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SOME AEROSPACE APPLICATIONS OF ALUMINIUM ALLOYS

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Abstract: *At present aluminium and its alloys are subject of growing interest from scientists and are widely used in many industries because of their advantages, which are due to their properties.. In this literature review paper we will briefly focus the attention on some of the existing and increasing applications of aluminium and aluminium alloys in aerospace and allied industries. A critical discussion is presented. Possible future extensions of the work in this field are considered.*

НЯКОИ АЕРОКОСМИЧЕСКИ ПРИЛОЖЕНИЯ НА АЛУМИНИЕВИ СПЛАВИ

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Ключови думи: *алуминий, алуминиеви сплави, аерокосмически и космически приложения, леки сплави, производство на Al, корозия, механични свойства*

Резюме*: В наши дни алуминият и неговите сплави са обект на нарастващ интерес от страна на учените и са широко използвани в много отрасли на промишлеността, поради техните предимства, които се дължат на свойствата им. В този кратък обзор на литературата ще фокусираме вниманието върху някои от съществуващите и нарастващи приложения на алуминия и алуминиевите сплави в космическата промишленост и свързаните с нея индустрии. Представена е критична дискусия. Представени са възможни бъдещи изследвания на работата в тази област.*

Introduction

The wide application of aluminium in our life began only some 100 years ago. But today aluminium (Al), its alloys and aluminium-based (Al-based) composites are the most important structural engineering materials, with a key role in aerospace, aircraft and missile technology, automotive and related industries [1-9]. Currently, in terms of production, aluminium ranks first among non-ferrous metals, and its production is constantly expanding. The production and widespread use of Al continues to grow, largely due to the excellent combination of its properties: a relatively inexpensive light metal; good ratio strength to density; good plasticity and mechanical properties; ease of assembly; to a certain extent good corrosion resistance; can be thermally processed and loaded to a relatively high stress level; it is one of the most easily produced by high-quality materials, resulting in lower production and maintenance costs. By comparison: aluminium has about three times lower density and modulus of elasticity than steel, but is considerably easier to process, including pouring, drawing and extruding.

The application of lighter aluminium alloys and Al-based composites, instead of the (dominating since 1920s) special steels, reduces the weight of the vehicles and hence fuel and energy savings, reducing exhaust emissions, and improving safety. The use of aluminium in the automotive industry has increased by over 80% in the last 5 years [2]. There are important recent achievements in aluminium aircraft alloys that can effectively compete with modern composite non-metallic materials [3,10]. Al alloys are frontrunners among the structural materials used in aerospace applications. The role of aluminium in future aircraft will probably be somewhat diminished by the increasing use of some, mainly polymer composite materials, but high-strength aluminium alloys are, and will remain, important and the main airframe materials.

Examples of some Al alloy applications used in aerospace

In the literature there are sufficient data for such Al alloy applications. The various types of aluminium may be divided into two general classes: (1) casting alloys (those suitable for casting in sand, permanent mold, or die castings) and (2) wrought alloys (those which may be shaped by rolling, drawing, or forging). From these two, the wrought alloys are the most widely used in aircraft construction, being used for stringers, bulkheads, skin, rivets, and extruded sections [5]. Die castings used in aircraft are usually aluminium or magnesium alloy. Magnesium alloy is lighter than aluminium alloy. However, aluminium alloy is frequently used because it is stronger than most magnesium alloys [5].

Dural or duraluminium (AA2017) is an alloy of aluminium, the main alloying (additional) metals of which are copper (4.4% of mass), magnesium (1.5%) and manganese (0.5%). Dural is durable, high-strength and lightweight, resistant to corrosion, deformation and environmental influences, aesthetic and easy to maintain, therefore it is one of the most demanded alloys in modern industry. Light alloy duraluminium is used in various fields such as: aviation, space, technology, electrical engineering, shipbuilding, construction, motor transport, at home. The first application of duraluminium is the manufacture of the skeleton of airships of rigid construction (see Figure 1). The new alloy has become one of the main structural materials in the aircraft industry, space technology, nuclear engineering, defense industry, and, of course, for the production of high-speed trains (see Figure 2). Despite competition from other materials, Al alloys still make up > 70% of structure of modern commercial airliner.

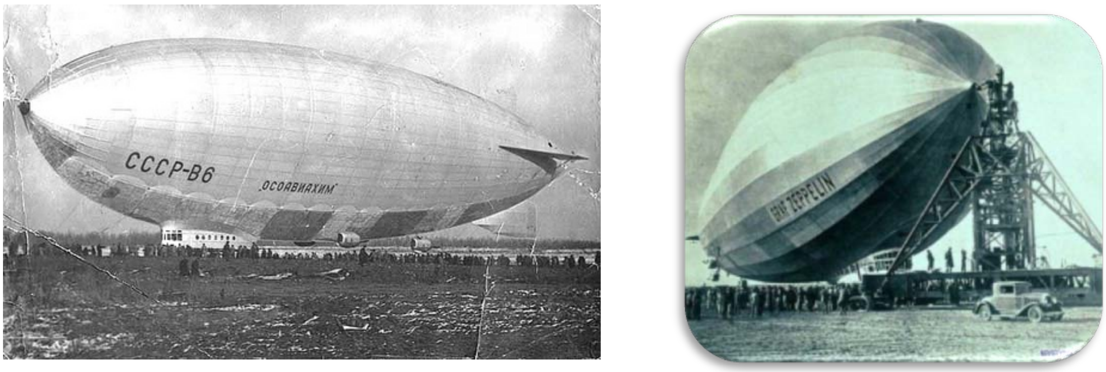

Fig. 1. Airships of rigid construction

Fig. 2. Airbus A340

Design requirements for application of aluminium alloys in aerospace mainly include careful balance of material properties. Components must be lightweight, damage tolerant, durable (corrosion resistant) and cost effective. Al alloy with other elements to improve strength and stiffness - results in alloys with properties well matched to aerospace requirements.

Typical materials used for the fuselage and wings of civil aircraft are:

• 2000 series aluminium alloys based on the aluminium – copper system;

• 7000 series aluminium alloys based on the aluminium – zinc – copper – magnesium system;

• aluminium – lithium alloys.

The 2xxx series (Al-Cu alloys) are heat-treatable, and possess in individual alloys good combinations of high strength (especially at elevated temperatures), toughness, and in specific cases, weldability; they are not resistant to atmospheric corrosion, and so are usually painted or clad in such exposures. The higher strength 2xxx alloys are primarily used for aircraft (2024) and truck body (2014) applications; these are usually used in bolted or riveted construction. Specific members of the series (e.g. 2219 and 2048) are readily welded, and so are used for aerospace applications where that is the preferred joining method. Booster rockets of the Space Shuttle are 2xxx alloys, originally 2219 and 2419, now sometimes Al-Li “Weldalite”alloy 2195 [4].

The 7xxx (Al-Zn alloys) alloys are heat treatable and among the Al-Zn-Mg-Cu versions provide the highest strengths of all Al alloys. There are several alloys in the series that are produced especially for their high toughness, notably 7150 and 7475, both with controlled impurity level to maximize the combination of strength and fracture toughness. The widest application of the 7xxx alloys is in the aircraft industry. The most common aluminium alloy used in aerospace is 7075, which has zinc as the primary alloying element. It is strong, with strength comparable to many steels, and has good fatigue strength and average machinability, but has less resistance to corrosion than many other aluminum alloys. The atmospheric corrosion resistance of the 7xxx alloys is not high, so in such service they are usually coated or, for sheet and plate, used in an alclad version. The use of special tempers such as the T73-type are required in place of T6-type tempers whenever stress corrosion cracking may be a problem [4].

In [6] we can see classification and marking of aluminium alloys (Russian and international (or USA)). It also tells us about modern perspective alloys on an aluminium basis with an application in airspace industry.

More specifically, the alloy property requirements vary depending on the application. A generic example is given in Fig. 2.7 (see in [7]), which illustrates the engineering property requirements for several of the main structural areas in a transport aircraft, namely (a) fuselage and pressure cabins, (b) wings and (c) empennage (horizontal and vertical stabilizers). The engineering properties required for these structures are strength (TS, CYS), stiffness (E), damage tolerance (DT: fatigue, fatigue crack growth, fracture toughness), and corrosion (general and stress corrosion). The rankings of the requirements differ for different areas, but there is much commonality. Table 2.4 (from [7]) presents a survey of the actual and proposed uses of conventional 2XXX and 7XXX aluminium alloys in airframe structures. Alloy producers develop basically similar alloys for different product forms and applications. The most important contribution to this flexibility is the development of a range of alloy tempers that allow optimizations and trade-offs of properties, and hence the ability to match the alloys to particular applications.

Traditionally aluminium alloys have been the favoured materials for airframe structures. However, polymer matrix composites with high-specific strength and modulus are serious challengers to the use of Al alloys, which inherently suffer from low stiffness. Significant improvements in specific elasticity cannot be achieved in conventional Al alloys. However, some publications have mentioned that a very light (density 2.1 g/cm^3) Al–Be alloy designated as AlBeMet AM162 can achieve a nearly four times higher specific modulus than the industry standard AA7075 alloy, with comparable strength and ductility but only half the fracture toughness and considerably increased toxicity (due to Be). Other possibilities for achieving high stiffnesses in Al alloys need to be explored [7].

In [8] a review is given of anodic alumina film formation on aluminium. A major use of porous anodic films is in keying layers for organic adhesives, primer coats and paint finishes. In addition to providing initial adhesion and bond durability, the finished system also retards corrosion in crucial situations, e.g. aerospace applications.

Severe operating conditions in air and space often limit the possibility of using some of these Al alloys directly and for a long time. Therefore, in order to reduce the impact of unfavorable environmental and space conditions, for successful use in the space industry and transport, aluminum alloys and their products require special surface treatment by coating. Nowadays there is a tremendous interest in extremely stable in space environment Al alloys coatings materials. The evidence is the space programs and enormous space budgets, which almost every country has. In the literature and industry there are sufficient data for such coatings on Al alloys, but the most extensive application finds electroless nickel coatings [12]. The unique combination of electroless nickel coating properties and electroless composite nickel coating, such as price, thickness, hardness, corrosion resistance and wear resistance, lubricity, connectivity and evenness of the coating, regardless of the substrate geometry make it ideal for wide application in many different industries. Today, these coatings are firmly established as functional coatings in electronics, oil and gas, chemical, aerospace and automotive industries.

In [11] are presented strong sun-absorbing black electroless nickel coatings on aluminum alloys for space application. Blackened electroless nickel coating provides a high absorption of solar energy and is particularly suitable as a solar absorbing coating for space and related applications. In aviation engines, turbine or compressor blades [11] are covered with electroless nickel as protection against corrosion. Piston heads are a good example of the successful combination of aluminium and electroless nickel in the aerospace industry. The light weight of aluminium allows the piston to work more efficiently, while the electroless nickel provides wear resistance that extends the useful life of the piston. The main shafts of aircraft engines are plated with electroless nickel to provide good bearing surfaces. An additional advantage of electroless nickel is realized when rebuilding of the shafts is required during maintenance overhauls. The rear compressor hub sleeves and bearing liners of the TF30 Jet engine are reconditioned and re-coated with electroless nickel, saving them from buying new components. The relatively low coefficient of friction of electroless nickel, coupled with its corrosion resistance, makes it useful in plating servo valves. Landing gear components are plated with 1 to 2 mils of electroless nickel to build up mismatched surfaces, as well as to provide corrosion resistance. Metallic optics is becoming widely used in spaceborne systems. In these applications, a strong coating must be deposited over a light, strong metal such as beryllium or aluminium. Special, high-phosphorus - from 12.2 to 12.7%, electroless nickel deposits have been polished to 9 Å, providing superior performance in space applications where high G forces are present and low inertia is required. Table 8.2 (see in [11]) summarizes the major uses of electroless nickel in the aerospace industry.

Corrosion in space is described in [13] by the action of atomic oxygen on several materials (Cu, Au, Al, Stainless Steel, Ta, Al alloys and Mo) exposed with and without coatings. The conclusion [12] is that the effect of atomic oxygen on surfaces in laboratory experiments might be different from the effect encountered during low earth orbit exposure. During the orbital movement, the exposed samples pass a thermal cyclic sequence of + 100 / -100 ° C. This can have a detrimental effect on some oxides. The simultaneous action of atomic oxygen attack and thermal cycling might be compared with such effects as static stress and corrosion (stress corrosion) and fatigue and corrosion (corrosion fatigue), where the result of the combined action is more than the sum of the separate effects. Every year in the USA is accepted Joint industry standards “Space Applications Electronic Hardware Addendum to IPC J-STD-001E Requirements for Soldered Electrical and Electronic Assemblies” [14]. In this important document is listed all necessary properties for coatings in space applications.

The reviews [15,16] are on the use of electroless nickel (also on Al alloys) in the aerospace industry. Chemical nickel is used to repair engine components and maintenance programs, in jet engines - on fuel control assemblies and bellows and in the space program, it has been used effectively on the docking, cargo bay and ruder mechanisms of the space shuttle. Chemical nickel is used in aircraft navigation systems, multiple airframe units (landing gear, frame locking systems and valve and actuator components), battery components, and satellite systems. Several parts of the Boeing 727's landing gear wheels are protected from corrosion and erosion by electroless nickel. Many of the Al components used in the space program are covered with electroless nickel to provide anti-corrosion protection, wear protection and excellent lubrication as required. These include components of the space shuttle mechanism used, for example, in fuel systems, gearing systems and fluid transmission systems.

In review [9] is given a brief overview on chromates, which are among the most common substances used as inhibitors or incorporated in anticorrosive pretreatments of aluminium alloys. The paper reviews progress from the literature published to date concerning the application of lanthanide compounds (ecological alternatives to chromates in corrosion protection) as corrosion inhibitors of aluminium alloys in aqueous solution. Here was proposed a two step, electrolytically activated pre-treatment based on cerium salts for the AA6061 alloy, self-named “stainless aluminium”. This process has been also successfully tested for aerospace aluminium alloys, such as AA7075 and AA2024.

As already mentioned above, Al alloys and Al-based composites constitute a very important class of engineering materials widely employed in the aircraft and aerospace industry for the manufacturing of different parts and components due to their high strength-to-density ratio and being the second cheapest of all commercially important metals after magnesium. In our department in SRTI-BAS was synthesized a new Al-based alloy, namely Al alloy B95 with certain additions of tungsten (W) and some nanodiamonds (ultrafine diamond particles, ND) [17-18]. Also some of us

(Z. Karaguiozova) [19-22] have experience in electroless nickel composite coatings with nanodiamond (ND) and other additives. The detonation nanodiamonds were used as strengthening particles for improving the mechanical properties of Al alloy and Ni coating. Several samples of the so modified, with nanodiamonds and W, aluminium alloy B95 (B95+W+ND), prepared in our department, arranged inside the box, were a part of the DP-PM module of the international outer space experiment "Obstanovka" (carried out in the Russian sector of the International Space Station). In the international project "Obstanovka" were involved six countries: England, Bulgaria, Poland, Russia, Ukraine and the Czech Republic, on the International Space Station. On 02.12.2013, at 0:40 pm., with the transport spacecraft "Progress 18M" on board of the International Space Station was supplied scientific equipment, including the DP-PM module (box) with our alloy. The box, on which were mounted the samples of the so modified (see above) Al alloy B95, was coated by a bilayer composite electroless Ni coating (Ni/Ni + ND) to improve the surface characteristics of the box alloy. The aim of this international space experiment was to investigate the two and a half years influence of the outer space environment on the properties of the alloy (B95+W+ND) and of the box, on which were mounted the samples of the so modified (see above) Al alloy B95 (for being exposed directly to the outer space conditions). After this exposure to the outer space influence, the samples with the box were returned to the Earth for future research. Today the comparative analysis of the properties of the materials, of the box and of the samples, (i.e. of the both types of materials, that were and that were not in the outer space) is under study.

Future of aluminium in aerospace industry and conclusions

Next generation aircrafts must be bigger and faster, and rely on advances in materials and assembly methods. For that reason the weight reduction is critical and it is achieved by two ways: (a) alloy optimization - by increase strength and stiffness and/or reduce density whilst maintaining other properties; (b) assembly optimization – by reduce weight associated with joints between components. Traditionally earlier, alloy design and process development were largely by trial and error based on metallurgical experience. Recently, emphasis has changed to designing alloys and processes to meet specific property goals. Now we have improved understanding of relationships between processing, microstructure, composition and properties. Applications of modeling help in development of models to predict alloy microstructure and performance. Models, on a range of length scales, give us different information:

- atomistic models (nm) - deal with only very small volumes of material;
- microstructural (nm-mm) - used to predict particle distributions, grain sizes etc., as function of alloy chemistry and processing conditions, often coupled to microstructure-property models;
- macro-scale (>mm) - widely used to predict performance of components during processing and service as a function of average material properties and stress, strain, temperature and so on.

Modeling examples:

- finite element modeling to optimize extrusion processing of aerospace Al-alloys;
- thermodynamic modeling for the development of weldable aerospace aluminium alloys;
- precipitation kinetics modeling for optimization of dispersoid particles in 7xxx Al alloys.

Emphasis should be placed on modeling for the design of new Al alloys and coatings that have specific and desirable properties.

Thanks to the unique combination of light weight, high strength and ease of manufacture, aluminium alloys and aluminium composites have been the foundation of the aerospace industry for almost a century. Despite the fact that polymer-based composites have appeared in recent years as formidable competitors in this respect, the predominance of Al alloys in civilian and military transport aircraft is not reduced, especially given their almost infinite capacity for recycling and fire resistance, which complicates and restricts the use of materials on based polymers. The most frustrating limitation is their inherently low modulus of elasticity, a problem that challenges a satisfactory solution from the metallurgical staple of the microstructural modification. To solve this problem, experience, new thinking and new ideas are required.

Our experience in the electroless nickel depositions and electroless composite coatings will be of great help in the future study of unknown coating properties, coating structures, new reinforcing particles (in composite coatings) for new potential Al alloys and Al-based composites aerospace and allied industries applications.

High-strength aluminium alloys are, and will remain, important and the main structural airframe materials.

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