S E S 2 0 1 6
Twelfth Scientific Conference with International Participation
SPACE, ECOLOGY, SAFETY
2– 4 November 2016, Sofia, Bulgaria

MAGNESIUM APPLICATION IN AEROSPACE INDUSTRY

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Key words: *magnesium, magnesium alloys, magnesium based alloys, aerospace and space applications, light alloys, manufacturing methods of magnesium, coatins*

Abstract: *At present magnesium and magnesium alloys are the subject of growing interest from scientists mainly due to his lightness combined with strength. This is the main reason magnesium and its alloys to be widely applicable in areas of the industries such as aerospace and aircraft production, automotive and missile construction, electronic, projectiles, powertrain and army applications. Application of magnesium and magnesium alloys leads to reduced weight, and consequently to fuel economy, and consequently decreasing the output of environmentally harmful substances. In this literature review we will briefly focused the attention on increasing applications of magnesium and magnesium alloys in aerospace and allied industries.*

ПРИЛОЖЕНИЕ НА МАГНЕЗИЯ В АЕРОКОСМИЧЕСКАТА ИНДУСТРИЯ

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Ключови думи: *магнезий, магнезиеви сплави, аерокосмически и космически приложения, леки сплави, производство на Mg*

Резюме: *В наши дни магнезият и магнезиевите сплави са обект на засилен интерес от учените, главно поради комбинацията на две техни основни свойства: те са леки и ковки. Това е причината, магнезият и неговите сплави, да бъдат широко приложими в области от индустриите като космическите изследвания и самолетостроенето, автомобилостроенето и ракетостроенето, електрониката, задвижващи системи и приложения в армията. Приложението на магнезия и магнезиевите сплави води до намаляване на теглото, и следователно до икономията на гориво, и като следствие - намаляване на продукцията на вредни за околната среда вещества. В този литературен обзор ние накратко ще фокусираме вниманието върху увеличаването на приложенията на магнезия и магнезиевите сплави в аерокосмическите изследвания и свързаните с тях промишлености.*

Introduction

The aerospace industry has a long history of using magnesium and magnesium alloys in many applications both civil and military. It is of prime importance to lower the weight of air and space craft, as well as projectiles, to aid in decreasing emissions and increasing fuel efficiency. These changes will result in a lower operational cost as well. Magnesium is an ideal material for use in these applications due to limited continuing improvements on aluminum weight reduction, the high cost of fiber metal laminates, and the poor impact, and damage properties of low density plastics when subjected to extreme temperatures. Magnesium can be found in the thrust reversers for the Boeing 737, 747, 757, and 767 as well as in engines and aircraft and helicopter transmission casings [1,2]. Spacecraft and missiles also contain magnesium and its alloys. Lift-off weight reduction is of high importance in design and a material is needed that can withstand the extreme conditions faced during operation.

Magnesium is capable of withstanding the extreme elevated temperatures, exposure to ozone and the impact of high energy particles and matter. It is also used in large quantity in intercontinental ballistic missiles such as Titan, Atlas and Agena.

As of 2013, magnesium alloy consumption was less than one million tons per year, compared with 50 million tons of aluminum alloys. Its use has been historically limited by its tendency to corrode, high-temperature deformation, and flammability [3]. For the chemical resistance improvement of magnesium and its alloys research and development are carried out an expanding the application areas to be achieved. One preferred method for surface properties improvement is metal deposition by electroless or electrochemical methods. The study [2] presents a short overview for some surface treatments of magnesium and magnesium alloys for achieving the better corrosion and wear resistance of the surface. Many authors focus their attention on the electroless and electrochemical plating methods for production of high quality coatings to expand the application areas of these materials.

Magnesium and its alloys serve as an alternative substitution to aluminum alloys (are widely used as a major structural material), titanium alloys, iron, plastics and steel due to their attractive technical and environmental properties [4]. Their major advantages are:

- Lightest structural material,
- Higher strength-to-weight ratio,
- Good castability,
- Good machinability,
- Acceptable weldability under controlled atmosphere,
- Recyclable and thus fewer raw resources are consumed.

However, the use of magnesium and its alloys is still restricted, due to the following drawbacks:

- Low elastic modulus,
- Limited cold workability and toughness,
- Restricted high strength and creep resistance at high temperature,
- Poor corrosion resistance (in some applications).

The most significant and economically competitive used magnesium alloys are based on the magnesium-aluminum system, such as AZ91 (Mg-Al-Zn) and A50/60 (Mg-Al-Mn). They offer good die-castability, reasonable room temperature strength or ductility, and even good corrosion resistance, but they have poor mechanical properties at elevated temperatures [4].

Magnesium is the lightest of all commonly used metals and is therefore very attractive for many industries. Several studies were undertaken in order to develop new magnesium alloys. As a result, various Mg-alloys were recently introduced to replace competitive lightweight materials. However, there is still a need to increase the quantity and variety of both cast and wrought Mg alloys. The aim of the study [4] was to develop new high temperature creep resistant Mg alloys based on Mg-Sn system with calcium (Ca) as a ternary alloying element. The series of the selected alloys Mg-Sn-Ca (TX-alloys) contain Sn and Ca in the ranges of 2-6 wt.-% and 0-3 wt.-%, respectively. They should exhibit better creep properties than the mostly used AZ91D-alloy and the high temperature creep resistant AE42-alloy. Therefore, AZ91D- and AE42-alloys supplied by Hydro were also cast as benchmark for this purpose. In addition, a participation of a development of ternary Mg-Sn-Ca phase diagram was raised after DTA and DSC measurements. The results of creep investigations show that a number of TX-alloys, which have a Sn:Ca ratio below 3:1 (in particular less than 2:1) exhibit better creep properties than cast AZ91D alloy and even better than AE42-alloy. On the other hand, the corrosion behavior and mechanical properties of these alloys need further improvement. Finally, the results of this work, in particular creep results, indicated that some of TX-alloys can be used in automobile industry and thus a contribution will help to develop new class of Al-free Mg-alloys. This development will enable to expand the use of Mg-alloys in elevated temperature airspace applications [4].

Magnesium is also used in conventional aircraft and helicopter engines and, to a lesser extent, in airframes and landing wheels [5]. However, these levels are well below potential usage because of real and perceived corrosion problems and the resultant construction mandates against magnesium. Use in helicopters, such as in the MD600 main transmission (Figure 2 [5]), has led to power increases in the rotor system when adequate corrosion- protection coatings have been applied, and, generally, the aerospace industry is taking a fresh look at magnesium. The use of magnesium in missiles and space applications has been widespread because of magnesium's strength and rigidity at minimum weight coupled with ease of fabrication. However, it possesses other characteristics, such as the ability to withstand temperature extremes; proximity of some components to liquefied fuels; exposure to ozone and free radicals in the upper atmosphere; and bombardment by shortwave electromagnetic radiation, high-energy particles, and small meteorites.

AZ91C has widespread use in both commercial and aerospace applications where lightweight and moderate strength are required. found a place in less critical aerospace castings. The availability of the highly corrosion resistant AZ91E offers obvious advantages for direct substitution, to improve corrosion resistance, although no improvement in mechanical properties or castability ensue. A wide range of properties can be achieved by the addition of a range of alloying elements. Although Al is incompatible with Zr, typical additions to Mg-Zr alloys include Zn, Ag and rare earth elements. These alloys have so far fulfilled the major requirements of aerospace applications. They have excellent castability, and can be cast into complex shapes virtually free of microporosity. The most widely used alloy is currently ZE41 (4.2% Zn, 1.3% Ce 0.6% Zr) which has moderate strength with a simple T5 heat treatment (cast then aged). Strength is maintained up to around 150 °C. ZE41 has been the preferred material for helicopter transmission applications for almost 20 years, where its combination of tensile properties, stiffness and good fatigue resistance are all fully utilised. It is also used in many other aerospace and similar high quality castings. More recently, properties have been further increased by the replacement of Zn and Ce with Ag and Nd/Pr, the improved solubility of which permits the alloy to be fully heat treated (T6) by solution, quenching then precipitation treatment. The higher mechanical properties achieved from these alloys are well maintained to 200 °C. In answer to these demands, Magnesium Elektron Ltd (MEL) have developed a new family of alloys based upon the Mg-Y-Nd RE system (R.E. = Rare Earths). Due to its combination of superior stability at temperature, and excellent mechanical properties, the alloy considered most suitable for aerospace applications is WE43 (4% Y, 2.25% Nd, 1% HRE*, 0.6% Zr). When WE43 is compared to commonly used aerospace Aluminium based alloys, such as A356 (Fig 7 [6]) and high temperature A203, it competes directly on a volume to volume basis, and can prove even better at elevated temperatures, with a dramatic potential weight saving of around 30%. In summary, WE43 should be very attractive to designers who wish to uprate current applications, where improved corrosion resistance is required compared to other Mg-Zr alloys and for new applications where all the benefits of high strength, high temperature capabilities and corrosion resistance need to be combined with minimum weight. New materials such as WE43, AZ91E and R.S.T. alloys have greatly improved resistance to general corrosion to the level of Aluminium base alloys, but protection is still necessary, for aerospace applications. Two main areas of corrosion protection must be addressed namely general surface protection and galvanic protection. Magnesium alloys and related processes are now available to the designer offering improved mechanical properties, high corrosion resistance and high temperature capabilities.

The development of more corrosion-resistant lightweight alloys, such as those based on magnesium, is critical for the extensive use of such materials in transport, infrastructure and airspace applications [7]. The magnesium alloy ZE41 is an aerospace alloy typically used for helicopter gear boxes because of its high castability and excellent strength up to 160 °C. In [7] the reactivity of two phosphonium cation based ILs with a ZE41 magnesium aerospace alloy was investigated using a combination of microscopy, electrochemical, and spectroscopic techniques. This will impact the further design of IL systems for application in tribology and corrosion engineering where the interphase that develops on the metal alloy surface is critical in extending the lifetime of metal-based structures.

AZ91D Mg alloys are popular and offer 20-25% weight saving over Al in transmission casings [8]. With the price trends of magnesium since 2001, magnesium gravity cast or low-pressure parts are also becoming cost-effective [9]. Despite the low creep resistance of pure magnesium, it is known that alloying has been quite successful in developing magnesium alloys for high temperature service for aerospace applications. This is evident in comparing the “maximum usefulness temperature” of various metals [9]. For magnesium, it can be observed that the best alloys (mainly rare earth containing and in the past thorium containing) can compete very well with aluminum alloys.

Mg alloys are extremely attractive structural materials for application in automotive and aerospace industries because they have unique combination of light weight, high specific strength and stiffness and high recycling capability. In [10] deformation behavior of pure Mg and Mg alloy were studied in the temperature range of 423 to 773K and at strain rates of 10^{-4} –10^{-2} s^{-1}. Plastic deformation can give wider implementation of sheet and extruded products from Mg-based alloys into commercial use can lead to new age of Mg in automotive and aerospace industries.

Today, magnesium application in the aerospace industry take place as sand cast (ZE41, EZ33, or WE43) or forged (AZ80 or ZK60) helicopter transmission housings [11]. The potential for new sand-casting alloys of exceptional creep resistance looks very promising.

In the study [12], the current advantages, limitations, technological barriers and future prospects of Mg alloys in the automotive and other industries are given. The usage of magnesium in automotive and airspace applications is also assessed for the impact on environmental conservation. Recent developments in coating and alloying of Mg improved the creep and corrosion resistance properties of magnesium alloys for elevated temperature and corrosive environments. The results of the study [12] conclude that reasonable prices and improved properties of Mg and its alloys will lead to massive use of magnesium. Compared to using alternative materials, using Mg alloys results in a 22% to 70% weight reduction. Lastly, the use of magnesium in various components is increasing as knowledge of forming processes of Mg alloys increases. Weight reduction has always been an important objective for aerospace industry. Aluminium is a traditional light metal for airborne structures. The alloys used today for aerospace applications are already optimized concerning aeronautic requirements such as strength, fatigue and damage tolerance properties. Therefore weight reduction is more and more difficult to be reached with small advances in aluminium material development. The family of magnesium materials and especially magnesium wrought materials could be an excellent alternative to aluminium because of their low density, rather good mechanical properties and metallic behaviour [13].

Magnesium was commonly defined as the metal of airborne construction. Historically, magnesium has been used in aircraft since the thirties of the last century. In the fifties, magnesium passed a "boom" when it was broadly used in aircraft structures and components. Military aircrafts and helicopters that were built in that period included hundreds kilograms of magnesium products (see Fig.1 from [13]). The aerospace industry of former Soviet Union also broadly used magnesium in military aircrafts. The significant difference of magnesium application in former Soviet Union from the Western countries is the relatively big amount of magnesium components in civil aircrafts. This fact may be explained by utilization of military plane structures for prototyping of civil aeroplanes. For example, if Boeing 737 (start of manufacturing in 1967) had only several small magnesium components in wing structures and door, Tupolev TU-134 (start of manufacturing in 1963) had 1325 magnesium components with total weight 780 kg (Fig. 5 [13]). Regarding the Western aerospace industry, up to now magnesium has not been used in structural applications by major aircraft manufacturers: Airbus, Boeing and Embraer. The situation is different for helicopter industry where magnesium is used in cast gearboxes and transmissions and some other non-structural elements.

Magnesium meets requirements of all active aerospace standards for material flammability resistance. Corrosion on magnesium alloys was the real main reason for decrease in magnesium applications [13]. The situation has changed with significant improvement of magnesium production technologies, as well as with developments in the last decade, of new magnesium surface treatment technologies such as PGA ALGAN 2M and composite coating Gardobond X4729 from Chemetall GmbH; and Magoxide and Magpass from AHC Oberflächentechnik. The technologies provide magnesium with similar to aluminum level of protection. Recently Magnesium Elektron Ltd. (UK) developed new high-strength alloys Elektron 21 and Elektron 675 which have mechanical properties comparable to aerospace aluminium structural alloys [13]. The above mentioned developments, as well as, strong demand for aircraft weight reduction and some dissatisfaction of aerospace industry with composite materials led to the beginning of serious investigation of magnesium comeback to aerospace industry.

The paper [14] provides an overview of various processes used for producing magnesium castings. Magnesium alloys have some unique solidification characteristics such as excellent fluidity and less susceptibility to hydrogen porosity, and thus, better castability over other cast metals such as aluminum and copper. Casting has been the dominant manufacturing process for magnesium components, representing about 98% of structural applications of magnesium. Gravity sand and permanent mold processes are used to produce high-performance aerospace and defense components. Emerging processes such as low pressure casting, squeeze casting, semi-solid casting, lost foam casting and ablation casting are also discussed. Magnesium is the third most-commonly used structural metal, following steel and aluminum. Structural applications of magnesium castings in automotive, aerospace and power tools industries are reviewed in this paper. The opportunities and challenges of magnesium alloys for structural applications are discussed at the end of [14].

Laser welding will be an important joining technique for magnesium alloys with their increasing applications in aerospace, aircraft, automotive, electronics and other industries. In the document [15] the research and progress in laser welding of magnesium alloys are critically reviewed from different perspectives. The aim of the report was to review the recent progress in laser welding of magnesium alloys and to provide a basis for follow-on research. Laser welding will probably become an important joining technique for magnesium alloys and can promote their wider uses in aerospace, aircraft, automotive, electronics and other industries.

Carbon fibre and textile reinforced lightweight materials with selected magnesium alloy matrices have been strongly considered nowadays [16] for lightweight applications under complex dynamic and static operating loads, e.g. in automotive engineering. Thereby, especially continuous fibre reinforcement increases the application potential of this novel material group considerably. The priority objectives of the reinforcement of magnesium are to increase the stiffness and strengths of the material and to reduce its pronounced tendency to creep, whereas the inserted fibre reinforcement effect directional-controlled material properties. Despite high manufacturing costs metal matrix composites (MMC) like carbon fibre reinforced magnesium are interesting materials for components with good wear resistance and high specific strength at low weight and advantageous thermal behaviors. Thereby, a potential field of application would be within robotic high-precision machining tools and positioning systems, textile techniques, aerospace industry and high-performance electronics.

Eco-friendly vanadia based chemical conversion coating was applied [17] for improving the corrosion resistance of a newly developed magnesium AZ31 HP–O alloy. The advanced magnesium alloys that are being developed and used in modern automotive and aerospace industries require high performance and more durable coating systems. The coating formed due to such a technique is characterized by a self healing ability. It is necessary to take into account that the vanadia surface treatment designed in this study would be only a pre-treatment trying to provide a self-healing functionality, and a final organic topcoat will be crucial to reach an adequate corrosion protection.

Magnesium and its alloys have wide applications in automotive and aerospace industries because of their low density and high specific strength. However, their poor resistance to corrosion is a serious impediment against their wider applications. Thus, many surface treatments, such as chemical conversion coating, anodizing, plating, sputtering compound coating, and laser surface melting, have been applied in Mg and its alloys to improve their corrosion resistance. On the other hand, aluminum and its alloys have high specific strength and good surface decoration characteristic, and they usually show excellent corrosion resistance. Therefore, it is of practical significance to coat Mg with Al, which may provide an alternative to improve the corrosion resistance of Mg [18]. To demonstrate the potential application of the Mg–Al eutectic alloy solder, magnesium plate was coated with aluminum foil by this process and its corrosion resistance was evaluated by electrochemical test. It shows that the corrosion resistance of the magnesium plate with aluminum coating was remarkably improved, which exhibits a similar corrosion behavior to that of aluminum. Mg and Al can be bonded conveniently by using Mg–Al eutectic alloy as the solder under pressure at 450℃ in atmosphere. The presence of eutectic solder with low melting point promotes the atom diffusion greatly and hence facilitates the bonding between Mg and Al. The bond strength increased obviously with the increasing of the holding pressure, and a bend strength as high as 22 MPa was obtained. In this way, Al-foil can be easily coated onto Mg and the Al-coated Mg exhibits a much improved corrosion resistance, than that of Al.

Since the 1940’s Mg-alloys have been used for military applications, from aircraft components to ground vehicles. The drive for usage was primarily availability and lightweighting of military systems. This review paper [19] covers historical, current and potential future applications with a focus on scientific, engineering and social barriers relevant to integration of Mg alloy. It has also presented mechanical and physical property improvements solutions which are currently being developed to address these issues.

Future of magnesium in aerospace industry

The future application of magnesium in aerospace industry will be probably based on present and future running R&D projects. Such kinds of projects are running at the present time in European Union, USA, Israel, France and Austria. European Framework Program 6th has three magnesium related projects in Aeronautic Priority: IDEA, AEROMAG and MagForming [13]. These types of projects may significantly influence on magnesium future in aerospace industry due to the active participation of major European aerospace companies and scientific communities. Major European aerospace industries seriously investigate magnesium as weight-reduction alternative for aluminum. New high-strength alloys and advanced surface treatment technologies are the real and reasonable base for magnesium comeback in aerospace industry.

Conclusions

Magnesium is the lightest of all the commonly used metals and is, thus, very attractive for aerospace applications. It also has a number of other desirable features, including good ductility, better damping characteristics than aluminum, and excellent castability.

Considering magnesium lightness combined with strength it is too promising to investigate novel protective coatings with improved properties in order to increase its applications in areas of the industry as aircraft production, automotive and missile construction, also space technology. With appropriate protection techniques, magnesium offers the aerospace engineer a valuable material choice now and into the 21st century.

Magnesium alloys have been used for many years, primarily because of their light weight (specific gravity 1.8), only 2/3 as dense as aluminium. Improvements in properties and castability achieved by magnesium in the last 30 years make magnesium alloys a prime choice for further application within the aerospace industry.

The advancements which have been made will further increase the use of magnesium in the aerospace industry where magnesium major advantage of light weight continues to be of paramount importance. To build a sustainable society in the future it will be necessary to reduce the weight of structural materials on earth and in the space, both to conserve energy and to minimize global warming. Today magnesium (Mg) alloys are recognized as present and future alternatives to iron and aluminium to reduce the weight of structural materials.

Our achievements [2] in recent years concerning improved properties of electroless nickel and composite nickel coatings give us a reason to be optimistic about possibilities for a bright future of protective coatings in magnesium and its alloys aerospace applications.

Acknowledgments

This survey was partially supported through the bilateral scientific cooperation project “Influence of nanosized additives on the physical and mechanical properties of the composite materials and coatings” (2015 - 2017), between the Bulgarian Academy of Sciences (Space Research and Technology Institute) and the Polish Academy of Sciences (Institute of Metallurgy and Materials Science of Polish Academy of Sciences (with support of the Institute of Precision Mechanics)).

References:

1. http://www.intlmag.org/page/app_aerospace_ima
2. Karaguiozova, Z., Electroless Deposition of Metalic Coatings on Magnesium Alloys, SES 2015, 2016, 376-382.
3. Ddodson, B. "Stainless magnesium breakthrough bodes well for manufacturing industries". Gizmag.com, Retrieved 29 08.2013.
4. Abu Leil, T., (2009), Development of New Magnesium Alloys for High Temperature Applications. Doctoral Thesis approved by the Faculty of Natural and Materials Sciences, Clausthal University of Technology. http://www.gbv.de/dms/clausthal/E_DISS/2010/db109602.pdf.
5. Froes, F.H., D. Eliezer, E. Aghion, The Science, Technology, and Applications of Magnesium, Light Metals, JOM, 1998, 30-34.
6. Lyon, P., J. F. King, G. A. Fowler, Developments in magnesium based materials and processes, ASME 1991 International Gas Turbine and Aeroengine Congress and Exposition. American Society of Mechanical Engineers, 1991, 1-8,
7. Forsyth, M., W. C. Neil, P. C. Howlett, D. R. Macfarlane, B. R. W. Hinton, N. Rocher, T. F. Kemp, M. E. Smith, New Insights into the Fundamental Chemical Nature of Ionic Liquid Film Formation on Magnesium Alloy Surfaces, Applied materials&interfaces, v. 1, No. 5, 2009, 1045–1052.
8. http://www.magnesium-elektron.com/
9. Pekguleryuz, M. O., A. Arslan Kaya, Creep Resistant Magnesium Alloys for Powertrain Applications, Magnesium: Proceedings of the 6th International Conference Magnesium Alloys and Their Applications. Edited by K.U. Kainer, Copyright © 2004 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, ISBN: 3-527-30975-6, 74-93.
10. Galiyev, A., O. Sitdikov, R. Kaibyshev, Deformation Behavior and Controlling Mechanisms for Plastic Flow of Magnesium and Magnesium Alloy, Materials Transactions, v. 44, No. 4, 2003, 426 to 435.
11. Agnew, S. R., Wrought Magnesium: A 21st Century Outlook, JOM, May, 2004, 20-21.
12. Kulekci, M. K., Magnesium and its alloys applications in automotive industry, Int J Adv Manuf Technol, 39, 2008, 851–865.
13. Ostrovsky, I., Y. Henn, Present state and future of magnesium application in aerospace industry, International Conference “NEW CHALLENGES IN AERONAUTICS”, ASTEC’07, August 19-22, 2007, Moscow.
14. Luo, A. A., Magnesium casting technology for structural applications, Journal of Magnesium and Alloys, 1, 2013, 2-22.
15. Cao, X., M. Jahazi, J. P. Immarigeon, W. Wallace, A review of laser welding techniques for magnesium alloys, Journal of Materials Processing Technology, 171, 2006, 188–204.
16. Hufenbach, W., M. Andrich, A. Langkamp, A. Czulak, Fabrication technology and material characterization of carbon fibre reinforced magnesium, Journal of Materials Processing Technology, 175, 2006, 218–224.
17. Hamdy, A. S., I. Doench, H. Möhwald, Smart self-healing anti-corrosion vanadia coating for magnesium alloys, Progress in Organic Coatings, 72, 2011, 387– 393.
18. Li, X., W. Liang, X. Zhao, Y. Zhang, X. Fu, F. Liu, Bonding of Mg and Al with Mg–Al eutectic alloy and its application in aluminum coating on magnesium, Journal of Alloys and Compounds, 471, 2009, 408–411.
19. Mathaudhu, S. N., E. A. Nyberg, Magnesium alloys in U.S. military applications: past, current and future solutions, Essential Readings In Magnesium Technology, Edited by Suveen N. Mathaudhu, Alan A. Luo, Neale R. Neelameggham, Eric A. Nyberg, and Wim H. Sillekens, 2014 The Minerals, Metals & Materials Society, Published 2014 by John Wiley & Sons, Inc.