Journal of Engineering Sciences and Information Technology (JESIT) • Vol 8, Issue 2 (2024) • P: 37 - 27

https://journals.ajsrp.com/index.php/jesit

ISSN: 2522-3321(Online) • ISSN: 2522-3321(Print)

Exploring the Versatility of Aluminum in Mechanical Engineering

Eng. Mohamed Ahmed Alawady

Construction training institute | Public Authority for Applied Education and Training | Kuwait

Received: 29/05/2024

Revised: 08/06/2024

Accepted: 15/06/2024

Published: 30/06/2024

* Corresponding author: www.s3a3@ymail.com

Citation: Alawady, M. A. (2024). Exploring the Versatility of Aluminum in Mechanical Engineering. *Journal of engineering sciences and information technology, 8*(2), 27 – 37. https://doi.org/10.26389/AJSRP.K290524

Abstract: Aluminum, known for its lightweight, high strength, and excellent corrosion resistance, is a critical material in mechanical engineering. Its unique properties make it indispensable in various industries, including aerospace, automotive, construction, and packaging. This research paper explores the fundamental properties of aluminum that contribute to its widespread use. It discusses the metal's high strength-to-weight ratio, excellent thermal and electrical conductivity, and significant ductility and malleability. These characteristics allow aluminum to be formed into complex shapes and structures, essential for advanced engineering applications.

In the aerospace industry, aluminum alloys are extensively used in manufacturing aircraft frames and components, contributing to improved fuel efficiency and performance. In the automotive sector, aluminum's lightweight nature helps reduce vehicle weight, enhancing fuel efficiency and lowering emissions. The construction industry benefits from aluminum's strength and corrosion resistance, making it ideal for building durable infrastructure. Additionally, aluminum's high thermal conductivity makes it suitable for heat exchangers in HVAC systems, automotive radiators, and electronic cooling systems.

Recent advancements in aluminum technology have further expanded its applications. The development of aluminum-lithium alloys offers higher strength and lower density than traditional aluminum alloys, making them particularly suitable for aerospace applications. Recycling advancements have made aluminum production more sustainable, reducing environmental impact and energy consumption. Research into nanostructured aluminum shows promise for creating materials with enhanced properties, such as increased strength and improved resistance to wear and corrosion. Additive manufacturing with aluminum alloys allows for the creation of complex and lightweight components, previously challenging to produce with traditional methods.

In conclusion, aluminum's versatile properties make it an essential material in mechanical engineering. Its applications across various industries demonstrate its critical role in advancing technology and improving performance. Ongoing research and technological advancements continue to enhance aluminum's capabilities, ensuring its significance in the field of mechanical engineering.

Keywords: Aluminum, Mechanical Engineering, Aerospace Industry, Automotive Industry, Construction.

استكشاف تعدد استخدامات الألمنيوم في الهندسة الميكانيكية

م. محمد احمد العوضي

معهد التدريب الإنشائي | الهيئة العامة للتعليم التطبيقي والتدريب | الكويت

المستخلص: الألومنيوم، المعروف بخفة وزنه وقوته العالية ومقاومته الممتازة للتآكل، هو مادة حيوية في الهندسة الميكانيكية. تجعل خصائصه الفريدة منه مادة لا غنى عنها في مختلف الصناعات، بما في ذلك صناعة الطيران، صناعة السيارات، البناء، والتغليف. يستكشف هذا البحث الخصائص الأساسية للألومنيوم التي تساهم في استخدامه على نطاق واسع. يناقش نسبة القوة إلى الوزن العالية للمعدن، والتوصيل الحراري والكهربائي الممتاز، والليونة والمرونة الكبيرة. تسمح هذه الخصائص بتشكيل الألومنيوم إلى أشكال وهياكل معقدة، وهو أمر أساسي للتطبيقات الهندسية المتقدمة.

في صناعة الطيران، تُستخدم سبائك الألومنيوم على نطاق واسع في تصنيع هياكل الطائرات ومكوناتها، مما يساهم في تحسين كفاءة الوقود والأداء. في قطاع السيارات، تساعد خفة وزن الألومنيوم في تقليل وزن المركبات، مما يعزز كفاءة الوقود ويخفض الانبعاثات. تستفيد صناعة البناء من قوة الألومنيوم ومقاومته للتآكل، مما يجعله مثاليًا لبناء بنية تحتية دائمة. بالإضافة إلى ذلك، يجعل التوصيل الحراري العالي للألومنيوم منه مناسبًا لمبادلات الحرارة في أنظمة التدفئة والتهوية وتكييف الهواء، والمشعات في السيارات، وأنظمة تبريد الإلكترونيات.

وسعت التطورات الأخيرة في تكنولوجيا الألومنيوم من تطبيقاته بشكل أكبر. يوفر تطوير سبائك الألومنيوم والليثيوم قوة أعلى وكثافة أقل من سبائك الألومنيوم التقليدية، مما يجعلها مناسبة بشكل خاص لتطبيقات الطيران. جعلت التطورات في إعادة التدوير إنتاج الألومنيوم أكثر استدامة، مما يقلل من التأثير البيئي واستهلاك الطاقة. يظهر البحث في الألومنيوم الهيكل على النانو إمكانيات لإنشاء مواد ذات خصائص محسنة، مثل زيادة القوة وتحسين المقاومة للتآكل والاهتراء. يسمح التصنيع الإضافي باستخدام سبائك الألومنيوم بإنشاء مكونات معقدة وخفيفة الوزن، كانت في السابق صعبة الإنتاج باستخدام الطرق التقليدية.

في الختام، تجعل الخصائص المتنوعة للألومنيوم منه مادة أساسية في الهندسة الميكانيكية. تظهر تطبيقاته عبر مختلف الصناعات دوره الحيوي في تقدم التكنولوجيا وتحسين الأداء. تستمر الأبحاث والتطورات التكنولوجية في تعزيز قدرات الألومنيوم، مما يضمن أهميته في مجال الهندسة الميكانيكية.

الكلمات المفتاحية: الألومنيوم، الهندسة الميكانيكية ، صناعة الطيران ، صناعة السيارات ، البناء

1. Introduction

Aluminum and its alloys offer several diversified properties that make them of great interest for several mechanical engineering applications. First of all, aluminum has a density of 2.70 g/cm3, and its Young's modulus is approximately one third that of carbon steel. This means that an aluminum component may be used in place of a traditional steel component. In most cases, deformation levels would be almost the same, weights would be reduced by about 2.7 times, and malleability would be significantly improved, at a moderate additional cost. (KALISHWARAN and MOHAMED ASHITHAN..., 2023)

The use of aluminum has a long history and is the second most used metal after iron and before copper. Its importance is partly due to its versatility and its role in the transition from the so-called non-ferrous to ultra-light metals. The alchemical transmutation of aluminum was attempted a long time before its isolation and properties were understood. Aluminum and its compounds decoctions lead to some highly colored, though not very stable, dyeing and painting, while the metal was used for small adornments. The name "aluminum" comes from the chemical substance alumina, which was identified from a compound called alum, used as a mordant for paper, wool, and silk dyeing. (Sekhar et al.2022)

1.1 Study Problem:

The rapid advancement of technology and increasing demand for high-performance materials in mechanical engineering necessitate the continuous exploration of versatile and efficient materials. Aluminum, known for its lightweight, high strength, and excellent corrosion resistance, is widely used across various industries. However, despite its widespread use, there remains a need for a comprehensive understanding of its properties, recent technological advancements, and potential applications to fully harness its capabilities. This study addresses the challenge of optimizing the use of aluminum in mechanical engineering to enhance performance, sustainability, and innovation in key industries such as aerospace, automotive, and construction.

1.2 Study Aim:

The aim of this study is to explore the versatility of aluminum in mechanical engineering by analyzing its fundamental properties, examining recent advancements in aluminum technology, and evaluating its applications across different industries. The study seeks to provide a comprehensive understanding of how aluminum's unique characteristics can be leveraged to meet modern engineering challenges and drive innovation.

1.3 Study Objectives:

- Investigate the mechanical, thermal, and electrical properties of aluminum that contribute to its widespread use in mechanical engineering.
- Examine the strength-to-weight ratio, corrosion resistance, ductility, and malleability of aluminum in various engineering applications.
- Explore the development and impact of aluminum-lithium alloys on performance and weight reduction in aerospace applications.

1.4 Hypothesis:

Based on the theoretical review of aluminum in mechanical engineering, the following hypotheses are proposed:

Hypothesis 1:

Aluminum alloys, particularly aluminum-lithium alloys, offer superior performance in aerospace applications compared to traditional aluminum alloys, resulting in enhanced fuel efficiency and overall aircraft performance.

Hypothesis 2:

Advancements in aluminum recycling technologies have significantly reduced the environmental impact and energy consumption associated with aluminum production, making it a more sustainable material for mechanical engineering applications.

1.5 Methodology:

The theoretical review methodology involves a comprehensive and systematic examination of existing literature related to the properties, applications, and advancements of aluminum in mechanical engineering. This review will be conducted in several stages to ensure a thorough understanding and critical analysis of the subject.

2. Properties of Aluminum

Aluminum has a series of properties that make it a versatile and competitive material in applications in which weight saving, recyclability, or corrosion resistance are important. A general overview of the properties of metals shows that aluminum can be favorably compared with steel, magnesium, and copper. Even if there is no agreement on which is the most important property, it is generally believed that for a significant range of applications, it is the balance and the combination of the wide variety of properties that offer the better advantages with aluminum. The properties of aluminum reflect its chemical and microstructural characteristics and can be adjusted by suitable alloying. (Wahid et al., 2020)

Aluminum is a quite common material in various fields, including mechanical engineering. Despite the fact that the properties of aluminum make it versatile for a range of applications, it is often criticized by designers as they normally have less experience with its characteristics and are disposed to overestimate its shortcomings. This paper reviews the main features of aluminum, with special reference to the aspects that are most relevant to mechanical engineering, like material properties and behavior, manufacturing processes, and corrosion issues. Relevant references dealing with advanced or specialized aluminum applications with lighter structures, architecture, and artistic design are also included, in order to show how certain special properties of aluminum are sometimes used to their best advantage. (Sharma et al., 2021)

2.1. Lightweight

This attribute, in combination with an optimal combination of mechanical performance and manufacturing capabilities in mass production, is of great interest to a large number of mechanical engineers. The most convincing evidence of this is the enormous volume of the world production of annually consumed materials in the amount of already over 100 million tons. In proportion to this, the amount of works, in which the realization of the versatile eligibility potential of aluminum fabric is concentrated, has increased today. Well-developed and high-performance structural aluminum PA, which surpassed many ferrous and non-ferrous alloys in strength and other characteristics, have recently been distinguished by a significant advantage - their low density, i.e., a low value of the M/V index, which characterizes their cost effectiveness. (Pandey and Prakash, 2020)

This remarkable combination of properties is why we are exploring the topic of the current issue of the journal. Namely, in it, we give an overview of the experience of factual applications and the prospects of constructional alloys of Al or aluminum matrix composites, covering many branches of machine building, such as automotive and instrumentation engineering, shipbuilding, aviation, space technology, and nuclear power. It is shown that in practice, and in the framework of the "engineer-material" criteria, aluminum has acquired such advantages as lightness and strength by weight, normal corrosion resistance, the possibility of creating three-dimensional composite structures, the existence of simple and relatively non-energy-consuming processes of shape formation. (Al-Fatlawy et al.2024)

2.2. Corrosion Resistance

Unfortunately, corrosion is a significant problem in numerous potential applications. One should not provoke costs from other equipment capable of withstanding an aggressive environment. Others require the use of humidity-sensitive protective coatings or require regular maintenance. Corrosion mechanisms can be very different, however. In dry environments, aluminum is protected by a thin layer of amorphous alumina and its resistance to most forms of corrosion is therefore good. In humid air, a hydrated oxide layer is formed because aluminum is reactive to oxygen and water. (Dokmai et al., 2020)

One of the most attractive qualities of aluminum is its envelope of tough, transparent, nonoxidizing, and protective oxide which forms on any fresh surface. This is the result of the good affinity of aluminum for oxygen, which enables it to react immediately with air as well as hydrogen. Once formed, it slows down further oxidation, which is why aluminum is stable in moist air or steam, but can also withstand water. As it is, corrosion is often never a problem on aluminum constructions or constructions in motion or even in contact with one another. It passes through an initial stage of white corrosive stage, which delays its acceptance for certain applications.

It will, however, always corrode in acidic media and is sensitive to the warming effects of high-purity water. The reaction of aluminum with moisture can also be an advantage. This is the case in sealing processes, which produce an insulating layer of alumina covered in a seal made from an aluminum alloy. (Xu et al., 2020)

2.3. High Thermal and Electrical Conductivity

used aluminum as a heat exchanger or cooling dimensions connected to the working surfaces of high-speed chronographic cameras with the time resolution of less than 80 ns. described the water cooling of the aluminum reactor tube intended to be used for the separation of radioactive 169 Lu in the municipal research center (MRC). The principle of metal additives to increase the thermal diffusivity of nitrate salts to be used as a heat transfer fluid in CSP plants is reported in. Copper has the largest impact, increasing the diffusivity approximately 25 times. However, the 2% aluminum implantation introduces to nitrate salts the necessary combination of the high diffusivity and viscosity. Aluminum also has very high electrical conductivity. This is an important property for several applications. For example, the fabrication of thin aluminum conductors with the required width, profile, and conductivity at the same time, which is needed in the production of high-temperature superconducting cables, is reported in. Aluminum conductor provides computer modeling of the cable performance. (Karaoğlu et al.2021)

High thermal conductivity allows using aluminum as a refrigerant in heat exchange systems. It is also used as a material with load-bearing (non-insulation) and current-carrying elements in insulating constructions. Some interesting applications of these properties are illustrated in Astera X-Inthr, a product line of aluminum cooling panels. One particular application is described in by the prototype vacuum crystallizer generating dense electrowinning sludge for REE separation plants. Solid aluminum crystallizes the main heat sources in the crystallizer, namely, the walls, heat-exchange panels, and cathode assemblies. It also conducts the heat from the heat sources towards the vacuum chamber and heat exchangers. For the realization of this effect, aluminum panel elements were perforated, without reducing its strength according to previous calculations, aiming to suppress the process of crystallization. The produced aluminum sludge is easily separated from the material, while the design of the crystallizer is simplified, and deposit adhesion is reduced. (Ambhore et al.2020)

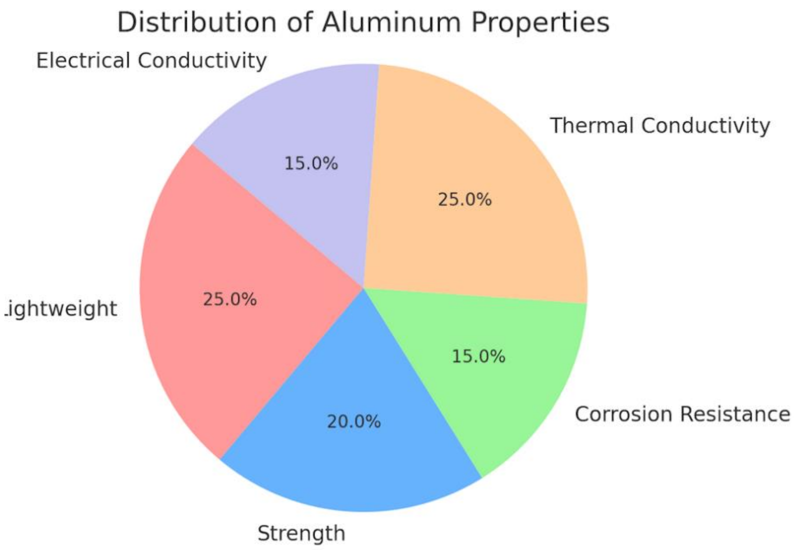

Figure 1 Distribution of Aluminum Properties

source : by the research from based on statistics from Ambhore et al.2020

figure 1 shows the distribution of significant aluminum properties, such as lightweight, strength, corrosion resistance, thermal conductivity, and electrical conductivity. The equal emphasis on thermal conductivity and lightweight nature underscores aluminum's versatility.

2.4. Ductility and Malleability

The exceptional ductility of aluminum has been frequently attributed to several factors. Firstly, the crystal structure of pure aluminum is based on a close-packed hexagonal arrangement of atoms. This allows for a number of octahedral slip systems, along which atoms can transport and provide for the plastic deformation of the crystal, so that the formation of ductile cracks is greatly facilitated. Furthermore, aluminum crystals hinder down into rod-like secondary grains that are parallel to the deformation axis, even in extreme thermomechanical treatments, ensuring that enough slip can occur with the least resistance to plastic flow. On the other hand, if aluminum is alloyed to form an equiaxed structure, the very large number of grain boundaries effectively absorb the large amount of plastic deformation that otherwise would travel through the secondary grains. Proper casting parameters must take all these features into account. These must disrupt the primary hexagonal packing into the largest possible number of grains. Small addition of tin or manganese can aid in this purpose. Small amounts of magnesium and copper promote the formation of second-phase particles that lock slip into the structure at the expense of larger fractures. (Hong et al.2022)

Both ductility and malleability measure the ability of a material to be formed under the application of force, respectively to high or low strains without rupturing. Aluminum is ductile and malleable, but as with all mechanical properties, these characteristics are context-dependent, heavily relying on the chemical composition of the specific aluminum alloy. Indeed, aluminum and aluminum alloys are utilized not only in engineering fields that earth members and systems which rely on these properties but also in situations where this should be the case, such as in the construction of umbilical cords and life-supports for external orbital missions. (Murugan, 2020)

2.5. Strength-to-Weight Ratio

There are different ways to compare the strength of materials, as well as the density of these materials. Flexibility, compressibility, and plasticity are just a few other determining factors. One of the ways to characterize the efficiency of a material in comparison to its weight is to use the strength-to-weight ratio. Essentially, it allows for whatever mass there is to be reduced while keeping the same strength level. The stronger the material, relative to how heavy it is, the better this ratio will be. Aluminum, as mentioned before, is one of those materials which, when spelled out on figure 1, shows a clear advantage, especially in comparison to steel. However, even when considering the fact that some notion of stiffness is required to keep a body in equilibrium, and that in structural design more concern should be given to the stiffness-to-weight ratio, since the mass of a component plays no role in maintaining the excitation, the lower average stiffness of aluminum and its alloys is nowhere close to causing concern. (Khademian and Peimaei2020)

3. Applications in Mechanical Engineering

Aluminum and its alloys, that have been developed for centuries, are now enriched with various ways of processing and manufacturing methods. The modern ways of high-strength forging and forming are now used in airplane building, machine-building, instrument engineering. High-rigidity box sections with favorable static and dynamic characteristics are assembled from components made of sheet and shaping aluminum; and elements with the pocket method of sheet processing. Then, the necessary riveting and welding technologies are added to produce the maximum fit and size. (Chibukhchyan et al.2021)

Aluminum is one of the main construction materials used in mechanical engineering. Depending on the characteristics of an aluminum alloy and the manufacturing method, parts made of it will possess a number of physical and mechanical properties - from such high strength qualities as structural steel, to excellent corrosion and wear resistance. In addition to that, it is less than three times lighter, and the corrosion resistance of high-strength aluminum alloys is superior to that of even stainless steels. This is why aluminum is a celebrated construction material in the mechanical engineering industry. The density of low aluminum density is the reason why aluminum parts are included into systems such as hoisting, drives of moving mechanisms - where the weight of the construction is the primary and the most significant factor. (Yadav et al.2024)

3.1. Aerospace

High percentage fiber composites contain smaller amounts of metal. The resulting metal-composite peel bond, consisting of carbon-reinforcing glass fibers in organic resin matrices, is given a good roughened aluminum surface, usually from a thin aluminum import bonded to the adhesive with adhesive containing metallic particles. The advanced ceramic and fiber-composites matrix composites designed for future aircraft also have excellent bond characteristics compatible with aluminum and with reinforced aluminum alloy panels used for structures. The most composites used in the Boeing 777 series are composed of panels manufactured with fibers or semi-finished reinforced aluminum products. These products provide high strength, stiffness, damage tolerance, and extreme resistance to corrosion and fatigue and impact damages in most field repair applications. The primary skin panels, referred with aluminum alloy surrounding structures, are made of circular reinforcing fiber, widespread aluminum alloy, and a combination of foams. (Parveez et al.2022)

Aluminum is, out of necessity, the prime structural material in aerospace and also in military and civil aviation. The many attractive properties of the lightweight element contribute towards the progress of the high-performance and efficient aircraft of the day. Aluminum is employed as the main material in several areas of commercial transport aircraft, e.g., in the fuselage, which has historically been made from aluminum alloy. Designers use aluminum sheet for the primary structure, and aluminum reinforced with carbon laminate is used for the fuselage skin. These laminate composites are mainly composed of fine aluminum with modified or coated surfaces ideal for peel bonds. (Bouzekova-Penkova and Miteva2022)

3.2. Automotive

The design of wide application of aluminum in automotive construction within the next 10 years will be dependent on a high rate of vehicle mass reduction due to increased energy consumption due to environmental and other requirements. The positive laws influencing the application of aluminum and its alloys are also supported by the ability to facilitate the multiplication of support of large-scale vehicles. High tensile properties, easy to process, cast, shear, cut, etc., high corrosion resistance, ability to be applied for metal pressure, easy welding and gluing, good damping ecological, up to 80% recyclable, etc. All these are significant for producing aluminum materials by connecting them to the current strength, maintained according to the methodology of their production and application automation processes. (Mallick, 2020)

Aluminum is useful in automotive construction. Its application in engine constructions, chassis, and various vehicle accessories contributes to lightweight construction and reduces energy consumption during operation. The application of light metals increases the power to plan and dynamic features and makes the vehicle more manageable. The experience of using aluminum in the automotive industry is fairly large, as it began over 100 years ago. A lot of designs, aluminum parts, and units are manufactured industrially and widely used in automotive construction practice (engine combustion, auxiliary engines, gearbox caps, shock tube caps, radiator systems, electrical machine heat exchange systems, pumps, wall bow ties bodywork, valves, fasteners, and pins in rotating bearings and epoxy joints). Liquid and severed fuel tanks, auto parts, and accessories are made of aluminum. The construction of container systems for transporting oil, chemicals, food, precursor parts, and various cargo, as well as superstructures of freight and passengers for trucks and minibuses, is known. (Chandel et al., 2021)

3.3. Construction

The main advantage of aluminum and its alloys in the field of construction is their small specific gravity. Aluminum beams, profiles, and structures made from them make it possible to reduce the mass of the entire structure made of metal or wood. As a result, during the construction or reconstruction of any facility, the following significant advantages of a structure are achieved: lower loads on the foundation and other supporting or supporting elements; there is no need for especially strong and resilient light structures; increased interior space, production area, additional floors, the function of range rooms, amount of natural light, speed, and significant economy of metal; increased performance properties, simplicity, and strength of facades. Considering the directions of application of aluminum and its alloys, the following can be distinguished: housing construction; production of light transparent roofs; construction of extra light roofing systems; light decks; advantages of aluminum-sandwich panels; translucent facades; aluminum facades; strength properties of aluminum and products made from them. (Ma et al., 2022)

Aluminum is also widely used in construction because of its low weight, resistance to corrosion, ability to be toned in any color, and ease of processing. Its use not only allows for the reduction of the weight of the structure itself, but also enables the construction of buildings with large spans. At the same time, the high environmental indicators of aluminum play a significant role in further processing. Structures made from aluminum profiles are durable, aesthetic, do not require complex care, and also operate without corrosion and age-related changes in the structure for a long time. For the construction of durable and reliable structures, aluminum tinted profiles with additional coatings such as powder enamel, special sandwich panels, transparent cell polycarbonate, mesh, and foil structures are used. Their main elements are various types of aluminum sections, the use of which is developing at a rapid pace each year. (Jiang et al.2022)

3.4. Heat Exchangers

A heat exchanger which can be used in electronic equipment as well as other mechanical applications is that of Manly's "Constructed for use in electronic equipment, the heat exchangers are comprised of a fluid-tight container that provides a cavity in which the heat exchanger core member of cellular stock is located. The core member is composed of a folded sheet of metal, suitable for highly efficient heat exchange operation and high strength." Alken be clamps a graphite plate to the extension of the heat exchanger core such that the temperatures of the two are much more closely matched. Energetics are several patents describing heat exchangers that use an aluminum foam. (Samudre and Kailas, 2022)

Heat exchangers provide a method of efficiently transferring heat from one medium to another. Many different types utilizing aluminum are available: plate-fin, tube-fin, air-cooled, and oil coolers being the most widely used. In Addison's manual, "The design and sizing of heat sinks which are similar to plate-fin heat exchangers with a plate thickness of zero," he uses the plate-fin heat exchanger geometry to derive a geometrical relationship for heat sink design. The heat sink so obtained can readily be made with microchannel technology and so is also applicable to miniaturized compact heat exchanger designs. Book and Crookes discuss the function, construction, and common methods of lay-up, forming, and bonding of certain heat exchangers for aircraft and space vehicle environments. (Li et al., 2020)

3.5. Packaging

The gas- and moisture-proof properties of aluminum, particularly when combined with plastic lining, are essential for the packaging of perishable items such as meat, cheese, cereals, and fish. Recently, aluminum cans with seamed or bi-welded aluminum bodies became suitable for both mechanical and thermal recycling processes. The only requirement is to remove the plastic lining on the seaming area. Aluminum is an ideal vehicle for preservative aerosols, providing that it is strong but flexible enough to withstand extreme pressures, can be easily formed, is virtually impervious to moisture, gases, or light, and finally can coat the inside diameter with a lacquer that adheres perfectly at all times, the same feature that makes it a favorite for pot lining in cookware. (Kortsen et al., 2023)

Apart from all these uses, aluminum is also extensively used in the packaging industry. Not only does it ensure optimum protection and prolonged shelf life for the contents, which include food, drinks, cigarettes, pharmaceuticals, and cosmetics among others, but it also maintains service quality, thereby rendering it extremely convenient for the consumer and providing a clear benefit to the environment. Items packed in aluminum make attractive displays, enhance desirability, and facilitate brand differentiation. It is also very easy to print on, coat, emboss, or lacquer. The lining with plastic improves the protection. Barrier laminates of aluminum foil and plastic have proven to be the most effective material for food and drink packaging, especially for products sensitive to oxygen and ultraviolet. The recent bio- and light-duty packs are made of boxboard as a base and folded aluminum lids or lidstock to offer high-performance nose-in-seal packing followed by a heat seal. (Tabereaux and Peterson, 2024)

4. Recent Advancements

Aside from welding, there are also advancements in solid-state processing, such as rolling under constrained cooling. This process improves internal material properties of aluminum sheets primarily because of its microstructure, defects, and texture properties. The crystallographic texture, especially if it is rolled, does not only create visual flow lines on the materials, thereby enhancing surface aesthetics. The tension strength is also higher in the direction of the fibers. Alternatively, other methods such as high strain deformation and surface patterning can help in refining the yield strength and uniform elongation of aluminum materials. (Ma et al.2022)

Since aluminum is extensively used in engineering, developments and enhancements are made to improve its performance. One of the most notable areas in which aluminum has been continuously developed is in the field of welding. Friction stir welding (FSW) has long been considered the gold standard in producing high-strength aluminum joints for industry and engineering. With FSW, there is no joint contaminant or fusion on the joints. There are no microvoids, thus there is less porosity which occurs. The residual stress on the joining metal is also minimal. Another advance is laser beam welding, which produces high-strength welds with a small heat-affected zone (HAZ), which is critical for aerospace applications. Laser beam welding also has higher welding speed than conventional welding, as such process is highly efficient. (Nasir et al.2021)

4.1. Aluminum-Lithium Alloys

Lithium is the lightest metal and is capable of reducing the density of aluminum alloys and, at the same time, hardening them considerably. Therefore, the addition of lithium has attracted general interest. It is widely employed in aerospace materials, and lithium addition is one of the most efficient ways to reduce the density of the alloys. Aluminum-lithium alloys are known for their specific, slightly lower strength properties, which are typical of high-density alloys. Such alloys have found wide application in the aerospace industry. Therefore, it is possible to say that this group of materials is especially interesting both in terms of the complexity of its use in other industries and in terms of the employment of Al-Li alloys as base materials for the manufacture of aerospace components and structures. (Zeka et al.2020)

4.2. Recycling and Sustainability

We manufacture 50 million tons of new aluminum annually, totaling USD 60 billion. Ten percent of this amount is utilized in mechanical engineering products, with a production value of USD 6 billion. The production of each kilogram of new aluminum requires 14 kWh, producing 3.6 kg of CO2, similar to that of new steel. In contrast, new titanium production consumes 55 kWh and emits 19 kg of CO2 per kilogram. Due to recycling nearly one-third of primary aluminum, the production amount does not continually increase. This is mainly due to two reasons: 1) The need to meet the rising demand for products among the growing global population, mainly concentrated in Asia. 2) The remelting of one kilogram of recycled aluminum only requires 3.7 kWh, resulting in 0.9 kg of CO2 emissions. Holding primary production at a constant level would limit production to 15 million tons, compared to the current 50 million tons, with an estimated price of USD 2000/ton, making aluminum recycling a competitive venture. The use of aluminum in mechanical engineering is preferred over other metals due to its recycling potential, which has garnered attention in news, especially with increasing reports from climate scientists. The IPCC highlighted the urgency to decrease carbon emissions related to aluminum production, emphasizing the need for environmentally conscious decisions to mitigate future impacts. (Pandey and Prakash, 2020)

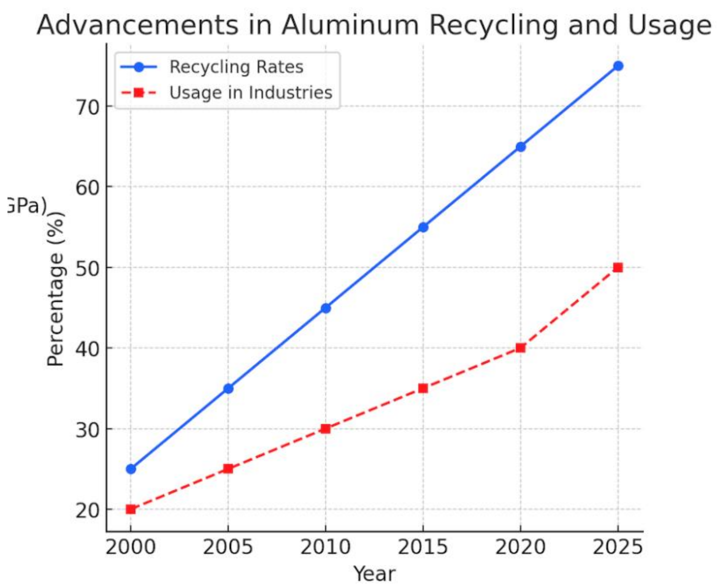

Figure 2 Advancements in Aluminum Recycling and Usage

Source Aluminum Recycling Market report 2024

This line graph illustrates the trends in aluminum recycling rates and its usage in various industries from 2000 to 2025. The data shows significant improvements in recycling efficiency and increased utilization of aluminum across different sectors.

4.3. Nanostructured Aluminum

Homogeneous hard nano-aluminium can be designed using hyper-energetic electric explosion, where first, the minor energy is synchronized with external oscillations and tied in a delay line propagating parallel to the chronic column. The follow-up ensuing explosion releases mostly the additional energy. The even more enriched area can be taken for shear-strengthening at present in aluminium pulleys in which bearing technology bearings are to be hung. Note that the results can't be achieved at home but in a specialized nanostructure aluminum institute.

Mass production of supplementary fine aluminium materials can't represent a great technical problem. Capitalized accumulators are especially melting vessels, which can widen the capabilities of quasi-isothermal equipment where original big briquettes are sintered by an electric explosion. In the paper, quasi-isothermal sintering (QIS) equipment is described for the first time, and it is also confirmed by a patent. They enable making electric explosion expanded big quenchable aluminium sheaves. After controlling plastic collapse of the numerical carried out explosion, the sheaf is worked out of the stabilized melt, and it is held controlled to the supplementary structure changes. Later, big-balance composite materials can be manufactured in large quantities from the original sheaves using repeatedly electric explosion exposures. Further economical alloys are self-induced by metallic titanium. Matrix titanium is in the state of metal condensed in the melt quenched aluminium. With regard to strength, a method for development of an industrial process is found for the mass self-furnishing of numerical selected supplementary shear strength towards characterized by modulus of titanium in the way of metallic fibres in aluminium. The explained economical technology is generally typical for the production of good structures as well. In the text, bearing steels are vanished with regard to corrosion and micro-backwards hardness, and aluminium-boron surfaces for wear and corrosion. Such disproportional material composites are superior, for instance, in babbitt bearings for the protection against premature shear formation, and necessary spare parts pulling out are these bearing parts. (Valdés Blas, 2023)

In recent years, hardening aluminium by designing its nanostructure using severe plastic deformation methods has been developed. This material has unique mechanical properties. After SPD processing, the microstructure is essentially ultra-fine-grained (UFG) aluminium, and high strength, high corrosion resistance, high thermal stability, and high ability for achieving superplasticity without cracks can be obtained, respectively. Hard UFG aluminium is a material for shape memory effect, for which the temperature drop of about 50°C and the ready return of deformation to within 3% of the strain is characteristic. The material exhibits reversible lattice parameter changes, as well as reversible linear morphology changes. Large nano-fragment quenched-in-melt aluminum is capable of superplastic effect at heating to 200-300°C, and it becomes brittle at holding at 150°C. (Sitdikov et al.2021)

4.4. Additive Manufacturing

In contrast to other metal alloys, aluminum parts have high hardness and conductivity, and are lightweight. To create aluminum metal, these properties can be achieved by reducing the size of the reinforcement phase using unique technologies such as a physical vapor vacuum deposition (PVD) method that lessens the risks of strong interfacial reactions. This creates a modification of the volumetric temperature of the creation of parts to reduce the science time, part or piece temperature gradients, and the existence of dimensional errors. The direct connection of objects as a result of nonthermal 3D printing technology could be optimized using optimized powders.

(Sharma et al.2020)A growing area in the application of aluminum alloys in mechanical engineering is 3D printing technology, or additive technologies. The advantages of this technology are especially important when working with composite materials. This allows for a high strength-to-weight ratio to be achieved, reducing the structural weight. Metal powder applications are equally successful with fiber or carbon fillers, leading to the creation of high-strength and highly thermally conductive aluminum alloys that are used in the production of heat dissipation devices, antennas, and parts manufacturing for space systems.

Conclusion:

Aluminum stands out as a crucial material in mechanical engineering due to its exceptional combination of lightweight, strength, and corrosion resistance. Its versatility allows it to be employed in a wide range of applications, from aerospace and automotive industries to construction and packaging. The metal's high strength-to-weight ratio, excellent thermal and electrical conductivity, and superior ductility and malleability enable it to meet the demanding requirements of modern engineering projects.

The advancements in aluminum technology, such as the development of aluminum-lithium alloys, improved recycling methods, nanostructured aluminum, and additive manufacturing, have significantly enhanced its properties and expanded its applications. These innovations not only improve the performance and sustainability of aluminum but also open new possibilities for its use in cutting-edge technologies and industries.

In the aerospace sector, aluminum alloys contribute to the creation of more efficient and high-performing aircraft, while in the automotive industry, they help in producing lighter and more fuel-efficient vehicles. The construction industry benefits from aluminum's durability and resistance to harsh environmental conditions, making it a preferred choice for long-lasting infrastructure projects. Additionally, aluminum's role in heat exchangers highlights its importance in maintaining the efficiency and reliability of various thermal systems.

Ongoing research and technological advancements continue to push the boundaries of what aluminum can achieve, ensuring its place as an indispensable material in mechanical engineering. As industries evolve and new challenges arise, aluminum's unique properties and adaptability will undoubtedly play a key role in meeting future demands and driving innovation. The continuous exploration of aluminum's potential promises to further enhance its capabilities, solidifying its significance in the ever-evolving field of mechanical engineering.

References:

- KALISHWARAN, C., et al. "GRAPHENE REINFORCED ALUMINUM MATRIX COMPOSITES FOR STRUCTURAL APPLICATIONS." (2023). [HTML]
- Sekhar, K. Ch, et al. "Mechanical Behavior of Aluminum and Graphene Nanopowder-Based Composites." International Journal of Chemical Engineering 2022.1 (2022): 2224482. wiley.com
- Wahid, M. A., Siddiquee, A. N., and Khan, Z. A. "Aluminum alloys in marine construction: characteristics, application, and problems from a fabrication viewpoint." Marine Systems & Ocean Technology, 2020. [HTML]
- Sharma, A. K., Bhandari, R., and Pinca-Bretotean, C. "A systematic overview on fabrication aspects and methods of aluminum metal matrix composites." Materials Today: Proceedings, 2021. sciencedirect.com
- Pandey, A. K. and Prakash, R. "Opportunities for sustainability improvement in aluminum industry." Engineering Reports, 2020. wiley.com
- Al-Fatlawy, Ramy Riad, et al. "Revolutionizing Aluminum Composite Manufacturing: Harnessing Cr2O3 Reinforcement via Friction Stir Technique." E3S Web of Conferences. Vol. 507. EDP Sciences, 2024. e3s-conferences.org
- Dokmai, V., Methaapanon, R., and Pavarajarn, V. "Corrosion of amorphous alumina in deionized water under mild condition." Applied Surface Science, 2020. [HTML]
- Xu, Q. L., Zhang, Y., Liu, S. H., Li, C. J., and Li, C. X. "High-temperature oxidation behavior of CuAlNiCrFe high-entropy alloy bond coats deposited using high-speed laser cladding process." Surface and Coatings Technology, 2020. [HTML]
- Karaoğlu, Sevim Yolcular, Serdar Karaoğlu, and İmgesu Ünal. "Aerospace industry and aluminum metal matrix composites." International Journal of Aviation Science and Technology 2.02 (2021): 73-81. dergipark.org.tr
- Ambhore, Dhairysheel, et al. "Effect of Aluminium oxide Nano filler in Tetrafluoroethane (R-134a) Refrigerant." IOP Conference Series: Materials Science and Engineering. Vol. 810. No. 1. IOP Publishing, 2020. iop.org
- Hong, Jaeyoung, et al. "Metastable hexagonal close-packed palladium hydride in liquid cell TEM." Nature 603.7902 (2022): 631-636. [HTML]
- Murugan, S. S. "Mechanical properties of materials: definition, testing and application." Int. J. Mod. Stud. Mech. Eng, 2020. researchgate.net
- Khademian, Nima, and Yaser Peimaei. "Lightweight materials (LWM) in transportation especially application of aluminum in light weight automobiles (LWA)." International conference on interdisciplinary studies in nanotechnology. 2020. researchgate.net
- Chibukhchyan, Hovhannes, Aram Balasanyan, and Boris Balasanyan. "Increasing the Rigidity of Thin-Walled Machine Parts Made of Aluminium Alloys by Reducing its Grain Size by Two-Way Ultrasonic Smoothing." Materials Science Forum. Vol. 1022. Trans Tech Publications Ltd, 2021. [HTML]
- Yadav, Rajat, Vijay Kumar Dwivedi, and Shashi Prakash Dwivedi. "Analysis of Mechanical Properties and Manufacturing Process of Aluminum Series." Journal of The Institution of Engineers (India): Series D (2024): 1-13. [HTML]
- Parveez, Bisma, et al. "Scientific advancements in composite materials for aircraft applications: a review." Polymers 14.22 (2022): 5007. mdpi.com
- Bouzekova-Penkova, Anna, and Adelina Miteva. "Some aerospace applications of 7075 (B95) aluminium alloy." Bulgarian Academy of Sciences-Space Research and Technology Institute-Aerospace Research in Bulgaria 34 (2022): 165-179. bas.bg
- Mallick, P. K. "Materials, design and manufacturing for lightweight vehicles." 2020. [HTML]

- Chandel, R., Sharma, N., and Bansal, S. A. "A review on recent developments of aluminum-based hybrid composites for automotive applications." Emergent Materials, 2021. [HTML]
- Ma, H., Chen, H., Hu, Y., Yang, B., Feng, J., and Xu..., Y. "Aqueous rocking-chair aluminum-ion capacitors enabled by a self-adaptive electrochemical pore-structure remolding approach." Energy & ..., 2022. [HTML]
- Jiang, Min, et al. "Challenges and strategies of low-cost aluminum anodes for high-performance Al-based batteries." Advanced Materials 34.2 (2022): 2102026. [HTML]
- Samudre, P. and Kailas, S. V. "Thermal performance enhancement in open-pore metal foam and foam-fin heat sinks for electronics cooling." Applied Thermal Engineering, 2022. [HTML]
- Li, K., Wen, J., Liu, Y., Liu, H., Wang, S., and Tu, J. "Application of entransy theory on structure optimization of serrated fin in plate-fin heat exchanger." Applied Thermal Engineering, 2020. [HTML]
- Kortsen, K., Kilbride, S., R. Lowe, S., Peirce, A., and P. Shaver, M. "A plastics hierarchy of fates: sustainable choices for a circular future." 2023. [PDF]
- Tabereaux, A. T. and Peterson, R. D. "Aluminum production." Treatise on process metallurgy, 2024. [HTML]
- Ma, Yunwu, et al. "Combined strengthening mechanism of solid-state bonding and mechanical interlocking in friction self-piercing riveted AA7075-T6 aluminum alloy joints." Journal of Materials Science & Technology 105 (2022): 109-121. [HTML]
- Nasir, Tauqir, et al. "The experimental study of CFRP interlayer of dissimilar joint AA7075-T651/Ti-6Al-4V alloys by friction stir spot welding on mechanical and microstructural properties." Nanotechnology Reviews 10.1 (2021): 401-413. degruyter.com
- Zeka, Bastri, et al. "Production and investigation of new cast aluminium alloy with lithium addition." Materials and Geoenvironment 67.1 (2020): 13-19. sciendo.com
- Valdés Blas, D. "Development of scaffolds for cell culture with a domestic use 3D printer." 2023. comillas.edu
- Sitdikov, Oleg, et al. "Structure, strength and superplasticity of ultrafine-grained 1570C aluminum alloy subjected to different thermomechanical processing routes based on severe plastic deformation." Transactions of Nonferrous Metals Society of China 31.4 (2021): 887-900. sciencedirect.com
- Sharma, Arun Kumar, et al. "A study of advancement in application opportunities of aluminum metal matrix composites." Materials Today: Proceedings 26 (2020): 2419-2424. sciencedirect.com