

DISSIMILAR METAL BONDING BY FRICTION STIR WELDING: MAGNESIUM TO STEEL JOINTS

Kapil B. Pipavat^{*1}, Hirenkumar I. Joshi², Ghanshyam D. Acharya³

¹Research Scholar, Gujarat Technological University, Ahmedabad, India.

²Research Supervisor, Gujarat Technological University, Ahmedabad, India.

³Professor emeritus, Atmiya University, Rajkot, India.

¹<https://orcid.org/0000-0002-2757-531X>, ²<https://orcid.org/0000-0001-7060-0536>, ³<https://orcid.org/0000-0002-3580-3116>

Email: *kapil.pipavat@gmail.com, - j_hiren@yahoo.com, gdacharya@rediffmail.com

ARTICLE INFO

Article History

Received: March 7, 2026

Reviewed: June 12, 2026

Accepted: July 12, 2026

Published: July 31, 2026

Keywords:

steel,
magnesium,
dissimilar welding,
process parameters,
friction stir welding

ABSTRACT

FSW - Friction stir welding has extended recognition as an effective non-fusion welding process for dissimilar materials, offering a solution to the limitations commonly encountered in conventional fusion welding techniques. This review paper focuses on the FSW of magnesium to steel, which has gained significant attention in different industries, like energy sector, aerospace, marine, automotive, etc. The paper presents an overview of the magnesium and steel materials, discusses the challenges and considerations specific to their dissimilar FSW, and provides insights into the mechanical characteristics, microstructural development, process parameters, and joint performance of the magnesium to steel welded joints. This paper highlights the current state of research, identifies knowledge gaps, and suggests future research directions. This information will be valuable for researchers, engineers, and practitioners involved in the development and application of dissimilar material joining techniques in various industries. The present review paper outlines FSW parameters including tool design, rotating speed, feed, tilt angle, pin offset, and the positioning of workpiece in a clamp for dissimilar FSW systems.



Copyright ©2026 by authors and Galileo Institute of Technology and Education of the Amazon (ITEGAM). This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

I. INTRODUCTION

It is a challenging task and a topic of interest for scientists, engineers, and researchers to find an effective and reliable weld joint of different material. Recently, there has been a lot of focus on lowering carbon dioxide emissions, and one effective way to combat this is to make cars lighter. Thus, it is desirable to employ light metals aggressively to address these environmental problems. However, in order to ensure their safety, all of the structures need to be strong enough. To satisfy these requirements, a dissimilar joint of strong and light metals is required [1]. Steels are utilised extensively for structural components because of their great absolute strength and good cost-effectiveness, while aluminium and magnesium are preferred light metals. Friction Stir Welding (FSW), as is widely known, is a helpful technique for creating a variety of dissimilar joints, and numerous studies have been published [1-11]. To achieve strong Mg-steel joints through fusion welding, coated steels or Cu/Ni interlayers are used as fillers. These promote beneficial interface structures and intermetallic compounds (IMCs), enhancing mechanical strength compared to conventional Mg-steel joints [12-22]. Manufacturing costs are raised by the use of coated steels and filler metals. Moreover, it is challenging to form strong magnesium-steel joints using traditional fusion welding because of their wide melting point differences (Fe: 1538 °C, Mg: 649 °C) and immiscibility in solid and liquid states. Weldability is further limited by the Mg-Fe binary system, which exhibits zero solubility of Mg in Fe and only 0.00041 at % solubility of Fe in Mg [4], [23-33]. Because of its environmental friendliness, energy economy, and adaptability, FSW is being used extensively [4], [16], [23], [34-35]. FSW joins similar and dissimilar materials such as Al, Mg, Cu, Pb, Zn, steel, and Ti without melting, for thicknesses of 1-50 mm. As a result, FSW avoids common fusion welding issues such as alloy segregation, wide heat-affected zones, residual stresses, weak joints, partial melting, hot cracking, porosity, oxidation, and slag inclusions [23], [35-41]. The UK's The Welding Institute (TWI) first introduced friction stir welding (FSW), a solid-state joining technique for aluminium alloys, in 1991 [11], [42-48]. Figure 1 presents the FSW setup in a butt joint configuration.

A non-consumable rotating tool is inserted at the plate edges and traversed along the joint line. The tool rotates anticlockwise, with its advancing side moving in the same direction as the traverse and the retreating side moving opposite [49-52].

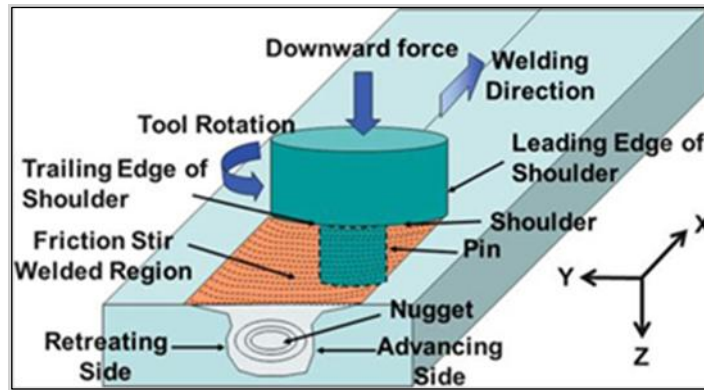


Figure 1: Illustration of friction stir welding in a butt joint configuration.
Source: [49].

Many industries, including aerospace, automotive, marine, railway, and construction, use friction stir welding [5], [49], [51]. The problems associated with joining of magnesium alloys must be resolved because of their increasing usage in industrial applications. Various Solid state welding and resistance welding methods like Friction Stir Welding [23], [53-66], Friction Stir Spot Welding [31], [67-74], Resistance spot Welding [69-77], Arc Spot Welding (ASW) [78], Resistance Element Welding (REW) [79], Resistance Rivet Welding (RRW) [80], Ultrasonic Spot Welding [12], [81-96], Ultrasonic Welding [91], Explosive Welding [92], Diffusion Bonding [93], fusion welding methods like Laser Welding [13], [97-104], Laser Welding–Brazing [99], [100-112], Laser-TIG [14-18], [21], [113-130], MIG – GMAW [125-129], MIG welding-brazing [130], TIG welding-brazing [131], TIG–MIG hybrid welding [132], Vacuum Electron Beam Welding [133], Cold Metal Transfer (CMT) [134-139], Cold Metal Transfer Spot (CMTS) [140], Diffusion-brazing [20], [141-147], Eutectic bonding [142], Impact welding - vaporizing foil actuator welding [143], Liquid Phase Bonding [144] Reactive transient liquid phase bonding [145], have been employed in the progress of magnesium to steel joints. The papers [35], [146-174]. This paper critically examines the current state of dissimilar material FSW, highlighting its challenges and opportunities. They extend a variety of alloy systems, such as different types of aluminium alloys [148], [150], [153], [175] aluminium/ magnesium [149], [176-178], and aluminium alloy/steel pairs [179-188]. It can be concluded from the literature that there hasn't been much work done to strengthen steel connecting in lap and butt configuration using FSW. So, this literature has been prepared to explore more about FSW of mg to steel.

II. MATERIALS AND METHODS

Several transportation industries are now more interested in using lightweight materials due to the need to reduce fuel consumption and component net weights [71], [189-199]. A nationwide survey indicated that cutting vehicle weight by 10% can improve fuel efficiency by about 5%. [195], [200-212]. A 100 kg weight loss in a car can lead to a 20 g/km drop in CO₂ [198]. Currently, steel makes up more than 50% of the weight of a typical automobile [199]. The average car uses 900 kg of steel, which is split up into 23% for the drive train, 12% for the suspension, 34% for the body construction, and 31% for the rest [200]. So, one easy way to make the car lighter is to use lighter materials for manufacturing instead of steel.

Table 1: Physical characteristics of steel, magnesium, and aluminium.

Metals	Fe	Al	Mg
Melting point °C	1536	660	650
Density (at 20 °C) (g/cm ³)	7.86	2.70	1.74
Tensile strength (MPa)	350	320	240
Modulus of elasticity (×10 ⁶ MPa)	206.842	68.947	44.126
Thermal expansion coefficient (×10 ⁶ /°C)	11.7	23.6	25.5
Lattice structure	HCP	FCC	BCC

Source: [213-215].

The automotive industry makes extensive use of polymers, magnesium, and aluminium to address weight-related issues [15], [20], [201], [202]. Magnesium and its alloys are well-suited for automotive applications due to their low density, good ductility, high specific strength and stiffness, and superior damping capacity [15], [201-203], [209-214]. However, because of the high cost of magnesium alloys, more aluminium alloys have been used than magnesium alloys [210], [211] and are particularly susceptible to corrosion [212]. The physical characteristics of magnesium, aluminium, and steel are listed in Table 1 [213], where it is evident that magnesium alloys can provide significant weight reductions when compared to steel and aluminium. Many industries, including shipbuilding, automotive, and aerospace, are interested in adopting hybrid constructions that produce desired weight savings because of the different properties of magnesium alloys [25], [27], [30], [109], [214]. Although magnesium alloys are the lightest structural metals, they show potential as alternatives to steel in automotive applications where weight reduction is desired. It becomes challenging to join or weld two dissimilar metals that have distinct melting conditions, flow strengths, and no congruent melting phases. They are also immiscible in both solid and liquid states. Strong magnesium-steel bonding is therefore challenging.

In order to determine if it is feasible to establish mechanical interlocking or metallurgical bonding for structural applications, FSW has recently been investigated on magnesium to steel dissimilar joint in lap configuration. It is unlikely that IMC will happen between magnesium and steel when welding two different metals together. However, there have been reports of IMC happening between aluminium and steel or magnesium and zinc. These depend on the conditions of the welding, the coating on the steel, and the amount of aluminium in the magnesium alloy [59], [216-218]. In the butt joint setup, steel was placed on the advancing side (AS) and magnesium on the retreating side (RS) during FSW [57]. The rotating pin was put into the magnesium plate [56]. In the lap joint, the AZ31B sheet was placed above the steel sheet, with overlap width set by design requirements and its rolling direction oriented transverse to welding [26-28]. In butt configuration, the magnesium side was favoured by the tool pin offset from magnesium/steel interface [57]. The base materials selected for the lap configuration experiments [23], [26-28], [50], [53], [55], [58], [60] and butt configuration [59], [62], [65-66] with Mg and Steel sheets; the dimension, and thicknesses were summarised in Table 2.

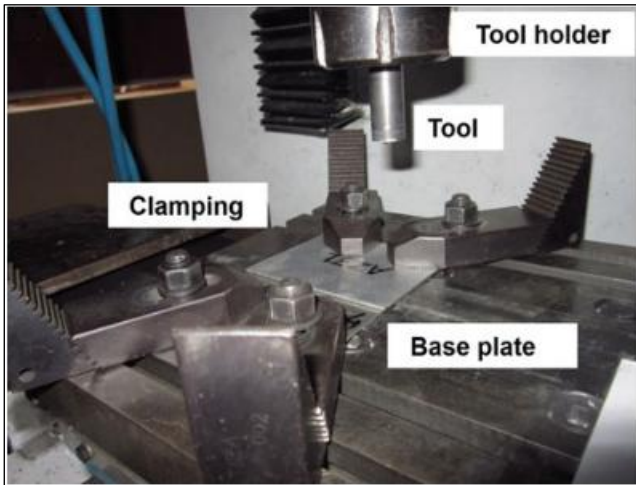


Figure 2: Schematic representation of a FSW setup.
Source: [60].

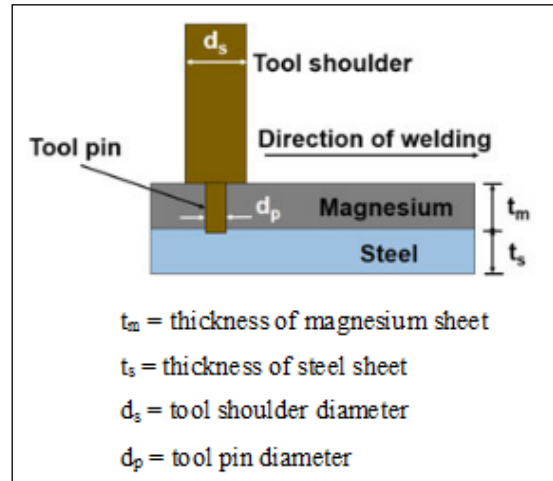


Figure 3: Representation of lap joint.
Source: [60].

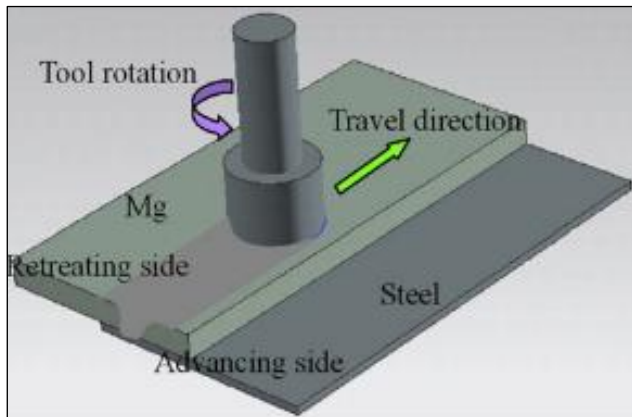


Figure 4: Experimental configuration: a friction stir lap welding process schematic.
Source: [50].

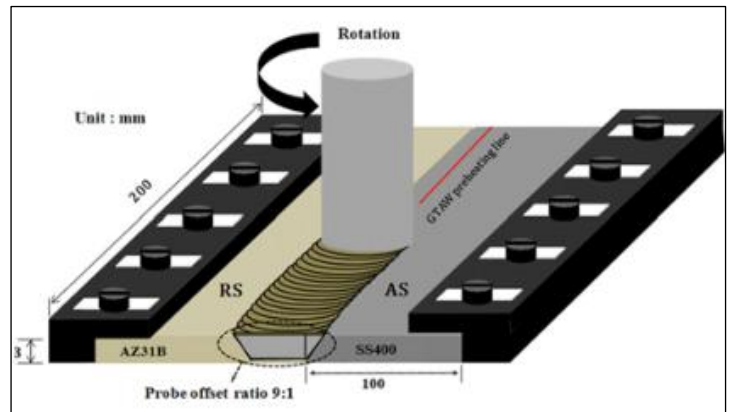


Figure 5: Schematic diagram of the HGTAFSW process.
Source: [54].

Figures 2 and 3 represent the precise welding configuration and arrangement [60]. Figure 4 illustrates the experimental configuration. As shown in Figure 4, the mg alloy has been compelled onto the steel in a lap pattern. As seen in Figure 5, the mild steel (MS) plate surface had previously GTAW preheated at a 60° angle adjacent to the intersection. This procedure guarantees improved material flow during welding and less tool wear. An anticlockwise (CCW) rotating tool was used to perform the welding operation. Positioning magnesium on the RS and mild steel on the AS produced higher joint strength compared to using a clockwise (CW) tool rotation. With tool rotation aligned to the welding direction, this configuration intensified stirring in the MS on the advancing side [54]. A high-stiffness, precision FSW machine was used to perform the welding in position-controlled mode [53].

III. FSW TOOL

In FSW, the tool plays a vital role. It generates heat and softens the workpiece to form a solid-state joint by transporting material around the pin. The tool's material and geometry are the two key factors governing its performance [11], [43-44], [46-48], [219]220]. In FSW, a non-consumable tool with a shoulder and pin generates heat, softens the workpiece, and directs material flow, thereby influencing joint formation, weld quality, mechanical properties, and process speed. [44][220-223]. Tool design is the most critical factor in advancing the FSW process. A general process development flow chart is shown in Figure 6. Reliable welds require the removal of all welding flaws, including voids and insufficient root penetration.

Despite the fact that the knowledge has mostly been empirical, appropriate tool material and tool geometry can be determined for a given joint (types of w/p material, thickness, and joint design). It is easy to achieve good metallurgical bonding between workpieces for similar material FSW. FSW of different materials is even harder when their melting or thermal properties and physical or chemical properties are very different. Weldability and tool life are affected when different workpieces are positioned on the AS or RS side in butt welding and lower or upper sheet in for lap welding, and the rotating tool is plunged to a specific location in relation to the joint interface. An optimized tool design helps suppress liquid film formation and limits brittle IMC generation when dissimilar materials exhibit strong chemical affinity at elevated temperatures. This facilitates the formation of eutectic structures at low melting temperatures and speeds up the growth of IMCs. Recent studies on FSW of dissimilar materials have largely focused on joining aluminum alloys with both low- and high-melting-point materials to evaluate joint structural performance. Several studies have also examined dissimilar FSW of high-melting-point materials, including steels and titanium alloys. For dissimilar FSW, the next sections mostly address tooling materials and tool shape design [216].

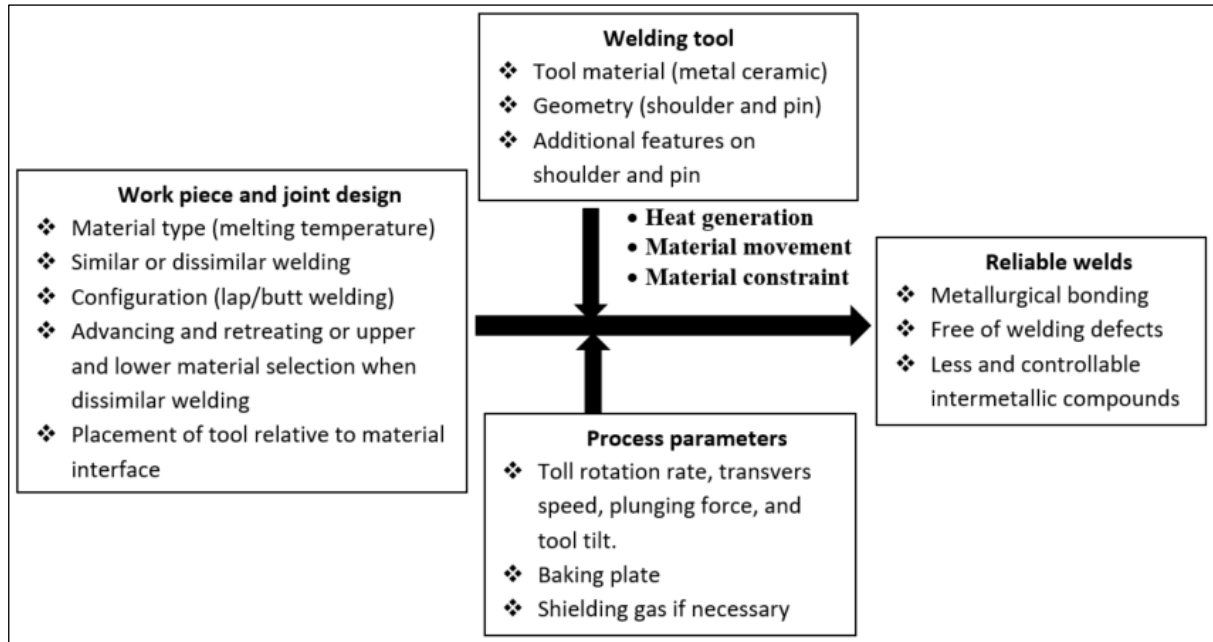


Figure 6: A typical flow chart for the development of the FSW process.
Source: [49].

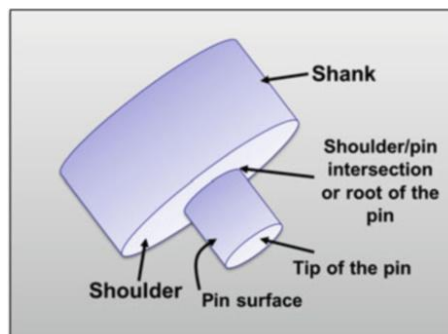


Figure 7: A friction stir welding tool.
Source: [49].

Figure 7 clearly illustrates the various features of the tool [49]. Table 2 summarizes the recommended FSW tool parameters, including tool material, shoulder profile, shoulder diameter, pin diameter, pin profile, pin length, shoulder-to-pin ratio, pin bottom diameter, and tip diameter.

III.1 TOOL MATERIAL

The right tool material must be used for the intended application in order to produce a satisfactory FSW joint. The need for welding materials like titanium, steel, and metal matrix composites has created new difficulties. An effective FSW tool must retain dimensional stability without failure or property loss during welding. The tool material should exhibit six key traits: strength at both room and process temperatures, high fatigue life, fracture toughness, wear resistance, thermal endurance, and chemical stability [49], [221]. Researchers have achieved FSW of steel to Mg alloys using H13 tool steel for the shaft and W-Re alloys for the pin [28]. Common tool materials include quenched and tempered steels, PCBN, and SKD61. For dissimilar FSW of steel to Mg, SKD61 and WC are often preferred; however, the high rotational speeds and intense forging action between steel and magnesium cause rapid tool wear and degradation. Therefore, careful selection of tool material, tool design, and process parameters is essential, as wear resistance and thermal stability limitations at high speeds remain the primary factors reducing tool life [24], [61], [223-226].

III.2 TOOL DESIGN AND GEOMETRY

FSW tool geometry strongly influences weld integrity, material flow, thermal input, and defect control. The tool has two main parts: the shoulder, which creates frictional heat and confines softened material, and the pin, which stirs and promotes mixing and recrystallization in the weld zone. Together, these factors affect flow behavior, heat distribution, force, torque, and defect prevention. A schematic of the tool is provided in Figure 8. [60]. Material flow behavior is primarily governed by the dimensions of the tool shoulder and probe. Thus, the tool profile is considered a critical factor in the FSW joining process [226], [227]. In figure 9, the stir pin was a WC rotary burr 6 mm dia. and on the cylindrical surface and 15 spiral cutting edges. The welding tool, PL=2.9, SD=25, was constructed by inserting the rotary burrs into an H13 steel holder. A penetration depth of tool 3.2 mm was applied for FSLW [50].

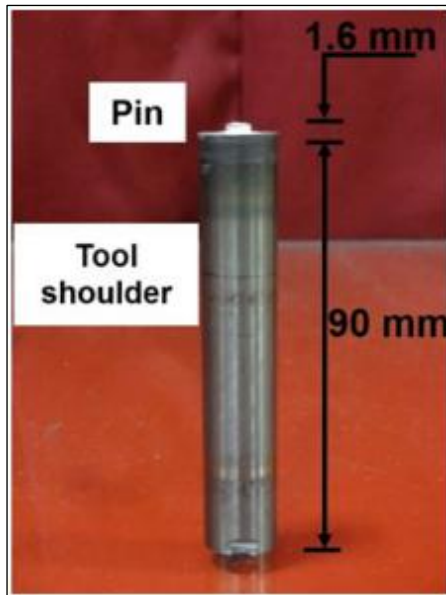


Figure 8: Schematic of FSW tool
Source: [60].

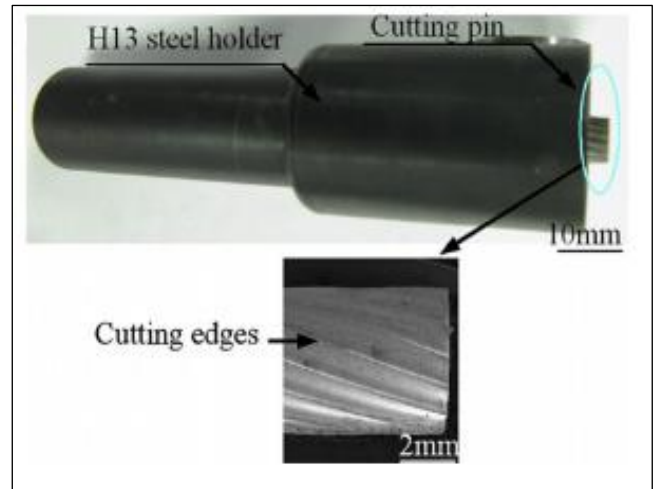


Figure 9: Appearances of the FSW tool with the design of the cutting pin.
Source: [50].

III.3 TOOL SHOULDER

The tool shoulder generates frictional heat in the surface and subsurface regions of the workpiece. In thin-sheet welding, it contributes most of the deformation and heat input [221]. In FSW, the shoulder diameter is the primary contributor to heat generation, with nearly 87% of the total heat produced through friction between the shoulder surface and the workpiece. Tool shoulder diameter and geometry surface characteristics have an impact on the FSW weld quality as they increase heat generation. Selecting the appropriate shoulder diameter is critical for producing high-quality FSW joints [48], [219], [220]. Early tool designs often used a shoulder-to-pin diameter ratio of 4:1. More recently, this ratio has been reduced to 3:1 or even 2:1 to better control heat input.

III.4 TOOL PROBES (PIN)

The tool probe generates both frictional and deformational heat. It shears material at the front, transports it to the rear, and influences the contact surfaces of the joint. The probe governs deformation depth and welding speed, while its geometry affects plasticized material flow and weld quality. Common probe designs include threadless, whorl, MX-triflute, truncated cone, triflute, trivex, and cylindrical types [44], [48], [221]. The ratio of shoulder to pin diameter (SPR) depends on the thickness of the workpiece. In dissimilar FSW, the SPR is generally higher than in similar joints, particularly for steel–magnesium alloys, where values are much greater than those for steel–steel or magnesium–magnesium welds. This is attributed to the higher hardness and lower thermal conductivity of steel compared to other materials of similar strength. Consequently, many researchers have adopted SPR values in the 4:1–10:1 range for steel–Mg dissimilar welding [228].

IV. FSW PROCESS PARAMETERS

The essential parameters of FSW are tool speed, welding speed, axial force, tilt angle, and pin offset. In addition to the criteria used for similar material systems, dissimilar FSW is further influenced by tool pin offset and the placement of base materials in the fixture [219]. Table 2 summarizes the recommended FSW tool parameters, including rotational speed, welding speed, tilt angle, plunge depth, plunge force, tool pin offset.

IV.1 ROTATIONAL SPEED

Rotational speed, defined as the revolution rate of the tool about its axis, is a key parameter influencing weld quality [229]. It accounts for nearly 40–50% of the overall effect in dissimilar FSW [44]. Higher speeds enhance the joint contact area and thermal input [30]. In dissimilar welding, tool rotation governs (i) plastic deformation through frictional heating and (ii) the plunge force, which impacts material flow, defect formation, stir zone (SZ) size, joint integrity, and tool wear. Conversely, insufficient rotation generates low heat and poor mixing, particularly in steel–Mg welds, making speed optimization essential [184], [224], [228], [229].

IV.2 WELDING SPEED OR TRAVEL SPEED

Welding or travel speed refers to the forward movement of the tool along the joint line. This parameter greatly affects the weld quality and microstructure in steel–Mg FSW, making its selection complex [230–232]. Alterations in travel rate often produce uncertain effects on joint properties [233]. Therefore, considerations such as joint configuration (butt or lap), tool rotation, plunge depth, and base material are crucial when determining the appropriate speed [228], [234–236].

IV.3 TOOL PIN OFFSET OR TOOL ECCENTRICITY

Tool pin offset is a critical parameter in dissimilar steel–Mg FSW. It refers to the displacement of the tool toward one of the base materials. In conventional (similar-material) welding, the pin is aligned at the joint center; however, applying this approach to dissimilar systems often leads to defective joints [59], [61], [69], [217], [237–242]. The distinct mechanical, chemical, and thermal characteristics of steel and magnesium—such as melting point and recrystallization temperature—make zero offset unsuitable, as it results in inadequate plastic flow and bonding [59], [228], [242–244]. Research shows that shifting the pin toward the softer or lower-conductivity material (Figure 10 (a) illustrates a central pin position (0 mm offset), while Figure 10 (b) shows a displacement of h mm toward the Mg side. With no offset, heat and deformation are insufficient due to property mismatches. Moving the tool toward magnesium increases heat generation on that side, while the steel side retains less due to its higher thermal expansion coefficient, promoting balanced stress distribution [219].

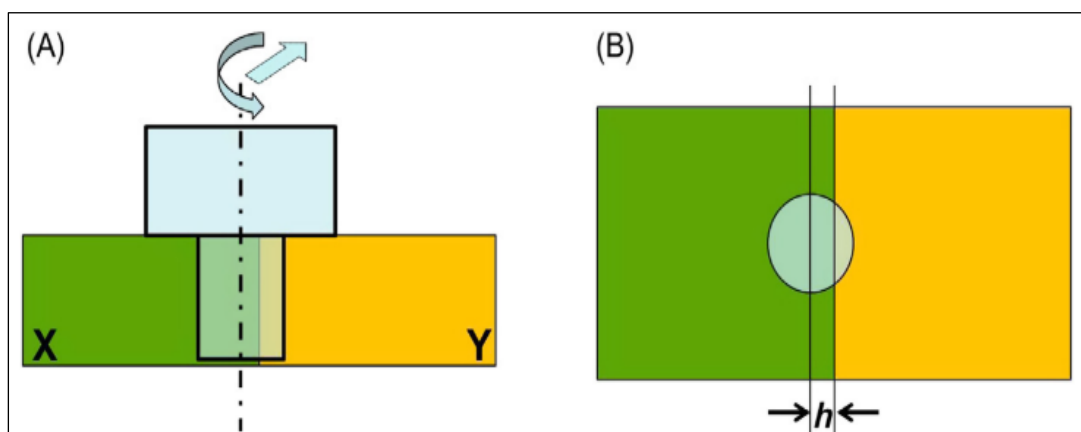


Figure 10: Tool pin offset concept (A) TPO 0 mm (B) TPO h mm w.r.t, weld centreline.

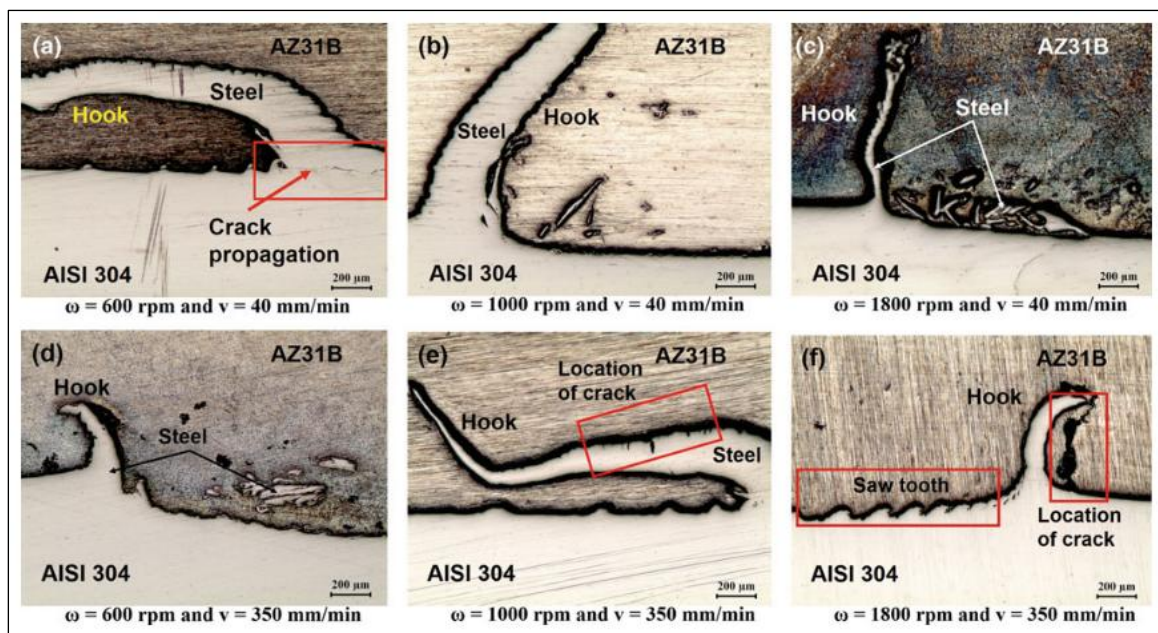
Source: [216], [219].

IV.4 TOOL TILT ANGLE

The tilt angle refers to the inclination of the FSW tool (e.g., 0° , 1° , 2° , or perpendicular to the workpiece surface) [219]. This parameter is critical for producing defect-free welds [245–248]. An optimized tilt angle provides two key benefits: (i) it confines the forged material beneath the tool shoulder with assistance from the pin [44]; and (ii) it enhances stirring, enabling uniform flow from front to rear and top to bottom, thereby ensuring proper mixing and joint quality [44], [228], [246].

V. MICROSTRUCTURES AND INTERMETALLIC COMPOUNDS

In FSW joints, the microstructure describes the grain arrangement, phase distribution, and defects observed at the microscopic scale. These features vary across weld zones as a result of heat input, plastic flow, and dynamic recrystallization. At the interface of dissimilar materials, diffusion and chemical reactions can lead to the formation of intermetallic compounds (IMCs), which significantly influence joint behavior. These compounds typically exhibit ordered atomic structures and possess properties that are distinct from those of the parent metals. Fractured surfaces from tensile specimens can be characterized using several analytical methods. Following ASTM E3-11 (2017), samples were prepared through sequential polishing with 220–2000 grit emery papers and diamond finishing to enable observation of microstructural changes induced by welding [249]. The polished samples were microetched in accordance with ASTM E407-07 [250] [251]. Metallographic characterization was performed using optical microscopy (OM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) coupled with energy-dispersive X-ray spectroscopy (EDS) [23], [50], [53–59], [251]. Post-tensile test fracture surfaces were further examined by X-ray diffraction (XRD) [55], [58], [251]. All interfaces showed bending, with dispersed steel fragments embedded in the magnesium. The probe action generated a fresh surface on the steel plate. Microstructural analysis revealed that iron was absent on the Mg side regardless of IMC thickness, while an Fe–Al intermetallic layer formed at the interface when Mg contained Al, and Mg was identified on the steel side. Thus, formation of the Fe–Al IMC layer occurs through new surface generation on the steel plate, requiring direct probe contact with the steel butt face [59].

Figure 11: Optical micrographs for different ω and v .

Source: [59].

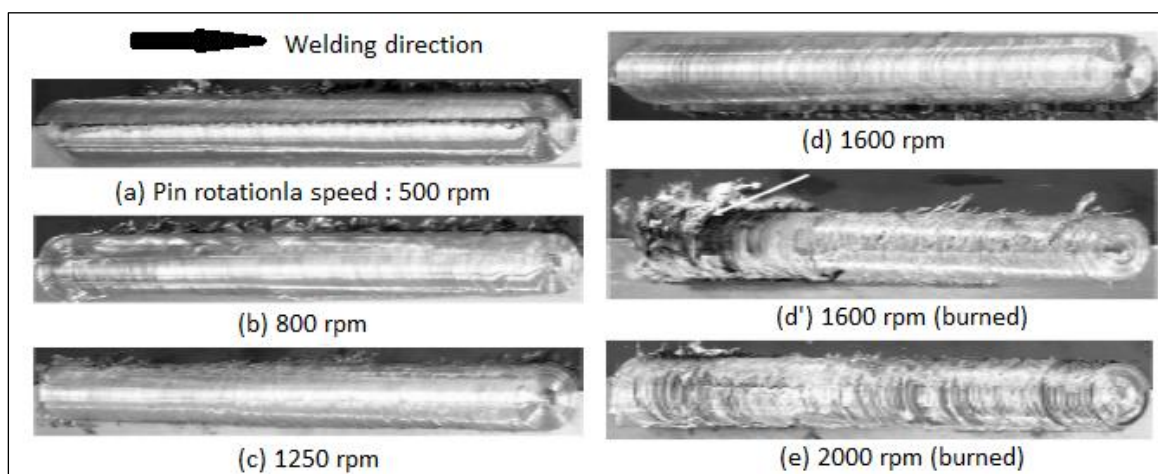


Figure 12: Effects of pin rotating speed on the surface view.

Source: [56].

Figure 12 presents weld surface features and cross-sectional morphologies. At 500 rpm, a groove-like defect appeared along the weld line due to insufficient plasticization of Mg caused by low heat input, precluding tensile evaluation. Conversely, at 2000 rpm, excessive heat led to severe ignition, producing a major root defect and resulting in very low tensile strength [56]. As indicated by the arrow in Figure 12(d'), magnesium ignition frequently occurred at a rotation speed of 1600 rpm, where the weld temperature approached its ignition limit. At 1250 rpm, the joint showed reduced tensile strength compared to 1600 rpm, with defects appearing near the root region [60]. At 800 rpm, inadequate plastic flow of magnesium produced flaws within the Mg zone, while fracture consistently propagated along the Fe–Mg interface. Alongside regions where Mg bonded to the Fe surface, flat zones were also observed (indicated by the arrow) where Mg failed to adhere. These unbonded regions are likely responsible for the reduced joint efficiency of about 70% [56]. The HGTAFS weld nugget showed a fully bonded structure without unjoined regions at the joint bottom, unlike FS welds, due to a composite of scattered mild steel fragments and recrystallized Mg grains. In the HAZ and TMAZ, Mg grains were slightly coarser in assisted FS because GTAW preheating provided additional gradual heating. Recrystallized grains in the stir zone resulted from intense plastic deformation. The steel nugget displayed finer grains at the top than the bottom, suggesting upper-section hardening from the combined influence of the rotating tool shoulder and GTAW preheating [54]. Section views of a group weld produced by FSLW at various travel speeds are displayed in Figure 13. The macrostructure characteristics of the connecting interfaces differ greatly from those of other typical FSLW (the pin without cutting the bottom metal) [252]. The steel surface layer was broken up into metal fragments and flashes by the stirring pin, which then transferred them into the magnesium base. It's possible that the pin rotation created the flower-like flashes. Figure 13.a illustrates these phenomena in vivid detail. The smooth joining interface with a few lengthy flashes remained after the scraps dropped and were destroyed as the transit speed increased. The evolution of the joining interface's macro-morphology could be attributed to the decreased friction heat input [253].

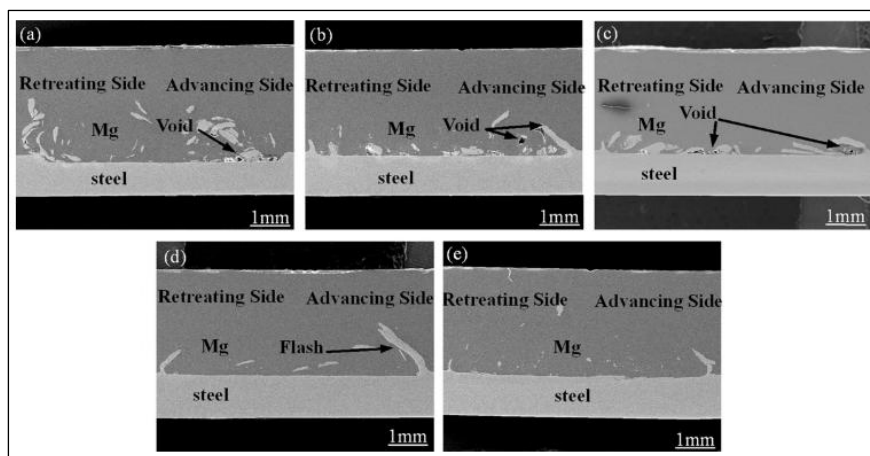


Figure 13: Interfacial macro-morphology by FSLW at welding speeds of (a) 60 mm/min, (b) 118 mm/min, (c) 150 mm/min, (d) 190 mm/min, and (e) 300 mm/min.

Source: [50].

As seen in Figure 13.e, the flashes decreased with increasing travel speed. The thinned flashes are easier for the stirring pin to cut away from the interface because less metal has been softened by friction heating at high travel speed. As shown in Figure 13.a–c, voids were discovered near the interface; however, as seen in Figure 13.d and e, they vanished when the transit speed was increased. Due to the oncoming filler metal's inadequate extrusion force at low travel speed, voids tend to form at the advancing side, as one may have observed. This phenomenon is somewhat analogous to the production of voids in FSW joints [254]. However, the joining strength may be somewhat enhanced by the decreased voids at high travel speeds [50]. As the probe length increased, the microstructure at the joining interface changed dramatically [58].

VI. MECHANICAL PROPERTIES OF DISSIMILAR MG-STEEL FSW SYSTEM

The mechanical behavior of Mg–steel dissimilar FSW joints differs markedly from similar-material welds due to the unequal properties of the base metals. Summary of recommended remarkable properties of joint welded by FSW systems, like IMCs, UTS, YS, TS, JE, Elongation, etc. shown in Table 2. Studies show that the ultimate tensile strength (UTS) of Mg–steel dissimilar FSW joints is typically lower than that of the base metals, indicating reduced efficiency compared with the weaker alloy. The UTS depends on IMC formation and joint microstructure, both of which are strongly affected by FSW process parameters. The majority of defects are caused by incorrect material flow between the steel matrix and magnesium particles, which is caused by non-optimized process parameters, and its lowers the UTS. Conversely, a reinforcing action that enhances the joint's ultimate tensile strength is conferred by small steel particles exhibiting suitable material flow inside the magnesium matrix. Thus, in order to achieve a greater UTS, the size of the steel particles is crucial. Furthermore, grain refining is strengthened by the vigorous stirring motion, which also raises the UTS. Owing to the inhomogeneous microstructure and unavoidable IMCs, these strengthening effects are insufficient to achieve a UTS greater than that of the base metals. The inherent characteristics of IMCs lower joint ductility within the stir zone, thereby reducing yield strength and fracture-to-elongation ratios [219]. Many studies employ fractography to examine the reduced fracture-to-elongation ratio, often linked to brittle fracture or finely recrystallized grains. Broken tensile specimens with flat surfaces and cracks demonstrate a mixed fracture mechanism characterised by both brittle and ductile patterns. Since a tensile specimen typically fractures in the TMAZ zone. Due to the existence of IMCs in these regions, TMAZ of the Cu side is thought to be responsible for brittle fracture [219], [247], [255], [256]. Future studies may focus on improving the tensile characteristics of dissimilar Cu–Al FSW [219].

VI.1 TENSILE STRENGTH

A UTM machine was used to test the tensile specimens. As shown in Figure 14, the AZ31B magnesium alloy was fixed in the driven crosshead to evaluate specimens under advancing side (AS) loading. Specimen dimensions followed ASTM E8M-04 standards, as illustrated in Figure 15 [54]. For testing, samples were prepared with the tensile axis oriented perpendicular to the weld line [59].

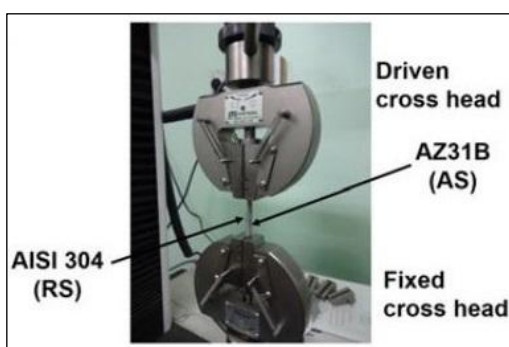


Figure 14: Tensile testing set-up.
Source: [60].

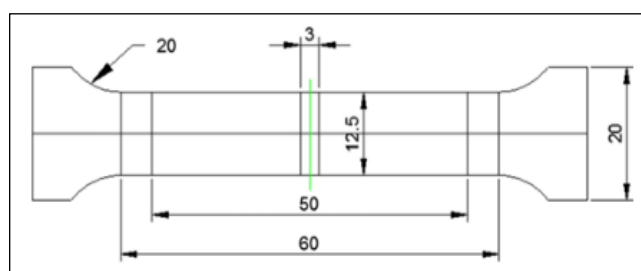


Figure 15: Geometry of the tensile test specimens.
Source: [54].

Figures 16 and 17 illustrate the relationship between RS (ω rpm) and TS (MPa), as well as WS (v mm/min) and TS (MPa), respectively. The TS of the joint diminishes as RS increases, while it consistently rises with an increase in WS. A maximum joint strength of 198.75 MPa, about 79% of the Mg base alloy was achieved at 600 rpm and 350 mm/min. All tensile samples fractured in the transition zone between the advancing side (AS) and the stir zone [60]. Joint strength is adversely affected by increased heat input and reduced cooling rates. The microstructure gets coarser with high heat input, which makes dislocation movement easier. Weld strength gradually decreased [60].

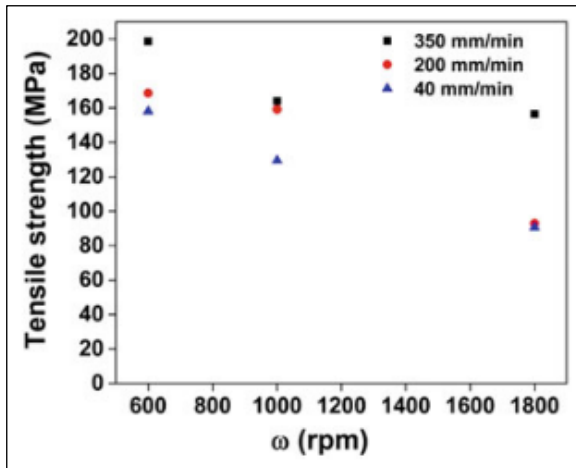


Figure 16: Tensile strength for different ω .
Source: [60].

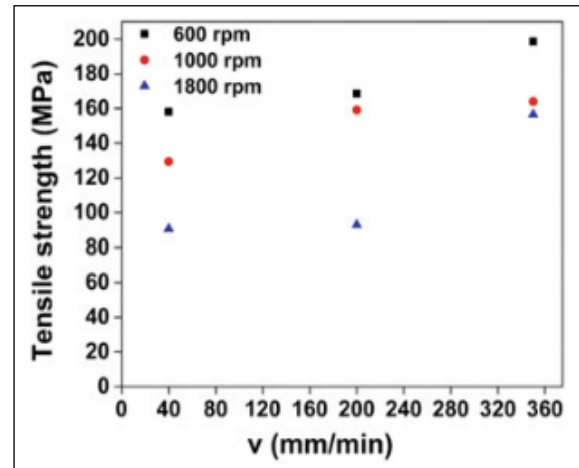


Figure 17: Tensile strength for different v .
Source: [60].

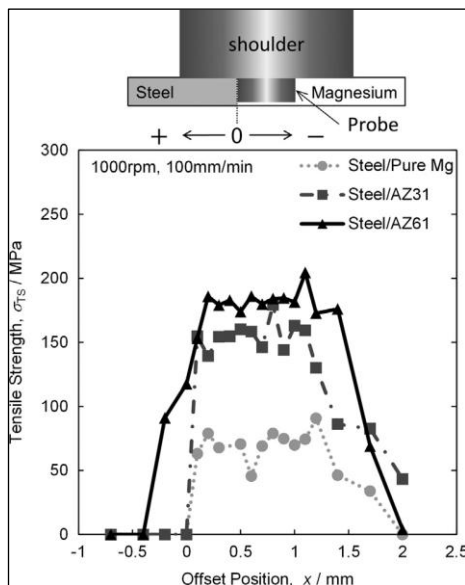


Figure 18: Relationship between joint tensile strength and tool pin offset position.
Source: [59].

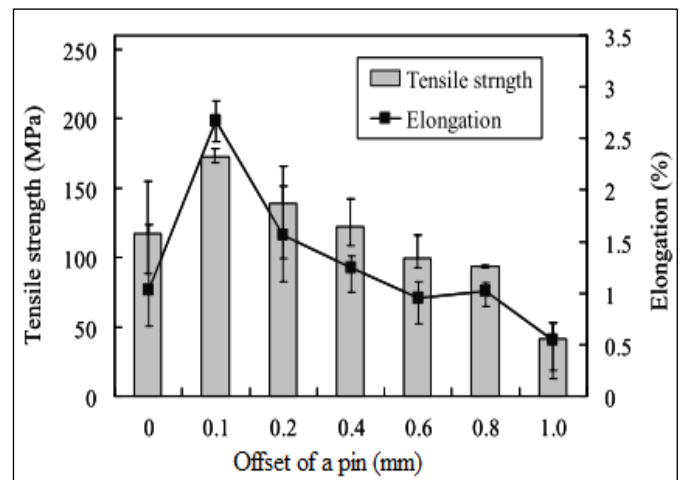


Figure 19: Relation between tensile strength, pin offset and elongation of joint.
Source: [56].

Figure 18 illustrates the correlation between tool offset position and TS at speed 1000 rpm and feed 100 mm/min. The joint between steel and various magnesium alloys, with an offset of +0.1 to +1.1 mm, demonstrated optimal high tensile strength. Numerous voids were present in the SZ when offset was excessively big in the direction of the steel-AS. In contrast, an intermetallic compound layer cannot develop when the offset position is negative (towards mg-RS). Thus, to achieve a suitable IMC layer and ensure bonding between steel and magnesium, the tool probe must contact the steel butt face [59]. Joint strength and elongation were investigated in relation to different pin offsets towards the Fe facing surface. Figure 19 shows the effect of tool pin offset on tensile strength and elongation at a welding speed of 100 mm/min and a rotation speed of 1250 rpm, with offsets between -0.2 mm and 1.0 mm. Maximum strength and elongation were achieved at a 0.1 mm offset, whereas tensile performance declined as the offset increased. At 0 mm offset strength was low, likely due to inadequate removal of the oxide film on the Fe surface. In all cases, fracture occurred along the Mg-Fe interface. Between 0.2 and 0.8 mm offsets, UTS was reduced because cracks initiated at the interface between Fe fragments dispersed in the Mg matrix and the surrounding Mg, compared with the 0.1 mm offset. At 1.0 mm, tool wear occurred, resulting in poor joint strength with bonding limited to the upper region [56]. For pure mg, and its alloy AZ31, and AZ61 plates, the average tensile strength is 170, 260, and 280 MPa, respectively. As the mg alloy's Al content increased, the joint strength increased because Al was being depleted at the mg side close to the interface. UTS of the steel/mg joint was substantially associated with the Al depletion on the mg side close to the joint edge. Under the optimal FSW conditions, the steel to mg joint failed on the mg side close to the joint interface. The improved TS resulted from the FSW's low heat input, which prevented Al depletion [59].

Figure 20 illustrates the relationship between RS, elongation, and joint TS. The fracture happens at the joint interface, and the maximum TS of a joint was approximately 70% of that of mg base metal. When the pin rotated slowly, the magnesium matrix of the joint developed a number of defects due to inadequate plasticization of the mg. Joint strength increased with pin rotation. As the mg plasticised, pushing it into an active steel surface produced pressure. However, excessive pin rotation speed caused magnesium to burn, reducing joint strength [56].

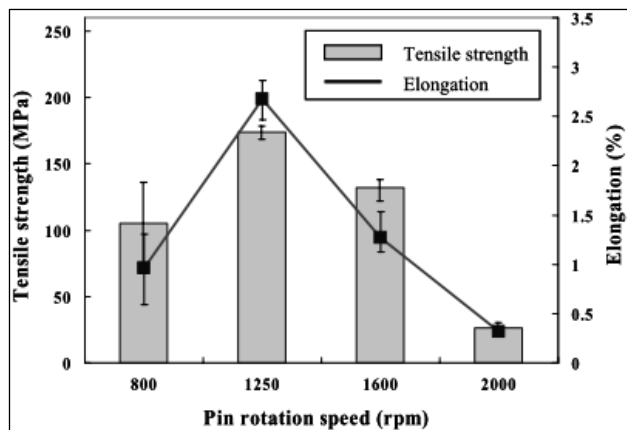


Figure 20: Relationship between TS, speed, elongation.
Source: [56].

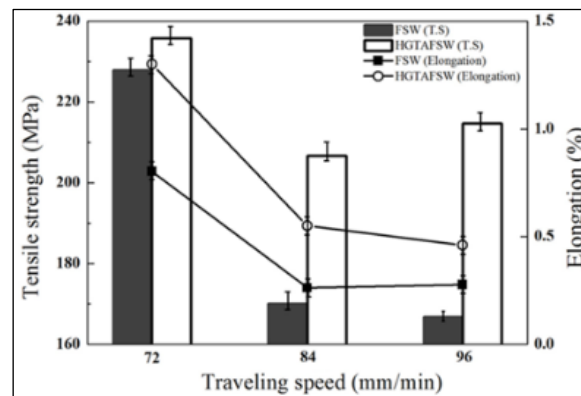


Figure 21: TS of the FSW and HGTAFSW welds.
Source: [54].

Figure 21 shows the effect of travel speed (72–96 mm/min) on the tensile strength (TS) of FSW and HGTAFSW joints. At the same speeds, HGTAFSW achieved higher TS than FSW, reaching a maximum of 237 MPa (~91% of Mg base metal) at 72 mm/min, compared with 226 MPa (~86%) for FSW. FS welds weakened with increasing speed, while HGTAFSW displayed a fluctuating trend. In FS welds, cracks often initiated at the lower joint region and propagated along the Mg–steel interface, whereas in HGTAFSW, fracture followed a similar path but with better elongation due to improved material flow and partial annealing. These findings highlight the role of steel-side preheating in enhancing joint strength [54]. Tensile properties of AZ31–SS316 and WE43–SS316 dissimilar welds were compared with their base metals, showing no significant difference between the two systems. The joints exhibited a UTS of ~160 MPa, about 73% of the Mg alloys. In both cases, fracture occurred at the weld interface due to the mismatch in elastic modulus between steel and Mg, leading to stress concentration. The presence of intermetallic compounds slightly reduced joint strength. Thermodynamic and kinetic simulations further suggested anomalous Al diffusion into Mn–Mo rich particles within SS316 during butt-welding of AZ31 and stainless steel 316 [57]. Steel and magnesium alloy are mechanically bonded together, with the bonding land only falling within the probe diameter's domain. As a result, brushed finish steel joints don't show much of failure load. AZ31–zinc-coated steel joints exhibited higher failure loads than AZ31–brushed steel joints, indicating that the zinc layer enhanced Mg–steel weldability.

A fresh metal surface was exposed as a result of the low melting eutectic phase's emergence and extrusion at the interface, increasing the mutual diffusion between steel and magnesium alloy [23]. As welding speed increases, the fracture strength (as illustrated in Figure 22) rises, and samples coated with zinc have a higher fracture strength than samples without coating. The true fracture strength of the steel–magnesium interface is greater than the measured values since all specimens fractured within the stir zone. During welding, the zinc coating on steel forms a liquid eutectic layer and acts as a flux, enhancing surface reactivity [28]. Figure 23 shows the effect of probe length on tensile strength and fracture location in AZ31–steel lap joints. Tensile testing revealed that probe length strongly influences joint properties under identical welding conditions. In zinc-coated steel joints, void defects in the stir zone limited the benefits of longer probes, while short probes produced defect-free, high-strength joints. For brushed finish steel, increasing probe length significantly improved failure loads. Similar tensile strengths for both zinc-coated cases indicated that probe extension had little effect. With a 1.5 mm probe, steel and Mg were mechanically bonded, whereas a 1.8 mm probe penetrated the steel underside, enabling stirring to create a new steel–Mg interface and promote thin diffusion bonding [58].

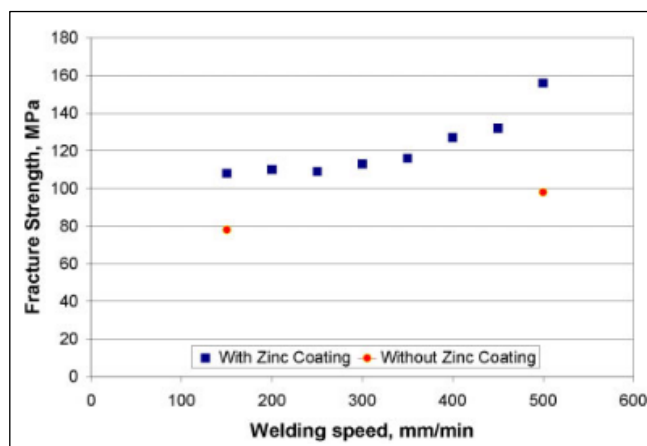


Figure 22: Influence of welding speed on fracture strength.
Source: [28].

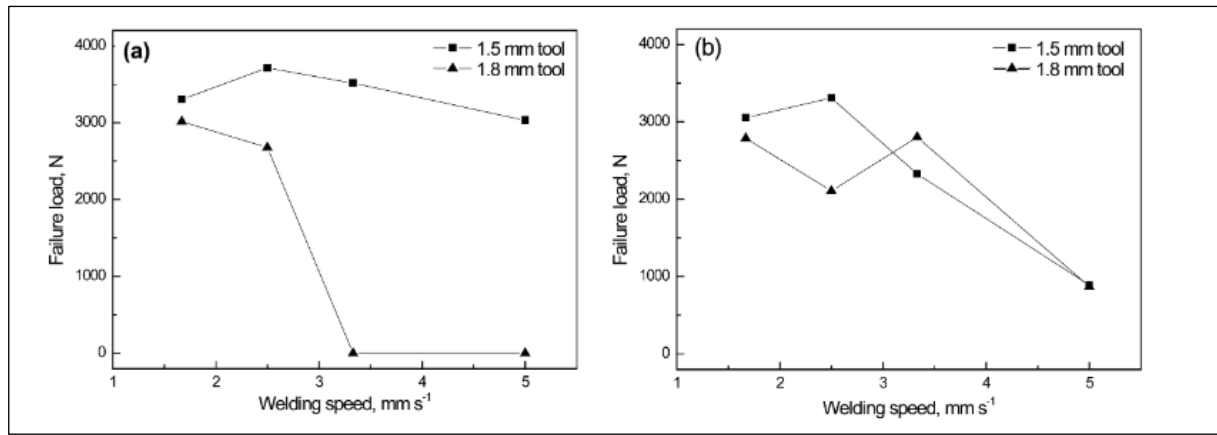


Figure 23: Effect of tool design on tensile strength: (a) brushed finish steel joints; (b) zinc-coated steel joints.

Source: [58].

Because of the intrinsic strength differential, joints manufactured of HSLA steel (1.5 mm) have a much higher failure load than joints made of MS (0.8 mm). Nevertheless, MS (0.8 mm) weld specimens sustained a significant amount of elongation before failure. All four lap shear specimens failed through interfacial separation between the top and bottom sheets. The principal mode of failure was determined as the fracture of the top magnesium layer. When tensile specimens are examined transversely, the percentage of elongation to failure decreases noticeably. Nonetheless, the percent elongation to failure is improved for the tensile specimens. In transverse tensile specimens, a reduction in yield strength and elongation indicates a compromised region within the weld cross-section. The research indicates that the weaker region is located on the advancing side [26].

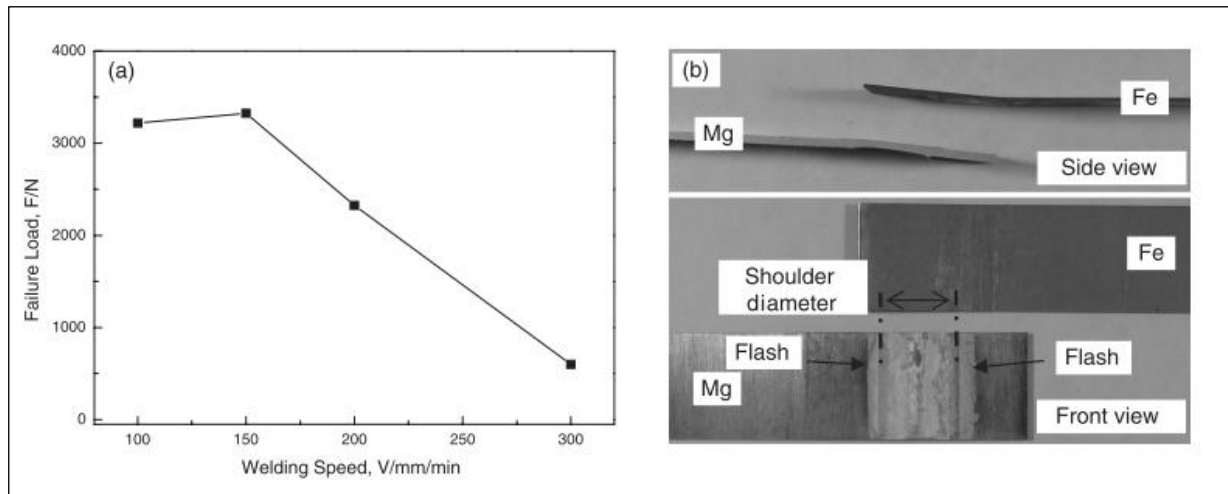


Figure 24: (a) welding speed to failure loads, and (b) fracture location.

Source: [55].

Figure 24 shows joint failure loads and fracture sites. At a WS 150 mm/min, the maximum failure load was 3.4 kN, which is about 65% of the zinc-coated steel base material. Increasing welding speed lowered the load, confirming that proper parameters are essential for strong Mg–steel lap welds. All fractures occurred at the interface, as seen in Figure 24(b). The bonded region extended beyond the probe and shoulder diameters, with solidified flash at its edges, but its width decreased sharply with higher welding speeds [55]. In friction stir welding, heat input is inversely related to travel speed and directly related to tool rotation. Thus, at constant rotation, heat input decreases as welding speed rises. Insufficient heat during higher travel rates reduces joint strength by limiting interaction between the magnesium alloy and zinc-coated steel. In contrast, excessive heat at lower speeds produces a thick reaction layer, diminishing mechanical performance. The zinc coating promotes eutectic formation at the Mg–Zn interface due to its low melting point [55].

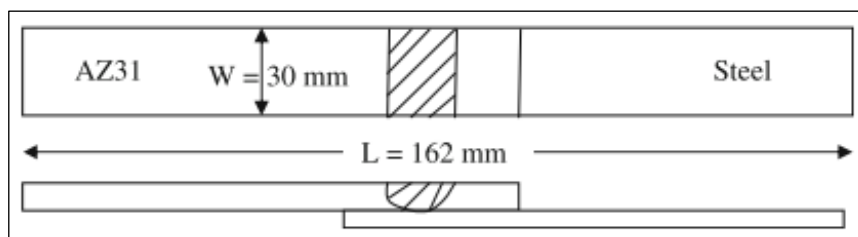


Figure 25: An illustration of the lap shear specimen.

Source: [27].

Figure 25 shows the lap shear specimen schematic. Average joint strengths were 5.1 ± 1.5 kN for AZ31 (0.8 mm) EG steel and 6.3 ± 1.0 kN for AZ31 (1.5 mm) HDG steel, with unguided lap shear tests showing peak loads of ~ 6 kN. FSW joints reached up to 80% of base metal strength, particularly in thinner 0.8 mm steel welds. Both failed by interfacial separation. Under the tool tip, the Mg/steel bond contained few Zn–Mg phases. Heat from welding melted the Zn layer, dissolving Mg and creating a Zn–Mg alloy, but much of this liquid was expelled, leaving a hardened layer without strong bonding. Thus, the thin Zn coating was ineffective as a brazing medium [27]. To guarantee that the complete shear force is applied to the joining contact, two notches were meticulously cut from the welded steel and mg, and the sample was sectioned parallel to the weld line, as shown in figure 26 [50]. Figure 27 illustrates the variation of tensile shear strength with travel speed. Strength increased with speed, peaking at 96.3 MPa at 190 mm/min, after which it declined. A dashed line marks the 88 MPa strength of an AZ31B FSW butt joint, while a horizontal line represents the 144 MPa shear strength of the AZ31 base metal [50].

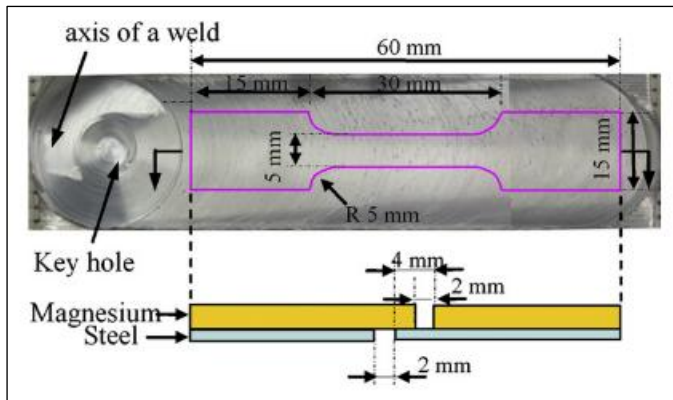


Figure 26: Tensile shear test sampling and weld appearance.
Source: [50].

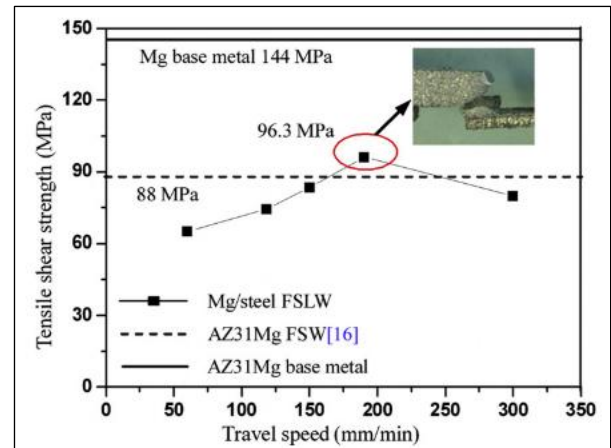


Figure 27: Joint tensile shear strength as a function of transit speed.
Source: [50].

The average minimum joint efficiency for AZ31/MS welds exceeds 60%, while for AZ31/HSLA welds using tool 1 (convex scrolled shoulder and a stepped spiral pin), it is approximately 40%. Process parameters showed an influence on joint efficiency. For AZ31/MS welds using tool 2 (Convex scrolled shoulder and a stepped spiral pin plus a short hard WC insert on the tool pin bottom), the combination of 500 RPM, 100 mm/min travel speed, and 2.47 mm plunge depth produced a weld efficiency of $> 90\%$. The AZ31/HSLA weld's weld efficiency, at the same process parameters, was around 52%, the highest in its class [53].

VI.2 HARDNESS

Microhardness of the weld zones was evaluated with a Vickers hardness tester following ASTM E384-16 standard [251]. From the mg surface to the steel surface, microhardness measurements were made in the thickness direction. When measuring hardness from the top magnesium surface, it was found that the hardness progressively increased until it reached the interface between magnesium and steel, after which it decreased when measured in steel. The hardness rises as we proceed from AS to RS. This effect may be attributed to grain refinement. The increased rate of cooling was the cause of the increase in magnesium hardness. Smaller grains with a higher hardness are produced by the faster cooling rate [60]. As shown in Figure 28, the stir zone (SZ) has higher hardness than the TMAZ, HAZ, and base metal (BM) of magnesium alloys in AZ31–SS316 and WE43–SS316 joints. No significant hardness variation was observed between AZ31 and WE43. In steel, the TMAZ exhibited greater hardness than its base material. The hardness rise in the SZ is attributed to recrystallization, whereas in the steel TMAZ it stems from work hardening followed by recrystallization [57].

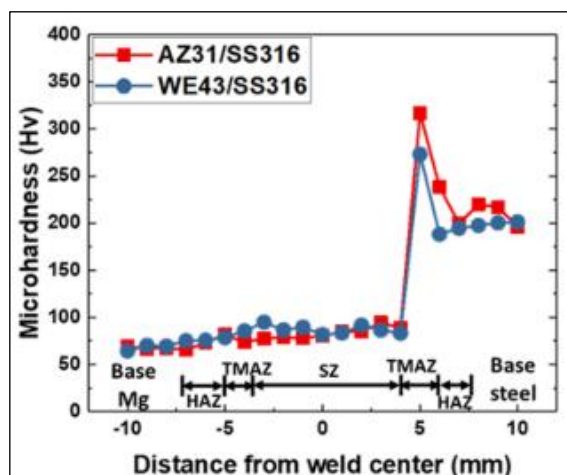


Figure 28: Microhardness profile of AZ31 to SS316 and WE43 to SS316 across the weld cross section.
Source: [57].

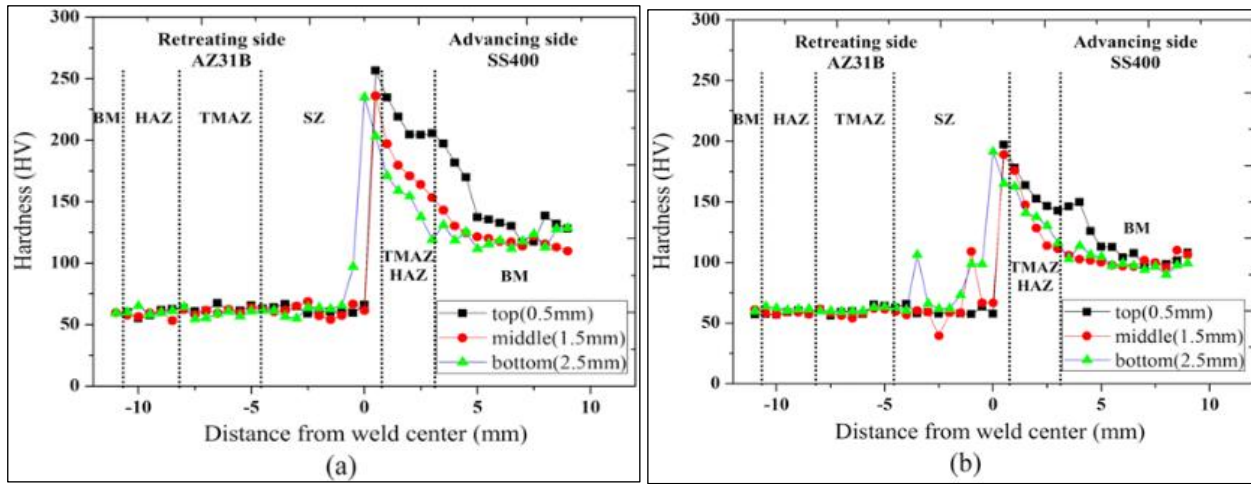


Figure 29: Cross-sectional hardness profiles (a) FS, (b) HGTAFS welds.

Source: Authors, (2026).

Figure 29 presents hardness profiles across the weld cross-section at 0.5 mm, 1.5 mm, and 2.5 mm from the top surface. Maximum values were ~250 HV in FS welds and ~190 HV in HGTAFS welds on the steel side. Hardness on the Mg retreating side was comparable to the base alloy. In steel, work hardening raised hardness in the TMAZ and HAZ, but values were slightly lower in HGTAFS than FS welds. This decrease was attributed to coarser recrystallized grains from GTAW preheating and higher frictional heat on the steel side. [54].

VII. WELDING DEFECTS OF DISSIMILAR MG-STEEL FSW SYSTEM

The various types of joining defects are caused by the incorrect joining approach and the use of non-optimal dissimilar FSW working constraints [44], [257]. Due to improperly deformed metal flow patterns and insufficient material inclusion in the FSW zone, both identical and dissimilar FSW welds are susceptible to a number of defects, including tunnel flaws, pinholes, kissing bonds, fractures, and pipe defects, among others [258-260]. A trustworthy technique for locating a number of concealed defects in the weld produced after FSW is the X-ray detection test [261]. Onion-ring defects are commonly observed in both steel and magnesium alloy with comparable FSW, frequently aggregating around the weld nugget zone (WZN). The dark and light alternating bands that define onion ring microstructures must have the same spacing between them as the tool moves forward in each revolution. Within the onion-ring microstructure, band discontinuity increases with weld length and is directly affected by tool rotation and material flow capacity [228], [262]. The primary cause of tunnelling defects is insufficient material mixing and forging action, which occurs when Welding variables including traverse speed, rotational speed, tilt angle, etc., are incompetent to generate necessary heat input for joining. In order to prevent tunnelling and void flaws during FSW, the ideal welding speed must be chosen. Future research in this area has to be properly investigated [228], [263-266]. Another type of FSW defect that can be found across the bonding surface is crack formation. Crack formation is mostly caused by small plunging depth, inappropriate pin offset, tool design, and incorrect w/p placement [267]. Cracks are typically detected in the SZ during different FSW and are classified as macro and micro-cracks. Cracks in the weld region are also likely to be caused by the development of IMCs and worse weld bonding in the SZ [268]. It is important to use appropriate parameters in FSW in order to prevent these kinds of flaws while connecting via FSW.

Defects involving fragmented or microscopic particles are uncommon in the Steel–Mg alloy welds produced by FSW and are often not present in FSW of similar and low-strength materials. Steel fragments within the Mg–Al metal matrix are regarded as defect formations. An uneven material flow fails to distribute the fine steel fragments uniformly, leaving sharp edges and surfaces unbonded, leading to voids and microcracks. This is caused by the high hardness, and reduced UTS in the stir zone. Optimizing process parameters, especially tool pin offset and feed rate can minimize fragmentation-related defects [30], [228], [269].

Lack of penetration is a common defect in dissimilar material FSW. This type of defect is typically located at the weld joint's lowest surface, and when the workpiece is isolated or lacks appropriate joints, the welds produce a weak joint. Under stress corrosion, crack initiation reduces fatigue toughness and tensile strength (weld efficiency), ultimately causing deformation or fracture. Factors like improper tool design, incorrect pin length, shallow plunging depth, varying plate thickness, and poor tool alignment influence FSW butt joints and worsen defects. Bend tests, which examine a material's ductility and soundness, can be used to find these kinds of defects [47], [228], [270]. During welding, high tool pin rotation generates intense heat around the weld interface, plasticization close to the tool shoulder and probe. This leads to excess material being expelled as surface flash. Penetration difficulties can result from variations in plunging depth (workpiece thickness variations) through the weld line and from pin lengths that are inappropriate in relation to the thickness of the w/p. Weld flash forms when softened material around the tool pin is expelled due to greater probe plunge depth. In addition, excessive tool tilt can limit softening of material filling the cavity above the weld nugget zone (WZN), causing extra flash on the retreating side (RS) [44], [30], [228]. The joint interface exhibits a "hook"-like features that increases joint strength at high welding speeds and decreases joint strength at low welding speeds. Similarly, the zipper effect, which eventually strengthens the weld's joint, is promoted by the "saw tooth" shape seen at the interface at high travel speeds [60].

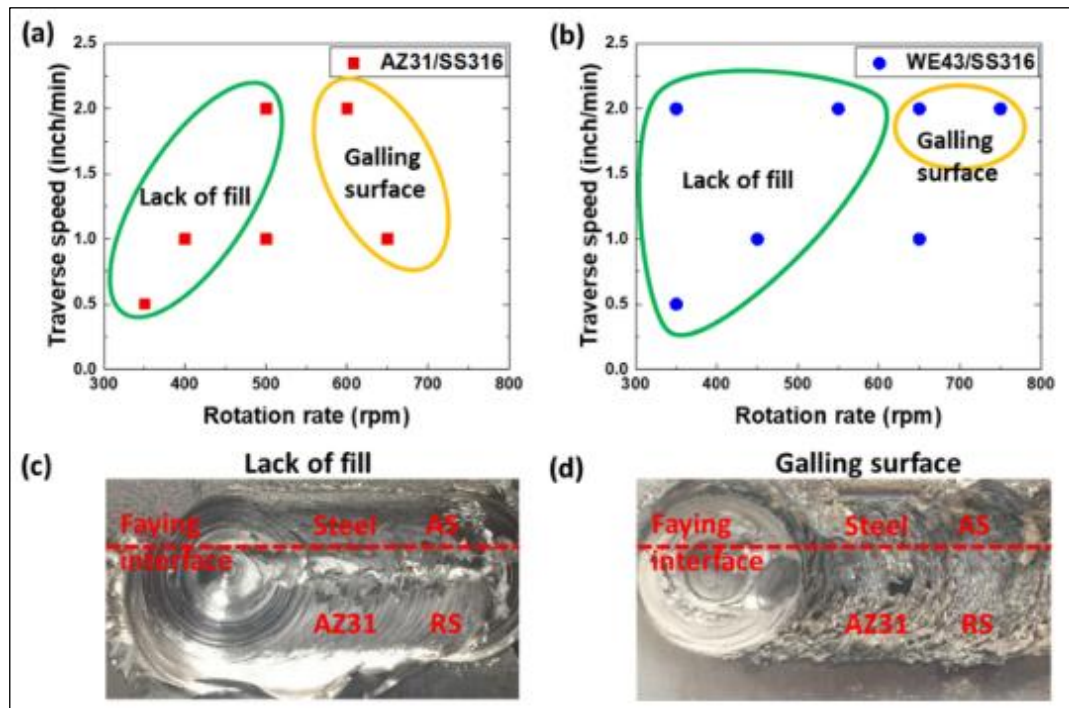


Figure 30: Relationship between FSW defects and welding parameters (a) AZ31 to SS316, (b) WE43 to SS316, (c) lack of fill and (d) galling surface.

Source: [57].

Figure 30 (a) and (b) present the rotation and travel speeds used for dissimilar butt welding of AZ31/SS316 and WE43/SS316, outlining the parameter window for defect-free joints. Two typical FSW defects were detected—lack of fill (Figure 30c) and galling surface (Figure 30d). The lack of fill was observed in magnesium near the faying interface under high travel speeds or low rotation speeds. The mg flow around the tool pin was impeded by inadequately plasticised steel. At high rotation rates, excessive heat generation led to a galling surface on the weld, caused by increased material sticking due to the elevated temperature [57].

Interfacial morphologies resembling flowers have been displayed using steel fragments and flashes. The remaining long flashes, measured in millimetres, created nail-effect bonding mechanisms as the travel speed increased, and the scraps dropped and caused damage. At the interface on the stainless-steel side, a sawtooth structure at the micron scale developed. Magnesium was used to fill the teeth, creating a Zipper effect enhances bond strength. The three bonding mechanisms are the metallurgical bonding effect by mutual diffusion, the zipper effect by the saw teeth, and the nail effect by the long steel flashes. Reduction in joint strength at high travel speeds (300 m/min) could be caused by two factors: the extended flashes' crashes could lessen the nail effect, and the decreased friction heat could weaken the metallurgical joint formation [50]. It was found that less material softens at high v because less heat is generated, resulting in thin flashes. Peeling off the flashes creates a macro-interlocked structure that results in a nail effect that strengthens the joining. Another notable feature resembling a saw-tooth pattern appeared, caused by the combined cutting and frictional action. Micro-interlocks at the weld joint may have formed as a result of the stirring force extruding magnesium into saw teeth. The zipper effect was facilitated by this interlocking. It has been discovered that the extended flashes that produce the nail effect saw tooth due to the zipper effect are responsible to enhance joint strength at higher traverse speeds. The study examined intermetallic compound formation at the AZ31/AZ61 joint interface and the effect of Al content on joint strength. Results showed that higher aluminum content in magnesium improves joint strength [60].

Zn–Mg solidification phases at the joint interface and hook-like features along the Mg/steel boundary serve as stress concentrators, reducing the fatigue resistance of FSW joints. To minimize porosity effects from solidification, fatigue studies of Mg/steel welds should be carried out with uncoated steel [26].

VIII. OBSERVATIONS

- (1) The experimental findings and literature evidence on Mg-steel friction stir welding demonstrate several significant behavioural trends. First, the rotational speed of the tool was found to strongly influence joint quality; insufficient rotation led to inadequate plasticization, while excessive rotation resulted in magnesium ignition and a consequential drop in joint strength. Similarly, weld travel speed exerted a dual effect: moderate welding speeds increased joint strength through enhanced mechanical interlocking phenomena, whereas very high speeds reduced heat input and deteriorated metallurgical bonding.
- (2) Tool pin offset was identified as another critical parameter governing weld performance. A slight positive offset toward the magnesium side produced the highest tensile strength, whereas both excessive and negative offsets resulted in interfacial weakening through void formation and insufficient IMC development, respectively. Furthermore, steel fragment dispersion into the magnesium matrix during the stirring process contributed to localized reinforcement and improved load transfer.
- (3) Microstructural analysis consistently revealed hook-like features at the interface, which acted as stress concentrators and reduced effective cross-sectional thickness. The formation of intermetallic compounds including Fe–Al and Mg–Zn—was observed to influence joint brittleness and fracture mode. In particular, zinc-coated steel enhanced metallurgical bonding by promoting eutectic layer formation, though the effectiveness diminished when excessive molten zinc was expelled during stirring.

- (4) Hardness profiling across the weld cross-section showed peak hardness in the stir zone due to dynamic recrystallization and refined grain structure. Tensile fracture primarily occurred at or near the Mg–steel interface, attributable to the elastic modulus mismatch and IMC-induced embrittlement. Finally, hybrid assisted FSW techniques such as GTAW preheating demonstrated superior joint integrity, leading to improved tensile performance relative to conventional FSW.

IX. CONCLUSION AND SUMMARY

IX.1 CONCLUSION

This review examined the current understanding of dissimilar friction stir welding (FSW) between steel and magnesium alloys. Existing studies emphasize the influence of process parameters such as tool rotation, welding speed, and plunge depth on microstructure, thermal response, and mechanical performance. The inherent difficulty of joining these alloys arises from their contrasting physical and chemical properties, including melting temperature, thermal conductivity, and the formation of intermetallic compounds (IMCs). Nevertheless, research demonstrates that with optimized parameters, reliable steel–magnesium joints can be successfully produced. The key findings drawn from the literature highlight both the complexity and potential of this welding process, emphasizing the need for precise control over processing conditions to overcome material incompatibility and promote joint integrity.

Mechanical Properties – While Mg-to-steel joints may not achieve the same strength as similar-material FSW joints, proper parameter selection and post-weld treatments can enhance mechanical performance.

Tool Design & Process Optimization – Specialized tool designs can improve bonding efficiency. Additionally, using interlayers such as aluminum or zinc can enhance weldability by reducing IMC brittleness.

Formation of IMCs – Intermetallic compounds such as Fe-Al, and Fe-Mg can form at the interface, affecting joint strength. Controlling the thermal input can help reduce excessive intermetallic compound (IMC) formation.

Applications & Future Research – Optimized FSW of steel–magnesium alloys holds strong potential for manufacturing weight-efficient structures, particularly in automotive and aerospace applications. Future studies should focus on refining process parameters, exploring alternative tool materials, and investigating hybrid techniques to improve joint integrity.

Sound welds are achieved within a very narrow range of welding parameters.

IX.2 FUTURE SCOPE

Materials like magnesium and steel, which have large differences in melting points and no mutual solubility, are notoriously challenging to join using conventional welding techniques. Traditional methods such as laser and hybrid welding often result in defects when applied to these dissimilar materials. In contrast, friction stir welding (FSW) offers a promising solid-state alternative, reducing welding defects and enabling effective joining. This study examines the potential of FSW for joining magnesium to steel. Building on this, future research could focus on extending these methods to more advanced steel grades, including high-strength steels (HSS) and advanced high-strength steels (AHSS). Successfully welding magnesium to AHSS could significantly reduce the weight of automotive components while maintaining or even improving strength and stiffness. Although aluminum-AHSS joints are already being used in automotive applications, magnesium offers an even lighter alternative, presenting new opportunities for further weight reduction. Expanding FSW to handle the transition from softer to harder materials like magnesium to AHSS will require advances in tool technology. Specifically, there's a need for cost-effective, wear-resistant, and reliable tools with a longer lifespan—although some innovative tool designs are already addressing these challenges. Looking ahead, critical areas for further research include improving the weldability of magnesium-steel joints, optimizing welding parameters, understanding fracture and corrosion behavior, and enhancing fatigue resistance. Special attention should also be given to controlling the formation and morphology of intermetallic compounds (IMCs), which play a major role in joint quality. Ultimately, the increasing demand in engineering industries for lightweight yet strong materials will continue to drive the development of FSW techniques for joining dissimilar materials like magnesium and steel.

Table 2: Summary of recommended assisted FSW type, workpiece materials & W/P design, FSW tool parameter, FSW process parameter, remarkable properties of joint welded by FSW systems.

TM: Tool Material, SD: Shoulder Diameter mm, PD: Pin Diameter mm, SSP: Shoulder Surface Profile, PL: Pin Length mm, TD: Tip Diameter mm, BD: Bottom Dia. of Pin mm, SPR: Shoulder to Pin Diameter ratio, PSP: Pin Surface Profile, RS: Rotational Speed, RPM, WS: Welding Speed, mm/min, PD: Plunge Depth, TPO: Tool Pin Offset mm, TTA: Tool Tilt Angle, UTS: Ultimate Tensile Strength Mpa, TS: Tensile Strength Mpa, JE: Joint Efficiency %, EL: Elongation %.

W/P Design (mm)	Workpiece Materials & Plate Thick. (mm)	FSW Tool Parameter	FSW Process Parameter	Remarkable Properties of Joint	References
-	AZ31B-O 2.32 mm thick, HDG- HSLA steel, EG-MS 1.5, 0.8 mm thick,	TM: H13 tool steel, WC insert on the tool pin bottom SSP: convex scrolled PSP: stepped spiral	RS: 500 WS: 100 PD: 2.47	JE: > 90% in AZ31/MS JE: ~52% in AZ31/HSLA	[53]
-	AZ31 3 mm thick, stainless steel	TM: H13 steel SD: 25	RS: 950 WS: 60, 118, 150,	- Flower-like morphologies with steel flashes.	[50]

	SUS302 1 mm thick,	PSP: rotary burrs PL: 2.9	190, 300 TTA: 0	- Shear strength lap joint: 96.3 MPa	
200×100	AZ31B 3 mm thick, SS400 mild steel 3 mm thick,	TM: WC-12% Co SD: 15 PL: 2.65 TD: 5	RS: 400 WS: 72-96 TTA: 3 Shielding gas: 13 l/min argon flow	UTS: 237, 226 JE: 91 % & 86 % FM: IF	[54]
100×305	AZ31B 2.33 mm thick, HDG- HSLA steel, EG-MS 1.5 0.8 mm thick,	TM: H13 tool steel SSP: convex scrolled shoulder SD: 12.8 PL: 2.34 TD: 4.9 38 mm overlap	RS: 700 WS: 100 PD: 2.45 TTA: 0	JE: 40, 60, 80 FM: IF - Peak load was noted to be ~6 kN. JS: 80 % of the parent metal strength	[27]
300×100	AZ31 1.6 mm, Low CS (zinc coated) 0.8 mm,	TM: SKD61 tool steel SD: 15 PL: 1.5 TD: 5	RS: 1500 WS: 100-300 TTA: 3	- Zn coating forms Mg–Zn eutectic. - Mg-steel weldability improved. FM: IF	[55]
140×40	AZ31B-O 2 mm, SS400 MS 2 mm,	TM: high-speed tool steel SD: 15 PL: 1.9 TD: 3	RS: 500, 800, 1250, 1600, 2000 WS: 100 TPO: -0.2 to 1.0 mm	JE: 78% FM: IF	[56]
-	AZ31, WE43, 6 mm, SS316 5.75,	TM: W-Re SD: 16 PSP: threaded conical pin PL: 3.8 BD: 7.6 TD: 5	RS: 350, 400, 500, 600, 650 WS: 0.5, 1, 2 (ipm) PD: 4.2 to steel TTA: 2.5 TPO: 2.5 to Mg	JE: 73% FM: IF	[57]
300×100	AZ31, 1.6 mm, low carbon steel (zinc coated, and brushed finish) 0.8 mm	TM: SKD61 tool steel SD: 15 PL: 1.5 TD: 5	RS: 25 rad s ⁻¹ WS: 3.5, 5 mm s ⁻¹ TTA: 3	- Mg alloy and brushed steel failed to weld under current conditions. FM: IF	[23]
300×100	AZ31, 1.6 mm, low carbon steel (zinc coated, and brushed finish) 0.8 mm	TM: Tool Steel SKD61 SD: 15 PL: 1.5, 1.8 TD: 5	RS: 25 rad s ⁻¹ WS: 1.67-5 s ⁻¹ TTA: 3	- Long probe weld fractured in Mg SZ; short probe at the interface. - Failure loads increased with increasing probe length. - Microstructure varied with the probe length FM : FZ, SZ	[58]
100×305	AZ31B-O 2.33 mm thick, HSLA steel MS 1.5 0.8 mm thick,	TM: WC SSP: convex scrolled shoulder PSP: stepped spiral pin 38 mm overlap	RS: 500 rev min ⁻¹ WS: 1.67 mm s ⁻¹ PD: 2.47	-	[26]
300×75	pure Mg, AZ31, AZ61 2 mm thick, low carbon steel 2 mm thick,	TM: WC SD: 12 TD: 4	RS: 250-3000 WS: 100 TTA: 3 TPO: -0.7 to 2.0 mm	- Probe-Steel contact needed for IMC formation. - Peak TS at +0.1 to 1.1 mm offset. FM: IF - Increased Al in Mg improved joint strength.	[59]
150×150	AZ31B-O 2 mm thick, ultra- low carbon steel	TM: Shaft - tool steel H13, pin - 75 % W and, 25 % Re,	RS: 1200 WS: 150, 500 PD : 0.15	- Interface fracture strength exceeds the measured value.	[28]

	DX54D 2 mm thick,	SD: 12.7 PL: 2 pin had a 3.3 × 3.3 mm square shape	TTA: 0 overlap width was 65 mm magnesium sheet was placed on top	- Fracture strength rises with increased welding speed. FM : SZ	
100×80	AZ31B 1.5 mm thick, AISI 304 1 mm thick	TM: WC-10%Co SD: 16 PSP: circular pin profile PL: 1.6 TD: 5	RS: 600, 1000, 1800 WS: 40, 200, 350 PD : 0.1 TTA: 1	JE: 79 - Joint interface microhardness is higher than that of the base material. FM : IF - Hook-like feature is observed	[60]

Source: Authors, (2026).

X. AUTHOR'S CONTRIBUTION

Conceptualization: Kapil B. Pipavat, Hirenkumar I. Joshi.

Methodology: Kapil B. Pipavat, Hirenkumar I. Joshi, Ghanshyam D. Acharya.

Investigation: Kapil B. Pipavat, Hirenkumar I. Joshi, Ghanshyam D. Acharya.

Discussion of results: Kapil B. Pipavat, Hirenkumar I. Joshi, Ghanshyam D. Acharya.

Writing – Original Draft: Kapil B. Pipavat,

Writing – Review and Editing: Kapil B. Pipavat, Hirenkumar I. Joshi, Ghanshyam D. Acharya.

Resources: Hirenkumar I. Joshi, Ghanshyam D. Acharya.

Supervision: Hirenkumar I. Joshi, Ghanshyam D. Acharya.

Approval of the final text: Hirenkumar I. Joshi, Ghanshyam D. Acharya.

XI. REFERENCES

- [1] Y. F. Sun and H. Fujii, "Microstructure and mechanical properties of dissimilar spot friction stir welded Zr55 Cu30 Al10 Ni5 bulk metallic glass to pure copper," *Intermetallics*, vol. 33, pp. 113–119, Feb. 2013, doi: 10.1016/J.INTERMET.2012.10.006.
- [2] Y. Dong, H. Fujii, Y. Sun, and H. Tanigawa, "Interface microstructure evolution of dissimilar friction stir butt welded F82H steel and SUS304," *Mater. Sci. Eng. A*, vol. 528, no. 18, pp. 5812–5821, 2011, doi: 10.1016/j.msea.2011.04.023.
- [3] Y. S. Sato, S. H. C. Park, M. Michiuchi, and H. Kokawa, "Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys," *Scr. Mater.*, vol. 50, no. 9, pp. 1233–1236, May 2004, doi: 10.1016/J.SCRIPTAMAT.2004.02.002.
- [4] M. Aonuma and K. Nakata, "Effect of alloying elements on interface microstructure of Mg–Al–Zn magnesium alloys and titanium joint by friction stir welding," *Mater. Sci. Eng. B*, vol. 161, no. 1, pp. 46–49, Apr. 2009, doi: https://doi.org/10.1016/j.mseb.2009.02.020.
- [5] H. Uzun, C. Dalle Donne, A. Argagnotto, T. Ghidini, and C. Gambaro, "Friction stir welding of dissimilar Al 6013-T4 To X5CrNi18-10 stainless steel," *Mater. Des.*, vol. 26, no. 1, pp. 41–46, 2005, doi: https://doi.org/10.1016/j.matdes.2004.04.002.
- [6] Y. F. Sun, H. Fujii, and N. Tsuji, "Microstructure and mechanical properties of spot friction stir welded ultrafine grained 1050 Al and conventional grained 6061-T6 Al alloys," *Mater. Sci. Eng. A*, vol. 585, pp. 17–24, 2013, doi: 10.1016/j.msea.2013.07.030.
- [7] C. M. Chen and R. Kovacevic, "Joining of Al 6061 alloy to AISI 1018 steel by combined effects of fusion and solid state welding," *Int. J. Mach. Tools Manuf.*, vol. 44, no. 11, pp. 1205–1214, Sep. 2004, doi: 10.1016/J.IJMACHTOOLS.2004.03.011.
- [8] Y. F. Sun, H. Fujii, N. Takaki, and Y. Okitsu, "Microstructure and mechanical properties of dissimilar Al alloy/steel joints prepared by a flat spot friction stir welding technique," *Mater. Des.*, vol. 47, pp. 350–357, 2013, doi: 10.1016/j.matdes.2012.12.007.
- [9] S. T. Auwal, S. Ramesh, C. Tan, Z. Zhang, X. Zhao, and S. M. Manladan, "Recent developments and challenges in welding of magnesium to titanium alloys," *Adv. Mater. Res. (South Korea)*, vol. 8, no. 1, pp. 47–73, 2019, doi: 10.12989/AMR.2019.8.1.047.
- [10] P. Pall et al., "Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000," *Nature*, vol. 470, no. 7334, pp. 382–385, 2011, doi: 10.1038/nature09762.
- [11] R. Nandan, T. Debroy, and H. K. D. H. Bhadeshia, "Recent advances in friction-stir welding – Process , weldment structure and properties," *Prog. Mater. Sci.*, vol. 53, pp. 980–1023, 2008, doi: 10.1016/j.pmatsci.2008.05.001.
- [12] V. K. Patel, S. D. Bhole, and D. L. Chen, "Formation of zinc interlayer texture during dissimilar ultrasonic spot welding of magnesium and high strength low alloy steel," *Mater. Des.*, vol. 45, pp. 236–240, 2013, doi: 10.1016/j.matdes.2012.09.018.
- [13] M. Wahba and S. Katayama, "Laser welding of AZ31B magnesium alloy to Zn-coated steel," *Mater. Des.*, vol. 35, pp. 701–706, 2012, doi: 10.1016/j.matdes.2011.10.031.
- [14] L. M. Liu and X. Zhao, "Study on the weld joint of Mg alloy and steel by laser-GTA hybrid welding," *Mater. Charact.*, vol. 59, no. 9, pp. 1279–1284, 2008, doi: 10.1016/j.matchar.2007.10.012.
- [15] C. Tan, L. Li, Y. Chen, and W. Guo, "Laser-tungsten inert gas hybrid welding of dissimilar metals AZ31B Mg alloys to Zn coated steel," *Mater. Des.*, vol. 49, pp. 766–773, 2013, doi: 10.1016/j.matdes.2013.02.049.

- [16] X. Qi and G. Song, "Interfacial Structure of the Joints between Magnesium Alloy and Mild Steel with Nickel as Interlayer by Hybrid Laser-TIG Welding," *Mater. Des.*, vol. 31, no. 1, pp. 605–609, 2010, doi: 10.1016/j.matdes.2009.06.043.
- [17] L. Liu and X. Qi, "Strengthening effect of nickel and copper interlayers on hybrid laser-TIG welded joints between magnesium alloy and mild steel," *Mater. Des.*, vol. 31, no. 8, pp. 3960–3963, 2010, doi: 10.1016/j.matdes.2010.03.039.
- [18] G. Song, G. An, and L. Liu, "Effect of gradient thermal distribution on butt joining of magnesium alloy to steel with Cu-Zn alloy interlayer by hybrid laser-tungsten inert gas welding," *Mater. Des.*, vol. 35, pp. 323–329, 2012, doi: 10.1016/j.matdes.2011.09.006.
- [19] Z. Z. Zeng Zhi, Li Xunbo, Miao, Yugang, Wu Gang, "Numerical and experiment analysis of residual stress on magnesium alloy and steel butt joint by hybrid laser-TIG welding," *Comput. Mater. Sci.*, vol. 50, 2011, doi: 10.1016/j.commatsci.2011.01.011.
- [20] W. M. Elthalabawy and T. I. Khan, "Microstructural development of diffusion-brazed austenitic stainless steel to magnesium alloy using a nickel interlayer," *Mater. Charact.*, vol. 61, no. 7, pp. 703–712, 2010, doi: 10.1016/j.matchar.2010.04.001.
- [21] X. D. Qi and L. M. Liu, "Investigation on welding mechanism and interlayer selection of magnesium/steel lap joints," *Weld. J. (Miami, Fla)*, vol. 90, no. 1, 2011.
- [22] A. M. Nasiri, D. C. Weckman, and Y. Zhou, "Interfacial microstructure of laser brazed AZ31B magnesium to Snplated steel sheet," *Weld. J.*, vol. 94, no. 3, pp. 61S–72S, 2015.
- [23] Y. C. Chen and K. Nakata, "Effect of surface states of steel on microstructure and mechanical properties of lap joints of magnesium alloy and steel by friction stir welding," *Sci. Technol. Weld. Join.*, vol. 15, no. 4, pp. 293–298, 2010, doi: 10.1179/136217109X12568132624325.
- [24] Y. C. Chen and K. Nakata, "Effect of tool geometry on microstructure and mechanical properties of friction stir lap welded magnesium alloy and steel," *Mater. Des.*, vol. 30, 2009, doi: 10.1016/j.matdes.2009.03.007.
- [25] Y. C. Chen and K. Nakata, "Friction Stir Lap Welding of Magnesium Alloy and Zinc-Coated Steel," *Mater. Trans.*, vol. 50, 2009, doi: 10.2320/matertrans.M2009022.
- [26] S. Jana and Y. Hovanski, "Fatigue behaviour of magnesium to steel dissimilar friction stir lap joints," *Sci. Technol. Weld. Join.*, vol. 17, no. 2, pp. 141–145, 2012, doi: 10.1179/1362171811Y.00000000083.
- [27] S. Jana, Y. Hovanski, and G. J. Grant, "Friction stir lap welding of magnesium alloy to steel: A preliminary investigation," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 41, no. 12, pp. 3173–3182, 2010, doi: 10.1007/s11661-010-0399-8.
- [28] C. Schneider, T. Weinberger, J. Inoue, T. Koseki, and N. Enzinger, "Characterisation of interface of steel/magnesium FSW," *Sci. Technol. Weld. Join.*, vol. 16, no. 1, pp. 100–106, 2011, doi: 10.1179/1362171810Y.00000000012.
- [29] H. Okamoto; M.E. Schlesinger; E.M. Mueller, Ed., *Binary Alloy Phase Diagrams*. 2016. doi: <https://doi.org/10.31399/asm.hb.v03.9781627081634>.
- [30] T. Liyanage, J. Kilbourne, A. P. Gerlich, and T. H. North, "Joint formation in dissimilar Al alloy/steel and Mg alloy/steel friction stir spot welds," *Sci. Technol. Weld. Join.*, vol. 14, no. 6, pp. 500–508, 2009, doi: 10.1179/136217109X456960.
- [31] H. K. Mao and P. M. Bell, "Equations of State of MgO and ϵ Fe Under Static Pressure Conditions," vol. 84, no. 8, pp. 4533–4536, 1979.
- [32] L. Liu, L. Xiao, J. Feng, L. Li, S. Esmaili, and Y. Zhou, "Bonding of immiscible Mg and Fe via a nanoscale Fe₂Al₅ transition layer," vol. 65, pp. 982–985, 2011, doi: 10.1016/j.scriptamat.2011.08.026.
- [33] Y. M. Baqer, S. Ramesh, F. Yusof, and S. M. Manladan, "Challenges and advances in laser welding of dissimilar light alloys : Al / Mg , Al / Ti , and Mg / Ti alloys," pp. 18–20, 2018.
- [34] N. Afrin, D. L. Chen, X. Cao, and M. Jahazi, "Microstructure and tensile properties of friction stir welded AZ31B magnesium alloy," *Mater. Sci. Eng. A*, vol. 472, 2008, doi: 10.1016/j.msea.2007.03.018.
- [35] Z. Y. Ma, "Friction Stir Processing Technology : A Review," *Miner. Met. Mater. Soc.*, 2008, doi: 10.1007/s11661-007-9459-0.
- [36] G. Padmanaban and V. Balasubramanian, "An experimental investigation on friction stir welding of AZ31B magnesium alloy," pp. 111–121, 2010, doi: 10.1007/s00170-009-2368-1.
- [37] Y. U. Sirong, C. Xianjun, H. Zhiqiu, and L. I. U. Yaohui, "Microstructure and mechanical properties of friction stir welding of AZ31B magnesium alloy added with cerium," *J. Rare Earths*, vol. 28, no. 2, pp. 316–320, 2010, doi: 10.1016/S1002-0721(09)60104-6.
- [38] B. R. Sunil et al., "Joining of AZ31 and AZ91 Mg alloys by friction stir welding," *J. Magnes. Alloy.*, vol. 3, no. 4, pp. 330–334, 2015, doi: 10.1016/j.jma.2015.10.002.
- [39] S. W. Kallee, W. M. Thomas, and E. D. Nicholas, "Joining Friction Stir Welding of Lightweight Materials".
- [40] A. Gerlich, P. Su, M. Yamamoto, and T. H. North, "Material flow and intermixing during dissimilar friction stir welding," *Sci. Technol. Weld. Join.*, vol. 13, 2008, doi: 10.1179/174329308X283910.
- [41] P. Su, A. Gerlich, T. H. North, and G. J. Bendzsak, "Intermixing in Dissimilar Friction Stir Spot Welds," 2007, doi: 10.1007/s11661-006-9067-4.
- [42] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Templesmith, and C. J. Dawes, "GB Patent application no. 9125978.8," *Int. Pat. Appl. no. PCT/GB92/02203*, 1991.
- [43] B. T. Gibson et al., "Friction stir welding: Process, automation, and control," *J. Manuf. Process.*, pp. 1–18, 2013, doi: 10.1016/j.jmapro.2013.04.002.
- [44] R. S. Mishra and Z. Y. Ma, "Friction stir welding and processing," *Mater. Sci. Eng. R Reports*, vol. 50, no. 1–2, pp. 1–78, 2005, doi: 10.1016/j.mser.2005.07.001.
- [45] T. W. M., "Friction Stir Welding-Process Developments and Variant Techniques," *SME Summit 2005, Oconomowoc, Milwaukee, USA, August 3-4th, 2005*, [Online]. Available: <https://cir.nii.ac.jp/crid/1571698601208037888>
- [46] W. M. Thomas, "Friction Stir Welding – Process Developments and Variant Techniques," no. January 2005, 2014.
- [47] M. W. Mahoney and R. S. Mishra, *Friction stir welding and processing*. ASM international, 2007.

- [48] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Church, P. Templesmith, and C. J. Dawes, "The Welding Institute," TWI, Int. Pat. Appl. no. pct/GB92/02203 GB Pat. Appl., no. 912598.8, 1991.
- [49] R. S. Mishra, P. S. De, and N. Kumar, "Friction Stir Welding and Processing," in *Friction Stir Welding and Processing*, Cham: Springer International Publishing, 2014, pp. 1–11. doi: 10.1007/978-3-319-07043-8_1.
- [50] Y. Wei, J. Li, J. Xiong, F. Huang, and F. Zhang, "Microstructures and mechanical properties of magnesium alloy and stainless steel weld-joint made by friction stir lap welding," *Mater. Des.*, vol. 33, no. 1, pp. 111–114, 2012, doi: 10.1016/j.matdes.2011.07.016.
- [51] P. Cavaliere and P. P. De Marco, "Superplastic behaviour of friction stir processed AZ91 magnesium alloy produced by high pressure die cast," *J. Mater. Process. Technol.*, vol. 184, 2007, doi: 10.1016/j.jmatprotec.2006.11.005.
- [52] C. L. and Z. W. Yajie Li, Fengming Qin, "A Review : Effect of Friction Stir Welding on Microstructure and Mechanical Properties of Magnesium Alloys," 2017, doi: 10.3390/met7120524.
- [53] S. Jana et al., "Solid State Joining of Magnesium to Steel," *Essent. Readings Magnes. Technol.*, vol. 9781118858, pp. 505–510, 2014, doi: 10.1002/9781118859803.ch82.
- [54] S. Joo, "Joining of dissimilar AZ31B magnesium alloy and SS400 mild steel by hybrid gas tungsten arc friction stir welding," *Met. Mater. Int.*, vol. 19, no. 6, pp. 1251–1257, 2013, doi: 10.1007/s12540-013-6016-9.
- [55] Y. C. Chen and K. Nakata, "Friction stir lap welding of magnesium alloy and zinc-coated steel," *Mater. Trans.*, vol. 50, no. 11, pp. 2598–2603, 2009, doi: 10.2320/matertrans.M2009022.
- [56] Y. Abe, T. Watanabe, H. Tanabe, and K. Kagiya, "Dissimilar metal joining of magnesium alloy to steel by FSW," *Adv. Mater. Res.*, vol. 15–17, pp. 393–397, 2007, doi: 10.4028/www.scientific.net/amr.15-17.393.
- [57] T. Wang, S. Shukla, B. Gwalani, M. Komarasamy, L. Reza-Nieto, and R. S. Mishra, "Effect of reactive alloy elements on friction stir welded butt joints of metallurgically immiscible magnesium alloys and steel," *J. Manuf. Process.*, vol. 39, no. November 2018, pp. 138–145, 2019, doi: 10.1016/j.jmapro.2019.02.009.
- [58] Y. C. Chen and K. Nakata, "Effect of tool geometry on microstructure and mechanical properties of friction stir lap welded magnesium alloy and steel," *Mater. Des.*, vol. 30, no. 9, pp. 3913–3919, 2009, doi: 10.1016/j.matdes.2009.03.007.
- [59] H. Kasai, Y. Morisada, and H. Fujii, "Dissimilar FSW of immiscible materials: Steel/magnesium," *Mater. Sci. Eng. A*, vol. 624, pp. 250–255, 2015, doi: 10.1016/j.msea.2014.11.060.
- [60] S. Sahu, O. Thorat, R. P. Mahto, S. K. Pal, and P. Srirangam, "A Review and Case Study on Mechanical Properties and Microstructure Evolution in Magnesium–Steel Friction Stir Welding," *Miner. Met. Mater. Ser.*, pp. 101–109, 2019, doi: 10.1007/978-3-030-05789-3_17.
- [61] Z. K. Zhang, X. J. Wang, P. C. Wang, and G. Zhao, "Friction stir keyholeless spot welding of AZ31 Mg alloy-mild steel," *Trans. Nonferrous Met. Soc. China (English Ed.)*, vol. 24, no. 6, pp. 1709–1716, 2014, doi: 10.1016/S1003-6326(14)63244-1.
- [62] X. Wang, C. Zhang, B. Li, and T. Li, "A preliminary investigation on friction stir spot welding of steel / Mg," *Appl. Mech. Mater.*, vol. 84–85, pp. 529–533, 2011, doi: 10.4028/www.scientific.net/AMM.84-85.529.
- [63] R. Z. Xu, D. R. Ni, Q. Yang, B. L. Xiao, C. Z. Liu, and Z. Y. Ma, "Influencing mechanism of Al-containing Zn coating on interfacial microstructure and mechanical properties of friction stir spot welded Mg–steel joint," *Mater. Charact.*, vol. 140, no. April, pp. 197–206, 2018, doi: 10.1016/j.matchar.2018.04.011.
- [64] X. J. Wang, Y. L. Wu, Z. K. Zhang, T. K. Guo, Y. X. Lu, and J. P. Shi, "The study of the microstructure and mechanical properties of friction stir spot welding joint between AZ31B magnesium alloy and steel," *Adv. Mater. Res.*, vol. 668, pp. 818–822, 2013, doi: 10.4028/www.scientific.net/AMR.668.818.
- [65] X. J. Wang, B. Q. Li, and C. Q. Zhang, "Study of friction stir spot welding of steel/magnesium," *Adv. Mater. Res.*, vol. 239–242, pp. 417–421, 2011, doi: 10.4028/www.scientific.net/AMR.239-242.417.
- [66] D. Control, "Friction Stir Spot Welding of AM60 Magnesium Alloy To DP600 Steel," vol. 2, doi: 10.21859/ijnr-12029.
- [67] Y. Uematsu, T. Kakiuchi, Y. Tozaki, and H. Kojin, "Comparative study of fatigue behaviour in dissimilar Al alloy/steel and Mg alloy/steel friction stir spot welds fabricated by scroll grooved tool without probe," *Sci. Technol. Weld. Join.*, vol. 17, no. 5, pp. 348–356, 2012, doi: 10.1179/1362171812Y.0000000014.
- [68] X. J. Wang, W. H. Li, and G. Zhao, "Connection mechanism research on friction stir spot welding without keyhole between magnesium and steel dissimilar alloys," *Mater. Res. Innov.*, vol. 18, pp. S21063–S21066, 2014, doi: 10.1179/1432891714Z.000000000471.
- [69] L. Liu, L. Xiao, J. C. Feng, Y. H. Tian, S. Q. Zhou, and Y. Zhou, "The Mechanisms of Resistance Spot Welding of Magnesium to Steel," *Metall. Mater. Trans. A*, vol. 41, no. 10, pp. 2651–2661, 2010, doi: 10.1007/s11661-010-0333-0.
- [70] K. Zhang, L. Wu, C. Tan, Y. Sun, B. Chen, and X. Song, "Influence of Al-Si coating on resistance spot welding of Mg to 22MnB5 boron steel," *J. Mater. Process. Technol.*, vol. 271, no. August 2018, pp. 23–35, 2019, doi: 10.1016/j.jmatprotec.2019.03.024.
- [71] W. Xu, D. L. Chen, L. Liu, H. Mori, and Y. Zhou, "Microstructure and mechanical properties of weld-bonded and resistance spot welded magnesium-to-steel dissimilar joints," *Mater. Sci. Eng. A*, vol. 537, pp. 11–24, 2012, doi: 10.1016/j.msea.2011.12.096.
- [72] G. Zhang, L. Liu, C. Tian, and R. Xu, "Interfacial structure of the joints between magnesium alloy and mild steel with nickel as interlayer," *Int. Conf. Logist. Eng. Manag. Comput. Sci. LEMCS 2014*, no. Lemcs, pp. 335–338, 2014, doi: 10.2991/lemcs-14.2014.79.
- [73] L. Liu, G. Zou, H. Mori, S. Esmaeili, and Y. N. Zhou, "Nanostructure of immiscible Mg-Fe dissimilar weld without interfacial intermetallic transition layer," *Mater. Des.*, vol. 92, pp. 445–449, 2016, doi: 10.1016/j.matdes.2015.12.072.
- [74] S. M. Manladan, F. Yusof, S. Ramesh, Y. Zhang, Z. Luo, and Z. Ling, "Microstructure and mechanical properties of resistance spot welded in welding-brazing mode and resistance element welded magnesium alloy/austenitic stainless steel joints," *J. Mater. Process. Technol.*, vol. 250, pp. 45–54, 2017, doi: 10.1016/j.jmatprotec.2017.07.006.
- [75] S. M. Manladan, Y. Zhang, S. Ramesh, Y. Cai, S. Ao, and Z. Luo, "Resistance element welding of magnesium alloy and austenitic stainless steel in three-sheet configurations," *J. Mater. Process. Technol.*, vol. 274, no. June, 2019, doi: 10.1016/j.jmatprotec.2019.116292.

- [76] L. Liu, L. Xiao, D. L. Chen, J. C. Feng, S. Kim, and Y. Zhou, "Microstructure and fatigue properties of Mg-to-steel dissimilar resistance spot welds," *Mater. Des.*, vol. 45, pp. 336–342, 2013, doi: 10.1016/j.matdes.2012.08.018.
- [77] D. Min, Z. Yong, and L. Jie, "Dissimilar spot welding joints of AZ31-443 ferritic stainless steel with cover plate," *Int. J. Adv. Manuf. Technol.*, vol. 85, no. 5–8, pp. 1539–1545, 2016, doi: 10.1007/s00170-015-8078-y.
- [78] D. Ren and L. Liu, "Interface microstructure and mechanical properties of arc spot welding Mg-steel dissimilar joint with Cu interlayer," *Mater. Des.*, vol. 59, pp. 369–376, 2014, doi: 10.1016/j.matdes.2014.03.006.
- [79] S. M. Manladan, F. Yusof, S. Ramesh, Y. Zhang, Z. Luo, and Z. Ling, "Resistance Element Welding of Magnesium Alloy/austenitic Stainless Steel," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 238, no. 1, 2017, doi: 10.1088/1757-899X/238/1/012004.
- [80] S. Niu, M. Lou, Y. Ma, B. Yang, H. Shan, and Y. Li, "Resistance rivet welding of magnesium/steel dissimilar materials," *Mater. Lett.*, vol. 282, p. 128876, 2021, doi: 10.1016/j.matlet.2020.128876.
- [81] T. Y. Pan, Z. Feng, M. Santella, and J. Chen, "Corrosion behavior of mixed-metal joint of magnesium to mild steel by ultrasonic spot welding with and without adhesives," *SAE Int. J. Mater. Manuf.*, vol. 6, no. 2, pp. 271–278, 2013, doi: 10.4271/2013-01-1017.
- [82] W. J. Lai and J. Pan, "Failure mode and fatigue behavior of weld-bonded lap-shear specimens of magnesium and steel sheets," *Int. J. Fatigue*, vol. 75, pp. 184–197, 2015, doi: 10.1016/j.ijfatigue.2015.01.017.
- [83] T. J. Franklin, J. Pan, M. Santella, and T. Y. Pan, "Fatigue Behavior of Dissimilar Ultrasonic Spot Welds in Lap-Shear Specimens of Magnesium and Steel Sheets," *SAE Int. J. Mater. Manuf.*, vol. 4, no. 1, pp. 581–588, 2011, doi: 10.4271/2011-01-0475.
- [84] Y. Feng, Y. Li, Z. Luo, Z. Ling, and Z. Wang, "Resistance spot welding of Mg to electro-galvanized steel with hot-dip galvanized steel interlayer," *J. Mater. Process. Technol.*, vol. 236, pp. 114–122, 2016, doi: 10.1016/j.jmatprotec.2016.05.015.
- [85] T. Y. Pan and M. Santella, "Ultrasonic Spot Welding of Galvanized Mild Steel to Magnesium AZ31B," *SAE Tech. Pap.*, pp. 0–5, 2012, doi: 10.4271/2012-01-0474.
- [86] T. Y. Pan, Z. Feng, M. L. Santella, and J. Chen, "Corrosion of ultrasonic spot weldbonds of magnesium to steel," *Magnes. Technol.*, pp. 491–496, 2014, doi: 10.1002/9781118888179.ch89.
- [87] T. Y. Pan and M. Santella, "Ultrasonic spot welding of AZ31B to Galvanized mild steel," *SAE Tech. Pap.*, vol. 3, no. 1, pp. 652–657, 2010, doi: 10.4271/2012-01-0474.
- [88] V. K. Patel, D. L. Chen, and S. D. Bhole, "Dissimilar ultrasonic spot welding of Mg-Al and Mg-high strength low alloy steel," *Theor. Appl. Mech. Lett.*, vol. 4, no. 4, p. 041005, 2014, doi: 10.1063/2.1404105.
- [89] M. Santella, E. Brown, M. Pozuelo, T. Y. Pan, and J. M. Yang, "Details of Mg-Zn reactions in AZ31 to galvanised mild steel ultrasonic spot welds," *Sci. Technol. Weld. Join.*, vol. 17, no. 3, pp. 219–224, 2012, doi: 10.1179/1362171811Y.0000000098.
- [90] V. K. Patel, S. D. Bhole, and D. L. Chen, "Characterization of ultrasonic spot welded joints of Mg-to-galvanized and ungalvanized steel with a tin interlayer," *J. Mater. Process. Technol.*, vol. 214, no. 4, pp. 811–817, 2014, doi: 10.1016/j.jmatprotec.2013.11.028.
- [91] H. Huang et al., "Surface engineering to enhance heat generation and joint strength in dissimilar materials AZ31 and DP590 ultrasonic welding," *Int. J. Adv. Manuf. Technol.*, vol. 111, no. 11–12, pp. 3095–3109, 2020, doi: 10.1007/s00170-020-06341-3.
- [92] J. Cheng, X. Hu, and X. Sun, "Molecular dynamics study on interface formation and bond strength of impact-welded Mg-steel joints," *Comput. Mater. Sci.*, vol. 185, no. April, p. 109988, 2020, doi: 10.1016/j.commatsci.2020.109988.
- [93] W. Elthalabawy and T. I. Khan, "Diffusion bonding of austenitic stainless steel 316L to a magnesium alloy," *Key Eng. Mater.*, vol. 442, pp. 26–33, 2010, doi: 10.4028/www.scientific.net/KEM.442.26.
- [94] D. W. Zhou, T. Li, S. H. Xu, and J. S. Liu, "Numerical and Experimental Investigations in Laser Welding for Steel and Magnesium Alloy," *Lasers Manuf. Mater. Process.*, vol. 5, no. 3, pp. 222–236, 2018, doi: 10.1007/s40516-018-0063-5.
- [95] C. W. Tan et al., "Influence of Al interlayer thickness on laser welding of Mg/steel," *Weld. J.*, vol. 95, no. 10, pp. 384s–394s, 2016.
- [96] D. Zhou, J. Liu, Z. Tan, and S. Xu, "Effects of Sn-foil addition on the microstructure and mechanical properties of laser welding joint for dual phase steel and magnesium alloy," *SN Appl. Sci.*, vol. 1, no. 7, 2019, doi: 10.1007/s42452-019-0729-4.
- [97] G. Casalino, P. Guglielmi, V. D. Lorusso, M. Mortello, P. Peyre, and D. Sorgente, "Laser offset welding of AZ31B magnesium alloy to 316 stainless steel," *J. Mater. Process. Technol.*, vol. 242, pp. 49–59, 2017, doi: 10.1016/j.jmatprotec.2016.11.020.
- [98] M. Windmann, A. Röttger, H. Kügler, and W. Theisen, "Laser beam welding of magnesium to coated high-strength steel 22MnB5," *Int. J. Adv. Manuf. Technol.*, vol. 87, no. 9–12, pp. 3149–3156, 2016, doi: 10.1007/s00170-016-8682-5.
- [99] C. W. Tan, L. Q. Li, Y. B. Chen, C. X. Mei, and W. Guo, "Interfacial microstructure and fracture behavior of laser welded-brazed Mg alloys to Zn-coated steel," *Int. J. Adv. Manuf. Technol.*, vol. 68, no. 5–8, pp. 1179–1188, 2013, doi: 10.1007/s00170-013-4910-4.
- [100] X. Zhao et al., "Effect of the Ni coating thickness on laser welding-brazing of Mg/steel," *J. Alloys Compd.*, vol. 769, pp. 1042–1058, 2018, doi: 10.1016/j.jallcom.2018.08.080.
- [101] L. Li, C. Tan, Y. Chen, W. Guo, and C. Mei, "CO₂ laser welding-brazing characteristics of dissimilar metals AZ31B Mg alloy to Zn coated dual phase steel with Mg based filler," *J. Mater. Process. Technol.*, vol. 213, no. 3, pp. 361–375, 2013, doi: 10.1016/j.jmatprotec.2012.10.009.
- [102] A. M. Nasiri, D. C. Weckman, and Y. Zhou, "Interfacial microstructure of diode laser brazed AZ31B magnesium to steel sheet using a nickel interlayer," *Weld. J.*, vol. 92, no. 1, 2013.
- [103] Y. G. Miao, D. F. Han, J. Z. Yao, and F. Li, "Microstructure and interface characteristics of laser penetration brazed magnesium alloy and steel," *Sci. Technol. Weld. Join.*, vol. 15, no. 2, pp. 97–103, 2010, doi: 10.1179/136217109X12518083193676.

- [104] L. Li, C. Tan, Y. Chen, W. Guo, and F. Song, "Comparative study on microstructure and mechanical properties of laser welded-brazed Mg/mild steel and Mg/stainless steel joints," *Mater. Des.*, vol. 43, pp. 59–65, 2013, doi: 10.1016/j.matdes.2012.06.057.
- [105] C. Tan et al., "Influence of Laser Power on the Microstructure and Mechanical Properties of a Laser Welded-Brazed Mg Alloy/Ni-Coated Steel Dissimilar Joint," *J. Mater. Eng. Perform.*, vol. 26, no. 6, pp. 2983–2997, 2017, doi: 10.1007/s11665-017-2726-3.
- [106] A. M. Hasiri and E. Al, "Interfacial Microstructure of Laser Brazed AZ31B Magnesium to Sn - Plated Steel Sheet," *Weld. J.*, vol. 94, no. 03, pp. 61–72, 2015.
- [107] L. Li, C. Tan, Y. Chen, W. Guo, and X. Hu, "Influence of Zn coating on interfacial reactions and mechanical properties during laser welding-brazing of Mg to steel," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 43, no. 12, pp. 4740–4754, 2012, doi: 10.1007/s11661-012-1266-6.
- [108] Y. Miao, D. Han, J. Yao, and F. Li, "Effect of laser offsets on joint performance of laser penetration brazing for magnesium alloy and steel," *Mater. Des.*, vol. 31, no. 6, pp. 3121–3126, 2010, doi: 10.1016/j.matdes.2009.12.035.
- [109] A. M. Nasiri, L. Li, S. H. Kim, Y. Zhou, D. C. Weckman, and T. C. Nguyen, "Microstructure and properties of laser brazed magnesium to coated steel," *Weld. J.*, vol. 90, no. 11, 2011.
- [110] Y. Miao, D. Han, X. Xu, and B. Wu, "Phase constitution in the interfacial region of laser penetration brazed magnesium-steel joints," *Mater. Charact.*, vol. 93, pp. 87–93, 2014, doi: 10.1016/j.matchar.2014.03.019.
- [111] C. W. Tan, Y. B. Chen, L. Q. Li, and W. Guo, "Comparative study of microstructure and mechanical properties of laser welded-brazed Mg/steel joints with four different coating surfaces," *Sci. Technol. Weld. Join.*, vol. 18, no. 6, pp. 466–472, 2013, doi: 10.1179/1362171813Y.0000000123.
- [112] C. Tan, X. Song, S. Meng, B. Chen, L. Li, and J. Feng, "Laser welding-brazing of Mg to stainless steel: joining characteristics, interfacial microstructure, and mechanical properties," *Int. J. Adv. Manuf. Technol.*, vol. 86, no. 1–4, pp. 203–213, 2016, doi: 10.1007/s00170-015-8165-0.
- [113] G. Song, T. Li, J. Chi, and L. Liu, "Bonding of immiscible Mg/steel by butt fusion welding," *Scr. Mater.*, vol. 157, pp. 10–14, 2018, doi: 10.1016/j.scriptamat.2018.07.031.
- [114] G. Song, T. Li, Z. Zhang, and L. Liu, "Investigation of unequal thickness Mg/steel butt-welded plate by hybrid laser-tungsten inert gas welding with a Ni interlayer," *J. Manuf. Process.*, vol. 30, pp. 299–302, 2017, doi: 10.1016/j.jmapro.2017.09.019.
- [115] X. D. Qi and L. M. Liu, "Comparative study on characteristics of hybrid laser-TIG welded AZ61/Q235 lap joints with and without interlayers," *J. Mater. Sci.*, vol. 45, no. 14, pp. 3912–3920, 2010, doi: 10.1007/s10853-010-4451-2.
- [116] L. Liu and R. Xu, "Investigation of corrosion behavior of Mg-steel laser-TIG hybrid lap joints," *Corros. Sci.*, vol. 54, no. 1, pp. 212–218, 2012, doi: 10.1016/j.corsci.2011.09.017.
- [117] L. Liu, X. Qi, and Z. Zhang, "The effect of alloying elements on the shear strength of the lap joint of AZ31B Magnesium alloy to Q235 steel by Hybrid Laser-Tig welding technique," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 43, no. 6, pp. 1976–1988, 2012, doi: 10.1007/s11661-011-1071-7.
- [118] G. Song, T. Li, and L. Chen, "The mechanical properties and interface bonding mechanism of immiscible Mg/steel by laser-tungsten inert gas welding with filler wire," *Mater. Sci. Eng. A*, vol. 736, pp. 306–315, 2018, doi: 10.1016/j.msea.2018.08.078.
- [119] L. M. Liu and C. Shan, "Study on laser-tungsten inert gas hybrid welding of dissimilar Mg alloy and steel with Ni as interlayer," *Materwiss. Werkstsch.*, vol. 40, no. 10, pp. 780–783, 2009, doi: 10.1002/mawe.200900497.
- [120] G. Song and C. Shan, "Microstructures of laser-tungsten inert gas hybrid welding of dissimilar AZ31 Mg alloy and Q235 steel with Ni as interlayer," *Mater. Res. Innov.*, vol. 15, no. 2, pp. 145–149, 2011, doi: 10.1179/143307511X12998222919074.
- [121] L. Liu and X. Qi, "Effects of copper addition on microstructure and strength of the hybrid laser-TIG welded joints between magnesium alloy and mild steel," *J. Mater. Sci.*, vol. 44, no. 21, pp. 5725–5731, 2009, doi: 10.1007/s10853-009-3797-9.
- [122] L. Liu, X. Qi, and Z. Wu, "Microstructural characteristics of lap joint between magnesium alloy and mild steel with and without the addition of Sn element," *Mater. Lett.*, vol. 64, no. 1, pp. 89–92, 2010, doi: 10.1016/j.matlet.2009.10.023.
- [123] G. Song, J. Yu, T. Li, J. Wang, and L. Liu, "Effect of laser-GTAW hybrid welding heat input on the performance of Mg/Steel butt joint," *J. Manuf. Process.*, vol. 31, pp. 131–138, 2018, doi: 10.1016/j.jmapro.2017.09.029.
- [124] G. Song, H. yang Wang, T. tao Li, and L. ming Liu, "Joining mechanism of Mg alloy/steel butt joints with Cu–Zn interlayer by hybrid laser–TIG welding source," *J. Iron Steel Res. Int.*, vol. 25, no. 2, pp. 221–227, 2018, doi: 10.1007/s42243-018-0024-4.
- [125] Y. Miao, B. Wu, X. Xu, and D. Han, "Effect of heat input on microstructure and mechanical properties of joints made by bypass-current MIG welding-brazing of magnesium alloy to galvanized steel," *Acta Metall. Sin. (English Lett.)*, vol. 27, no. 6, pp. 1038–1045, 2014, doi: 10.1007/s40195-014-0118-3.
- [126] X. Y. Wang, X. Y. Gu, D. Q. Sun, and C. Y. Xi, "Interface characteristics and mechanical behavior of metal inert-gas arc welded Mg-steel joints," *J. Mater. Res.*, vol. 31, no. 5, pp. 589–598, 2016, doi: 10.1557/jmr.2016.43.
- [127] S. Liu, D. Sun, X. Gu, and H. Li, "Microstructures and mechanical properties of metal inert-gas arc welded joints of Mg alloy and ultra-high strength steel," *J. Mater. Res.*, vol. 32, no. 4, pp. 843–851, 2017, doi: 10.1557/jmr.2016.515.
- [128] X. Y. Wang, D. Q. Sun, and Y. Sun, "Influence of Cu-Interlayer Thickness on Microstructures and Mechanical Properties of MIG-Welded Mg-Steel Joints," *J. Mater. Eng. Perform.*, vol. 25, no. 3, pp. 910–920, 2016, doi: 10.1007/s11665-016-1945-3.
- [129] X. Y. Wang, D. Q. Sun, S. Q. Yin, and D. Y. Liu, "Microstructures and mechanical properties of metal inert-gas arc welded Mg-steel dissimilar joints," *Trans. Nonferrous Met. Soc. China (English Ed.)*, vol. 25, no. 8, pp. 2533–2542, 2015, doi: 10.1016/S1003-6326(15)63872-9.
- [130] M. Kang, C. Kim, and Y. M. Kim, "Joining of AZ31 magnesium alloy and steel sheet under four different coating conditions based on gas metal arc weld-brazing," *Mater. Trans.*, vol. 58, no. 1, pp. 95–102, 2017, doi: 10.2320/matertrans.M2016224.
- [131] S. Kotari, E. Punna, S. M. Gangadhar, M. Cheepu, P. Sarkar, and S. Venukumar, "Dissimilar metals TIG welding-brazing of AZ31 magnesium alloy to 304 stainless steel," *Mater. Today Proc.*, vol. 39, no. xxxx, pp. 1549–1552, 2020, doi: 10.1016/j.matpr.2020.05.553.

- [132] M. Ding et al., "TIG-MIG hybrid welding of ferritic stainless steels and magnesium alloys with Cu interlayer of different thickness," *Mater. Des.*, vol. 88, pp. 375–383, 2015, doi: 10.1016/j.matdes.2015.09.022.
- [133] R. Z. Xu et al., "Influencing mechanism of Al–Zn coating addition on interfacial microstructure and mechanical property of vacuum electron beam welded Mg/steel joint," *Vacuum*, vol. 158, pp. 31–38, 2018, doi: 10.1016/j.vacuum.2018.09.026.
- [134] Q. Lin, F. Yang, R. Cao, J. Chen, and T. Guo, "Wetting and Interfacial Characteristics of Mg AZ61 Alloy/Galvanized Steel in Cold Metal Transfer Process," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 46, no. 9, pp. 3793–3796, 2015, doi: 10.1007/s11661-015-3005-2.
- [135] R. Cao et al., "Weldability and distortion of Mg AZ31-to-galvanized steel SPOT plug welding joint by cold metal transfer method," *J. Manuf. Sci. Eng. Trans. ASME*, vol. 139, no. 2, pp. 1–11, 2017, doi: 10.1115/1.4034009.
- [136] C. Zhang, M. Wu, Y. Wang, and J. Pu, "Microstructure and mechanical properties of cold metal transfer welded galvanized steel/magnesium alloy dissimilar joints," *Int. J. Mod. Phys. B*, vol. 34, no. 1–3, pp. 1–7, 2020, doi: 10.1142/S0217979220400603.
- [137] R. Cao, J. Y. Yu, J. H. Chen, and P. C. Wang, "Feasibility of cold-metal-transfer welding magnesium AZ31 to galvanized mild steel," *Weld. J.*, vol. 92, no. 9, 2013.
- [138] R. Cao, H. X. Zhu, Q. Wang, C. Dong, Q. Lin, and J. H. Chen, "Effects of zinc coating on magnesium alloy–steel joints produced by cold metal transfer method," *Mater. Sci. Technol. (United Kingdom)*, vol. 32, no. 18, pp. 1805–1817, 2016, doi: 10.1080/02670836.2016.1148107.
- [139] R. Cao, J. H. Chang, Q. Huang, X. B. Zhang, Y. J. Yan, and J. H. Chen, "Behaviors and effects of Zn coating on welding-brazing process of Al-Steel and Mg-steel dissimilar metals," *J. Manuf. Process.*, vol. 31, pp. 674–688, 2018, doi: 10.1016/j.jmapro.2018.01.001.
- [140] J. Chen, B. Shalchi Amirkhiz, and R. Zhang, "Continuous nanoscale Al₂Fe transition layer strengthened magnesium-steel spot joints," *Mater. Lett.*, vol. 196, pp. 242–244, 2017, doi: 10.1016/j.matlet.2017.03.020.
- [141] X. J. Yuan, G. M. Sheng, J. Luo, and J. Li, "Microstructural characteristics of joint region during diffusion-brazing of magnesium alloy and stainless steel using pure copper interlayer," *Trans. Nonferrous Met. Soc. China (English Ed.)*, vol. 23, no. 3, pp. 599–604, 2013, doi: 10.1016/S1003-6326(13)62505-4.
- [142] W. M. Elthalabawy and T. I. Khan, "Eutectic bonding of austenitic stainless steel 316L to magnesium alloy AZ31 using copper interlayer," *Int. J. Adv. Manuf. Technol.*, vol. 55, no. 1–4, pp. 235–241, 2011, doi: 10.1007/s00170-010-3026-3.
- [143] J. Cheng, X. Hu, X. Sun, A. Vivek, G. Daehn, and D. Cullen, "Multi-scale characterization and simulation of impact welding between immiscible Mg/steel alloys," *J. Mater. Sci. & Technol.*, 2020, doi: 10.1016/j.jmst.2020.04.049.
- [144] W. Elthalabawy and T. Khan, "Liquid Phase Bonding of 316L Stainless Steel to AZ31 Magnesium Alloy," *J. Mater. Sci. Technol.*, vol. 27, no. 1, pp. 22–28, 2011, doi: 10.1016/S1005-0302(11)60020-0.
- [145] T. Araki, M. Koba, S. Nambu, J. Inoue, and T. Koseki, "Reactive transient liquid phase bonding between AZ31 magnesium alloy and low carbon steel," *Mater. Trans.*, vol. 52, no. 3, pp. 568–571, 2011, doi: 10.2320/matertrans.M2010359.
- [146] T. P. Chen and W. Lin, "Optimal FSW process parameters for interface and welded zone toughness of dissimilar aluminium – steel joint," vol. 15, no. 4, pp. 279–285, 2010, doi: 10.1179/136217109X12518083193711.
- [147] M. P. Miles, Z. Feng, K. Kohkonen, B. Weickum, R. Steel, and L. Lev, "Spot joining of AA 5754 and high strength steel sheets by consumable bit," vol. 15, no. 4, pp. 325–331, 2010, doi: 10.1179/136217110X12707333260491.
- [148] K. Kumar and S. V. Kailas, "Positional dependence of material flow in friction stir welding: Analysis of joint line remnant and its relevance to dissimilar metal welding," *Sci. Technol. Weld. Join.*, vol. 15, no. 4, pp. 305–311, 2010, doi: 10.1179/136217109X12568132624280.
- [149] Y. S. Sato, A. Shiota, H. Kokawa, K. Okamoto, Q. Yang, and C. Kim, "Effect of interfacial microstructure on lap shear strength of friction stir spot weld of aluminium alloy to magnesium alloy," vol. 15, no. 4, pp. 319–324, 2010, doi: 10.1179/136217109X12568132624208.
- [150] S. M. O. Tavares, R. A. S. Castro, and P. Vilac, "Friction stir welding of T-joints with dissimilar aluminium alloys : mechanical joint characterisation," vol. 15, no. 4, pp. 312–319, 2010, doi: 10.1179/136217109X12562846839114.
- [151] D. Choi et al., "Effect of fixed location variation in friction stir welding of steels with different carbon contents," vol. 15, no. 4, pp. 299–304, 2010, doi: 10.1179/136217109X12577814486737.
- [152] L. E. Murr, L. E. Murr, and E. Paso, "A Review of FSW Research on Dissimilar Metal and Alloy Systems," vol. 19, no. November 2010, pp. 1071–1089, 2024, doi: 10.1007/s11665-010-9598-0.
- [153] V. Tran and J. Pan, "Failure modes of friction stir spot welds in cross-tension specimens of dissimilar aluminium sheets," vol. 15, no. 4, pp. 286–292, 2010, doi: 10.1179/136217109X12568132624361.
- [154] V. Pratap, S. Kumar, A. Ranjan, and B. Kuriachen, "Recent research progress in solid state friction-stir welding of aluminium – magnesium alloys : a critical review," *Integr. Med. Res.*, no. x x, pp. 1–40, 2020, doi: 10.1016/j.jmrt.2020.01.008.
- [155] R. Arun, P. Kumar, and R. Shimpi, "Materials Today : Proceedings Friction stir welding parameters and application : A review," *Mater. Today Proc.*, no. xxxx, pp. 1–5, 2019, doi: 10.1016/j.matpr.2019.07.613.
- [156] T. Debroy and H. K. D. H. Bhadeshia, "Friction stir welding of dissimilar alloys – a perspective," vol. 15, no. 4, pp. 266–270, 2010, doi: 10.1179/174329310X12726496072400.
- [157] M. S. Sidhu and S. S. Chatha, "Friction Stir Welding – Process and its Variables : A Review," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 2, no. 12, pp. 275–279, 2012.
- [158] J. P. VERMA, S. M. & MISRA, "A Critical Review of Friction Stir Welding Process," in *DAAAM INTERNATIONAL SCIENTIFIC BOOK 2015*, no. September, 2015. doi: 10.2507/daaam.scibook.2015.22.
- [159] R. P. Singh, S. Dubey, A. Singh, and S. Kumar, "Materials Today : Proceedings A review paper on friction stir welding process," *Mater. Today Proc.*, no. xxxx, pp. 5–10, 2020, doi: 10.1016/j.matpr.2020.05.208.
- [160] A. A. Luo, "Magnesium : Current and Potential Automotive Applications," pp. 42–48, 2002.

- [161] E. Mg-ai-zn, "Magnesium alloys and applications," vol. 10, no. January 1994, 2023.
- [162] Miklós Tisza, "Development of Lightweight Steels for Automotive Applications," in *Engineering Steels and High Entropy-Alloys*, 2020.
- [163] M. K. Singh, "Application of Steel in Automotive Industry Application of Steel in Automotive Industry," no. February, 2017.
- [164] B. Beheshtipour, K. Janie, H. Krawczynski, R. W. Hall, A. Foster, and H. Praturlon, "Application and development trends in high strength steel and aluminium Application and development trends in high strength steel and aluminium", doi: 10.1088/1757-899X/448/1/012031.
- [165] R. Neugebauer, C. Kraus, and S. Dietrich, "CIRP Annals - Manufacturing Technology Advances in mechanical joining of magnesium," vol. 57, pp. 283–286, 2008, doi: 10.1016/j.cirp.2008.03.025.
- [166] X. Hu, *Advanced High-Strength Steel — Basics and Applications in the Automotive*, no. April. 2021.
- [167] A. A. Luo and A. K. Sachdev, *Applications of magnesium alloys in automotive engineering*. Woodhead Publishing Limited, 2012. doi: 10.1533/9780857093844.3.393.
- [168] S. C. Kil and H. T. Kim, "Welding Technology of Lightweight Alloys," vol. 582, pp. 75–80, 2008, doi: 10.4028/www.scientific.net/MSF.580-582.75.
- [169] L. Liu, *Welding metallurgy of magnesium alloys*. Woodhead Publishing Limited, 2010. doi: 10.1533/9780857090423.1.9.
- [170] F. Czerwinski, "Welding and Joining of Magnesium Alloys," no. January, 2016, doi: 10.5772/13947.
- [171] "Services to the Automotive Industry Automotive at TWI".
- [172] K. Singh, G. Singh, and H. Singh, "Review on friction stir welding of magnesium alloys," *J. Magnes. Alloy.*, vol. 6, no. 4, pp. 399–416, 2018, doi: 10.1016/j.jma.2018.06.001.
- [173] A. Gullino, P. Matteis, and F. D. Aiuto, "Review of Aluminum-To-Steel Welding Technologies for Car-Body Applications," pp. 1–28, 2019, doi: 10.3390/met9030315.
- [174] A. Benay, "Next-Generation Automotive Manufacturing Materials and Processes," pp. 1–5, 2021.
- [175] S. K. Park, S. T. Hong, J. H. Park, K. Y. Park, Y. J. Kwon, and H. J. Son, "Effect of material locations on properties of friction stir welding joints of dissimilar aluminium alloys," *Sci. Technol. Weld. Join.*, vol. 15, no. 4, pp. 331–336, 2010, doi: 10.1179/136217110X12714217309696.
- [176] T. Sun, J. Jin, and J. Lu, "Investigation on Friction Stir Welding of Mg / Al T- Joints," 2021.
- [177] A. A. Mclean, G. L. F. Powell, I. H. Brown, and V. M. Linton, "Friction stir welding of magnesium alloy AZ31B to aluminium alloy 5083," pp. 1–3, doi: 10.1179/136217103225009134.
- [178] Y. J. Kwon, I. Shigematsu, and N. Saito, "Dissimilar friction stir welding between magnesium and aluminum alloys," vol. 62, pp. 3827–3829, 2008, doi: 10.1016/j.matlet.2008.04.080.
- [179] S. A. Hussein, A. S. M. Tahir, and A. B. Hadzley, "Characteristics of aluminum-to-steel joint made by friction stir welding: A review," *Mater. Today Commun.*, vol. 5, pp. 32–49, 2015, doi: 10.1016/j.mtcomm.2015.09.004.
- [180] H. Aghajani and F. Khodabakhshi, "Simulation and experimental study of underwater dissimilar friction-stir welding between aluminium and steel," *Integr. Med. Res.*, no. x x, 2020, doi: 10.1016/j.jmrt.2020.02.003.
- [181] H. Das, S. S. Jana, T. K. Pal, and A. De, "Numerical and experimental investigation on friction stir lap welding of aluminium to steel," *Sci. Technol. Weld. Join.*, vol. 19, no. 1, pp. 69–75, 2014, doi: 10.1179/1362171813Y.0000000166.
- [182] K. Kimapong and T. Watanabe, "Lap Joint of A5083 Aluminum Alloy and SS400 Steel by Friction Stir Welding," vol. 46, no. 4, pp. 835–841, 2005.
- [183] M. Kimura, H. Ishii, M. Kusaka, K. Kaizu, and A. Fuji, "Joining phenomena and joint strength of friction welded joint between aluminium – magnesium alloy (AA5052) and low carbon steel," vol. 14, no. 7, pp. 655–662, 2009, doi: 10.1179/136217109X12464549883411.
- [184] T. Watanabe, H. Takayama, and A. Yanagisawa, "Joining of aluminum alloy to steel by friction stir welding," vol. 178, pp. 342–349, 2006, doi: 10.1016/j.jmatprotec.2006.04.117.
- [185] W. Lee, M. Schmuecker, A. Mercardo, G. Biallas, and S. Jung, "Interfacial reaction in steel – aluminum joints made by friction stir welding," vol. 55, pp. 355–358, 2006, doi: 10.1016/j.scriptamat.2006.04.028.
- [186] L. Wan and Y. Huang, "Friction stir welding of dissimilar aluminum alloys and steels: a review," *Int. J. Adv. Manuf. Technol.*, vol. 99, no. 5–8, pp. 1781–1811, 2018, doi: 10.1007/s00170-018-2601-x.
- [187] W. H. Jiang and R. Kovacevic, "Proceedings of the Institution of Mechanical Engineers , Part B : Journal of Engineering Manufacture Feasibility study of friction stir welding of 6061-T6 aluminium alloy with AISI 1018 steel," 2004, doi: 10.1243/0954405042323612.
- [188] A. Elrefaey, M. Gouda, M. Takahashi, and K. Ikeuchi, "Characterization of Aluminum/Steel Lap Joint by Friction Stir Welding," vol. 14, no. February, pp. 10–17, 2005, doi: 10.1361/10599490522310.
- [189] A. HIROSE, "Trends of Applications and Joining Technologies of Aluminum Alloys in Automobiles," *J. Soc. Automot. Eng. Japan*, vol. 61, no. 4, pp. 18–23, 2007, [Online]. Available: <https://cir.nii.ac.jp/crid/1571980075716616064>
- [190] D. S. Kumar, C. T. Sasanka, K. Ravindra, and K. N. S. Suman, "Magnesium and Its Alloys in Automotive Applications – A Review," vol. 4, no. 1, pp. 12–30, 2015, doi: 10.7726/ajmst.2015.1002.
- [191] A. Manabe and M. E. Div, "Weight Reduction of Vehicles and Light Metals," vol. 468, pp. 463–468, 1999.
- [192] A. M. Nasiri, "Laser Brazing of Magnesium to Steel Sheet," University of Waterloo, 2013.

- [193] S. T. Auwal, S. Ramesh, F. Yusof, and S. M. Manladan, "A review on laser beam welding of titanium alloys," 2018.
- [194] S. SASABE, "Dissimilar metal joining technology of aluminum alloy to steel," J. JSAE, vol. 61, pp. 24–29, 2007, [Online]. Available: <https://cir.nii.ac.jp/crid/1570291225856347520>
- [195] M. A. Omar, The automotive body manufacturing systems and processes. John Wiley & Sons, 2011.
- [196] H. C. Kim and T. J. Wallington, "Life-Cycle Energy and Greenhouse Gas Emission Bene fits of Lightweighting in Automobiles : Review and Harmonization," 2013.
- [197] F. Humpenöder et al., "Land-use and carbon cycle responses to moderate climate change : implications for land-based mitigation ?," 2015, doi: 10.1021/es506201r.
- [198] T. Ishikawa et al., "Overview of automotive structural composites technology developments in Japan," Compos. Sci. Technol., vol. 155, pp. 221–246, 2018, doi: 10.1016/j.compscitech.2017.09.015.
- [199] M. and C. Cars and Metal, "The World Steel Association," 2008.
- [200] The World Steel Association, "Steel in automotive," 2019.
- [201] T. Senuma, "Physical Metallurgy of Modern High Strength Steel Sheets," vol. 41, no. 6, pp. 520–532, 2001.
- [202] Office of Energy Efficiency & Renewable Energy, "Lightweight materials for cars and trucks," 2014.
- [203] P. K. Sahu and S. Pal, "Influence of metallic foil alloying by FSW process on mechanical properties and metallurgical characterization of AM20 Mg alloy," Mater. Sci. Eng. A, vol. 684, 2017, doi: 10.1016/j.msea.2016.12.081.
- [204] W. Lafayette, "Magnesium Alloys 2003," vol. 422, pp. 43–50, 2003, doi: 10.4028/www.scientific.net/MSF.419-422.43.
- [205] L. Liu, D. Ren, and F. Liu, "A Review of Dissimilar Welding Techniques for Magnesium Alloys to Aluminum Alloys," pp. 3735–3757, 2014, doi: 10.3390/ma7053735.
- [206] S. M. Manladan, F. Yusof, S. Ramesh, and M. Fadzil, "A review on resistance spot welding of magnesium alloys," 2020, doi: 10.1007/s00170-015-8258-9.
- [207] S. T. Auwal et al., "Influence of electrodeposited Cu-Ni layer on interfacial reaction and mechanical properties of laser welded-brazed Mg / Ti lap joints," J. Manuf. Process., vol. 37, no. November 2018, pp. 251–265, 2019, doi: 10.1016/j.jmapro.2018.11.029.
- [208] S. R. Agnew, "Wrought Magnesium : A 21st Century Outlook," no. May, 2004.
- [209] H. Watarai, "Trend of Research and Development for Magnesium Alloys-Reducing the Weight of Structural Materials in Motor Vehicles," 2006.
- [210] W. J. Joost, "Reducing vehicle weight and improving U.S. energy efficiency using integrated computational materials engineering," Jom, vol. 64, no. 9, pp. 1032–1038, 2012, doi: 10.1007/s11837-012-0424-z.
- [211] S. Whalen, N. Overman, V. Joshi, T. Varga, D. Graff, and C. Lavender, "Magnesium alloy ZK60 tubing made by Shear Assisted Processing and Extrusion (ShAPE)," Mater. Sci. Eng. A, vol. 755, no. March, pp. 278–288, 2019, doi: 10.1016/j.msea.2019.04.013.
- [212] S. Kleinbaum, C. Jiang, and S. Logan, "Enabling sustainable transportation through joining of dissimilar lightweight materials," MRS Bull., vol. 44, no. 8, pp. 608–612, 2019, doi: 10.1557/mrs.2019.178.
- [213] L. Liu, "Welding and joining of magnesium alloys to aluminum alloys," in Welding and Joining of Magnesium Alloys, Elsevier, 2010, pp. 38-63e. doi: 10.1533/9780857090423.1.38.
- [214] V. K. Patel, S. D. Bhole, and D. L. Chen, "Influence of ultrasonic spot welding on microstructure in a magnesium alloy," Scr. Mater., vol. 65, 2011, doi: 10.1016/j.scriptamat.2011.08.009.
- [215] V. V. Joshi, D. Orlov, J. B. Jordon, and N. R. Neelameggham, Magneisum Technology 2019. 2019.
- [216] N. Kumar, W. Yuan, and R. S. R. S. Mishra, Friction Stir Welding of Dissimilar Alloys and Materials. 2015. doi: 10.1016/C2014-0-01707-8.
- [217] N. Kulkarni, R. S. Mishra, and W. Yuan, Friction stir welding of dissimilar alloys and materials. Butterworth-Heinemann, 2015.
- [218] M. Abbasi, A. K. Taheri, and M. T. Salehi, "Growth rate of intermetallic compounds in Al / Cu bimetal produced by cold roll welding process," vol. 319, pp. 233–241, 2001.
- [219] K. P. Mehta, V. J. Badheka, K. P. Mehta, and V. J. Badheka, "A Review on Dissimilar Friction Stir Welding of Copper to Aluminum : Process , Properties , and Variants," vol. 6914, no. December 2015, 2016, doi: 10.1080/10426914.2015.1025971.
- [220] D. Lohwasser and Z. Chen, Friction stir welding: From basics to applications. Elsevier, 2009.
- [221] V. Infante and C. Vidal, Tool and welding design. Woodhead Publishing Limited, 2014. doi: 10.1533/9780857094551.199.
- [222] R. Rai, H. K. D. H. Bhadeshia, and T. Debroy, "Review : friction stir welding tools," vol. 16, no. 4, pp. 325–342, 2011, doi: 10.1179/1362171811Y.0000000023.
- [223] N. Sharma, Z. A. Khan, and A. N. Siddiquee, "Friction stir welding of aluminum to copper - An overview," Trans. Nonferrous Met. Soc. China, vol. 27, no. 10, pp. 2113–2136, 2017, doi: 10.1016/S1003-6326(17)60238-3.
- [224] T. Watanabe, K. Kagiya, A. Yanagisawa, and H. Tanabe, "Solid state welding of steel and magnesium alloy using a rotating pin," Q. J. Japan Weld. Soc., vol. 24, no. 1, pp. 108–115, 2006.
- [225] A. Esmaeili, H. R. Zareie Rajani, M. Sharbati, M. K. B. Givi, and M. Shamanian, "The role of rotation speed on intermetallic compounds formation and mechanical behavior of friction stir welded brass/aluminum 1050 couple," Intermetallics, vol. 19, no. 11, pp. 1711–1719, 2011, doi: 10.1016/j.intermet.2011.07.006.
- [226] H. Fujii, L. Cui, M. Maeda, and K. Nogi, "Effect of tool shape on mechanical properties and microstructure of friction stir welded aluminum alloys," vol. 419, pp. 25–31, 2006, doi: 10.1016/j.msea.2005.11.045.

- [227] Y. N. Zhang, X. Cao, S. Larose, and P. Wanjara, "Review of tools for friction stir welding and processing," *Can. Metall. Q.*, vol. 51, no. 3, pp. 250–261, 2012, doi: 10.1179/1879139512Y.0000000015.
- [228] V. P. Singh, S. K. Patel, N. Kumar, and B. Kuriachen, "Parametric effect on dissimilar friction stir welded steel-magnesium alloys joints: a review," *Sci. Technol. Weld. Join.*, vol. 24, no. 8, pp. 653–684, 2019, doi: 10.1080/13621718.2019.1567031.
- [229] A. Barcellona, G. Buffa, L. Fratini, and others, "Process parameters analysis in friction stir welding of AA6082-T6 sheets," 2004.
- [230] E. Akinlabi and A. Els-Botes, "Effect of Travel speed on Joint properties of Dissimilar Metal Friction Stir Welds.," *News.Mak.Ac.Ug*, no. March, pp. 155–161, 2011.
- [231] K. K. Ramachandran, N. Murugan, and S. Shashi Kumar, "Influence of tool traverse speed on the characteristics of dissimilar friction stir welded aluminium alloy, AA5052 and HSLA steel joints," *Arch. Civ. Mech. Eng.*, vol. 15, no. 4, pp. 822–830, 2015, doi: 10.1016/j.acme.2015.06.002.
- [232] S. S. Sabari, S. Malarvizhi, and V. Balasubramanian, "Influences of tool traverse speed on tensile properties of air cooled and water cooled friction stir welded AA2519-T87 aluminium alloy joints," *J. Mater. Process. Technol.*, 2016, doi: 10.1016/j.jmatprotec.2016.06.015.
- [233] T. Sakthivel, G. S. Sengar, and J. Mukhopadhyay, "Effect of welding speed on microstructure and mechanical properties of friction-stir-welded aluminum," *Int. J. Adv. Manuf. Technol.*, vol. 43, no. 5–6, pp. 468–473, 2009, doi: 10.1007/s00170-008-1727-7.
- [234] Z. Shen, Y. Ding, J. Chen, and A. P. Gerlich, "Comparison of fatigue behavior in Mg/Mg similar and Mg/steel dissimilar refill friction stir spot welds," *Int. J. Fatigue*, vol. 92, pp. 78–86, 2016, doi: 10.1016/j.ijfatigue.2016.06.033.
- [235] M. Ericsson and R. Sandström, "Influence of welding speed on the fatigue of friction stir welds, and comparison with MIG and TIG," *Int. J. Fatigue*, vol. 25, no. 12, pp. 1379–1387, 2003, doi: 10.1016/S0142-1123(03)00059-8.
- [236] B. L. Prasad et al., "Joining of AZ91 Mg alloy and Al6063 alloy sheets by friction stir welding," *J. Magnes. Alloy.*, vol. 6, no. 1, pp. 71–76, 2018, doi: 10.1016/j.jma.2017.12.004.
- [237] M. Pourali, A. Abdollah-zadeh, T. Saeid, and F. Kargar, "Influence of welding parameters on intermetallic compounds formation in dissimilar steel/aluminum friction stir welds," *J. Alloys Compd.*, vol. 715, pp. 1–8, 2017, doi: 10.1016/j.jallcom.2017.04.272.
- [238] H. Okamura and K. Aota, "Joining of dissimilar materials with friction stir welding," *Weld. Int.*, vol. 18, no. 11, pp. 852–860, 2004, doi: 10.1533/wint.2004.3344.
- [239] Y. S. Sato, T. W. Nelson, C. J. Sterling, R. J. Steel, and C. O. Pettersson, "Microstructure and mechanical properties of friction stir welded SAF 2507 super duplex stainless steel," *Mater. Sci. Eng. A*, vol. 397, no. 1–2, pp. 376–384, 2005, doi: 10.1016/j.msea.2005.02.054.
- [240] S. Tan, F. Zheng, J. Chen, J. Han, Y. Wu, and L. Peng, "Effects of process parameters on microstructure and mechanical properties of friction stir lap linear welded 6061 aluminum alloy to NZ30K magnesium alloy," *J. Magnes. Alloy.*, vol. 5, no. 1, pp. 56–63, 2017, doi: 10.1016/j.jma.2016.11.005.
- [241] E. T. Akinlabi, A. Els-Botes, and H. Lombard, "Effect of tool displacement on defect formation in friction stir welding of aluminium and copper," in *Proceedings of the 8th International Friction Stir Welding Symposium*, Hamburg, Germany, 2010, pp. 76–78.
- [242] Y. Chen, J. Chen, B. Shalchi Amirkhiz, M. J. Worswick, and A. P. Gerlich, "Microstructures and properties of Mg alloy/DP600 steel dissimilar refill friction stir spot welds," *Sci. Technol. Weld. Join.*, vol. 20, no. 6, pp. 494–501, 2015.
- [243] M. M. Attallah and H. G. Salem, "Friction stir welding parameters : a tool for controlling abnormal grain growth during subsequent heat treatment," vol. 391, pp. 51–59, 2005, doi: 10.1016/j.msea.2004.08.059.
- [244] S. Zhao et al., "Effects of tool geometry on friction stir welding of AA6061 to TRIP steel," *J. Mater. Process. Technol.*, vol. 261, pp. 39–49, Nov. 2018, doi: 10.1016/j.jmatprotec.2018.06.003.
- [245] M. Akbari, R. Abdi Behnagh, and A. Dadvand, "Effect of materials position on friction stir lap welding of Al to Cu," *Sci. Technol. Weld. Join.*, vol. 17, no. 7, pp. 581–588, 2012, doi: 10.1179/1362171812Y.0000000049.
- [246] A. Arici and S. Selale, "Effects of tool tilt angle on tensile strength and fracture locations of friction stir welding of polyethylene," *Sci. Technol. Weld. Join.*, vol. 12, no. 6, pp. 536–539, 2007.
- [247] K. P. Mehta and V. J. Badheka, "Effects of tilt angle on the properties of dissimilar friction stir welding copper to aluminum," *Mater. Manuf. Process.*, vol. 31, no. 3, pp. 255–263, 2016, doi: 10.1080/10426914.2014.994754.
- [248] M. H. Tolephih, H. M. Mahmood, A. H. Hashem, and E. T. Abdullah, "Effect of tool offset and tilt angle on weld strength of butt joint friction stir welded specimens of AA2024 aluminum alloy welded to commercial pure copper," *Chem. Mater. Res.*, vol. 3, pp. 49–58, 2013.
- [249] ASTM E3-11(2017), "Standard Guide for Preparation of Metallographic Specimens," ASTM Int. West Conshohocken, PA, 2017, doi: <https://doi.org/10.1520/E0003-11R17>.
- [250] ASTM E407-07(2015)e1, "Standard Practice for Microetching Metals and Alloys," ASTM Int. West Conshohocken, PA, 2015, doi: <https://doi.org/10.1520/E0407-07R15E01>.
- [251] ASTM E384-17, "Standard Test Method for Microindentation Hardness of Materials," ASTM Int. West Conshohocken, PA, 2017, doi: <https://doi.org/10.1520/E0384-17>.
- [252] Y. C. Chen, T. Komazaki, Y. G. Kim, T. Tsumura, and K. Nakata, "Interface microstructure study of friction stir lap joint of AC4C cast aluminum alloy and zinc-coated steel," *Mater. Chem. Phys.*, vol. 111, no. 2–3, pp. 375–380, 2008, doi: 10.1016/j.matchemphys.2008.04.038.
- [253] P. Ulysse, "Three-dimensional modeling of the friction stir-welding process," *Int. J. Mach. Tools Manuf.*, vol. 42, no. 14, pp. 1549–1557, 2002, doi: 10.1016/S0890-6955(02)00114-1.
- [254] H. J. Zhang, H. J. Liu, and L. Yu, "Microstructure and mechanical properties as a function of rotation speed in underwater friction stir welded aluminum alloy joints," *Mater. Des.*, vol. 32, no. 8–9, pp. 4402–4407, 2011, doi: 10.1016/j.matdes.2011.03.073.
- [255] X. Zhao, F. Dong, G. Su, and L. Guo, "Weld Quality Improvement with Hybrid FSW Technology assisted by Preheating for Copper T2 / Aluminium 5A06 Dissimilar Materials," vol. 126, pp. 1707–1711, 2012, doi: 10.4028/www.scientific.net/AMM.121-126.1707.

- [256] H. J. Liu, J. J. Shen, L. Zhou, Y. Q. Zhao, C. Liu, and L. Y. Kuang, "Microstructural characterisation and mechanical properties of friction stir welded joints of aluminium alloy to copper," vol. 16, no. 1, pp. 92–99, 2011, doi: 10.1179/1362171810Y.0000000007.
- [257] S. Shah and S. Tosunoglu, "Friction Stir Welding : Current State of the Art and Future Prospects," pp. 1–6, 2012.
- [258] W. M. Thomas, K. I. Johnson, and C. S. Wiesner, "Friction Stir Welding – Recent Developments in Tool and Process Technologies," Adv. Eng. Mater., vol. 5, no. 7, pp. 485–490, Jul. 2003, doi: 10.1002/adem.200300355.
- [259] W. M. Thomas, D. G. Staines, I. M. Norris, and R. De Frias, "Friction stir welding tools and developments," Nov. 07, 2003. doi: 10.1007/BF03266403.
- [260] U. Singarapu, K. Adepu, and S. R. Arumalle, "Influence of tool material and rotational speed on mechanical properties of friction stir welded AZ31B magnesium alloy," J. Magnes. Alloy., vol. 3, no. 4, pp. 335–344, 2015.
- [261] A. Esmaeili, M. K. B. Givi, and H. R. Z. Rajani, "Investigation of weld defects in dissimilar friction stir welding of aluminium to brass by radiography," Sci. Technol. Weld. Join., vol. 17, no. 7, pp. 539–543, 2012.
- [262] K. N. Krishnan, "On the formation of onion rings in friction stir welds," Mater. Sci. Eng. A, vol. 327, no. 2, pp. 246–251, 2002.
- [263] Y. Zhao, L. Zhou, Q. Wang, K. Yan, and J. Zou, "Defects and tensile properties of 6013 aluminum alloy T-joints by friction stir welding," Mater. & Des., vol. 57, pp. 146–155, 2014.
- [264] R. Crawford, G. E. Cook, A. M. Strauss, D. A. Hartman, and M. A. Stremler, "Experimental defect analysis and force prediction simulation of high weld pitch friction stir welding," Sci. Technol. Weld. Join., vol. 11, no. 6, pp. 657–665, 2006.
- [265] K. Kumar and S. V. Kailas, "The role of friction stir welding tool on material flow and weld formation," Mater. Sci. Eng. A, vol. 485, no. 1–2, pp. 367–374, 2008.
- [266] M. Tabatabaeipour, J. Hettler, S. Delrue, and K. Van Den Abeele, "Non-destructive ultrasonic examination of root defects in friction stir welded butt-joints," Ndt & E Int., vol. 80, pp. 23–34, 2016.
- [267] M. Girard, B. Huneau, C. Genevois, X. Sauvage, and G. Racineux, "Friction stir diffusion bonding of dissimilar metals," Sci. Technol. Weld. Join., vol. 15, no. 8, pp. 661–665, 2010.
- [268] C.-Y. Lee, D.-H. Choi, Y.-M. Yeon, and S.-B. Jung, "Dissimilar friction stir spot welding of low carbon steel and Al–Mg alloy by formation of IMCs," Sci. Technol. Weld. Join., vol. 14, no. 3, pp. 216–220, 2009.
- [269] U. F. H. Suhuddin, V. Fischer, A. Kostka, and J. F. dos Santos, "Microstructure evolution in refill friction stir spot weld of a dissimilar Al–Mg alloy to Zn-coated steel," Sci. Technol. Weld. Join., vol. 22, no. 8, pp. 658–665, 2017, doi: 10.1080/13621718.2017.1300744.
- [270] I. Hejazi and S. E. Mirsalehi, "Effect of pin penetration depth on double-sided friction stir welded joints of AA6061-T913 alloy," Trans. Nonferrous Met. Soc. China, vol. 26, no. 3, pp. 676–683, 2016.