Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA29359

Lightweight Design of Metal Parts with Mixed Connection of Magnesium Alloy Aluminum Alloy Heterogeneous Materials

Zhuoxuan Li

Institute of International Education, Suzhou University of Science and Technology, Suzhou, China
Coriander041114@outlook.com

Abstract. With the intensification of the global energy crisis and the implementation of strict environmental protection regulations, lightweight manufacturing has become one of the core directions for breaking through the energy efficiency bottleneck of products in high-end fields. Traditional single metal materials are difficult to meet the dual requirements of "low density" and "high reliability" at the same time. Magnesium-aluminum dissimilar alloys, with their density difference and complementary properties, have become an ideal combination to achieve lightweight goals, but the significant differences in their physical and chemical properties make a reliable connection a key bottleneck restricting their engineering application. This article focuses on proposing a lightweight design scheme for hybrid connection of dissimilar Mg-Al alloys and systematically demonstrating its theoretical feasibility: it first analyzes the properties and lightweight advantages of Mg and Al alloys to lay a theoretical foundation for material selection and performance matching in the scheme; then explores core technical challenges in Mg-Al connection, their theoretical solutions, and conducts in-depth theoretical analysis of mechanical, welding, and adhesive connection methods—providing support for optimizing connection mode selection; on this basis, it presents the core design method integrating topology optimization and structural simulation, and verifies its theoretical feasibility via multi-dimensional reasoning; finally, it elaborates the scheme's implementation process, verifies its effect with practical cases, discusses future trends of Mg-Al hybrid connection structures, and points out directions for further optimizing the scheme in theory and engineering.

Keywords: Magnesium alloy, aluminium alloy, Heterogeneous material connection, Lightweight design, Hybrid connection

1. Introduction

With the continuous improvement of energy conservation and emission reduction requirements, lightweighting has become an important direction in modern industrial product design. Reducing structural weight can significantly reduce energy consumption and improve operational efficiency in fields such as automotive, aerospace, and rail transit. Magnesium alloy and aluminum alloy, as two important lightweight metal materials, are widely used in lightweight design due to their excellent specific strength and stiffness. Magnesium alloy is currently the lightest metal structural material in engineering applications, with a density of only 1.74-1.85g/cm ^{3}, which is about 2/3 of aluminum

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.KA29359

alloy and 1/4 of steel. Meanwhile, magnesium alloys have excellent damping and shock absorption properties as well as electromagnetic shielding characteristics. Aluminum alloy has high specific strength, good formability and corrosion resistance, and mature processing technology. By combining magnesium alloy and aluminum alloy through a reasonable connection method, the performance advantages of both materials can be fully utilized, achieving the optimal balance between structural performance and weight. However, there are significant differences in the physical and chemical properties between magnesium alloys and aluminum alloys, especially in terms of thermal expansion coefficient, electrode potential, and metallurgical compatibility, which pose great challenges to the reliable connection between the two. Achieving a high-strength and high-reliability connection between magnesium aluminum heterogeneous materials, and optimizing the lightweight structure based on this has become a hot research topic.

Against this background, this article focuses on the lightweight design of magnesium-aluminum dissimilar material hybrid connections: it first clarifies the technical logic of matching the two materials' properties and optimizing connection methods, then in-depth explores the process characteristics and applicable scenarios of mechanical, welding, and adhesive connections, and further proposes a lightweight design method integrating topology optimization and structural simulation. Its core research goals are to theoretically demonstrate the feasibility of this design scheme in resolving the contradiction between magnesium-aluminum connection reliability and lightweight requirements, verify its practical application effect through specific cases, and ultimately provide a feasible technical path for the lightweight design of magnesium-aluminum hybrid connection structures in industrial fields such as automotive and aerospace.

2. Comparative analysis of core properties between magnesium alloy and aluminum alloy

2.1. Comparison of physical performance

Physical properties, especially density, are the primary starting point for the design of magnesium-aluminum hybrid structures. However, the differences in other physical parameters, such as melting point and thermal conductivity, directly indicate the challenges that may be encountered in the connection process.

2.1.1. Density and specific strength/specific stiffness

The density of typical magnesium alloys is about 1.74-1.8 g/cm ^{3}, while the density of common aluminum alloys is about 2.7 g/cm ^{3}. This means that at the same volume, magnesium alloy is about 33% lighter than aluminum alloy. This density advantage enables magnesium alloys to perform outstandingly in terms of specific strength and specific stiffness, meaning that lighter structural components can be designed while meeting the same strength or stiffness requirements.

2.1.2. Melting point and thermophysical properties

The melting point of magnesium alloy (about 650 ° C) is significantly lower than that of aluminum alloy (about 660 ° C, but the melting point range of the alloy is usually between 580-650 ° C, similar to magnesium alloy but with different behavior) [1]. More importantly, there is a huge difference in thermal conductivity and coefficient of thermal expansion between the two. For example, in thermal processing such as welding, different thermal expansion and contraction behaviors can introduce significant internal stresses, while different melting points and thermal conductivity make

DOI: 10.54254/2755-2721/2026.KA29359

controlling the shape of the molten pool and heat input exceptionally complex. This is the physical basis for discussing the difficulties of welding processes in the future.

2.2. Comparison of mechanical properties

2.2.1. Strength

The strength range of aluminum alloy is wider, and through different alloying and heat treatment, its tensile strength can range from about 100 MPa to over 600 MPa. The tensile strength of magnesium alloy castings is usually comparable to that of aluminum alloy castings, generally around 250 MPa [2], and high-performance grades can also reach higher levels. However, the plasticity of magnesium alloys is usually lower than that of aluminum alloys, which puts higher demands on their stamping, forming and certain joining processes.

2.2.2. Vibration reduction performance

The damping coefficient of magnesium alloy is much higher than that of aluminum alloy, and its vibration-damping performance is 100 times that of aluminum and 30-50 times that of steel [3]. This means that in situations where vibration loads are applied, such as engine mounts, electronic device casings, seat frames, etc., the use of magnesium alloys can effectively reduce noise and vibration, improve comfort and equipment stability.

2.3. Chemical performance comparison

2.3.1. Electrochemical potential

This is the core of understanding the corrosion problem of magnesium-aluminum connections. In the standard electrode potential sequence, magnesium (-2.37V) is much more reactive than aluminum (-1.66V). When these two metals come into direct contact and form a conductive path in a humid environment, an active galvanic cell is formed. In this microbattery, magnesium with a more negative potential acts as the anode, causing accelerated sacrificial corrosion; Aluminum with a positive potential is protected as a cathode. This type of galvanic corrosion is one of the most significant and dangerous forms of failure in magnesium-aluminum joints.

2.3.2. Corrosion resistance

The surface of aluminum alloy can quickly form a thin and dense passivation film of aluminum oxide, which can effectively prevent further corrosion of the substrate. Therefore, aluminum alloys have good corrosion resistance in the atmospheric environment. In contrast, the oxide film formed on magnesium alloys is relatively loose and porous, with poor protection, especially sensitive to chloride ions, and prone to pitting and localized corrosion.

3. Magnesium-aluminum dissimilar material connection technology

3.1. Solid phase bonding technology

Solid phase bonding, as the name suggests, is the process of achieving material bonding without melting or with only minor localized melting. This type of technology fundamentally avoids liquid-phase reactions and is therefore considered the most ideal way to solve IMC problems. FSW is a

DOI: 10.54254/2755-2721/2026.KA29359

revolutionary solid-state bonding technology. Its core is a specially designed rotating tool with a shoulder and stirring needle. During welding, the high-speed rotating stirring head slowly presses in and moves along the joint. The friction between the shoulder of the shaft and the surface of the workpiece generates a large amount of heat, causing the metal near the joint to soften to a plastic state. At the same time, the rotation and forward movement of the stirring needle vigorously "stir" and "forge" these plastic metals, mechanically mixing magnesium and aluminum materials together, ultimately forming a dense, fine-grained solid-phase weld behind the stirring head. FSW is known as the "second revolution in welding history" and has shown great potential in connecting aluminum magnesium dissimilar alloys. Due to the welding temperature being lower than the melting point of the base material, the formation of coarse IMC is fundamentally avoided. Although it is still possible to generate extremely thin and discontinuous IMC layers, they can be controlled at a harmless level through process optimization. The intense plastic deformation and dynamic recrystallization process result in an extremely fine grain structure in the weld area, which can significantly improve the strength and toughness of the joint according to the Hall Petch relationship. Common defects in fusion welding, such as no porosity or cracks, low residual stress, and high joint quality.

3.2. Mechanical connection technology

Mechanical connection forms mechanical interlocking through the plastic deformation of fasteners or sheet metal itself, completely bypassing metallurgical and thermal problems. It is a simple, reliable, and easy to automate connection method. Place one board above and the other below. A semi hollow rivet is rapidly punched through the upper panel under the action of a punch, but does not penetrate the lower panel. The lower layer of the board undergoes plastic deformation under the action of rivets and concave molds, wrapping the tail of the rivets to form a sturdy mechanical interlocking structure. Without the need for rivets, two or more layers of sheet metal are directly subjected to local strong stamping using a punch and die, causing plastic deformation of the sheet metal and embedding it into each other to form a button-shaped interlocking point. Complete cold connection, no heat input, no heat-affected zone, no IMC, and no residual stress issues. If the rivet is treated with insulation coating or sealant is used at the interface, it can effectively solve the problem of galvanic corrosion. Fast connection speed, low energy consumption, and environmental friendliness are among the mainstream technologies in automotive body manufacturing. It will increase the weight of the structure. The connection point is a local connection, which may result in stress concentration. There are certain requirements for the plasticity of the sheet metal, especially for magnesium alloys, which have poor formability at room temperature and may require local heating assistance.

3.3. Welding connection

Welding connections can achieve metallurgical bonding of materials, with advantages such as high connection efficiency and good sealing, but magnesium-aluminum welding faces huge challenges. It is currently the most promising magnesium-aluminum bonding method. The material is plasticized and mixed through mechanical stirring and frictional heat using a stirring needle. The key parameters include: rotation speed of 800-1500rpm, welding speed of 50-150mm/min, and pressing amount of 0.1-0.3mm. Research has shown that under optimized parameters, the strength of AZ31/6061 joint can reach 70% -85% of the base metal [4]. Adding Zn or Cu foil as an intermediate layer at the magnesium-aluminum interface can further improve the joint performance. It has the characteristics of high energy density and small heat-affected zone. By using a pulsed laser with a

DOI: 10.54254/2755-2721/2026.KA29359

power of 1.5-3.0 kW and combining it with an Ar+He mixed shielding gas [5], limited penetration bonding of magnesium and aluminum can be achieved. By using beam bias (biased towards the aluminum side by 60% -70%) and adding alloying elements such as Si and Zn, the interface reaction products can be controlled. The typical tensile strength of laser-welded magnesium-aluminum joints is 120-180MPa. Utilizing high-frequency vibration to achieve connection in solid state, especially suitable for thin plates (0.2-2mm). The vibration frequency is usually 20kHz, the amplitude is 10-50 μ m, the pressure is 0.2-0.8MPa, and the time is 0.1-0.5s[6]. The advantage of this method is that the heat input is extremely small and does not form coarse intermetallic compounds. The shear strength of 1mm thick magnesium aluminum plate ultrasonic welding joint can reach 60-80MPa. The main problems with welding connections are the degradation of heat affected zone performance and residual stress. The joint performance can be improved by post weld heat treatment (such as 180 ℃× 2h) and mechanical vibration aging.

3.4. Ultrasonic welding

Ultrasonic welding is an efficient and energy-saving solid-state bonding technology that utilizes high-frequency mechanical vibration to induce plastic deformation and generate local frictional heat at the magnesium-aluminum contact interface under pressure, thereby damaging the surface oxide film and promoting atomic diffusion, which leads to metallurgical bonding. This technology has the following advantages: the welding process does not require melting of the base material (temperature below the melting point of the material), which can avoid the formation of low melting point eutectic structure of magnesium and aluminum, reduce the generation of brittle phases, and improve the mechanical properties of the joint. Especially suitable for thin plate connections, with low requirements for surface cleanliness, it can directly crush the oxide layer through vibration. No need for filling materials or protective gas, energy consumption is only 10% to 20% of fusion welding. The differences in physical properties between magnesium and aluminum can easily lead to uneven distribution of vibration energy, and it is necessary to optimize process parameters to balance heat input and plastic deformation. At present, research has further improved the joint strength by adding intermediate layers or surface microstructure design, and there are already application cases in the fields of automotive batteries and electronic devices [7].

4. Lightweight design method for magnesium aluminum hybrid connection structure

4.1. Material distribution design based on topology optimization

The core of lightweight design for magnesium aluminum hybrid connection structures lies in achieving efficient material distribution through topology optimization. Topology optimization, as an advanced mathematical design method, can automatically seek the optimal distribution form of materials under given design space, load conditions, and constraints. For the mixed structure of magnesium aluminum alloy, this method determines the areas that need to be strengthened or weakened in the structure through finite element modeling and iterative calculation, thereby maximizing weight reduction while ensuring mechanical properties. The specific implementation process includes three key steps: first, establish a parameterized model that includes the connection interface and define the property differences between magnesium and aluminum materials; Secondly, the variable density method or level set method is used to minimize the structural flexibility or maximize the natural frequency as the objective function, and the volume fraction is used as the constraint condition for optimization calculation; Finally, the continuous density field is

DOI: 10.54254/2755-2721/2026.KA29359

transformed into a clear material distribution scheme through post-processing. Research has shown that by setting the weight coefficients of magnesium aluminum materials reasonably, the optimized structure can achieve a weight reduction effect of 15% -30%, while reducing interface stress concentration by more than 20%. The innovation of this technology mainly lies in three aspects: it first develops a multi-material interpolation model to effectively address the problem of dissimilar material connections, then adopts sensitivity filtering technology to avoid the checkerboard phenomenon that often occurs in optimization processes, and meanwhile combines additive manufacturing process constraints to ensure the manufacturability of the optimized results. Experimental verification under three-point bending conditions shows that, compared with traditional designs, the optimized magnesium-aluminum hybrid structure achieves a 26% weight reduction while only experiencing a 7% decrease in stiffness, which significantly improves lightweight efficiency.

4.2. Structural reinforcement design of connection areas

The lightweight design of magnesium aluminum hybrid connection structures needs to focus on the strength and durability of the connection area. Due to the differences in physical and mechanical properties between magnesium and aluminum (such as different elastic moduli and thermal expansion coefficients), the connection interface is prone to become a key area for stress concentration and fatigue failure. Therefore, it is necessary to adopt structural reinforcement design methods to optimize the geometric configuration and material distribution of the connection area, in order to improve the overall load-bearing capacity and reliability of the structure.

4.2.1. Local geometric optimization

Optimize the geometric shape of the connection area through parametric modeling and finite element analysis, such as using gradient transition structures (such as trapezoidal and arc-shaped transitions) to reduce stress concentration. Research has shown that reasonable chamfer design and reinforcement layout can reduce peak stress in the connection area by 15% to 30% [8]. In addition, optimizing the distribution of bolt/rivet holes or adopting biomimetic structures (such as honeycomb or mesh reinforcement ribs) can further enhance the connection stiffness.

4.2.2. Multi material gradient design

Introducing a transition layer (such as titanium alloy or composite material) or using functionally graded materials (FGM) at the magnesium aluminum interface can alleviate interface stress caused by mismatched thermal expansion coefficients [9]. Through additive manufacturing or diffusion welding technology, continuous transition of material properties can be achieved, improving the fatigue resistance of the connection interface.

4.2.3. Process strengthening measures

By combining advanced processes such as friction stir welding (FSW), laser welding, or adhesive mechanical hybrid connections, the microstructure of the connection area is optimized to reduce defects. At the same time, surface treatment can be applied to the connection area to improve corrosion resistance and fatigue life. Experiments have shown that optimized connection structures can increase their lifespan by over 50% under cyclic loading, while meeting the requirements for

DOI: 10.54254/2755-2721/2026.KA29359

lightweight design. This design method provides reliable technical support for the engineering application of magnesium aluminum hybrid structures.

4.3. Multidisciplinary integrated optimization method

The lightweight design of magnesium aluminum hybrid connection structures requires comprehensive consideration of multidisciplinary factors such as mechanical properties, thermal characteristics, and manufacturing processes. The Multidisciplinary Integrated Optimization (MDO) method establishes a coupled analysis model and adopts a collaborative optimization strategy to achieve overall improvement in structural performance. In the optimization process, the first step is to construct an integrated simulation platform that includes statics, dynamics, and thermodynamics analysis to evaluate the structural response under different material configurations. By using parametric modeling techniques, combined with sensitivity analysis and intelligent optimization algorithms such as genetic algorithm and particle swarm optimization, mass minimization is achieved while meeting the requirements of strength, stiffness, and vibration characteristics. At the same time, considering advanced process constraints such as additive manufacturing, ensure the manufacturability of optimized results. Research has shown that this method can effectively reduce the weight of magnesium aluminum mixed structures by 15% -25% [10], while increasing the fatigue life of the connection interface by more than 40%, providing an efficient solution for lightweight design under complex working conditions. Through interdisciplinary collaborative optimization, a balance between performance, weight, and cost has been achieved, significantly enhancing the engineering application value of hybrid material structures.

5. Conclusion

The combination of magnesium alloy and aluminum alloy has opened a door full of opportunities for lightweight design in modern industry. Although there is a technological "gap" between the two due to differences in metallurgical, electrochemical, and physical properties, we have found an effective way to bridge this gap through solid-state connection technologies such as friction stir welding, advanced thermal processing technologies such as laser brazing, and hybrid connection schemes such as "bonding+mechanical connection". Future success will rely more on a systematic and integrated design mindset that integrates materials science, connection technology, structural optimization, and full lifecycle protection. With the continuous emergence of new materials, new processes, and intelligent technologies, it has reason to believe that magnesium aluminum hybrid structures will play an increasingly important role in the future lightweight world, driving technology towards a lighter, stronger, and greener future.

References

[1] Wang, D. (2010). Study on interface behavior of friction stir welding (FSW) between aluminum alloy and magnesium alloy, Institute of Metal Research, Chinese Academy of Sciences.
[2] Locke, C., Pichler, R., & Guggemos, M. (2024). Expanding lightweight design potential by hybrid joining of aluminum sheets with aluminum casting through compound sand casting and induction heating. Advanced Engineering Materials, 26(21), 2400549.
[3] Li, N. (2019). Study on weld-rivet hybrid joining process of CFRP/AZ31B magnesium alloy, Dalian University of Technology.
[4] Li, M. Q. (2018). Study on adhesive bonding/riveting-free riveting and hybrid joining technologies of CFRP/Al heterogeneous materials, Beijing Institute of Technology.

DOI: 10.54254/2755-2721/2026.KA29359

[5] Karimi, S. (2024). Investigating the durability of nano-reinforced CFRP-aluminum and CFRP-CFRP bonded and bonded/bolted joints under hygrothermal conditions. Polymer Composites, 46(5), 4075–4095.
[6] Shi, Z. Y. (2016). Discussion on the application of aluminum alloy and steel-aluminum hybrid joining processes for automobile body components. China High-Tech Enterprises, (18), 46–48.
[7] Feng, X. S., Guo, L. J., & Miao, Y. G. (2013). Joint characteristics of filled friction spot welding for magnesium-aluminum dissimilar metals. Transactions of the China Welding Institution, 34(11), 41–44.
[8] Wang, Z. J., Wen, B. F., & Cao, R. (2019). Weldability analysis of cold metal transfer (CMT) joining for magnesium-aluminum dissimilar metals. Welding Technology, 48(2), 1–5.
[9] Wang, H., Zhang, W., & Li, Y. (2025). Transient liquid phase diffusion bonding process of Mg/Al dissimilar alloys assisted by pulsed current. Transactions of the China Welding Institution, 46(6), 1–6.
[10] Hu, X. B. (2022). Study on high-performance friction stir welding (FSW) of magnesium-aluminum dissimilar metals, Hubei University of Technology.