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Review Article

Aerospace Industry and Aluminum Metal Matrix Composites

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Abstract

Researchers have turned to search for new materials that will meet all the aerospace industry requirements. When it is almost impossible to achieve this with a single material, composite materials have been studied, and there have been great developments in this field. Many elements are used in aircraft construction, but aluminum is the most preferred due to its low density, good castability, high strength, corrosion resistance, and good fatigue strength. However, its strength and stiffness limit its usability. To solve this problem, aluminum is combined with various elements. Aluminum metal matrix composites are an example of this. Aluminum metal matrix composites are preferred in aircraft applications due to their high specific modulus and good mechanical and thermal properties. This review provides information on the use of aluminum metal matrix composite materials in the aerospace industry.

Keywords

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1. Introduction

The search for new and advanced materials will continue, with modern technological developments and consumers' demands for lighter, energy-efficient, stronger, and cost-effective systems and machines. The properties of the materials used in aerospace are constantly improved in line with technological developments to meet safety and operational standards.

Aluminum-based metal matrix composites can be used in many industries. In recent years, the use of aluminum matrix composites in aviation has become widespread. Materials in aircraft must be lightweight and able to withstand high temperatures for extended periods in harsh environments. Aluminum composites are the preferred choice for aircraft fuselage, wing, and support structures. The fuselage of an airplane consists of approximately 80% aluminum by weight. Offering lower production costs, the ability to create complex shapes, and the inclusion of innovative design concepts, aluminum die casting technology is gaining importance. Aluminum metal matrix composites are preferred because of their lower density, excellent specific strength and hardness, high modulus, good thermal properties, better wear, and corrosion resistance (Nturanabo et al., 2019). Aluminum metal matrix composites are attractive materials for thermal management and have a high volume reinforcement fraction (Raju et al., 2016). It is possible to further improve the thermal conductivity of the composite material by using high thermal conductivity reinforcements. In the metal matrix composites, aluminum and copper were often used as matrices due to their high thermal conductivity. Their reinforcements consisted of carbon, SiC, and diamond. There is a growing interest in using Metal matrix composites in the aircraft industry (Akhil, 2018). Because of their great

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potential for the production of lightweight, structurally efficient aircraft components, these materials are usually selected for their lightweight and ability to withstand the stresses generated during operation, aluminum metal matrix composites have been used in these studies (Kolia et al., 2015) (Kaushik et al., 2015).

This article evaluates increasing efforts to exploit the potential of these materials in the aerospace industry. There are some studies about the new types of these aluminum composite materials currently in research. The studies about aluminum-based composites can improve their use in aircraft applications. Their properties were reviewed, and the results were introduced as reinforcement contents increased in the matrix material, the hardness of the composites also increased with an increase in tensile strength and decrease in elongation. Studies on this subject can provide better properties in aluminum matrix composites for aircraft applications. This study introduces the use of aluminum metal matrix composite materials in the aircraft industry. It will give general information about these materials, their different applications, and their advantages and disadvantages. Aluminum-based metal matrix composites can be used with their desired properties for specific

2. Material Selection in Aerospace Industry

Material selection is one of the most important functions of effective engineering design as it determines the industrial and economic reliability of the design. A great design may not be a profitable product if it cannot find optimal material combinations. So it is vital to know what the best materials for a particular design are. For this reason, engineers use several facts of materials to arrive at the most reasonable decision. They are mainly concentrated on the properties of the materials, which are identified as the potential materials for that specific design.

Material selection is a conflicting decision-making process. Because mostly, lightweight materials may not have sufficient strength, and brittle materials will not be suitable for fatigue resistance, stiffness, or toughness. Moreover, it is almost impossible to find one single material that provides all desired properties for engineering applications. Additionally, material properties are strongly affected by the working environment, such as temperature, pressure, humidity, and the nature of loading such as gradual, fluctuating, impact, fatigue. Accordingly, there is a need to combine two or more materials as alloys or composites so can take advantage of the different useful properties offered by combining different materials. In the aircraft industry, aluminum alloys/composites overtake other metals, especially due to their mechanical stability, thermal management, and lightness (Nturanabo et al., 2019).

There are some metal matrix composites types such as nickel, aluminum, refractory, and etc. Fillers in the metal matrix composites are silicon carbide, aluminum oxide, titanium carbide, and other fillers. The industries which use the metal matrix composites are aerospace and defense, automotive and locomotive, electrical and electronics, industrial, and other end-user industries (Metal Matrix Composites Market - Growth, Trends, COVID-19 Impact, and Forecasts, 2021).

Aluminum matrix composites have been used in many different sectors, such as the aerospace industry, automobile production, or power electronics. Aluminum matrix composites produced by equal channel angular extrusion have very high strength. This is due to a very fine-grained structure. However, they are very temperature-sensitive. An adapted joining technique is required. In this respect, soldering offers some advantages compared to other joining processes such as welding or bonding. Sn-based filler metals are suitable for this purpose due to their low melting range below 300 °C; Ag and Cu are common alloying elements. Disadvantageous features are low strength and creep resistance of the joints. The improvement of these properties can be achieved by the development of Sn-based composite fillers by adding ceramic reinforcement particles such as Al_2O_3 or SiC. Investigations were made towards the formation of an interfacial reaction layer between the reinforcement particles and the filler matrix. Ti was alloyed as the active element to improve the bond between the matrix and the particles. In such studies, the microstructure observed by SEM can be evaluated by associating it with the results of the tensile tests (Wielage et al., 2010).

The chemical composition of Al alloys affects their electrochemical potential and the distribution of the various phases in the microstructure, as well as the corrosion behavior. Corrosion forms depending on the structure, e.g., intergranular attack, exfoliation, and stress corrosion cracking (SCC) were encountered with heat treatable, high strength alloys, preventing exploitation of maximum potential strength of wrought products. Corrosion resistance was improved with new metallurgical processes and compositional modifications. Exfoliation corrosion and SCC behavior can be significantly improved for copper-bearing 7XXX series alloys by duplex aging; however, strength is compromised. In recent years an optimum combination of strength and corrosion characteristics was provided by the development of optimized heat treatment procedures (Peters and Leyens, 2009).

3. Metal Matrix Composites

Metal matrix composites are modern and well-developed lightweight materials composed of an element or an alloy matrix. This matrix consists of two-phase; the second is fixed into the surface and then distributed to provide some developments. Depending on the size, shape, and amount of the second phase, the composite property varies. Composite has excellent benefits due to the combined metallic and ceramic properties, and accordingly, it provides improved physical and mechanical properties. It represents a new generation of engineering materials in which strong ceramic recruitment is integrated into a metal matrix to improve its properties as a specific strength, specific stiffness, wear resistance, corrosion resistance, and elastic modulus. Whereby composites, the metallic properties of matrix alloys such as ductility and toughness are combined with the ceramic properties of reinforcements such as high strength and high modulus, thus providing greater strength in shear and compression and higher service temperature capabilities. These properties help to understand the scientific, technological, and commercial importance of composites (Vijayaram and Baskaralal, 2016).

Metal matrix composites are composed of a metallic matrix and a dispersed phase which a second phase or phases have been artificially introduced. This is in adverse to conventional alloys whose microstructures are produced by phase transformations that occur naturally during processing. Metal matrix composites are differentiated from the resin matrix composites with their metallic nature and being appropriate to conventional metallurgical processing operations. Metal matrix composites more comprehensively improved resin matrix composites by the preference of their metallic nature. This can be explained by their physical and mechanical properties and by their ability to lend themselves to conventional metallurgical processing operations. Some of the properties that differentiate metal matrix composites from resin matrix composites can be indicated as electrical conductivity, thermal conductivity, and non-inflammability, matrix shear strength, ductility and abrasion resistance, ability to be coated, joined, formed and heat treated. These composites have been developed for weight-critical applications in the aerospace industry, and they are a class of advanced materials. Composites reinforced with isotropic properties can be formed in a three-dimensional or planar region. This shows that they are suitable to be developed for requirements (Vijayaram and Baskaralal, 2016).

Table 1 shows the typical reinforcement used in metal matrix composites. Metal matrix composites can be defined as the materials with microstructures that involve a continuous metallic phase into a second phase, or phases, have been artificially introduced. This is in contrast to the situation where the microstructures of conventional alloys are produced by phase transformations during processing.

Table 1. Typical types of reinforcements used in metal–matrix composites (Chawla, 2012) (Akhil, 2018)

Type	Aspect ratio	Diameter	Examples
Particle	1–4	1–25 μm	SiC, Al_2O_3, BN, WC
Short fiber (whisker)	10–10000	1–5 μm	C, SiC, Al_2O_3, SiO_2 + Al_2O_3
Continuous fiber	> 1000	3–150 μm	SiC, Al_2O_3, C, B, W, Nb + Ti, Nb_3Sn
Nanoparticle	1–4	< 100 nm	C, Al_2O_3, SiC
Nanotube	> 1000	< 100 nm	C

Table 2 gives applications of metal matrix composites in the aircraft industry and space applications as an overview.

Much of the research in the aircraft industry is to develop the thrust-to-weight ratio of their engines. This can be done either by enhancing thrust or by decreasing the weight. They stress the materials and also increase the working temperature, which affects the entire range of engine parts, e.g., blades, shrouds, and discs. Metal matrix composites can be used in the aircraft industry and space applications. Titanium-matrix composites with silicon carbide or boron reinforcement display good characteristics at room temperature and elevated temperatures. This makes it a good material for fan blade applications at elevated temperatures. One recent improvement was in the precipitation-hardenable aluminum alloys, Al-Li alloys. When Li is alloyed to AI, it decreases the density and increases the elastic modulus of the alloy.

4. Aluminum Metal Matrix Composites

The aluminum alloys have low density, good corrosion resistance, capability to be strengthened by precipitation, high vibration damping capacity, and high thermal and electrical conductivity. Due to these properties, aluminum alloys are very favorable for metal matrix composites. Aluminum matrix composites have been used since the 1920s. They can be used in a large area due to a variety of mechanical properties because of the chemical composition of the aluminum matrix. Some of the applications of Al MMCs are shown in Figure 1 and Figure 2.

They are usually reinforced by aluminum oxide, silicon dioxide, silicon carbide, carbon, boron nitride, graphite, boron, boron carbide, etc. And aluminum nitride is also dispersed in the matrix (Sayuti et al., 2016). In the transportation industries, discontinuously reinforced aluminum matrix composites began to be developed in the 1980s. Their isotropic mechanical properties make them very attractive, and additionally, the costs are lower.

Table 2. An overview of various applications of metal matrix composites in the aircraft industry and space applications (Akhil, 2018).

	Components	Property requirement	Currently Using MMC	Literature
Aircraft	Engines	Improved high-temperature strength, creep resistance, stiffness.	Nextel/Al, Cu-Nb, Cu-Nb3Sn	(Haghenas, 2016) (Mavhungu et al., 2016)
	Airframe	Improved strength and stiffness	B/Al	(Rawal, 2001)
Space	Satellites	Lower (zero) CIE, higher stiffness,	B/Al	(Rawal, 2001)
	SDI	Higher thermal conductivity with high temperature strength.	Gr/Al	(Rawal, 2001) (Badiey and Abedian, 2010)
	Space panels	Higher-strength at temperature and low density.	Gr/Al, SiCp /Al	(Rawal, 2001)

Fig. 1. Applications of Al MMCs
(a) Piston,
(b) engine with cylinder barrel,
(c) piston connecting rod,
(d) brake system made of aluminum
(Al) metal matrix composites (MMCs). {2019} {Vikas Verma and Alexandra Khvan}. Originally published in {IntechOpen Book Series} under {Creative Commons Attribution 3.0 Unported (CC BY 3.0)} license. Available from: {10.5772/intechopen.83584},

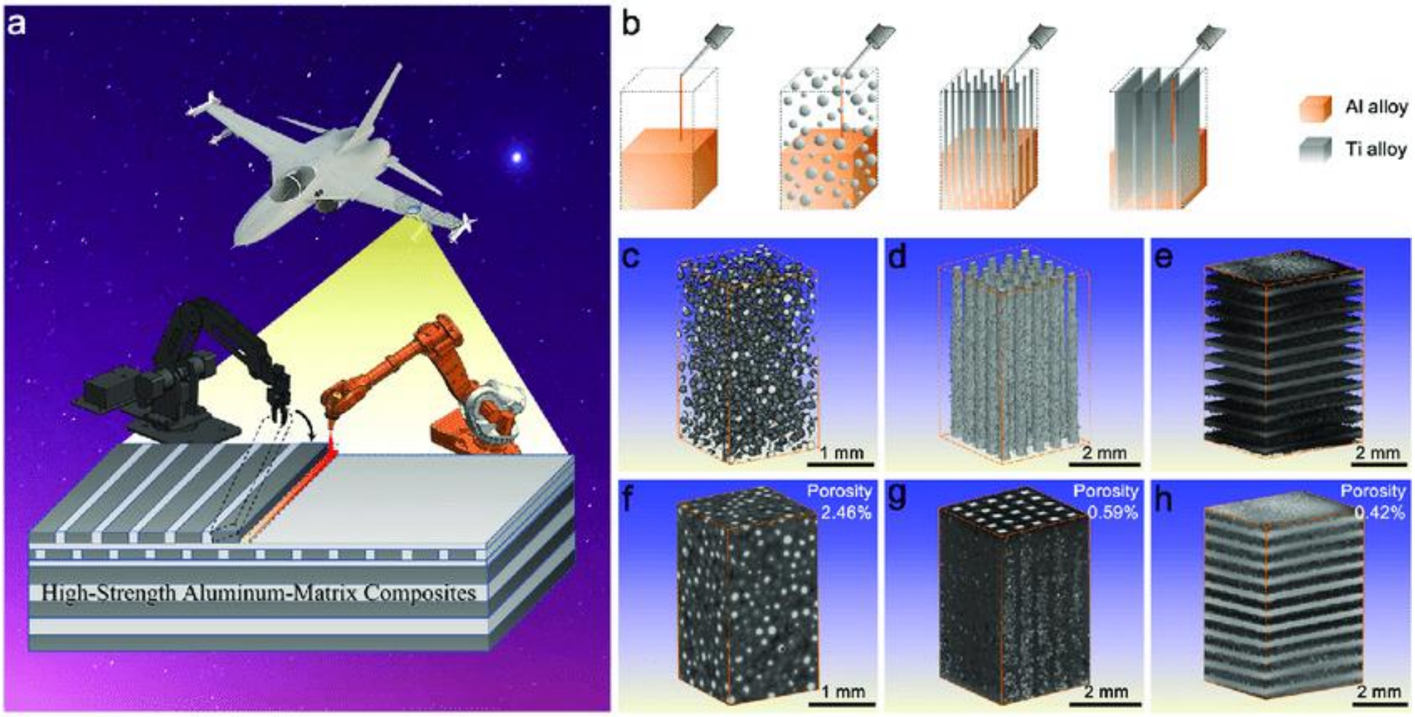

Fig. 2. Application and fabrication of high-strength aluminum–matrix composites (AMCs).
(a) Schematic illustration of high-strength AMCs potentially applied in the aerospace industry.
(b) Illustration of typical Al–Ti composites fabricated by a microcasting process.
(c–e) Perspective view of the Ti–6Al–4V skeletons in actual AMCs imaged by high-resolution X-ray tomography:
(c) ball-reinforced AMC,
(d) rod-reinforced AMC, and
(e) plate-reinforced AMC.
(f–h) Corresponding overall morphology for the three reinforced AMCs. {2019} {Shao, C., Zhao, S., Wang, X., Wang X., Zhu Y., Zhang Z., and Ritchie R. O.} Originally published in {NPG Asia Mater 11} under {Creative Commons Attribution 4.0 International License} license. Available from: {10.1038/s41427-019-0174-2}

The properties of composites of MMCs are like a compromise between matrix properties and reinforcement phases properties. The composition and properties of the matrix phase affect the properties of the composite both directly and indirectly. It can be explained as normal strengthening mechanisms in a direct way, and chemical interactions at the reinforcement/matrix interface are indirect way. Aluminum-based composites which are reinforced with ceramic particles offer some improvements over the matrix alloy. These are higher elastic modulus than of 70GPa, thermal expansion coefficient which is closer to that of steel or of cast iron, greater and improved resistance against thermal fatigue and rupture stress. Additionally to these benefits, observed that decreases in elongation to failure and fracture toughness.

Increasing the weight fraction percentage of silicon carbide particulates addition in the LM6 alloy matrix has increased ultimate tensile stresses, modulus, yield but a reduced strain to fracture (Chawla and Shen, 2001) (Sayuti et al., 2016). Therewithal, it appears that the silicon content of the matrix has a more dominant effect in reducing the fracture sequence than the increase in silicon carbide particle addition (Sayuti et al., 2016).

Primary compositing processes of aluminum metal matrix composites for industrial-scale manufacturing can be divided into two main groups as liquid-state processes and solid-state processes. Liquid state processes are classified as a liquid metal mixing processes and liquid metal infiltration processes. Liquid-metal mixing is the primary means of compositing the production of materials intended for solid-state processing for high volume automotive applications, high volume electronic packaging applications, liquid-metal infiltration, and high-performance aerospace applications (Nturanabo et al., 2019).

Considering the ease of production and the final quality of the desired composite, the processing methods of aluminum matrix composites are constantly changing. The best-known processing techniques of aluminum matrix composites are stir casting, powder metallurgy, spark plasma sintering, squeeze casting, friction stir processing, liquid metal infiltration, spray code position, and reactive in situ techniques have elaborated here with their respective distinguishing features and mechanical properties of the fabricated composites. The type of processing method, the processing parameters, and the type, size, and composition of the reinforcement material affect the mechanical properties of aluminum matrix composites. Relatedly, the mechanical properties of aluminum and its alloys are greatly improved by adding various reinforcing materials with a wider spectrum (Aynalem, 2020).

Reinforced graphite fibers with aluminum and magnesium matrices are utilized in satellites, missiles, and helicopter structures in order to make storage-battery plates, lead matrix composites having graphite fibers are used. Graphite fibers embedded in the copper matrix are used to produce electrical contacts and bearings. Boron fibers in aluminum are harnessed as structural supports and compressor blades. The same fibers in magnesium are used in the construction of antenna structures. Titanium-boron fiber composites are used in jet engine fan blades (Meetham, 1989) (Vijayaram and Baskaralal, 2016). In order to make high-temperature engine components, molybdenum and tungsten fibers are dispersed in cobalt-base superalloy matrices. Squeeze cast MMCs have much better reinforcement distribution compared to composite cast materials generally. The reason for this is the use of a ceramic preform that contains the desired weight fraction of reinforcement rigidly attached to one another so that movement is inhibited (Rizkalla and Abdulwahed, 1996) (Vijayaram and Baskaralal, 2016). As a result, clumping and dendritic segregation are eliminated. Since pressure is used to force the metal into interfiber channels, displacing the gases Porosity is also minimized. Because of heat flow patterns, grain size and shape can vary along the infiltrated preform. Since the lower freezing solute-rich regions diffuse toward the fiber ahead of the solidifying matrix, secondary phases typically form at the fiber-matrix interface. Recently, the automotive, aerospace, and military industries have been promoting composite materials technological development to achieve good stiffness/density ratio and mechanical strength/density. Particulate reinforced metal matrix or modern fiber-reinforced composites are produced by casting techniques. Table 3 shows the industrial applications of these metal matrix composites and their special futures (Polmear, 1981) (Vijayaram and Baskaralal, 2016). High longitudinal and transverse strengths at various temperatures, near-zero coefficients of thermal expansion, good electrical and thermal conductivities, and perfect antifriction, anti-abrasion, damping, and machinability are some of the properties (Vijayaram and Baskaralal, 2016).

The application of composite materials has come to a good position in aircraft technology over time. It is now applied in fuselage-production technologies as well as in jet engine development. Although not as common as in aircraft technology, application in car technology is also growing very rapidly (Patridge, 1989) (Vijayaram and Baskaralal, 2016). Its applications in the electronics industries are also growing significantly. The main reasons for this are its mechanical, electrical, and heat resistant properties. Compared to traditional materials used in laser and computer parts, composite material parts applied in electronic sub-assemblies create a more efficient working environment and are durable at higher temperatures (Vijayaram and Baskaralal, 2016).

Aluminum alloys and composites have played a major role in the development of aircraft and rocket technology. Aluminum created and developed humanity's potential to fly around Earth and into space. It would not be wrong to say that the Wright brothers pioneered this because they used aluminum in the engines of their first biplane. And it is known that NASA used an aluminum-lithium alloy in its spacecraft (Nturanabo et al., 2019).

Aluminum alloys and/or composites are preferred for the fuselage, wing, and support structures in commercial and military aircraft or cargo aircraft. Aluminum makes up 80% of the weight of the fuselage of a typical modern commercial transport aircraft. Today, the focus is on aluminum casting technology, which offers lower production costs, the ability to create complex shapes, and the flexibility to combine innovative design concepts (Nturanabo et al., 2019).

Since the launch of Sputnik 1 on 4 October 1957, aluminum metal matrix composites have been the material of choice for space structures of all kinds. Aluminum metal matrix composites and alloys were selected for their ability to withstand the stresses occurring during launch and operation in space. Their lightweight specification was used in the Apollo spacecraft, Skylab, space shuttles, and the International Space Station. Aluminum alloys/composites overtake other metals, especially due to their mechanical stability, thermal management, and lightness (Nturanabo et al., 2019).

Metal matrix composites are candidates for use in aerospace industries because of their high elastic modulus, strength, and low density. The requirements for improved performance and higher trust-to-weight ratio in aerospace industry applications have resulted in the use of Ti which has high strength and density. The fatigue strength of composites is advantageous. Another advantage is the ability to adjust the orientation of fibers to the principal axis of stress. This allows designing the material for the application. Problems with the application of metal matrix composites include a lack of experience and confidence as well as current costs. These include costly fabrication techniques that can be used in the manufacture and in the field repair or overhaul provisions and specific application problems such as foreign object damage and erosion in engine fan components. Fabricating Be/Ti calls for the hygienic precautions needed for using Be in any form. The additional ventilation sampling and health check add to the cost. An emotional reaction to the use of Be must always be coped with (NMAB ad hoc Committee on Metal-matrix composites, 1974).

5. Commonly Used Aluminum Alloys in The Aerospace Industry

The most common aluminum alloys used for aerospace applications are AA 2014, AA 2024, AA 5052, AA 6061, AA 7050, AA 7068, AA 7075. The less common aluminum alloys used for aerospace applications are AA 2219, AA 6063, AA 7475 (Danylenko, 2018). The Wright brothers used aluminum for their first manned flight in 1903. This is also the first use of an aluminum alloy by heat strengthening. With this use, the preference for aluminum in aerospace engineering has increased. In recent years, materials with different properties have been needed in the aviation industry. It has been determined that extremely durable and fatigue-resistant materials are needed in aviation. Thus, the development and use of various types of aluminum alloys have been achieved. Table 4 gives the typical mechanical properties of some commonly used aerospace aluminum alloys.

Table 3. Characteristic features and applications of metal matrix composites (Polmear, 1981) (Vijayaram and Baskaralal, 2016).

Metal Matrix Composite Type	Industrial Application	Special Features
Graphite reinforced in Aluminum	Bearings	Cheaper, lighter, self-lubricating, conserves Copper, Lead, Tin, Zinc
Graphite reinforced in Aluminum, Silicon Carbide reinforced in Aluminum, Aluminum Oxide reinforced in Aluminum	Automobile pistons, cylinders liners, piston rings, connecting rods	Reduced wear, anti-seizing, cold start, lighter, conserves fuel, improved efficiency
Graphite reinforced in Copper	Sliding electrical contacts	Excellent conductivity and anti-seizing properties
Silicon Carbide reinforced in Aluminum	Turbocharger impellers	High temperature use
Glass or Carbon bubbles reinforced in Aluminum		Ultra-light material
Cast Carbon fiber reinforced Magnesium fiber composites	Tubular composites for space structures	Zero thermal expansion, high temperature strength, good specific strength, and specific stiffness
Zircon reinforced in Aluminum-Silicon alloy, Aluminum Silicate reinforced in Aluminum	Cutting tool, machine shrouds, impellers	Hard, abrasion-resistant material

Table 4. Typical mechanical properties of some commonly used aerospace aluminum alloys (Prasad and Wanhill, 2017)

Alloy	Temper	Density (g/cm^3)	Elastic Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fracture Toughness (MPa$\sqrt{m}$)
2014	T6	2.80	72.4	415	485	26.4
2219	T62	2.84	73.8	290	415	36.3
2024	T4	2.77	72.4	325	470	22.0
7050	T74	2.83	70.3	450	510	38.5
7075	T6	2.80	71.0	505	570	28.6

6. The Future of Aluminum Alloys in Aircraft Technology

The future of aluminum alloys in aircraft technology looks bright. The demand for aluminum is expected to increase in the coming years. Therefore, there is increasing interest in recycled alloys to meet the ever-increasing demands in the aerospace industry. In addition, many studies are carried out to improve the materials used. For example, aluminum-lithium alloys were developed for the aerospace industry by reducing the weight of airplanes and then increasing the performance of airplanes. These alloys have high specific modulus, excellent fatigue, low density, and cryogenic toughness properties. They are advanced materials by these properties. In the coming years, there will be more innovations in aluminum alloys in increasing studies.

Scientists have created superior materials by metals with other alloys, ceramics, and other organic compounds in order to improve the properties of standard materials. E.g., aluminum can be reinforced with boron, carbon, silicon carbide, alumina, or graphite to create a composite that is 30% to 40% stronger and more rigid than barebones aluminum. Metal matrix composites break down into four different categories; dispersion hardened and particles, layer composites, fiber composites, and infiltration composites. Some of the advantages of using metal matrix composites are; higher temperature capability, fire resistance, higher transverse stiffness, and strength, no moisture absorption, higher electrical and thermal conductivities, better radiation resistance. The design required to make products lighter but still maintain their productivity has increased the demand for metal matrix composites. These materials are being used in a variety of industries, including automotive and aerospace applications. Manufacturers then utilize these composites to create better, more stable, and lighter-weight products for various industries (i.e., automotive, aerospace, and defense). The need for lightweight and high tensile strength parts are the driving factor for the demand for aluminum to soar. Aluminum will continue to grow and be the leader of metal matrix composites. Refractory matrix metals, metals that contain ceramic material, are poised to be the second-largest metal matrix composites market. Their demand will grow due to its multifunctional properties. They can be used for tools, nuclear radiation control rods, solar panels, spacecraft exteriors, and catalysts in chemical reactions. They have high tensile strength, malleability, and ductility. It looks like the future is here. Metal matrix composites are going to change industrial fabrication for years to come. That being said, researchers admit that they have only just begun to explore the possibilities of these new materials. However, the use of custom-designed metal matrix composites will continue to expand into an enormous number of applications (Barret, 2017).

7. Results and Discussion

In recent years, a lot of research has been done and improved on materials in the aircraft industry. The materials must be lightweight and be able to withstand hard conditions. Aluminum alloys and composites are very important in the development of aircraft and rocket technology. Aluminum alloys and composites give better results than other metals in some areas, e.g., mechanical stability, damping, thermal management, and reduced weight. Aluminum metal matrix composites are appropriate materials for thermal management as they have a high volume reinforcement ratio. Aluminum's lightness, transportation costs, and volume are superior to other materials.

Aluminum metal matrix composites are considered as potential material candidates for a wide variety of structural applications in the transportation, automobile, and sports goods manufacturing industries due to the superior range of mechanical properties they have. The primary benefit of these composites is the adaptability of their mechanical and physical properties to meet specific design criteria.

8. Conclusions

Due to their properties, aluminum metal matrix composites are suitable for different special applications and are also used in the aircraft industry. Research and developments can increase the use of aluminum metal matrix composites in the aircraft industry. Aluminum metal matrix materials have some advantages, such as low cost and ease of processing. They are preferred because of their high specific modulus, good mechanical and thermal properties for aircraft applications. The development of aluminum matrix composites is very important in meeting the requirements in various industries. These composite materials are constantly replacing traditional engineering materials due to their properties, such as low density, better corrosion resistance, high abrasion and wear resistance, high thermal conductivity, high specific modulus.

CRediT Author Statement

Sevim Yolcular: Conceptualization, methodology, validation, investigation, resources, writing original draft, writing review and editing, visualization, supervision.

Serdar Karaoğlu: Conceptualization, methodology, validation, investigation, resources, writing original draft, writing review and editing, visualization, supervision.

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