International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 09 September 2025
Page No: 3534-3563
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0519

Lightweight Multi-Material Laminates Through the Routes of Friction Stir Additive Manufacturing

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Abstract

Multi-material design is a novel approach to cater the needs of nowadays aircraft, marine and automobile applications. To meet wholesome characteristics, material laminates are articulated. The aircraft and automobile industries are striving to overcome challenges of light weight, economical and green design of materials. The demand of varied characteristics can be better fulfilled by multi-material laminates. Combining similar or dissimilar alloys to customise the material is a novel technique which overcomes issues related to versatile characteristics required in material. Fabrication of desired properties can be achieved by joining different alloys in the form of laminated structure. Aluminium alloys that are preferred in aircraft structural components can be replaced with multi-material Al, Mg, Cu, Ti laminates to get added benefits in terms of cost, environmental impact and light weight design. Presently, many methods of material fabrication are available either fusion based or solid state. The friction stir additive manufacturing, a solid state joining method can be effectively used for lightweight multi-material design. This paper examines various fusion-based and solid-state methods for multi-material manufacturing, with a particular emphasis on the innovative Friction Stir Additive Manufacturing (FSAM) technique. The attention of researchers is drawn towards challenges associated with joining dissimilar materials.

Keywords: *Friction Stir Additive Manufacturing; Lightweight structures; Multi-material; Solid state joining*

1. Introduction

The aerospace and automotive sectors increasingly adopt multi-material designs to meet stringent demands for performance, efficiency, and sustainability. Modern vehicles and aircraft require structures that combine disparate materials, such as lightweight alloys, advanced composites, and high-strength materials. This integration allows for optimized property distributions, leading to reduced weight, enhanced fuel economy, and improved structural integrity [1]. Modern transportation sectors, encompassing aerospace, marine, and automotive industries, persistently pursue advancements in performance, efficiency, and sustainability. A central strategy for achieving these objectives involves the judicious integration of diverse materials within single structural components or systems [2]. Material combinations enable designers to achieve specific performance targets, including superior strength-to-weight ratios and tailored energy absorption capabilities. Historically, designs relied heavily on monolithic materials, often leading to compromises between conflicting property requirements such as strength, weight, corrosion resistance, and cost. [3,4]. Designing multi-material assemblies involves a holistic approach that considers material selection, joint geometry, and manufacturing process capabilities concurrently. Designers must account for the anisotropic properties of composites and the varying mechanical responses of metals under different loading conditions. The primary design criterion for aerospace and automotive applications frequently involves optimizing for lightweighting while maintaining or improving strength, stiffness, and fatigue resistance. This optimization necessitates advanced computational modelling and simulation tools to predict component behaviour under operational loads [5]. Furthermore, considerations for manufacturability, inspectability, reparability, and end-of-life recycling must be integrated early in the design phase. The judicious combination of materials and intelligent joint design aims to leverage the strengths of each constituent while mitigating their individual weaknesses within the assembly. Designers must keep eye on intermaterial relationships and interface interaction. [6]. There is a frequent need to enhance performance and cost-effectiveness while combining the advantages of different materials within a single structure. In fact, multi-material design has been recognized as the most effective strategy for reducing weight, balancing costs, and minimizing environmental impact [7-9]. Recently, there has been a surge of interest in multi-material design to take benefits of the desired blend of properties. The potential for hybrid structures made from Mg/Al, Al/Ti, and Ti/Mg is exciting, as they can offer remarkable benefits tailored to specific needs. However, one must acknowledge the challenges that often emerge when joining dissimilar materials into one unit, especially articulating Al/Mg, Al/Ti, and Mg/Ti structures. Despite the sophistication of advanced techniques like laser welding, additive manufacturing routes, tackling these tasks remains a formidable challenge due to the several differences in the physical and metallurgical properties of materials to join. Factors such as variations in crystal structure, melting points, thermal conductivity, and coefficients of linear thermal expansion create substantial obstacles. To overcome these hurdles, we must embark on a quest for innovative solutions that truly push the boundaries of the current multi-material design and manufacturing scenario [10-11].

2. Multimaterial Structures for Aviation, Marine and Automobile Sector

Modern transportation relies on efficient yet eco-friendly, reliable but low cost, lightweight but comfortable solutions may be aerospace, surface transport or marine. The most developing aviation industry faces an urgent need for lightweight structures that can lead to significantly reduced fuel consumption, greater payload capacities, and lower emissions. Aircraft designers are tasked with innovative solutions that not only meet these rigorous demands but also ensure optimal performance and safety [3,4]. In parallel, marine vessels require the development of exceptionally strong and corrosion-resistant structures, and longevity in seawater. These vessels must be engineered to withstand harsh marine environments while minimizing operational costs and their ecological footprint, making efficiency a top priority for shipbuilders [5, 6]. Meanwhile, the automotive industry is driven by the necessity for substantial weight reduction, which directly influences fuel economy and crashworthiness [7, 8]. Engineers are continually exploring cutting-edge materials and designs that enhance both performance and safety ratings in vehicles. To meet these diverse and pressing needs, multi-material solutions emerge as a transformative approach. By skilfully combining the unique properties of various alloys, these solutions enable the optimization of multiple performance metrics—ensuring that the innovations in lightweighting do not compromise strength, safety, and functionality [12]. Lightweighting is a primary driver for multi-material adoption in both aerospace and automotive industries. In aerospace, every kilogram of weight reduction translates into significant fuel savings and increased payload capacity, directly impacting operational efficiency and environmental footprint. For example, a 1% reduction in aircraft weight can yield a 0.75% fuel saving. This drives the use of lightweight materials like aluminum, magnesium, titanium, and steel. Similarly, in the automotive industry, lightweighting reduces fuel consumption for internal combustion engine vehicles and extends range for electric vehicles [13]. Lighter structures also contribute to improved handling, acceleration, and braking performance. Multi-material construction, strategically placing optimal materials where needed, facilitates these weight reductions while maintaining structural integrity and crashworthiness [14]. Multi-material manufacturing offers compelling sustainability advantages, primarily through lightweighting which reduces energy consumption during operation. For instance, lighter aircraft and vehicles consume less fuel, resulting in decreased greenhouse gas emissions [15]. The enhanced durability and corrosion resistance of multi-material components can extend product lifespan, reducing the frequency of replacement and associated resource consumption. Furthermore, advanced solid-state manufacturing processes often generate less material waste compared to subtractive manufacturing [16].

The aerospace sector extensively utilizes Al, Mg, and Ti alloys for their high strength-to-weight ratios, crucial for fuel efficiency and performance [3]. Multi-material integration is applied in various aircraft components. Aluminium alloys, such as 2xxx and 7xxx series, are prevalent in airframes and structural elements, often combined with titanium for high-stress areas or specific functional requirements like fasteners [3, 17]. For example, titanium alloy fasteners offer high strength levels, replacing heavier steel or nickel fasteners [17]. Multi-material structures also appear in engine components, where Ti alloys withstand extreme temperatures and fatigue, while Al alloys are used in less thermally demanding sections [18, 19]. Multi-material design stands at the cutting edge of the lightweight revolution in automotive mass production. While the incorporation of weight adding safety features, advanced cruise control systems, and sophisticated infotainment technologies is essential for modern driving, it is imperative that multi-material structure offset this weight burden by innovatively reducing the weight of individual components. At the same time, pressure from economical design practices, the pursuit of compactness and stringent emission control regulations also impose vital constraints on vehicle weight. Striking the perfect balance between these elements is key to achieving the future of efficient and cutting-edge automotive engineering [20-24]. Multi-material solutions, integrating Al, Mg, and high-strength steels, are pivotal in achieving these goals while maintaining or enhancing crashworthiness. Aluminium alloys are widely used for body structures, engine blocks, and chassis components due to their low density and high strength [25-27]. Magnesium alloys, offering even greater weight savings, are finding applications in interior components and increasingly in structural parts where their formability challenges can be addressed by techniques like semi-solid metal processing[28,29]. Multi-material designs optimize energy absorption during collisions by strategically placing different materials to manage deformation. For instance, a combination of Al alloys and advanced high-strength steels or magnesium can create tailored crash zones. Solid-state joining methods are particularly relevant here, as they enable robust connections between dissimilar metals without compromising the integrity of lightweight structures [30-33]. Marine environments pose unique challenges due to high corrosivity, demanding materials with exceptional resistance and structural integrity. Aluminium alloys, like AA5754, are common in shipbuilding and marine applications, particularly for their lightweight properties [34]. Multi-material constructs often combine aluminium with other alloys to optimize performance. For example, nickel alloys are extensively applied in shipbuilding and marine engineering, including high elastic limit steels. Titanium alloys, such as Ti-6242, are selected for marine gas turbine engine compressor components due to their superior performance in corrosive conditions [35]. Beyond lightweighting, multi-material structures must satisfy rigorous durability and safety standards. Components in aircraft and automobiles endure complex loading conditions, including fatigue, impact, and corrosion. Multi-material designs can enhance these properties by combining materials that excel in specific performance areas; for instance, a composite structure for stiffness paired with metal inserts for impact energy absorption. Regulatory bodies impose strict requirements on structural integrity, crash safety, and material traceability. This necessitates extensive testing and validation of multi-material joints and assemblies to ensure compliance. The long service life of aerospace components, often decades, demands exceptional durability and resistance to environmental degradation. In automotive applications, crash energy management and passenger safety are paramount, influencing the selection and integration of materials with specific deformation characteristics. The ability to predict and control the behaviour of complex multi-material interfaces under various service conditions is therefore critical [36]. Multi-material solutions fundamentally transform the performance capabilities of structures across aerospace, marine, and automotive sectors. By selectively deploying Al, Mg, and Ti alloys, engineers can achieve an optimal balance of properties that monolithic materials cannot provide. For aerospace, multi-material designs directly contribute to significant weight reductions, translating into lower fuel consumption, increased payload capacity, and extended range for aircraft [3]. The strategic placement of high-strength titanium in critical load-bearing areas, combined with lightweight aluminium or magnesium in less stressed regions, enhances overall structural efficiency and fatigue life [16]. In marine applications, multi-material approaches improve resistance to harsh corrosive environments while reducing vessel weight, thereby increasing speed, stability, and operational lifespan [18]. Automotive designs benefit from reduced vehicle mass, which directly leads to improved fuel economy, lower emissions, and superior acceleration [2]. Furthermore, the tailored mechanical properties of multi-material structures can enhance crashworthiness by distributing impact energy more effectively across diverse materials, improving occupant safety [7, 37].

3. Multimaterial Manufacturing

A wide range of manufacturing methods are being used for production of multi-material laminates. Selection of proper process depends upon materials being used, desired properties in final product, extent of defects, volume of structure and economy. Conventional methods like casting, forging, joining, and machining for manufacturing of multi-material structures are replaced by advanced methods to take advantage of economy, ability to process complex shapes with higher accuracy. Different fusion based and solid state techniques are being used to develop multi-material structures. The emerging Additive Manufacturing technology offers green solutions and stands tall in dealing with complex shapes, quality and durability [38]. With the rise of industrialization and market globalization, there is a growing demand for efficient manufacturing processes that can support a rapidly expanding economy. The ideal manufacturing approach should be reliable, offer shorter lead times, provide greater material adaptability, minimize waste, require little to no post-processing, utilize inexpensive tools, and be cost-effective in terms of materials and storage. While traditional manufacturing methods have been widely adopted across various industries, they often fall short of meeting the diverse requirements of modern products. In recent decades, additive manufacturing (AM) has emerged to bridge this gap [39-41]. Additive manufacturing is emerging as a remarkably versatile production technique poised to revolutionize traditional manufacturing methods in the near future. Recently, multi-material additive manufacturing (MMAM) has captured attention for its ability to efficiently fabricate intricate structures, drastically reducing both production timelines and material costs [42]. A diverse array of innovative MMAM technologies has been developed, actively making waves across various industries and reshaping the landscape of manufacturing as we know it [43]. Today's additive manufacturing (AM) technologies have revolutionized the creation of innovative geometries. Future AM systems that enable the simultaneous processing of multiple materials in a single build will unlock new product functionalities that traditional manufacturing methods simply cannot match. The field of multi-material additive manufacturing, which integrates dissimilar materials into complex three-dimensional objects, is advancing with great promise, even if the progress has been varied [44]. We are boldly moving beyond homogeneous materials by embracing multi-materials, gradient materials, and functional and responsive materials, as well as those with heterogeneous and graded properties. This evolution clearly shows that a single additive process based on either energy delivery or material deposition alone will not be adequate. We are ready to redefine what is possible in manufacturing [45-46].

3.1. Fusion-Based Manufacturing Approaches for Multi-material Structures

Fusion-based techniques, including various additive manufacturing processes and laser welding, provide enhanced design flexibility and often higher production rates, particularly for complex geometries and tailored material distributions.

3.1.1. Laser welding

Laser welding is a high-energy density fusion process that precisely melts and fuses materials using a concentrated laser beam. Its localized heat input and rapid cooling rates minimize the heat-affected zone and distortion. This characteristic is particularly beneficial for joining dissimilar metals, where the formation of intermetallic compounds can be a concern. Advanced fusion methods, such as electron beam welding and specialized arc welding techniques with modified heat input profiles, are used in applications where high joint strength, hermetic seals, and minimal thermal distortion are critical. Examples include components in aerospace engines and structural elements in the automotive industry. The controlled energy delivery in these methods allows for effective management of melt pool and solidification characteristics, which are essential for joining multiple materials [47-50]. A major concern when welding aluminium (Al) and magnesium (Mg) alloys is the formation of brittle intermetallic compounds (IMCs), such as Al_3Mg_2 and $Mg_{17}Al_{12}$, which can negatively impact joint performance. Similarly, during the welding of aluminium/titanium (Al/Ti) alloys, brittle IMCs like Ti_3Al, TiAl, $TiAl_2$, and $TiAl_3$ may form[51-53]. To suppress the formation of these IMCs, one effective approach is laser weld bonding (LWB), which uses structural adhesives, interlayer or filler metals, or a combination of both. LWB is a hybrid joining technique that merges laser welding with adhesive bonding. In this process, a structural adhesive is applied between the two materials to be joined, followed by laser welding, and the assembly is then cured at the appropriate temperature for a suitable duration. The joints produced through this method exhibits superior properties compared to those made by conventional laser welding or adhesive bonding alone [54–57]. Additionally, the laser-adhesive-interlayer hybrid technique has been successfully developed and applied to join Al/Mg alloys, resulting in joints of even higher quality than those produced by either weld bonding or using interlayers alone[58,59]. Interlayers are commonly utilized as barrier materials in the welding of dissimilar materials. Their primary purpose is to prevent or reduce the interaction between the base metals, which helps limit the formation of intermetallic compounds (IMCs). Various interlayers and filler metals, including mild steel foil[60], cerium (Ce) foil[54], titanium (Ti) foil[61], nickel (Ni) foil[62] and zinc-aluminium (Zn-Al) filler metal[63], have been successfully employed to join aluminium (Al) and magnesium (Mg) alloys using laser welding techniques[64,65].

3.1.2. Fusion based Additive Manufacturing

Additive Manufacturing (AM) is a well-established leading-edge technology that is used to create artefacts of simple as well as complicated shapes. Human involvement in AM is minimal and additionally it is cost effective [66-69]. Amount of engineering wastage while utilizing AM techniques is significantly less and these processes are more eco-friendly [70-73]. Materials used in AM include metals and alloys, ceramics, polymers, composites, smart materials, concrete, and biomaterials [74]. Additive manufacturing (AM) offers unparalleled flexibility in creating complex geometries and multi-material structures layer by layer. As per ASTM standards, AM technology can be majorly classified into seven types viz: directed energy deposition (DED), binder jetting, powder bed fusion (PBF), sheet lamination, VAT photo polymerization, material extrusion, and material jetting [11,34]. The DED, PBF, sheet lamination and binder jetting offer interesting potential for fabrication of metallic parts required for industrial applications [75-77]. Rest of the AM processes like electron beam melting, selective laser melting, and laser engineered net shaping involve the addition of an alloy or metal, layer-by layer and track-by-track, which is achieved by melting & solidification of the powders resulting in near-net-shaped parts. Directed Energy Deposition (DED) and Powder Bed Fusion (PBF) are prominent AM processes used for metals. DED, for example, involves melting and fusing material as it is deposited, enabling the creation of functionally graded materials or multi-material components by switching feedstock during the build [78]. PBF methods, such as Selective Laser Melting

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Page No: 3534-3563
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0519

(SLM) and Electron Beam Melting (EBM), precisely fuse powdered materials. While typically single-material processes, advancements explore multi-material PBF through techniques like multi-powder feeders or segmented powder beds. Multi-Photon Polymerization (MPP) also enables multi-material artifacts by independently manipulating microparticles within a photopolymer structure [79]. These capabilities support the fabrication of components with spatially tailored properties, crucial for aerospace and automotive applications requiring optimized performance and weight. The control over local material composition allows for advanced design possibilities [80, 81]. Compared to conventional manufacturing methods, the MAM offers several advantages: the capability to produce parts with many materials in any configuration, near-net-shaped parts with high design freedom, less material wastage, reduced part fabrication time, and cost. Multi-material additive manufacturing (MMAM) offers several opportunities for designing complex, functional, highly personalized, and high-value products with improved properties. Recently, direct energy deposition (DED) has been attracting considerable attention in metal additive manufacturing due to its capability of producing multi-materials and composition gradient materials with a high degree of geometrical design freedom and relatively high productivity compared to powder bed fusion processing. During multi-material fabrication using DED processing, metal powders are injected through different powder-feeding nozzles by controlling the feeding rates in a high-energy laser beam. The molten material is deposited as a thin layer, and several such layers are deposited one over the other to produce a 3D part so that various types of parts of locally different chemical compositions and properties can be manufactured. Layered structured materials (i.e., clad materials) are the simplest configuration of the multi-materials [82]. In a multi-material combination with soft and hard materials, the hard domain contributes high strength whereas shock absorption can be secured from the soft domain. These hybrid structures are highly desirable in automobile industries [83]. A new approach for multiple material SLM by combining powder-bed spreading, point-by-point multiple nozzles ultrasonic dry powder delivery, and point-by-point single layer powder removal to realize multiple material fusion within the same layer and across different layers. A clear distinct sandwich layer distribution and a good metallurgical bonding were obtained at the material interfaces for the material combinations using stainless steel powder and Nickel powder (316L/In718) and (stainless steel and Copper alloy powder) 316L/Cu10Sn[84]. The multi-metal processing by laser powder bed fusion (L-PBF) causes additional complications such as loss of alloying elements, intermetallic phases, and unmelted particles apart from balling, porosity, cracking, and oxide inclusions [85]. Steel/copper multi-material parts which combine the good strength and corrosion resistance of steel with the high heat conduction and wear resistance of copper may be a promising solution for the fusion reactors, conformal cooling channels, automobile, rail and aviation industries [86]. Multi-material FDM is achieved by employing multiple extrusion heads where nozzle temperature, printing speed, and resolution can be individually controlled as necessary. However, some drawbacks of multi-head FDM still exist, such as inherent poor surface finish with ridges, limited printing resolution, slow build speed, and low interfacial bonding strength. In particular, low interfacial bonding is a critical issue in producing 3D parts with dissimilar materials. Multi-material printing with Material Jetting (MJ) has been easily implemented following the same approach using multiple jetting heads [87,88] supplying multiple photo-curable materials and support materials are processed through jetting heads. However, multi-material printing with Material Jetting faces difficulty in processing high viscosity material and also demands keen monitoring and control system [89, 90]. Multi-material additive manufacturing (MMAM) with SLA requires material exchange from one liquid to another in the vat. Initially manual changing and later, a rotating vat carousel system was used to automate material change. Recently, an aerosol jetting system has been employed in SLA to directly supply different materials [91]. The aerosol system has multiple the material containers and atomizers that transform liquid material into small droplets [92]. MMAM offers an excellent tool to directly manufacture parts with geometrical complexity as well as material variety. Multi-material AM (MMAM) methods have recently been applied to fabricate complex structures in an efficient way to save production time and the cost of the materials used [93]. With the advantage of fabricating multiple materials in a single manufacturing process, it is possible to produce functionally graded materials (FGM) with improved material interface characteristics. Multi-functional 3D parts may lead to revolutionary solutions in a variety of fields including biomedical engineering, soft robotics, and electronics. Despite the remarkable advances in MMAM in the past few years, there are still many outstanding challenges to be addressed including low production throughput, poor scalability and surface finish, limited material selection, high cross-contamination, and low interfacial bonding between different materials [94].

3.1.3. Challenges In Fusion Based Processes

Despite advancements in fusion-based metal additive manufacturing (MAM), the structural integrity of the products often falls short, leading to inadequate load-bearing capacity [95-98]. The layers of 3D printed parts are created through a layer-wise deposition of melted filler material, similar to the fusion welding process. This can result in various non-equilibrium solidification defects, such as cracking and porosity, which can adversely affect the performance of the produced parts. Induced porosity is a common defect in fusion-based MAM [99-101]. When excessive energy is applied during the process, issues like porosity and material contamination can occur due to the ejection of spatter. Conversely, insufficient energy from the electron or laser beam may prevent complete melting, leading to the formation of incomplete fusion holes. Additionally, during alloy solidification, low-melting point particles may be rejected at the solid-liquid boundary, creating a thin liquid layer between solidified dendrites [102]. This can result in solidification shrinkage, causing hot cracking or tearing, particularly in non-weldable alloys such as high-strength aluminium alloys [103,104]. Other concerns include anisotropy, distortion of manufactured parts, and residual stresses [103,105,106]. During the deposition of consecutive layers, reheating of previously deposited layers can lead to unwanted phase transformations. The presence of residual stresses in parts created by these techniques remains a challenge. The tendency for large grain sizes and segregation in formed components results in an inhomogeneous structure. Focusing on refining processing parameters and developing new alloy compositions may help achieve a more uniform microstructure [107-109]. Consequently, there is a pressing need for the development of new technologies to address these issues associated with traditional fusion-based MAM methods [95,110]. Defects like pores, cracks, and insufficient fusion can be addressed by promoting further research into process optimization and materials selection, particularly, for alloys that are more susceptible to hot cracking [111-113]. By exploring advanced techniques for stress management and component design, enhancement in the structural integrity of the materials facing the issue of rapid solidification leading to significant deformation and residual stress can be achieved [114]. Understanding the above-mentioned challenges in fusion-based additive manufacturing (AM) can pave the way for improvements and innovations. Refining fusion-based AM technologies can unlock their full potential for manufacturing high-quality components.

3.2. Solid State Manufacturing Approaches for Multi-Material Structures

Due to the intricate liquid-to-solid phase transformation process, components created through fusion-based MAM methods often display anisotropic behavior and diminished transverse strength which limits their suitability for structural applications, urging us to rethink their utilization. This fundamental fabrication problem of fusion-based MAM attracts the attention of researchers. In response to these concerns, many researchers have focused on eliminating MAM's limitations and have proposed innovative approaches. One promising method involves incorporating solid-state friction-based techniques into additive manufacturing. Various friction-based additive techniques (FATs) are currently in practice [115-120].

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Page No: 3534-3563
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0519

3.2.1. Diffusion Bonding

Diffusion bonding is a solid-state joining technique that creates atomic bonds between mating surfaces through the application of heat and pressure. This process typically occurs at temperatures below the melting point of the materials, relying on atomic diffusion across the interface. It offers advantages for joining dissimilar metals and alloys, including those with significantly different melting points or prone to forming brittle intermetallics upon melting. Diffusion bonding often produces joints with properties very close to the parent materials, particularly in terms of ductility and fatigue strength, due to the absence of a distinct weld bead or fusion zone. Variants of solid-state joining include explosive welding, which uses a high-velocity impact to create a metallurgical bond between two metals [121-123]. These methods are often employed for critical applications requiring high integrity and minimal distortion, such as in aerospace components. This process is suitable for complex geometries and dissimilar material combinations, including Ti alloys, where high-integrity joints are required without macroscopic melting. Hot Isostatic Pressing (HIP) and Spark Plasma Sintering (SPS) are related techniques that apply high pressure and temperature to consolidate powders or bond components. SPS, for instance, offers fast heating rates and shorter sintering times, enabling the production of high-density materials with controlled grain growth, particularly for high entropy alloys. The FAST-forge process, combining Field Assisted Sintering Technology (FAST) with hot forging, effectively recycles Ti-6Al-4V swarf into components with properties comparable to melt-wrought material, demonstrating its utility for titanium alloy processing [124-126].

3.2.2. Solid State AM Approaches

Solid-state additive manufacturing (AM) methods offer unique advantages for creating complex multi-material geometries, especially for Al, Mg, and Ti alloys. These techniques build parts layer-by-layer without exceeding the melting point, reducing thermal distortions and residual stresses common in fusion-based AM [127,128]. Additive Friction Stir Deposition (AFSD), as mentioned, can repair and build features on existing components, offering flexibility for complex repairs in alloys like Al7075 [129]. Cold Spray, another solid-state AM method, involves accelerating metal powder particles to high velocities, causing them to plastically deform and bond upon impact with a substrate. This process is effective for depositing various metals, including Al and Ti, and can create functional multi-material layers without significant heat input [130,131]. Hybrid additive manufacturing, which combines AM with traditional methods, also broadens design possibilities, allowing for the creation of parts with tailored properties on existing substrates [132].

3.2.3. Friction Stir Welding and Allied Processes

Friction Stir Welding (FSW) is a solid-state joining process particularly suited for dissimilar material combinations, including aluminium alloys, magnesium alloys, and even aluminium to steel. The process involves a non-consumable tool rotating and traversing along the joint line, generating frictional heat that softens the material without melting it. This solid-state nature avoids many issues associated with fusion welding, such as solidification defects, liquation cracking, and excessive distortion [121-123]. FSW produces fine-grained microstructures in the stirred zone, leading to improved mechanical properties compared to conventional fusion welds. Variants like friction stir spot welding (FSSW) and friction stir processing (FSP) further extend the applicability of this technology to complex joint geometries and surface modifications for multi-material systems. FSW's capability to join traditionally unweldable alloys makes it highly relevant for lightweight structures in transport applications. Solid-state methods, like FSW and diffusion bonding, operate below the melting point, thus minimizing issues related to solidification defects, residual stresses, and the formation of brittle intermetallic compounds, particularly when joining materials with vastly different melting temperatures. These processes often yield joints with properties closer to the parent materials, especially regarding ductility and fatigue resistance. However, solid-state techniques typically require precise surface preparation, high clamping forces, and can be slower for certain applications. Fusion-based methods, including traditional welding and additive manufacturing, offer higher process speeds and greater flexibility in joint geometry for many material pairs. Additive manufacturing, in particular, enables unprecedented design freedom and the creation of functionally graded materials or complex multi-material structures [133-136]. Conversely, fusion processes generally introduce larger heat-affected zones, more significant residual stresses, and can lead to metallurgical incompatibilities when joining highly dissimilar materials. The choice between solid-state and fusion approaches depends on the specific material combination, desired joint properties, production volume, and cost considerations. Friction stir-based technologies are the newest addition to the additive manufacturing technologies, and there is a lot of unrealized potential. [137-140].

3.2.4. Friction Stir Additive Manufacturing (FSAM)

Friction Stir Additive Manufacturing is a state of art process. FSAM demonstrates significant opportunities notably in the aerospace, automobile, marine and defence sector. This cutting-edge technique has the ability to efficiently manufacture multifunctional, lightweight, high-strength structural parts to cater to the needs of aircraft and other technical parts. A key application of FSAM in aerospace is the production of stiffeners and stringers, which are vital for structural integrity. FSAM opens up new horizons for manufacturing large components, paving the way for the creation of entire satellite and spacecraft structures. Reports of Boeing [141] and Airbus 2006 [142] had explored the potential of FSAM particularly, in the aerospace industry. As FSAM technology continues to advance, it is poised to effectively tackle a range of challenges in metal additive manufacturing, affirming its role as a game-changer in the industry. White [143] filed a ground-breaking patent for a Friction Stir Additive Manufacturing (FSAM) process in 2002 that consolidates metal powders and materials using friction joining. Three years later, in 2005, Thomas et al. [144] unveiled a revolutionary application of friction stir welding-based processes for additive manufacturing. In 2006, Airbus demonstrated the incredible potential of friction-based additive manufacturing technology by fabricating 2050 Al-Li wing ribs, showcasing its ability to create low-cost, lightweight components [145,146]. By 2012, Boeing recognized the transformative power of friction-based additive manufacturing for the pre-forming of structural components, paving the way for rapid manufacturing and significantly enhancing material utilization [107,142]. High strength multi-material structures can be effectively built by this game changing technique. Designing a customized variety of multi-layered alloys along with functionally graded structures can be fabricated by FSAM method. Overall refinements in mechanical, metallurgical properties with fine equiaxed microstructure have been reported by latest research on FSAM [147-150]. Traditional additive manufacturing (AM) techniques encounter challenges when producing graded components due to variations in thermomechanical properties, thermal expansion coefficients, and melting points of parent materials. The formation of undesirable intermetallic compounds (IMCs) can weaken welds. However, these issues can be addressed through Friction Stir Additive Manufacturing (FSAM) [151,154]. In FSAM, the thermal expansion problem is mitigated as melting of materials to join is completely avoided, permitting only localized heat transfer due to its solid-state nature. The intense plastic motion and shearing action in FSAM facilitate the distribution and control of the size and uniformity of IMCs at the interface. Notably, FSAM processes can generate custom materials and alloys in a single operation. They also allow for the manipulation of alloy composition and microstructure by controlling the mixing of materials. Therefore, FSAM can be considered one of the most viable techniques to produce light weight multi-material structures [155-157]. FSAM has proven to be an effective method for producing defect-free components with excellent, uniform mechanical properties, an equiaxed refined grain structure, and a rapid production rate. This approach effectively addresses the limitations of existing melting-based additive manufacturing processes. Additionally, FSAM can be utilized to create bulk materials with an ultrafine grain structure.

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https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0519

The main challenge of this innovative process lies in eliminating defects by controlling the process parameters. Most studies have focused on basic parameters such as rotation speed, transverse speed, and tilt angle. However, there is a need to explore and investigate additional process parameters to achieve a sound microstructure and optimal mechanical properties [158]. FSAM, which combines the advantages of the AM (Additive Manufacturing) and FSW (Friction Stir Welding) methods, offers several benefits over traditional fusion welding methods. These advantages include energy efficiency, environmental friendliness, the ability to weld similar or dissimilar alloys, and reduced distortion. FSW is an effective welding process for joining dissimilar materials, resulting in lightweight and high-performance final products.[159] All the methods introduced above are free from the solidification-related imperfections often found in fusion-based processes. Key benefits of FSAM include reduced distortion, lower porosity, and the potential to fabricate larger parts, the capability for multi-material bonding, improved reproducibility, exceptional metallic properties, and the ability for microstructural engineering through tailored microstructures [160]. Currently, FSAM is at manufacturing readiness levels that allow for compact designs and scalability in high-technology applications [161]. FSAM induces complex material flow in the stir zone due to the rotating tool's stirring motion, which homogenizes the microstructure and promotes dynamic recrystallization. This leads to the formation of fine, equiaxed grains with improved mechanical properties as compared to the base metals or fusion welds exhibiting coarse grains and segregation. In multilayer FSAM, repeated thermal cycling due to subsequent passes affects microstructure progression. Grain sizes may vary along the build height, and multiple passes can refine precipitates and dissolve coarse intermetallics, further enhancing properties. Dynamic recrystallization also helps in redistributing alloying elements uniformly and eliminating defects like voids and cracks. The thermal cycles during layering control precipitate coarsening, dissolution, and refinement, which influence hardness, tensile strength, and ductility [162]

3.3. Hybrid Solid-State Processes for Dissimilar Material Integration

Hybrid solid-state processes combine two or more joining mechanisms to leverage their individual strengths for enhanced multi-material integration. Multi-materials can combine friction stir technique with other methods to improve joint quality and extend the range of compatible materials. These hybrid approaches aim to overcome limitations of single processes, such as achieving higher joint strengths or reducing processing time for complex geometries. An example includes the combination of mechanical fastening with solid-state bonding, forming a hybrid joint that benefits from both load-bearing mechanisms. Another area involves integrating material deposition techniques with solid-state joining to create functionally graded interfaces, thereby mitigating abrupt property changes between dissimilar materials. The objective is to produce robust and durable multi-material structures that withstand demanding operational environments in aircraft and automobiles [163-164]. Weflen et al. (2021) introduced a method for fabricating multi-material objects by combining additive and subtractive manufacturing techniques. This hybrid approach allows for a diverse range of material compositions, enabling more effective fulfilment of functional requirements compared to using homogeneous materials produced through a single manufacturing process. The development of multi-material objects made from different materials has faced challenges due to the absence of a compatible structural interface suitable for in-envelope hybrid manufacturing. This study aims to expand design possibilities and optimize performance metrics [165]. Hybrid friction stir channelling (HC) represents a novel manufacturing technique that innovatively merges solid-state friction stir welding with friction stir processing. This sophisticated method not only facilitates the simultaneous welding of multiple components but also carves out intricate sub-surface channels precisely where they are needed in the stir zone. HC demonstrates an approach for unobstructed

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 09 September 2025
Page No: 3534-3563
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0519

sub-surface channelling and welding for multi-material components, significantly enhancing both their physical and chemical performance. A remarkable demonstration of HC's capabilities was achieved using a multi-material system comprising an 8 mm thick Aluminium-Magnesium alloy (designated as AA5083) and a 3 mm thick oxygen-free copper (Cu-OF) plate by Karvinen et.al. (2023). This process seamlessly crafted a multi-material Al-Cu component, showcasing its potential. A striking sub-surface quasi-rectangular channel, measuring 9.6 mm in width and 3.3 mm in height, was skillfully produced within the AA5083 alloy, while simultaneously ensuring defect-free welding with the thin Cu-OF plate situated just beneath the channel area. The resulting sub-surface channel revealed captivating wall surface features, boasting non-uniform and non-oriented surface roughness that are perfectly suited for activating turbulent fluid flow. Moreover, microhardness assessments unveiled a domain of heightened strength within the stirred material at the ceiling of the sub-surface channel, surpassing the properties of the base materials. This remarkable advancement not only highlights the ingenuity of HC but also opens new horizons for multi-material applications [166]. The solid-state welding method known as hybrid metal extrusion and bonding (HYB) has been developed relatively recently and was originally intended for butt joining aluminium (Al) plates and profiles. The HYB method works by filling the weld groove between the base materials (BMs) to be joined with a solid filler metal (FM), utilizing the principles of continuous extrusion. This process involves a specially designed extruder tool that features a non-consumable rotating steel pin equipped with a set of moving extrusion dies at its lower end. Research conducted by Bergh et al. (2023) explores the potential of this method by characterizing a unique butt joint made from aluminium, copper, steel, and titanium (Al–Cu–steel–Ti) created in a single pass. Their characterization highlights the significant potential of HYB for multi-material joining and provides essential insights into solid-state welding involving the bonding of aluminium to titanium, steel, and copper [167].

4. Material Lamination Architectures through FSAM

Different layers of material are stacked and joined to compile the required height of FSAM built. According to application area, surrounding environment, service condition and blend of customized properties, a number of layers of material are processed into a single working unit. Variation in material and geometrical dimensions of FSAM built give rise to different laminate architecture.

4.1.Identical Material Laminates

Laminates created out of stacks of the same material like Al Alloy laminate, Mg Alloy Laminate, Cu material laminates are fabricated using the FSAM process. This is eventually needed to build a larger height from average thickness plates [168].

4.1.1. Aluminum Based Laminates

Palanivel et al. (2015) in describing FSAM as an additive technique manufacturing high strength build fabricated by FSAM, laminated a total height of 11.2 mm from four sheets each of thickness 3.17 mm of aluminum alloy Al-5083 and found finer grain size, increased hardness in the build as compared to parent material. Improvement in both yield and ultimate tensile strength was also reported [142]. The work published by Palanivel laid the foundation stone for researchers. Yuqing et al. (2015) fabricated a height of about 42 mm from the nine-layer FSAMed unweldable Al 7075 (Al-Mg-Zn-Cu) alloy build. They reported increasing grain sizes in layers from top to bottom. Gradual increase in the strength and decrease in elongation in the direction of the build was reported [149]. Z. Zhao et al.(2019) stacking 2 mm thick Al-Li 2195-T8 alloy revealed inhomogeneous hardness and ductility throughout the build length[169]. Zhang et. al. (2019) created an integrated model after experimenting on 4 mm thick AA6061-T6 plates and concluded that the hardness and yield strength increases with the increase in building height as an effect of the decrease in reheating peak temperature. Smaller average grain size was observed with the increase in building height. He et.al. (2020) investigated microstructural evolution and changes in microhardness and tensile properties variation along building direction of 4mm thick 12 sheets of 7N01-T4 (Al–Zn–Mg) aluminum

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 09 September 2025
Page No: 3534-3563
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0519

alloy resulting in 42mm build height. The precipitates in the non-overlapping interface regions and the grain size were found to be increasing from the top to the bottom of the build [170]. Study made by M. Srivastava et. al. (2021) involving six layers of 4 mm thick plates of Al-5059 alloy showed higher hardness and thereby strength of laminated composite Lu et.al.(2021) fabricated two stacked lap weld builds with cast and wrought AA2050 (Al–Cu–Li). Cast AA2050 stack had no significant impact on the mechanical performance. Inhomogeneous distribution of hardness was reported along the vertical length [171]. Z. Shen et.al.(2022) fabricated defect-free build from unweldable Al 2195 alloy with 1mm thick three rolled plates and investigated influence on the microhardness and mechanical properties aiming at controlling and optimization of microstructure for further improvement of mechanical properties [172]. Li et. al. (2022) conducted underwater FSAM of Al–Zn–Mg–Cu alloy of plate thickness 3.5 mm followed by natural aging for 7 days which revealed overaging in the low hardness zone (LHZ) of the build suggested low-temperature aging treatment to overcome over aging and improvement in microhardness and both yield and ultimate strength of laminate [173]. Hassan et.al. (2023) fabricated 4 layered laminates from aerospace aluminum alloy Al-7075. In order to optimize process parameters, understand material mixing and heat generation phenomenon experiments were conducted at different speed, feed and using different tool pin profiles. Mixing behavior using plain cylindrical, cylindrical threaded, and taper threaded pinned tools was analysed. It was observed that the taper threaded tool rotating at 500 and 1200 rpm gives good results [174].

4.1.2. Magnesium Based Laminates

Magnesium though lighter material was less experimented till date as compared to Aluminium alloys. Palanivel et al.(2015) built a multilayered stack consisting of four sheets of an WE43, Mg based alloy through FSAM to build height of 5.6 mm. Experimentation showed extremely fine, uniform and densely populated coherent precipitates resulted into superior strength and concluded that FSAM can be an effective route to fabricate high performance magnesium alloy components[117]. A seven-layer laminate from AZ31 magnesium alloy 5-mm-thick plates was constructed by Wlodarski et al.(2021) produced structurally sound metallurgical bonding between layers without any volumetric welding defects and found microhardness variation in vertical height and in horizontal cross section[175]. Ho et al. (2020) have ingeniously crafted a stacked composite of AZ31B magnesium and hydroxyapatite using the innovative FSAM method. This composite not only tackles the persistent challenges of corrosion but also significantly enhances apatite formation and promotes better cell adhesion on the surface of the magnesium alloy. The findings compellingly demonstrate the superior corrosion resistance of AZ31B, validated through rigorous in-vitro testing conducted by the author [176,177].

4.2. Multi-material Laminates

To address the need of multifunctional laminates with tailored properties and refined microstructure, a variety of materials are designed and stacked to form multi-material laminates [168].

4.2.1. Fully Gradient structure

Fully gradient composite from 3 mm thick plates of Mg-AZ91, Cu, and Al-7075 was constructed by Srivastava et.al.(2021) [178]. Jha et.al.(2022) fabricated gradient structure using three Al alloys Al-5083-O, Al-6061-T6, and Al-7075-T6 formed height of 8.8 mm to develop a microstructure gradient composite [179].

4.2.2. Alternative Gradient Structure

Eight sheets of multi-layered polymer-steel composite were alternately stacked by H. Derazkola et.al. (2020) and evaluated mechanical properties, particularly, hardness, flexural bending and tensile strength to sought solution in the automobile industry[180]. Later on Derazkola et.al. (2022) proposed composite laminate utilizing the same technique for polypropylene (PP) and textile stainless steel material[181]. The flexural and tensile strength was reported to be greater than PP. Venkit et.al. (2022) constructed 18 mm thick laminate from 3mm thickness alternate seven layers of aluminium alloys AA6061-T6 and AA7075-T6. The grains in the bottom layers were observed to be coarser, while those in the top layers were finer. Additionally, certain banded grains with a coarser texture form in the overlapping transition zones. The precipitate particles generated shown similar trends in their distribution, size, and structure. The study concluded that the FSAM approach holds tremendous potential for fabricating large structures that are not only free of defects but also exhibit expected mechanical properties. As a result, this innovative composite emerges as a compelling alternative to the conventional AA6061 material used in automobile components, offering significantly enhanced performance that can redefine industry standards [182]. Five alternate layers of AA6061-T6 and AA7075-T6 alloys were welded by one over the other in the research made by Kundurti et.al. (2023). AA7075-T6 being harder was kept at top as it can be flown easily into comparatively softer AA6061-T6 alloy. AA6061/AA7075 metal matrix composite manufactured through the FSAM route showed promising results with enhanced microhardness and tensile strength [157].

4.2.3. Sandwich Structure

Laminated composites are materials made up of several layers of different substances, widely used across various industries. Interstitial-free (IF) steel sheets are known for their excellent drawability and surface quality, although they have lower strength compared to low carbon steel sheets like St52. In contrast, St52 steel sheets offer good strength but tend to have lower surface quality. By combining the properties of these two types of steel sheets, a laminated structure was created by Roodgari et.al. (2020) that incorporates the strengths of both. This approach is particularly useful in automotive components, such as pillars, which require high strength for safety alongside very good surface quality. The IF/St52 steel laminated composite, with thicknesses of 0.7mm and 2mm, respectively, is prepared using the FSAM method. The results indicated that the layers exhibited strong bonding, and the interface was well-defined at lower travel speeds. However, as the traverse speed increased, diffusion occurred at the interface [183]. Tan et.al. (2021) used FSAM method to produce aluminium matrix composites reinforced with nanoparticles. In the initial stirring process, two 4 mm thick slotted plates and one 2 mm thick cover plate are stacked. To investigate the effect of re-stirring, an additional 4 mm thick plate is stacked for the second layer. The slots designed to hold the nanoparticles are 1.5 mm wide and 2 mm deep. All plates, including the slotted and cover plates, are made from AA6061-T6 aluminium alloy. Samples that include Al2O3 nanoparticles exhibit finer grain distributions and increased hardness when processed using FSAM. The re-stirring process in FSAM reduces the aggregation of nanoparticles, resulting in greater hardness and a decrease in grain size [184].

4.3. Similar Multi-Material Laminates

FSAM offers a novel pathway to fabricate layered or composite multi-material structures by exploiting the solid-state joining of similar or dissimilar Al and Mg alloys. The primary objective is to develop defect-free, high-strength joints with controlled microstructure and reduced formation of detrimental phases such as thick IMCs. This is achieved by precise control over thermal cycles, tool design, and process parameters thereby enhancing bonding effectiveness and mechanical properties of the joined components [185]. The approach holds significant industrial relevance, especially in sectors requiring complex geometries, lightweight materials with high structural integrity, and corrosion-resistant joints. By building multi-layered composites incorporating alternating or hybrid layers of aluminium and magnesium alloys, FSAM enables customization of mechanical and functional properties tailored to application needs in aeronautics, automotive parts manufacturing, and marine structures. The method's ability to minimize secondary machining and produce large, defect-free builds further adds to its economic and technical potential.[186] In joining similar Al alloys such as AA6061 and AA7075 via FSAM, microstructural evolution is characterized by dynamic recrystallization producing refined and equiaxed grains in the stir zone [187]. The process disrupts initial coarse grain structures and precipitate clusters, leading to a more homogeneous microstructure with optimized distribution of strengthening phases. Thermal cycling during multi-layer additive building impacts precipitate size, morphology, and distribution, influencing the hardness and strength gradients throughout the build height [188]. Magnesium alloys such as AZ31 and AZ61 exhibit unique challenges in FSAM due to their high chemical reactivity and limited ductility. The process induces grain refinement through dynamic recrystallization, resulting in finer equiaxed grains in the stir zone. Variations in alloying elements and process conditions influence phase transformations and precipitate dissolution during the thermal cycles inherent in FSAM [189]. FSAM's controlled heat input minimizes detrimental overaging or dissolution of beneficial strengthening precipitates, preserving or enhancing mechanical properties in the joints. The microstructure typically shows uniform grain refinement and reduced segregation, which are directly correlated with mechanical performance improvements noted in these alloys. The refined microstructure enhances mechanical uniformity and eliminates casting defects present in base materials. Grain size control via optimal welding speeds and rotation rates is essential to achieving consistent properties across the additive build. FSAM processing of Mg alloys improves hardness, tensile strength, and wear resistance significantly [190].

4.4.Dissimilar Multi-Material Laminates

Dissimilar welding, which refers to the process of joining two or more materials that have different compositions, presents a range of challenges compared to welding similar materials. Joining Al and Mg alloys through FSAM inherently leads to the formation of intermetallic compounds such as Mg_2Al_3 and Al_3Mg_2 at the interface. These IMCs form thin but brittle layers that can severely compromise joint ductility and tensile strength. The interface morphology is characterized by a complex arrangement of diffusion layers, oxide inclusions, and fragmented IMC particles [191,192]. The integration of diverse materials, particularly aluminium (Al), magnesium (Mg), and titanium (Ti) alloys, presents compelling metallurgical challenges when employing conventional fusion welding. These challenges often manifest as the formation of brittle intermetallic compounds (IMCs) and significant residual stresses [193]. However, solid-state manufacturing processes offer a sophisticated solution by enabling the joining or consolidation of materials below the melting point of the constituent alloys. This innovative approach not only preserves the intrinsic properties of the base materials but also minimizes distortion, allowing for the creation of robust metallurgical bonds between otherwise incompatible alloy systems. It's a transformative method that unlocks new possibilities in materials engineering [194,195]. Dixit et.al. (2023) developed a multipurpose three-layered multifunctional laminated composite from magnesium-based AZ31B–Zn and Al 1100 as demanded in electronics and biomedical fields through the FSAM route. Conventional Mg alloy implants release hydrogen gas and thereby the body cell gets detached from the bone. The proposed FSAM method adds a biocompatible layer to overcome this issue. The microstructure of the developed composite revealed a significant improvement in the grain structure at the interfaces of the dissimilar materials. The crystallographic structure is effectively oriented from the advancing side to the retreating side, featuring equiaxed and refined grains that contribute to a high density of grain boundaries. This refinement, combined with the microstructural modification techniques employed in Friction Stir Additive Manufacturing (FSAM), not only enhances the grain characteristics but also leads to notable improvements in the overall mechanical properties of the composite [196].

4.5.Challenges in Dissimilar Welding

In the context of dissimilar welding, it is essential to acknowledge and thoughtfully consider several important challenges [197-200], including: Incompatibility of Material: Dissimilar materials often possess varying melting points, thermal conductivities, and coefficients of thermal expansion. Such differences can result in challenges, including cracking, distortion, and residual stresses during the welding process. To ensure effective fusion and metallurgical bonding between these diverse materials, it is imperative to meticulously control welding parameters and apply the appropriate techniques. This strategic approach will enhance the overall quality and integrity of the weldment. Microstructural inhomogeneity: When dealing with dissimilar materials, it is essential to acknowledge that they may exhibit distinct microstructures, grain sizes, and phases. By understanding these variations, we can effectively address the potential differences in mechanical properties within the weld joint. Aiming for a more uniform microstructure can help reduce localized stress concentrations, thereby enhancing the joint's resilience to cracking or failure under mechanical or thermal loads. This thoughtful approach can greatly improve the overall integrity of the weld. Corrosion susceptibility: dissimilar materials are prone to galvanic corrosion due to formation of bimetallic couples at the weld interface. The differing electrochemical potentials between these materials can significantly elevate corrosion rates, posing a serious threat to the long-term durability of the weld joint. To safeguard against these risks, it is vital to select the right filler materials and to employ effective post-weld treatments. By doing so, we can enhance the resilience of our welds and ensure their integrity for years to come.

IMC Formation: When dissimilar materials are fused together, intermetallic compounds (IMCs) can form at the interface. These compounds have the potential to dramatically affect both the mechanical properties and the corrosion resistance of the welded joint. The presence of brittle IMCs can severely compromise the integrity of the weld, resulting in diminished strength and ductility. Thus, the quest to create robust welds while effectively reducing IMC formation presents a formidable challenge in the realm of dissimilar welding—a challenge that calls for innovation and precision.

Thermal Gradient Effects: Dissimilar welding creates significant thermal gradients in the weld zone because of the differences in thermal conductivity and heat capacity of the materials being joined. These thermal gradients can result in distortion, warping, and residual stresses, especially in thicker or more complex structures. Effectively managing these thermal gradients is crucial for preventing weld defects and ensuring dimensional stability.

Complexity In Process Optimization: Welding dissimilar materials presents a fascinating challenge that it requires control over various parameters, including heat input, travel speed, shielding gas composition, and interpass temperature management. The intricate interplay among these factors and their profound impact on weld quality and performance call for thorough experimentation and meticulous validation of the welding process. Successfully navigating the complexities of dissimilar welding demands not only a deep understanding of material properties, welding techniques, and joint design considerations, but also a passion for innovation. To meet these challenges head-on and push the boundaries of dissimilar welding technology, we must embrace cutting-edge welding methods, engage in advanced material characterization, and leverage sophisticated computational modelling techniques. Mitigation of these challenges requires carefully balancing heat input and manipulating interfacial reactions. The use of interlayers, such as thin nickel foils, has been demonstrated to alter intermetallic chemistry, forming more ductile phases (e.g., Mg_2Ni) and increasing the effective load-bearing area within the weld nugget. These advances have led to tensile strength improvements exceeding 10% compared to joints without interlayer. Witnessing the advantages of multi-material approaches for part manufacture confirms that there is a need to generate different combinations of materials. These multi-material parts or structures need to be carefully designed and examined to take full advantage. Economy, investment, quality, energy level, minimal material wastage, lightweight production, low-cost processes and its ability to easily fabricate complex shapes, along with being affordable and environmentally friendly.

Conclusion

Multi-material manufacturing techniques play a pivotal role in designing lightweight, energy efficient, economical structures in tailored fashion. This review explores the unique advantages and challenges of both solid-state and fusion-based approaches. Achieving successful integration hinges on precise interface engineering, effective management of residual stresses, and ensuring material compatibility. Friction stir additive manufacturing (FSAM), a subset of friction stir welding (FSW), offers a reliable solid-state method for fabricating multi-material laminates, particularly those made from aluminium (Al) and magnesium

(Mg) alloys, which are in high demand in the aerospace, automotive, and marine sectors. This technology effectively addresses the challenges associated with fusion welding, such as solidification defects and microstructural degradation, especially in light alloys. Key findings reveal that FSAM consistently generates fine-grained, equiaxed microstructures in the stirred zone through dynamic recrystallization, which enhances crucial mechanical properties, including tensile strength and hardness. Although creating dissimilar Al/Mg joints presents its own set of difficulties, careful control of process parameters enables us to prevent the formation of brittle intermetallic compounds, opening the door to significant advancements in the field. Further research should concentrate on expanding high-fidelity computational models that accurately predict microstructural evolution, residual stress profiles, and fatigue performance for complex multi-pass and multi-material FSAM processes is essential for design and optimization. Additionally, continued investigation into novel interlayers, surface treatments, and post treatment to effectively manage and control intermetallic compound formation at dissimilar Al/Mg interfaces will improve joint reliability and broaden application scope. Furthermore, the integration of AI tools for real-time monitoring and adaptive control that integrate thermal data, material flow characteristics, and defect detection algorithms would enable more consistent and higher-quality manufacturing outcomes.

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