of the copper content resulting in a lighter alloy. This alloy was developed during WWI, but because of the war, most of this work was not published until 1921 in the XIth Report to the Alloys Research Committee.[84] The "Y" alloy proved to have remarkable tensile properties at elevated temperatures. It is a casting alloy used for the manufacture of products with complex geometrical shapes. Therefore, it was mainly used for pistons and cylinder heads.[85] In other nations, equivalents are known as the "Y" alloy in France. In the United States, this alloy was known as 122, or 142 alloy for the cast version[86] and 18S for the forging version. In Germany, the equivalent to the British "Y" alloy, also referred to as "Y legierungen", was designated by 3157.[87] An intelligence document made cooperatively by British and American Intelligence in 1946, revealed that constructors' designation was still used even at the end of the Second World War. Mahle K. G., a piston plant near Bad Constatt was the largest German manufacturer of aluminum alloys pistons.[88] This plant was using its own designation and did not follow the military standard designation. It was the main

manufacturer of both cast and forged aluminum alloys for aircraft pistons (and other fields such as tanks, submarine, and other internal-combustion engines). During WWII, various alloys were used depending on the size and usage of the pistons. The three types of aluminum alloys manufactured at Mahle K. G. plant, their name, and use are presented hereafter (see table 3).

Table 3. Elemental composition of the alloys used for the manufacture pf pistons in Mahle's company.

Mahle's aluminium alloys used for pistons' designation	Percentage of alloying element (wt.%)						
	Si	Ni	Cu	Mg	Fe	Al	Usage
Mahle 124 (low X)	11.5-12.5	0.8-1.1	0.8-1.1	0.8-1.3	0.6 max	base	Regular for forge and cast
Mahle 138	16-18	0.8-1.1	0.8-1.1	0.8-1.3	0.6	base	Special for small castings and forgings
RR (Expr.No.214)	-	0.6	2	1.5	1.3	base	Good creep strength, high expansion
--	1.5	-	0.6	5.0	0.8	base	Exper. For large pistons

NASM Archives, *Technical Wright Field Section- Captured German and Japanese Air Technical* documents-microfilms, REEL3653-frame1030, *Mahle, K.G. piston plant, near Bad Cannstatt/Stutt-* date:unknown.

42 The alloy containing nickel was first used in the cast form but the wrought version was later used for forging. By 1948 the cast version had largely been replaced in Britain by a more recent one, the RR 53. [89]

3. 2. 2. The addition of magnesium leading to the Super Duralumin

43 One of the first improvements applied to the original Duralumin was the increase of its mechanical properties. Therefore, it evolved from the duralumin to the "Super Duralumin". This change consisted in the increase of the copper (up to 4.5 wt%) and magnesium (up to 1.5 wt%) content, while reducing the silicon and iron content (below 0.5 or 0.2 wt%). This modification proved to be quite efficient, the new alloy

exhibited not only higher yield and tensile strengths but also presented no loss of ductility. This improvement was first made by the United States in 1931, with their 24S alloy. It is remarkable, since the United States were the last nation amongst the four presented in this paper, to develop their version of Duralumin, the 17S. Nonetheless, they managed to catch up and progress with the 24S. A similar alloy appeared in France in 1935 under the name of Duralumin F.R. In Germany, an equivalent version was known as 3125 (DIN 1725). In England, what seems to be the closest alloy is the Hiduminium RR 72 alloy. The implementation of these alloys depended on the country. For example, in 1937 in the United States, 24S alloy was used in the manufacture of the DC-3, [90] then its use widespread in aircraft construction. In Germany, this alloy was used according to the manufacturer in charge of aircraft construction. In France, it was apparently not used until the end of WWII. [91] The Super Duralumin family of alloys was considered to be the main high-strength aeronautical alloys until the appearance of aluminum-zinc-magnesium-alloys.

3. 2. 3. The Extra Super Duralumin, when zinc additions result in higher mechanical properties

44 Another aspect of the evolution of light aluminum alloys was the copper substitution by zinc resulting in the Al-Zn-Mg alloys. Zinc was chosen as it is a metal with similar qualities as those of copper. Alloys containing zinc as a major alloying element exhibit very high strengths and are more corrosion resistant. Without consultations, almost every nation worked on the elaboration of Al-Zn-Mg alloys. Germany was the first nation to investigate the copper substitution by zinc, mainly because of the fear of copper shortages. It started as early as the Zeppelin. As previously mentioned, although the research and development around Al-Zn-Mg alloys started really early, the material was not available and produced until 1942. The alloys were known under the generic name *Constructal*. Britain studied these alloys in the early 1920s. [92] The research gave birth to the E (Al-20%Zn-2,5%Cu-1.5%Mg-0.5%Mn) and S (Al-8%Zn-1.5%Mg-0.5%Mn) alloys that were developed by Rosenhain, entailing the RR77 and the RR88 alloys respectively, marketed by High Duty Alloys in 1937. [93] The first ones to implement Al-Zn-Mg alloys in aircraft construction were the

Japanese. The development of these alloys was made by Dr. Igarashi at Sumitomo Metals Industries in Japan, in 1936. After WWI, Sumitomo sent engineers to Dürener Metallwerke in order to gain knowledge on the aluminum production technology. He then, worked on improving the mechanical properties of the Duralumin. Ahead of everybody's research, Sumitomo patented his alloy in 1936. The chemical composition was (Al-8%Zn-1.5% Mg-2%Cu-0.5%Mn-0.2%Cr). Sumitomo developed this alloy based on the British E and S alloys, and by analyzing scraps from a Zeppelin made of Duralumin. The alloy was therefore named Extra Super Duralumin (ESD). It was used on the Mitsubishi Zero fighter around 1939, one of the many reasons for the lightness of this aircraft.[94] French laboratories such La Société des Tréfileries et laminoirs du Havre and La Compagnie Alais Forges et Camargue (along with La Société du Duralumin) started the research on Al-Zn-Mg alloys in 1938. It resulted in the development of the T60 alloy, leading to the Zicral which was apparently available before the Second World War, yet not used until 1946.[95] After the new normalization (AFNOR 1946), this alloy would be referred to as A-Z8GU. In the US, ALCOA worked on these alloys for at least 15 years before the commercialization of the 76S in 1940. It was not until the examination of a Zero fighter wrecked in 1942, that the 75S alloy, currently known as the 7075, was developed.[96] This alloy was used in the making of the famous state-of-the-art Boeing B-29 propeller-driven bomber, that would later (1945) be used to drop the first atomic bomb on Hiroshima.

45 All these alloys were developed independently in various nations, yet the different research resulted in the development of similar alloys, which proves the seriousness of these research. However, the transition from the experimental stage to the industrial mass production is an interesting aspect of the evolution of light aluminum alloys.[97]

3. 3. Aluminum supplies and volume of production, an important factor mastered by the Germans and their creation of an aluminum industry from scratch, the United States and their colossal aluminum production, the British lack of resources compensated by their colonial empire and the French leadership in bauxite production

46 The supplies and volumes of production are an important factor which influenced the evolution of light alloys in the aircraft industry. In Europe, Germany managed to build an aluminum industry inspite of the absence of bauxite on German soil. Indeed, apart from the small factory in Rheinfelden in Baden, which supplied around 800 tons of aluminum per year and belonged to a Swiss company, Germany had no aluminum factory.[98] In 1943, after the seizure of numerous bauxite plants, Germany had control over the light metal industries of several European countries such as Austria, Czechoslovakia, Norway, France, Hungary, Yugoslavia and Italy. Within few years, Germany had risen from a non-significant position being by far the largest producer and consumer of aluminum (155.000 t / year over the period 1936-1940), far ahead of France (45.000 t / year) and the United Kingdom (around 25.000 t / year).[99] Even if France held the first position regarding the production of bauxite in 1938, it was only at the fifth position when it came to aluminum production. No figures later than 1940 are available, since most of the French aluminum production was confiscated by the Germans. In aeronautics, particularly in Britain, production volumes did not reflect the situation. In fact, Britain imported most of its aluminum from Canada or the United States. In addition, Britain's secondary aluminum industry made a significant contribution to the total Aluminum production, bringing the aluminum available to a total of almost 83.000 tons in 1939 and almost 363.000 tons in 1943 (see fig. 1). Even before entering the war, the United States began a great defense program in 1940, which

meant an expansion of the aluminum production. By 1943 the American aluminum production reached the colossal number of almost 900.000 tons.

47 The interwar period was very beneficial for the development of the aluminum industry. The Second World War brought a great demand of aluminum mainly for the aircraft industry which led to more improvements in the production of this metal.

4. The tremendous production needs of the Second World War and its numerous shortages led to the development of more efficient fabrication processes, the development of a secondary aluminum industry and the return to wood in aircraft construction

48 Governments have invested in the vast technological system that has enabled the mass production of aluminum. This mobilization revolutionized the production and distribution of aluminum during the Second World War and shaped the history of the post-war metal. World aluminum production and consumption in the early 21st century is based on decisions taken in the 1930s and 1940s. [100]

4. 1. Improving the fabrication processes to meet the war demands: a fundamental aspect

49 Innovations in distinct fields were observed, and intertwined. Indeed, discoveries and innovations were made in the scientific field. The research in this domain have a more fundamental aspect. There was also the research undertaken in the applied sciences. In this field, metallurgy, for instance used the knowledge obtained by fundamental

research and tested it with the aim of finding practical applications. The final step was the development stage and the industrialization of the product. During the war years, the transformation of industrial and maintenance resources, observed in the interwar period was even more accentuated. Various technological processes were invented or improved, allowing lower costs, larger quantities, better reproducibility.[101] Because of the enormous numbers of aircraft required for the war demand, the aircraft industry had to work on various means to improve its productivity. Inevitably, the aluminum industry had to do the same. The expansion of the aircraft industry was only possible because the aluminum industry developed new products and new techniques. Accordingly, technical advances mainly focused on the search for automation of factories to reduce the workforce, speed up the production pace, and improve reproducibility. The aircraft industry also proved to be quite flexible by incorporating any advances or innovations. The drop-hammer is an innovation worth mentioning.[102] It was used for straining alloys. It is a technique essentially based on the application of a sufficient force which causes permanent deformation. Prior to that, the force was applied by hand using a hammer. During WWII, it was done through machines of large load-capacities called drop-hammers. The automation of this process resulted in a metal with a more regular texture and a more homogeneous composition. Another major improvement in the production and shaping of aluminum and its alloys was the continuous casting and rolling on a four-roll mill. The alloy is first prepared directly in a melting furnace by mixing primary aluminum and additives. The metal is then cast in two forms, a plate for rolling or a billet for spinning. At the end of the Second World War, Americans improved the cold working technique[103] in which the sheet is passed through two pairs of oppositely driven cylindrical rolls.[104]

50 Other improvements allowed the manufacturing of new products. Although tremendous advances were made in the fabrication processes, because of the huge amount of aluminum required, almost every country involved in this war had to face numerous difficulties and delays in production.[105]

4. 2. Aluminum reduction and scrap recovery, a field in which Britain was dominant unlike Germany

51 Secondary aluminum, *i.e.* aluminum recovered from scraps, first appeared during the depression years 1933-1934 in Britain. However, it should be mentioned that no pre-war data regarding this phenomenon are available.[106] In this part, the focus is on comparing the British and the German secondary aluminum industries during WWII. At the time, they were the most significant. France was occupied since 1940. Consequently, the French secondary aluminum industry was almost inexistent. Although in 1934, 42.1 tons of secondary aluminum were produced in the US. The American secondary industry was not significant until quite late, which is well-illustrated by this quote from Donald Marr Nelson (1888-1959): "We the people of United States have had a land of plenty, resources to burn which were burnt but while we were throwing away, the axis was picking up. Germany and Japan scream while US squander. Today we need all these things thrown away."[107]

52 The development of the secondary aluminum industry involved:

- The establishment of raw material reclaiming depots;
- The transportation (usually by train) of the aircraft scraps to the recovery plants;
- The preparations and segregation of scraps and swarfs;
- The implementation of smelters and melting techniques;
- The refining processes;
- The cost of treating aircraft scrap.

53 As previously mentioned Britain relied mainly on imports for the bauxite and aluminum supplies. When supplies were uncertain due to various blockades or when Germany invaded France, and therefore cut the bauxite exports, Britain developed a well-organized secondary aluminum industry. Britain is well-known for manufacturing high quality metal, even when confronted with a war assignment of building planes in unprecedented numbers to defend its territory. After 1940, the Battle of Britain left a colossal number of scraps from crashed aircraft (even enemy's aircraft), which contributed to the war

effort. Various measures were taken to ensure that recycling aluminum was a priority.

54 On the other hand, in the early years of the war Germany was assured of plentiful supplies of raw materials thanks to occupied European countries. Even though Germany acknowledged early the value of the recovery of aluminum from scrap, it was not done until fairly late in the war, when supplies were no longer assured.[108] Consequently, improvised methods were adopted. Recovery scheme on a national scale was planned but not well organized. Wrecked aircraft were classified (instruments, engines, tires and most of the non-metallic parts were removed). However, most melting was done on the as-received metals without neither sorting nor cleaning or removing contaminating metals, resulting in ingots of varying composition and quality. Scraps from aircraft of different nations were not differentiated, especially when it comes to the aero-engine parts. It is well known that these nations used different alloys for the construction of their fleet, especially knowing that the RR alloys used by the British often contained nickel. For all these reasons, German secondary aluminum contained such high percentage of impurities that it was often necessary to dilute it with virgin aluminum. Hence, new methods of refining processes such as electrolytic process, Mercury process, Beck process and Zincal process were investigated and developed.[109] Once the secondary metal was manufactured, specifications were to be implemented in order to sell the secondary aluminum. Table 4 presents three German specifications issued by Vereinigung der deutsche Aluminum VddA[110] of 1942, and the British secondary aluminum specification of the corresponding alloy. Marked differences are observed when comparing the specification limits.

Table 4. Elemental composition of the corresponding German and British secondary aluminum alloys (all figures are maxima).

	No.	Symbol	Percentage of alloying elements (wt%) of secondary aluminum alloys							
			Cu	Mg	Si	Mn	Fe	Ni	Zn	Pb
Germany*	111	UV-Al-Cu-Mg-I	5.5	2.0	1.0	1.5	0.5	0.3	0.1	0.1
	112	UV-Al-Cu-Mg-II	5.5	2.0	1.0	1.5	0.7	0.6	0.2	0.1
	113	UV-Al-Cu-Mg-III	5.0	1.5	1.0	1.5	1.0	0.7	0.7	*
Britain**	DTD.479	-	3.5-4.5	0.4-1.0	0.7	0.4-0.7	0.8	0.25	0.2	0.05

* Vdda Secondary Aluminum Alloys Specifications- Composition limits.
** British secondary aluminum alloy specification limits.

55 The corrosion resistance of these low-grade alloys is lower because of the impurities content. This explained the lower price of these low-grade alloys, and ensured them a steady market.

56 To conclude, the recycled aluminum has been a particularly important contributor to the total metal supply during the Second World War in both Britain and Germany. It represented one third of the total British needs. In Britain minimum contamination has been a dominating factor which is not the case when comparing it to the German practice. Therefore, the methods employed by Germans for the recovery of aluminum from aircraft scraps were inferior to the British ones, but Germany compensated with the development of new refining techniques.

4. 3. Wood in WWII aircraft

57 Although in 1939, Duralumin was the material of modern aviation, wooden aircraft were still used during the Second World War. Indeed, nations that were facing severe shortages of raw materials such as Britain or Germany used wood for aircraft construction. Britain continued to use wood as an aeronautical construction material throughout the Second World War. For example, the Mosquito,[111] which is an emblematic WWII fighter-bomber, was almost entirely made in wood. British aeronautics during the Second World War

proved the competitiveness of wood as a material. The use of wood in aircraft construction was a way of staying independent to aluminum imports. The return to wood for the military aircraft was not observed in the US. France on the other hand, still had fighters not entirely made of metal such as the MS 406. This was mainly due to the numerous delays and the late preparation for WWII. Besides, after the French annexation by the Nazi government the aircraft production in France drastically slowed down. One nation that was forced to resort to the use of wood was Germany. Numerous reports reveal that Germans were forced to use secondary aluminum, made of metal scrap salvaged from crashed aircraft in order to face the various shortages.[112] Moreover, towards the end of WWII, the return of wood in Germany's aviation was not only observed but the use of wood spread in order to face the raw materials shortages. Indeed, in August 1944, the replacement of aluminum by wood was planned or made for various fighters and bombers such as Me 262, Do 335 B-2, FW 190, and Ar 234[113]. In a German official document titled "Replacing metal by wood", performances and capacities of wood and metal parts were compared and investigated. The investigation also focuses on the wood-to-metal bond.

58 World War II was marked by the extensive research funded by governments, and although the return to wood was observed, great technical progress was made along two main axes:

- The establishment of a secondary aluminum industry;
- The innovations in the manufacturing processes (large scale production, reduction in costs…).[114]

59 By the end of the war, in Britain the peak of scrap consumption was reached in 1944 when 96.000 tons of secondary aluminum ingots were produced, which allowed Britain to be less dependent on the imports of aluminum.[115] The same year, the smelting capacity of Germany reached 50.000 tons, which was non-negligible considering the shortages of raw materials Germany had to deal with.[116] The expansion of the aluminum industry was surely stimulated by the aircraft requirements. Technical improvements along with large scale production led to a reduction of prices not only in aluminum industry but also in the aircraft industry.

60 The innovations and development in the aircraft industry can be summarized by the following quote of the wartime president of Lockheed Aircraft Corp, Robert Gross "To build thousands of something it had built only dozens of before. It was like a youth who is suddenly expected to go to college before he was graduated from primary school."

61 In 1938, only 900 aircraft were produced for the whole year, in the United States whereas, from 1940 to 1945, more than 300.000 units were produced. This was only possible because the construction moved to line production which was already used in the automobile industry. Hence, in numerous factories a line of machines and workers were set up to allow the movement of a product while being produced. Each machine or worker performs a particular task that war finished before the product moved to the next position in the line. New tools, processes and techniques had to be devised to meet the demands of line production resulting in an entirely new manufacturing technique. In France, in 1938, only 533 war aircraft were produced,[117] whereas in Britain by spring of that year 150 military aircraft a month were delivered.[118] The urgency brought by the upcoming war forced these two nations to order aircraft and machine tools from other countries such as the US.

5. Regardless of the geopolitical situation, the synergy between industrialists, scientists and governments was the backbone of the development of both aluminum and aviation industries

62 As previously mentioned, during this period, it was clear that no "internationalism of science" was possible. Enemy captured aircraft were almost systematically analyzed and scrutinized in order to evaluate the enemy's knowledge and potential technical advances.[119] Yet, exceptions can be seen amongst allies or members of the axis. The

US and the UK signed the interchangeable agreement to facilitate technology exchange.

63 During the late 1920s and early 1930s an acceleration of technical progress was observed,[120] which led to significant improvements in both aluminum and aeronautic industries.[121] This was only possible because of the birth of what would later be referred to as a "military-industrial complex".[122] In fact, there was a synergy in the academic, military and industrial world. Modern aircraft industry is the result of the collaboration between scientists, engineers and metallurgists. The development of aluminum industry was only prospering due to the increasing needs in aircraft industry, created by the upcoming war, and the constant government demands. War has always had an effect on the development of knowledge. In other words, it stimulates improvements.[123] After the Great War, the interest of aeronautics in air superiority was undeniable.[124] The support provided by political powers to research and investment, was determinant not only for R&D activities, but worked as a driving force for the development of both aluminum and aircraft industries. Government interventions are multiple and are listed hereafter:

64 – Early on, governments have sponsored numbers of international exhibitions to showcase the advances in aviation. The first one was held in Reims, France. The competition *La Grande semaine de Champagne* was held from August 22nd to August 29th 1909. This exhibition gathered 500.000 spectators throughout the week. The success of the Reims air-meeting led to other air-meetings almost everywhere in the world: Le *Salon international de l'aéronautique et de l'espace* at Paris-Le Bourget, France (1909). The first German air exhibition was held on the 26th September in 1909 in Berlin. In Britain, the Doncaster meeting took place in 1909, and the first American meeting was held in Los Angeles in January 1910.[125] Inspite the fact that airplanes have gotten faster spectators are still present even today. Modern air shows are still a constant source of entertainment, for instance *Le Salon du Bourget* gathered 375.000 spectators in its 2019 edition.[126]

65 – Governments also funded several research programs. For instance, *La politique des prototypes* launched by Albert Caquot, in the perspective to revitalize an out-of-date aviation industry, led to numerous record breaking.[127] This policy was launched in 1928 and lasted

until 1933. Leaders were constantly seeking faster, lighter, stronger and more reliable airplanes. This was mainly rendered possible by improving motorization and industrial production. However, continuous developments of lightweight construction methods would not have been possible without the necessarily parallel development of materials. Metallurgist were mandated by government to improve the properties of light alloys by experimenting and developing different versions of alloys. Numerous patents, articles or reports were translated in order to stay up-to-date.

66 – On the eve of the Second World War, governments financed the expansion of the aluminium industry and created new plants that were operated by private companies. Efforts were made to increase output by every possible means. In the US several government-sponsored production programs led to the creation of two alumina plants and nine new smelters. All but one plants were operated by ALCOA for the Defense Plant Corporation.[128] A very similar action was observed in Britain.[129] Governments also charged companies such as BACo or ALCOA to establish controls over existing supplies. The aim was to restrict the use of aluminium in civilian industry. In Britain, control was done in collaboration with the Government and aimed to plan the ingots supplies, BACo acted as the buyer for the Ministry of supply.[130]

67 – Governments also encouraged small manufacturers to merge, or even nationalized aeronautical industries. The increasing intervention of political powers in the aeronautic industry is observed in all four nations. More precisely in the French government when the *Front Populaire* nationalized the armament industries. The nationalization resulted in the creation of six companies: *Les Sociétés Nationales de Construction Aéronautique* (SNCA) which were divided by region: South-West, North, South-Est, Center… These national companies were owned by two-thirds by the French government and one-third by private investors.[131]

68 The expansion of both the aluminum and aviation industry would not have been possible without governments acting as an investor and as a consumer by funding R&D programs and by buying aircraft, and therefore ensuring a steady market for both aluminum products and aircraft.

Conclusion

69 This paper presented the evolution of light aluminum alloys used in aircraft construction, their history, their nomination and physical properties. Their development was marked by the influence of the aircraft industry, whether it is the military aviation, during both WWI and WWII, or the civil aviation during the interwar period. Aluminum alloys also played a significant role in the aircraft industry. In short, the development of one industry could not have been possible without the other.

70 Various aspects were distinguished, yet the constant factor is governments' involvement. Throughout this period, politicians have realized the strategic role aviation had. Therefore, nations thrived to have the state-of-the-art aviation which meant being at the forefront of the technology. Consequently, governments funded numerous fundamental research. Duralumin is a good illustration of this aspect. Governments were also involved in the technical innovations behind the automation of various processes. The geopolitical situation played an essential role, forcing governments to be more involved via the translation of scientific papers to keep their scientists, metallurgists, aviators up to date.[132]

71 The axes along which the development of aluminum alloys happened are:

- The improvements of the mechanical properties;
- The technological innovations;
- The recovery of aluminum alloys.

72 The development of aluminum alloys for aircraft construction was an epic adventure that involved many actors in the political, scientific, industrial and aircraft manufacturing world. The role of each actor was undeniable. This osmotic development of both aluminum and aircraft industries led to numerous innovations and improvements. These innovations were rendered possible because of many personalities such as: personalities in the governments, namely Caquot and his prototype policy, Roosevelt and the push for aviation, the third Reich with their program of armament, British and American governments via the BIOS and NACA organizations.

73 Key figures played a significant role whether in the scientific world or in the aviation industry. Their contribution was largely discussed throughout this paper but to emphasize their part, a summary is given here.

74 Indeed, numerous scientists were devoted to understand and develop new materials, that would later be responsible for the material revolution seen in the first three decades of the 20th century. With his Duralumin, Wilm made a crucial discovery that was going to change both the aluminum and aircraft industries. Rosenhain and his work on high strength material greatly contributed to the improvement of engines and therefore to the improvement of aircraft performances. Blough and his 17S alloy marked the starting point of the expansion of the US aluminum industry. Bengough with his anodizing process, brought a solution to the corrosion issue, which represented the first step towards a greater use of aluminum. The corrosion issue was definitely solved when Dix and his colleagues from ALCOA developed the Alclad. The German Dr. Sterner-Rainer also worked on corrosion resistant products for engines. Merica's work on the comprehension of the hardening greatly helped the scientific world. Finally, Guinier and Preston simultaneously helped understanding the age hardening of aluminum alloys.

75 The innovations in aviation were marked by other emblematic figures, particularly the Wright Brothers and their first powered flight, Lord Von Zeppelin for his work in aviation, Junkers and his first all-metal airplane, Breguet for his implementation of Duralumin in aircraft, Ford for his 4-AT trimotor airplane, Boeing for their implementation of the anodized aluminum 17S in the Boeing 247, and other aircraft manufacturers mentioned in this paper such as Mitsubishi, Mitchell, Dornier, Rohrbach, Saulnier, Messerschmitt, Dewoitine, Douglas…

76 Aluminum became the most important non-ferrous metal and is still used today. Tremendous remains of this period are now exhibited in air and space museums. Nowadays these aircraft represent a huge source of information for historians. Indeed, when archives are sparse and dispersed, the material itself becomes the new source of information. The metallurgical examination of these ancient alloys

helps documenting these artefacts and broadening the knowledge on the properties of ancient age-hardened aluminum alloys.

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RÉSUMÉS

English

The evolution of aluminum alloys from the discovery of the Duralumin to the end of WWII, was marked by a blast of innovations and improvements. This paper looks back at the history behind the use of Duralumin in aircraft construction, starting from the first use of aluminum, going through the hurdles that it faced, the improvements of the alloys, and the difficult implementation of the alloys in industry. This paper also relates the governments' involvement which was a driving force in the evolution of these alloys.

Français

L'évolution des alliages d'aluminium depuis la découverte du duralumin jusqu'à la fin de la Seconde Guerre mondiale a été marquée par une explosion d'innovations et d'améliorations. Ce document retrace l'historique de l'utilisation du duralumin dans la construction aéronautique, en commençant par la première utilisation de l'aluminium, en passant par les obstacles auxquels elle était confrontée, les améliorations des alliages, et la difficile mise en œuvre des alliages dans l'industrie. Ce document décrit également l'implication des gouvernements, qui a joué un rôle moteur dans l'évolution de ces alliages.

INDEX

Mots-clés

alliages d'aluminium, patrimoine aéronautique militaire, duralumin, naissance de l'aviation, Seconde Guerre mondiale, Europe de l'ouest

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