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Challenges and Advances in Welding and Joining Magnesium Alloy to Steel

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Abstract

Hybrid structures built using Mg/steel are expected to have an increasing impact on the future developments of the manufacturing sector, especially where lightweight structures are required in order to reduce fuel consumption, greenhouse gases and improve efficiency of energy-converting systems. To this end, there is a pressing need for a joining technology to produce effective and low-cost dissimilar Mg/steel joints. Joining of these materials has always been a challenging task for researchers, due to the wide discrepancies in physical properties and lack of metallurgical compatibilities that make the welding process difficult. Based on the existing literature, a successful joint between magnesium alloys and steel can be achieved by inserting an interlayer at the interface or mutual diffusion of alloying elements from the base metal (BM). Thus, intermetallic phases (IMCs) or solid solutions between Mg and the interlayer and also the interlayer and Fe formed at the interface. However, the interfacial bonding achieved and the joints performance depend significantly on the intermediate phase. This paper reviewed the research and progress in the area of joining of Mg alloys to various grades of steel by variety of welding processes, with focus on the techniques used to control the morphology and existence state of intermediate phase and improving the mechanical properties.

Keywords: review, Mg/steel dissimilar welding, intermetallic compounds (IMCs), microstructure, and mechanical properties

1. Introduction

With the growing concerns on global warming and energy prices, the demand for environmentally friendly vehicles with better fuel efficiency is increasing [1–3]. These issues can be addressed by reducing car weight, lowering travel resistance, advancing drive-train efficiency, developing new sources of power, and so on. Vehicle weight reduction using advanced lightweight structural materials, such as Mg, Al, and Ti, is considered as one of the most promising strategies to address these issues [4–10]. Generally, for every 10% weight reduction, the specific fuel consumption could reduce by 3–7%, while maintaining the same functionality [11, 12]. Thus, the use of lightweight alloys as structural materials is considered as the factor for development

of aerospace and automotive manufacturing sectors in the future. To achieve light-weight, safety, and low cost, the multi-material structure using steels, Al, Mg alloys is considered to be efficient [9]. Therefore, effective dissimilar joining process of such light metals and steels is essential.

As the lightest structural material, Mg alloys receive great attention due to their high specific strength, sound damping capabilities, hot formability, good castability, recyclability among others [13–18]. Potential applications of Mg alloys in an automobile include seat components, bracket carrier, roof, bonnets, cylinder head, wheels, etc. [8, 19]. Steel is currently the automaker's material of choice, due to its inherent properties, including high strength and toughness, good ductility, and low cost [8, 20–22]. Recently, it has been demonstrated through the next-generation vehicle project that stainless steels are promising candidates for vehicle construction, and they can be used replaced carbon steels, especially in crash-relevant components such as door pillars.

Therefore, for practical applications in automotive industries, Mg alloys will have to be joined with existing steel parts. Recently, many automotive components have been produced using a combination of Mg alloys and steels, but the major issues arise from the joining techniques and corrosion of the joined parts [23–26]. Thus, attaining reliable Mg/steel hybrid joints is paramount for facilitating lightweight industrial fabrication and expanding the industrial applications of Mg alloys in automotive industries [21, 27–29].

Joining Mg alloys directly to steel is extremely difficult because of the huge differences in their physical and metallurgical properties, the lattice mismatch between Fe and Mg is very large and there is almost zero solubility between Mg and Fe [27, 29–35]. Hence, an appropriate technique that overcomes the aforementioned problems is very much desired.

Generally, a successful joint between Mg and steel can be achieved by inserting an intermediate material at the interface or diffusion of alloying elements from the BM. At present, several authors have focused on joining magnesium alloys to different grades of steel, using various welding technology, such as friction stir welding (FSW), ultrasonic spot welding (USW), diffusion and eutectic bonding, resistance spot welding, laser welding brazing, laser-TIG hybrid welding and gas metal arc weld-brazing. In these studies, various interlayer elements and alloys such as Zn, Ni, Cu, Cu-Zn, Sn, Al, and Ag have been explored. In contrast to direct joining of magnesium to steel, which is mainly a mechanical bonding, with insertion of the interlayer elements, formation of intermetallic phases or solid solutions between Mg and the interlayer and also the interlayer and Fe indicated that metallurgical bonding is achieved. However, the joint performance and the interfacial bonding achieved depend significantly on the IMC phase formed [31, 36–38]. To control the morphology and existence state of the intermediate phase, the selection of suitable interlayer material and joining techniques are essential. Generally, choosing the suitable interlayer for joining Mg alloys to steel largely depends on the interlayer composition that gives excellent wetting and bonding without generating thick layers of hard and brittle IMCs at the joint interface [31, 35, 39–41]. Moreover, when choosing the joining process that will be used, minimization of the thickness of any brittle intermetallic compounds along the interfaces of the magnesium alloy-interlayer-steel joint and minimization of intermixing between the Mg and Fe in the molten-state are the main factors that must be considered [8, 21, 42, 43].

Currently, a great deal of research has been conducted on the interface characteristics and mechanical performance of Mg alloys to steel joints, particularly under static loading. Under optimized processing conditions, excellent static strength has been achieved, even surpassing that of Mg alloy base metal with insertion of Ag, Cu, and Ni intermediate

elements [38, 44]. However, few experiments have been carried out on the corrosion behavior of the jointed parts and the joints performance under dynamic loading [45–48].

With the continuously increasing usage of Mg alloys in industries and the large number of potential applications of Mg/steel hybrid structures, two of the specific areas of concerns for broader utilization of magnesium alloys are reliable joining techniques and corrosion behavior of the jointed parts. To better understand and address these challenges, there is a need to comprehensively review the research conducted so far and provide the most efficient strategies to address the challenges. This paper presents a review on Mg alloys/steel joining techniques, with focus on the techniques used to control the morphology and existence state of intermetallic compound (IMC) and improving mechanical properties. The general motives behind this review are to obtain a better understanding on the weldability issues associated with joining magnesium alloys to steel. It would also establish global, state-of-the-art welding techniques of Mg alloys to steel.

2. Weldability of Mg alloys to steel

Some of the inherent properties of Mg include high thermal conductivities and coefficients of thermal expansion, large solidification temperature ranges, strong tendency to oxidize, low viscosity and surface tensions, high solidification shrinkage, low melting and boiling temperatures, a tendency to form low melting point constituents and high solubility for hydrogen in the liquid state [8, 30, 49]. It is obvious that the properties of Mg differ significantly from those of Fe. For instance, the melting points of magnesium and iron are 649°C and 1536°C, respectively. This wide discrepancy in melting points makes it very difficult to melt the base materials at the same time as might be required in fusion-welding process [21].

In addition, the crystal structure of Iron at room temperature is body-centered cubic (BCC), whereas that of magnesium is close-packed hexagonal (HCP). Crystallographic analysis has shown that the lattice mismatch of Fe and Mg is very large [34, 50, 51]. Although the welding process itself is a non-equilibrium process, phase diagram has always been an effective tool to predict the reactions formed during welding process and serves as a reference to examine the feasibility of achieving a metallurgical bonding between the metals. According to the Mg/Fe binary phase diagram, the maximum solid solubility of iron in magnesium is 0.00043 wt.% while that of magnesium in iron is nil, and the Mg concentration at the eutectic point is estimated to be less than 0.008 at.% [34, 52–54]. Therefore, magnesium and steel are immiscible (neither the formation IMC nor atomic diffusion occurs between them after solidification), thereby presenting difficulty in joining them together.

3. Joining of Mg to steel: state of the art

In recent years, numerous techniques have been applied to bond Mg alloys to various grades of steels. These techniques can be broadly classified into solid-state joining (friction stir welding, ultrasonic spot welding, diffusion-welding processes) and fusion welding (resistance spot welding, laser welding brazing, laser hybrid welding, and arc welding). Review of the literature reveals that metallurgical bonding along the Mg/steel interface can be achieved with addition of suitable interlayers (which possess a substantial solid solubility in both Mg and Fe) or inter-diffusion of the alloying element

from the BM. Therefore, the joint quality is significantly influenced by the interlayer characteristics (forms, thickness, and compositions). Among the joining techniques, a variety of thin interlayers such as Zn, Cu, Al, Ni, Sn, Cu-Zn, and Ag has been reported to improve the interfacial reaction between magnesium alloys and steel. In this section, the potential of several methods for joining magnesium and steel will be discussed.

3.1 Solid-state joining processes

Solid-state joining technology has been applied to bond Mg alloys to steel and get high-quality joints than fusion-welding processes because of the added advantage of minimal oxidation because of the solid-state nature of the process. Solid-state joining processes, such as friction stir welding (FSW), ultrasonic spot welding (USW), and diffusion and eutectic bonding, have been used to join Mg alloys to steel. Generally, for solid-state bonded Mg alloys-interlayer-steel joints, the joint performance is influenced by the intimate contact between the dissimilar materials, and the micro-structure, particularly the formation of IMCs [55, 56].

3.1.1 Friction stir welding (FSW)

FSW is a solid-state welding technique invented by Thomas et al. [57]. The combined action of pressure and stirring during the FSW led to mutual diffusion of the alloying elements from the BM, which promoted metallurgical bonding at the interface and improved the joint performance. Some of the unique advantages of FSW include low distortion and residual stresses due to low heat input and absence of melting, filler metal is not required and the heat efficiency is very high relative to traditional fusion-welding processes [58, 59]. Joining Mg alloys to steel by FSW has been extensively studied.

Watanabe et al. [60, 61] investigated the weldability of AZ31 Mg alloy to uncoated SS400 steel joints by FSW. Under optimum joining condition (0.1 mm tool pin offset toward steel plate, 1250 rpm pin rotation speed, and welding speed of 100 mm/min), a joint with maximum strength of about 70% of the Mg BM was obtained. The low joint strength was associated with insufficient plasticization and presence of steel fragments in the Mg matrix. Considerable number of authors observed that the presence of zinc coating on the steel surface played an important role in the bond formation between the Mg alloys and steel [21, 27, 56, 62, 63]. For instance, Schneider et al. [63] and Jana et al. [27] joined AZ31B alloy to Zn-coated steel by FSW. It was found that the Zn coating enhanced the bondability of the Mg alloy/steel. The authors noted that the strength of the FSW welded AZ31B/galvanized steel was significantly superior to that of AZ31B/uncoated steel. The presence of Zn coating promoted the formation of liquid low melting Mg-Zn eutectic products at the interface. The liquid products, broken oxides, and other contaminants were forced out of the joining interface by the high pressure produced by the tool, exposing the fresh interfaces. As a result, mutual diffusion between magnesium alloy and steel was achieved.

Friction stir spot welding (FSSW) a variant of FSW, has also been used to join Mg alloys to steel. Liyanage et al. [29] joined AM60 to DP600 dual-phase steel by FSSW, and the welds showed no evidence of intermetallic formation. They reported that a Zn layer on DP600 steel resulted in melted eutectic material (α Mg + MgZn) and cracking in the joints. The feasibility of joining 3 mm thick AZ31 Mg alloy to 1 mm 302 stainless steel by FSW was also reported [64]. The results showed that the combined action of pressure and stirring led to mutual diffusion of the alloying elements from the BM at

the interface. Under optimum condition, the joints shear strength reached a maximum of 96.3 MPa. However, void and microtype defects at the interface were observed.

Joo et al. [65] reported that an acceptable AZ31B/SS400 steel joints with higher strength, sufficient material flow and tool wear reduction were obtained using hybrid gas tungsten arc welding (GTA) and friction stir welding. The tensile strength of the hybrid friction stir welds increased to 237 MPa about 91% of the Mg BM, compared to 226 MPa for conventional friction stir welds.

The prior research proved that refill friction stir spot welding (RFSSW) has many advantages for joining of Mg alloys/steel dissimilar welds [48, 66, 67]. Zhang et al. [67] joined 3 mm AZ31B to 1 mm galvanized steel joints by friction stir keyholeless spot welding (FSKSW) and reported that the stacking sequence of the workpieces played a significant role in determining the mechanical properties. Under optimum joining condition, the maximum joint strength of 8.7 kN was achieved. Furthermore, 1.53 mm ZEK100 Mg alloy was welded to 1 mm Zn-coated DP600 steel with 10 μ m Zn coating by RFSSW [66]. The authors observed that the sleeve did not plunge into the bottom steel. A thin interfacial layer with thickness of <100 nm identified as FeAl₂ by TEM was observed at the interface, which accommodates bonding between the immiscible Mg and Fe and appeared to have originated from Zn-based galvanized coating on steel. Under optimum process parameters (tool speed of 1800 rpm, welding time of 3.0 s, and penetration into the upper ZEK100 of 1.5 mm), the joints shear strength of 4.7 kN was achieved.

However, numerous studies focused on characterizing the Mg alloys to steel joints under dynamic loading condition [20, 48, 68]. For example, the fatigue behavior of FSW-produced by AZ31 and two types of Zn-coated steels (HSLA steel or mild steel (MS)) lap joints has been investigated [20]. It was found that the performance of friction stir welded joints under fatigue load is limited due to 'hook'-like features formed along the magnesium/steel interface, which act as stress raisers. Uematsu et al. [68] investigated the static and dynamic behavior of dissimilar lap joining of 2 mm AZ31 Mg alloy to 2 mm cold-rolled low carbon steel by FSSW. The results showed that fatigue crack grew through the interface, regardless of load levels. The authors noted that the effective nugget size could be the controlling factor of the fatigue strengths of dissimilar welds, and it is essential to increase the effective nugget size to improve the fatigue performance of dissimilar welds. Shen et al. [48] compared the static and dynamic behavior of 1.5 mm ZEK100 Mg alloy/0.9 mm galvanized DP600 steel dissimilar spot welds to Mg/Mg similar welds produced by RFSSW. It was observed that the static and dynamic behaviors of the magnesium/steel welds were superior to that of Mg/Mg similar spot welds. The higher joint performance observed for Mg to Zn-coated steel was associated with an increase in effective bonded area, compared to Mg/Mg spot welds due to the presence of displayed Zn-coated layer. Furthermore, the analysis of the dynamic behavior of the Mg alloys to galvanized steel joints revealed that the Zn brazing quality directly influences the fatigue life. Therefore, optimization of the welding parameters to facilitate this brazing to magnesium is necessary [48].

Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by FSW and FSSW are shown in **Table 1**. In FSW welding, prior studies placed Mg alloys as the top sheet while the tool plunge depth was carefully controlled to avoid contacting the steel tool to the bottom ferrous substrate. However, this arrangement resulted in a low joint strength [64]. Interestingly, with recent RFSSW, the sleeve did not lunge into the bottom steel, which significantly increased the effective bond area and improved the joints performance [66–71]. During FSW and FSSW, the processing heads impose size and shape limitation, the process is best used with long and straight welds, and keeping the interlayer at the interface between the steel

and Mg alloy is very difficult due to the stirring action of the pin and material flow with high plasticity along the interface. Thus, limited the wide range of application of these techniques in industries [48, 72]. The comparison of the joint properties reveals that good static weld strength can be obtained between magnesium alloys to galvanized steel by a diffusion and braze-bonding mechanism [48, 66]. Most studies focused on using Zn interlayer, and there is a need to experiment with other interlayers. Furthermore, no study focused on the corrosion behavior of the joined parts.

Techniques	Materials	Joint design	Transition material	Maximum tensile shear strength (MPa)	Failure mode	References
FSW	2 mm AZ31B-O/2 mm SS400 mild steel	Butt (Offset 0.1 mm toward steel)	No interlayer	178.5 MPa	Interfacial	[60, 61]
FSW	1.6 mm AZ31/0.8 mm Zn-coated steel	Lap (Mg on top)	Zn coating	3.7kN	Interfacial	[21, 62]
	1.6 mm AZ31/0.8 mm Brushed finished steel		Uncoated	2.9kN	Stir zone	
FSW	2.33 mm AZ31B/1.5 mm HDG steel	Lap (Mg on top)	Hot dip Zn coating	6.3 ± 1.0 kN	Interfacial	[27]
	2.33 mm AZ31/0.8 mm HSLA electrically galvanized steel		Electro-galvanized Zn coating	5.1 ± 1.5 kN		
FSW	2 mm AZ31B/2 mm DX54D	Lap (Mg on top)	Uncoated	98 MPa	Stir zone	[63]
			Zn coating (15 µm thick)	158 MPa		
FSSW	1.2 mm AM60/1.8 mm DP600	Lap (Mg on top)	Zn coating	2.4 ± 0.5kN	AM60 BM	[29]
FSSW	2 mm AZ31 Mg alloy/2 mm cold-rolled low carbon steel	Lap (Mg on top)	No interlayer	32 MPa	Interfacial	[68]
FSW	3 mm AZ31/1 mm SUS302	Lap (Mg on top)	No interlayer	96.3 MPa	Stir zone	[64]
GTA-FSW	3 mm AZ31B/3 mm SS400	Butt	No interlayer	237 MPa	Interfacial	[65]
FSW				226 MPa		
FSKSW	3 mm AZ31B/1 mm Q235	Lap (Steel on top)	Zn coating	8.7kN	Not reported	[67]
RFSSW	1.55 mm ZEK100/1 mm DP600	Lap	Zn coating	4.7kN	Interfacial	[66]
RFSSW	1.5 mm ZEK100/0.90 mm DP600	Lap	Pure Zn coating (10 µm thick)	3.6kN	Interfacial	[48]

Table 1.
Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by FSW and FSSW.

3.1.2 Ultrasonic spot welding (USW)

USW is also a solid-state welding technique that generates coalescence through a concurrent application of localized high-frequency vibratory energy and slight clamping force [73]. At present, the research conducted on joining magnesium alloys to steel using USW is limited.

Santella [74, 75] joined 1.6 mm thick AZ31B-H24 to 0.8 mm HDG mild steel by USW. The authors noted that the presence of Zn improved the bonding mechanism, but the Mg-Zn phases were completely squeezed from the spot weld and only thin Al₅Fe₅ phase was formed at the interface. Under optimum welding parameters, a joint with maximum lap shear strength of 4.2 kN was achieved. In another related study, Patel et al. [73] also noted that Mg and Zn combined to form Mg-Zn IMCs, while Fe and Zn combined to form a solid solution to create the weld joint. The results of these studies could suggest that no melting on the steel side occurs during USW. In comparison, Patel et al. [76] observed that the shear strength of the magnesium alloy/bare steel with the addition of Sn interlayer was higher than that of magnesium alloy/bare steel and magnesium alloy/galvanized steel joints, due to the solid solutions of Sn formed with magnesium and iron, as well as Sn and Mg₂Sn eutectic.

On the other hand, it was demonstrated that corrosion could impair the mechanical performance of Mg alloy/steel USW joints [46]. However, the details of corrosion mechanisms required further study.

Table 2 compares maximum tensile shear strength of the Mg alloys/steel joints produced by USW. The USW techniques involved the use of an interlayer to achieve interfacial reactions. The highest joint strength (about 88% of Mg/Mg ultrasonic spot weld) was obtained using Sn interlayer due to the solid solutions of Sn formed with magnesium and iron, as well as Sn and Mg₂Sn eutectic structure. Therefore, using Sn interlayer resulted in better joining mechanism and mechanical performance and is thus more suitable [76]. Thus, choosing of suitable interlayer is essential for successful joining. The possibility of using different transition materials should be explored. Furthermore, studies on dynamic and corrosion behavior of the USW joint parts should be given attention.

Techniques	Materials	Joint design	Transition material	Maximum tensile shear strength	Failure mode	References
USW	1.6 mm AZ31B-H24/0.8 mm HDG mild steel	Lap	Zn coating (9 µm thick)	4.2kN	Through the AZ31 BM	[74, 75, 77]
USW	2 mm AZ31B-H24/0.8 mm HSLA	Lap	Zn coating (10 µm thick)	47 MPa	Interfacial (cohesive failure)	[76]
			Uncoated	Sample failed during specimen mounting	—	
			Uncoated with Sn interlayer (50 µm thick)	71 MPa	Partial nugget pull-out	

Table 2.
Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by USW.

3.1.3 Diffusion and eutectic bonding

Diffusion methods have been used to successfully join both similar and dissimilar materials combinations, including Mg alloys/steel [37, 78]. During the diffusion process, formation of uniform and thin IMC along the Mg alloy/steel interface is the key for successful bonding. The number of research suggested that interfacial bonding could be achieved by either addition of interlayer or some alloying elements in the Mg BM. The benefits of using Cu [78–80], Ni [37, 80], and Ag [44, 81] interlayers during diffusion bonding of Mg alloy/steel have been demonstrated.

Tachibana et al. [82] studied the influence of the Zn insert on the bondability of Mg/steel lap joints. It was found that the AZ31 and cold-rolled steel plate (SPCC) could not bond due to the oxide films formed on the AZ31 that prevented the bonding, while AZ31/Zn-coated steel (GI) was bonded successfully. The presence of zinc coating enhanced the bondability of Mg alloy/steel and removed the oxide films on AZ31. The weldability of 5 mm AZ31 Mg alloy to 1 mm thick 316 L steel joints using a diffusion brazing process with addition of Cu and Ni interlayers was also reported [37, 79, 80, 83]. Solid-state diffusion of the interlayer into the magnesium alloy, eutectic formation, and the formation of ternary IMCs was observed at the joint interface. The interfacial reaction was intense in the liquid state, inducing the excessive formation of brittle and thick IMC layers, which was detrimental to the joint strength. The maximum joint strength of 57 MPa (69% of that of AZ31 BM) with Cu interlayer was obtained compared to 32 MPa for Ni added joints. The high interfacial bond obtained for Cu-added joint was associated with confined intermetallics at the bonded interface compared to dispersed intermetallics for Ni added joint [80].

Some authors focused on bonding magnesium alloys to steel using reactive transient liquid phase bonding (rTLP) to improve the joints strength between dissimilar metals. During the rTLP process, eutectic melting and subsequent isothermal solidification occurred between the interlayer and the magnesium, while the formation of a thin continuous layer between the melt and the steels resulted in interfacial bonding of the steel with the magnesium substrate [44, 81]. The bondability of AZ31 to low carbon steel with the addition of Ag interlayer using rTLP process showed that isothermal solidification of the eutectic melt was formed at the Mg alloy side through the diffusion of Ag into the magnesium BM. Thin and uniform Fe_2Al_5 layer was observed at the steel side, which significantly improved the joint strength to 201 MPa [44, 81]. In contrast, coarse, non-uniform IMC intermittently formed at the interface without Ag interlayer, which deteriorates the joint performance.

Table 3 gives a comparison of the Mg alloys/steel joints maximum tensile shear strength produced by diffusion and eutectic bonding. The literature reveals that the interlayer material has significant influence on the bondability of the Mg alloys to steel by diffusion and eutectic bonding process. The use of Cu, Ni, and Ag as intermediate elements has been studied. The major challenge associated with this technique is that the formation of ternary IMCs which could not be controlled and have detrimental effects on the joint performance [80]. A comparison of the joints strength shows that excellent static strength of Mg/steel joints has been achieved using rTLP techniques, even surpassing that of AZ31B Mg alloy BM with addition of Ag interlayer [44]. The rTLP unique qualities of short process time, coupled with forming a thin and continuous intermediate layer through the formation of a transient liquid interlayer, were responsible for the high joint performance obtained. The possibility of improving the joint performance using more interlayers should be explored.

Techniques	Materials	Joint design	Transition material	Maximum tensile shear strength (MPa)	Failure mode	References
Diffusion bonding	AZ31/SPCC	Lap	Uncoated	—	No reported	[82]
	AZ31/GI		Pure Zn coating (6 μ m thick)	40		
	AZ61/GI		Pure Zn coating (6 μ m thick)	70		
Diffusion brazing	5 mm AZ31/1 mm 316 L	Lap	Pure Cu (20 μ m)	57	Mg BM	[80]
			Pure Ni (20 μ m)	32	Steel/Ni interface	
rTPL bonding	AZ31B/Low carbon steel	Lap (Mg on top)	—	40	Interfacial	[44, 81]
			Pure Ag (1 μ m)	201	Mg BM	

Table 3.
Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by diffusion and eutectic bonding.

3.2 Fusion-welding processes

Fusion welding involves joining the surface of the materials through melting and solidification to produce the bonding. Fusion-welding technologies based on resistance spot welding [4, 32, 84–86] laser braze [41, 43, 87–92], laser hybrid [33, 35, 36, 38–40, 47, 93–98] and arc welding [72, 99–102] have been investigated for joining magnesium alloys to steels. In general, the insertion of an interlayer or mutual diffusion of alloying elements from the BM has been adopted to improve interfacial bonding. The addition of suitable interlayer improves the spreadability and the nucleation of magnesium on steel.

3.2.1 Resistance spot welding (RSW)

RSW is the most widely used welding technology in the auto industry [103] due its low cost, high speed, ease of operation, and automation [17, 32, 86]. Despite the inherent advantages of RSW, very limited work has been published in joining Mg alloy to steel. This include AZ31B Mg alloy/Zn-coated DP600 steel [32], AZ31 Mg alloy/HDG steel with pre-coated nanoscale Fe₂Al₅ layer [34], AZ31B-H24 Mg alloy/HDG HSLA steel [4], AZ31B Mg alloy/HDG HSLA steel [84] and AZ31B Mg alloy/electro-galvanized DP600 steel [86].

Most of the works focused on joining magnesium alloys to galvanized steel. Liu and his co-workers developed a novel technique (asymmetric electrode) to lap weld 1.5 mm AZ31B to 1.2 mm HDG DP600 steel successfully by RSW [32]. It was found that the Zn interlayer was squeezed out of the bond region producing deal condition for intimate contact of fresh Mg and steel surfaces. The joining mechanism consisted of braze welding, solid-state bonding, and soldering. Under optimum parameters, a joint with tensile shear strength of 5.0 kN was obtained. Xu et al. [4] compared the microstructure and

mechanical performance of AZ31B to HDG HSLA steel joints by RSW and weld-bonding (WB), which combines the RSW and adhesive bonding. It was found that the peak shear load and energy absorption of the weld-bonded magnesium to steel joints were higher than that of resistance spot welded magnesium to steel joints. In another similar study, AZ31B was joined to HDG HSLA steel by RSW under dynamic loading [84]. It was found that the microstructure of the Mg/steel spot welds was different from that of Mg/Mg spot welds, but owing to similar crack propagation and failure mode, both welds had an equivalent fatigue resistance. Interestingly, Feng et al. [86] joined AZ31 to electro-galvanized DP600 steel by RSW process with and without HDG Q235 interlayer. Contrary to the previous studies [4, 32, 84] that used hot-dip Zn coating, the thin and compact features of electro-galvanized zinc layer prevented the zinc-coated layer on the steel to be squeezed out of the nugget. However, with insertion of HDG Q235 interlayer, the zinc-coated layer was squeezed out of the nugget and a peripheral soldered region was formed during the welding process, which significantly improved the joint tensile shear load from 4.14 kN to 5.49 kN. The feasibility of joining AZ31B Mg alloy to DP600 steel via pre-coated nano-scaled Fe_2Al_5 interlayer was also investigated [34]. The analysis of the interface characteristics revealed that metallurgical bonding was achieved due to the formation of the semi-coherent interfaces of Mg/ Fe_2Al_5 /Fe with well matching lattice.

However, RSW of Mg alloy to stainless steel is more challenging because of the absence of any Zn coating. However, Mg alloy to stainless steel joints has been reported [85, 104]. Min et al. [104] investigated the 0.4-mm thick AZ31B sheets, and 0.4-mm thick 443 ferritic stainless steel welded joints using the RSW with 443 ferritic stainless steel cover plates. It was found that Fe-Al IMC layer was formed at the interface, and the molten Mg could wet the surface of the interface layer. However, cracking was observed in the nugget. The crack was associated with the possible thermal behavior of various elements in the nugget during spot-welding process. Recently, Manladan [85] compared the microstructure and mechanical performance of 1.5 mm thick AZ31 Mg alloy/0.7 mm thick 316 L austenitic stainless steel joints by RSW and resistant element welding (REW). In comparison with two-zone FZ, consisting of peripheral FZ on the ASS side and main FZ observed for REW, the RSW joints were produced through welding-brazing mode, in which the Mg alloy melted and spread on the solid steel, forming the nugget only on the Mg side. The RSW produced the weak joint with a peak load of 2.23 kN and energy absorption of 1.14 J, whereas REW produced the strong joint with a peak load of 3.71 kN and energy absorption of 10.2 J.

Generally, in the RSW process of Mg alloys, large electric currents are always needed due to its high electrical and thermal conductivity, which commonly results in expulsion and electrode stick. In addition, RSW created only a localized joint, which may not be particularly strong [105].

A comparison of the Mg alloys/steel joints maximum tensile shear strength produced by RSW is shown in **Table 4**. It can be seen that limited research has been conducted on magnesium alloys/steel. The presence of zinc layer was crucial for successful welding of magnesium to steel. The predominant failure mode observed is interfacial (IF). This is the kind of failure mode commonly observed when conducting tensile shear tests on spot welds, in which the crack propagates through the nugget. A comparison of the joints performance shows that good static strength has been achieved, almost 95% Mg/Mg spot joint strength by RSW [32]. However, the research on the fatigue performance of Mg/steel dissimilar welds is still at its infancy due to the special geometry of the spot welds; it is hard to predict the crack initiation and propagation rate as reported by Liu et al. [84]. Among the RSW techniques, weld bonding produced the joint with highest mechanical resistance with joint failure on the Mg

Techniques	Materials	Joint design	Transition material	Maximum tensile shear strength (kN)	Failure location	References
RSW	1.5 mm AZ31/ 1.2 mm Zn-coated DP600	Lap (Mg on top)	HDG Zn-coated (9 μ m to 12 μ m)	5.0	Interfacial failure (IF) mode	[32]
RSW	1.5 mm AZ31/ 1.2 mm HDG DP600	Lap (Mg on top)	Bare steel	0.0	Not reported	[34]
			Fe ₂ Al ₅	4.8	Not reported	
RSW	1.5 mm AZ31B/0.77 mm HSLA steel	Lap (Mg on top)	HDG Zn-coated (11 μ m)	2.0	Interfacial failure (IF) mode	[84]
RSW & WB	2 mm AZ31B-H24/0.7 mm HSLA steel	Lap (Mg on top)	HDG Zn-coated (11 μ m)	RSW 4.80 WB 10.0	IF (RSW) Mg BM (WB)	[4]
RSW	2 mm AZ31B/ 1.2 mm Electro-galvanized DP600	Lap (Mg on top)	No transition material	4.14	IF	[86]
			HDG Q235 (0.6 mm)	5.49	IF	
RSW & REW	1.5 mm AZ31/0.7 mm 316 SS	Lap (Mg on top)	No transition material	RSW 2.23	IF	[85]
				REW 3.71	PO	

Table 4.
Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by RSW.

BM. Weld-bonding joining techniques has the advantages of low manufacturing costs, higher static and fatigue performance, and improved corrosion resistance [106, 107].

3.2.2 Laser beam welding

Laser beam welding presents a viable option for welding Mg alloys to steel due to its versatility, high specific heat input, and flexibility [55, 108–111]. Although fusion welding resulted in severe vaporization of Mg alloy at typical welding temperatures, the selection of optimum welding conditions is crucial for successful joining. Therefore, to control the severe vaporization of Mg, considerable number of authors concentrated on laser welding brazing and laser hybrid techniques.

Laser welding brazing (LWB) techniques offered additional advantages such as increased flexibility and adoptability when welding dissimilar metals [28, 91, 92, 112, 113]. To this end, LWB technique is suitable for joining dissimilar materials having large differences in melting points such as Mg/Ti [18, 114–116], Al/Ti [117], and Al/steel [118, 119]. In particular, welding of magnesium alloys to steel by LWB process was achieved with addition of third material or mutual diffusion of alloying elements. Thin interlayers such as Al [28, 120, 121], Ni [90, 113], Sn [31], Zn [41, 42, 87, 88, 91], and Fe-Al [41], have been used to improve the interfacial bonding between the immiscible Mg and Fe. Miao demonstrated the feasibility of joining 2.4-mm AZ31B Mg alloy to 1.7 mm Q235 steel by laser welding brazing process using

high power CO₂ laser without welding wire [122–124]. The analysis of the interface characteristics revealed that transition layer consisted mainly of IMCs, and metal oxides were observed at the interface. The compounds were identified by TEM as Al-rich phases, such as Mg₁₇Al₁₂, Mg₂Al₃, FeAl, and Fe₄Al₁₃ [124]. Although tensile strength of the butt joints could reach 182 MPa (81% of Mg alloy BM), but severe oxidation and vaporization of the magnesium alloy, coupled with immiscibility between magnesium and iron, led to weld defects such as spatters and porosity.

Therefore, to address the severe vaporization of the Mg, laser brazing or laser welding brazing with magnesium-based filler wire was proposed [28]. The benefits of using Al-12Si [28], Ni [113], Sn [31], and Zn [42] as transition material between Mg alloy to steel were explored by Nasiri and co-workers. It was found that the presence of the interlayer significantly improved the spreadability of the liquid magnesium-based filler on steel surface but deteriorated the joint performance because of the weak bonding of IMCs products formed along the interface.

However, several authors observed mutual diffusion of alloying elements when joining Mg alloys to different grades of stainless steel [92, 125, 126]. For instance, [92] compared the joint performance of lap welded 1.5 mm-AZ31B/1.5 mm-mild steel (MS) joints and 1.5 mm-AZ31B/1.5 mm 201 stainless steel (SS) joints produced by LWB. Mechanical bonding was observed for Mg alloy to MS joints, whereas for Mg alloy to SS joints, thin reaction layer identified as FeAl by TEM as shown in **Figure 1**. The Al diffusion from magnesium BM to the interface was accelerated by

Figure 1.
Mg/201 stainless steel interface characteristics [73].

chemical potential induced by alloying elements of Cr and Ni was responsible for the interfacial reaction layer obtained.

A comparison of the Mg alloys/steel joints maximum tensile shear strength produced by LWB is shown in **Table 5**. The selection of suitable interlayer is crucial for successful bonding. For instance, using Ni and Sn interlayers, which led to formation of the Fe(Ni) and Al₈Mn₅-Fe(Al) reaction products along the α -Mg-Fe interface, respectively, resulted in formation of strong interfaces with low mismatch strain energy and strong bonds. Therefore, using both Ni and Sn interlayers is recommended for dissimilar joining of steel sheet to magnesium sheet. Furthermore, the diffusion of the alloying elements in BM and the bonding mechanism were extensively studied. A comparison of the joints properties reveals that relatively good static strength of magnesium alloy to steel joints has been obtained [126]. However, the behavior of the Mg alloys/steel joint under dynamic loading is yet to be explored. Among the LWB techniques, dual-beam mode with flux produced joint with an excellent mechanical resistance. To further enhance the reliability of the joint and improve its performance, the possibility of using different interlayers should be explored.

The excessive evaporation of magnesium during fusion welding can be overcome through the method of TIG-assisted laser process [33]. Generally, the addition of TIG could improve absorption of laser power and penetration of molten pool. During laser-TIG process, the TIG torch melts the magnesium, whereas, the laser is used to create deep penetration into the steel [36, 39]. Several authors reported that conventional fusion-welding technology such as TIG or laser welding alone could not be competent for joining of magnesium to steel [33, 89, 94]. For instance, [33, 89] demonstrated during TIG welding of Mg alloy to steel with higher heat input, either the magnesium alloys melt but the steel remained in solid state or the steel melt while blowholes formed in the magnesium alloys. In both cases, the bonding between the immiscible couple could not be obtained. Similarly, for conventional laser-welded magnesium alloys to steel joints, the immiscible materials could be joined with poor weld appearance and poor strength, coupled with large amount of electricity consumed by laser due to low absorptivity of magnesium alloys at room temperature [127]. For TIG-assisted laser process, the reflectivity of the magnesium to laser was reduced and thus the absorption of laser beam improved, creating a deeper penetration in the steel [33, 35, 128]. Consequently, laser-TIG process offers great potential for improving the joint performance for both similar and dissimilar metal welding [33, 39, 40, 89, 129, 130].

Like other joining techniques, interfacial bonding between magnesium alloy to steel could be achieved by insertion of third material or mutual diffusion of alloying elements from the BM [95]. Therefore, the benefits of using Cu [35, 39, 40], Ni [35, 36, 40, 93, 96], Sn [94], Zn [89], Cu-Zn [40, 97] to bond magnesium to steel had been extensively studied. These interlayers formed Mg₂X IMC (where X is the interlayer elements) and a solid solution of interlayer in iron along the joint interface, which consequently enhanced the joints mechanical strength [40].

Liu examined the weldability of AZ31B/304 SS by laser-GTA process. A transitional zone consisting of Mg-Fe and magnesium diffusion into the matrix of iron in the form of oxide was observed at the interface. The formation of the complex MgO, ZnO, Fe₂O₃, or Al₂O₃ oxides deteriorates the joint strength [39, 94]. Furthermore, the use of laser-TIG techniques to join AZ31B and Q235 steel with Ni, Cu, Sn, and Cu-Zn interlayers was also explored [35, 36, 38–40, 93, 94]. These interlayers were heated and melted to react with magnesium and steel, and formed a transitional layer in the FZ and solid solution along the steel side. The analysis of the strengthening

Techniques	Materials	Joint design	Transition material	Maximum strength	Failure mode	References
Laser welding	3 mm AZ31B/1.2 mm SP781 steel	Lap (Mg on top)	Zn Coating	6182 N	AZ31B FZ & Transition zone	[43]
Laser penetration brazing	2.4 mm AZ31B/1.7 mm Q235 steel	Butt (0.6 mm offset on Mg)	No interlayer	182 MPa	Interface	[122–124]
Laser brazing	2 mm AZ31B-H24/1 mm Al-12Si coated steel 2.4-mm- Dia Ti-Braze Mg 600 wire	Single flare bevel Lap (Mg on top)	Al-12 wt-% Si coating (20 ± 2 µm thick)	767 ± 138 N	Interface	[28]
Laser brazing	2 mm AZ31B-H24/1 mm Al-12Si coated steel 2.4-mm- Ti-Braze Mg 600 wire	Single flare bevel Lap (Mg on top)	Pure Ni coating(5 µm)	1506.3 ± 24.5 N	FZ	[113]
Laser brazing	2 mm AZ31B-H24/0.6 mm AISI 1008	Lap (Mg on top)	Pure Sn coating (3.7 ± 0.7 µm thick)	2064 ± 85 N	Steel BM	[31]
Laser brazing	2 mm AZ31B-H24/0.8 mm AISI 1008	Lap (Mg on top)	Pure Zn coating (2.6 ± 0.5 µm thick)	1086.4 ± 150.2 N	Interface	[42]
Laser welding brazing	1.5 mm AZ31B-H24/1.5 mm DP980	Lap (Mg on top)	uncoated	160 N/mm	Interface	[87, 88, 91]
			Zn coated (10 to 15 µm)	228 N/mm		
Laser welding brazing	1.5 mm AZ31B-H24/1.5 mm DP980 with 1.2 mm AZ31 filler	Lap (Mg on top)	uncoated	190 N/mm	Interface	[41]
			Zn + Fe-Al Phase	180 N/mm	Interface	
			Zn coating (10 µm)	160 N/mm	Interface	
			Fe-Al coating (0.9 µm)	240 N/mm	Weld Seam	
Laser welding brazing	1.5 mm AZ31/1.5 mm 22MnB5 with 1.2 mm AZ61 filler	Lap (Mg on top)	AlSi10Fe3-coating	3090 N	AZ61 filler	[121]
Laser welding brazing	1.5 mm AZ31B/1 mm Q235	Lap (Mg on top)	Al (0.3 mm)	133 N/mm	FZ	[120]
Laser welding brazing	1 mm AZ31B-H24/1 mm Q235A with 1.2 mm AZ92D filler	Lap (Mg on top)	Ni coating (4.5 ± 0.5 µm)	190 N/mm	FZ	[90]

Techniques	Materials	Joint design	Transition material	Maximum strength	Failure mode	References
Laser Welding brazing	AZ31B/mild Steel	Lap (Mg on top)	No interlayer	142 N/mm	Interface	[92]
	AZ31B/stainless steel			270 N/mm	Mg FZ	
Laser welding brazing	1.5 mm AZ31B-H24/1.5 mm 201 stainless steel and 2 mm AZ31 Filler	Lap (Mg on top)	No interlayer	274.5 N/mm	Mg HAZ	[125, 126]
Laser offset welding	3 mm AZ31/3 mm AISI 316	Butt (3 mm Offset on Steel)	No interlayer	100 MPa	AZ31 BM	[30]

Table 5.
Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by laser welding brazing.

mechanism revealed that with the addition of suitable interlayers, the joint shear strength could reach a significantly high value or even surpasses Mg alloy BM.

Generally, the corrosion behavior of magnesium alloys is affected by the micro-structural variation imposed by welding process [27, 43, 56, 63, 64, 125, 126, 131]. For similar Mg/Mg welds, the grain refinement imposed by welding process was reported to improve the corrosion resistance [132]. However, Liu et al. studied the corrosion behavior of the magnesium to steel joints produced by TIG-assisted laser process in NaCl solution. It was found that the grain refinement and iron splashes imposed by welding process were observed in the weld, which accelerated the corrosion of the magnesium alloy. Interestingly, the use of Al coating was reported to raise the lifespan of the dissimilar joints [47].

A comparison of the Mg alloys/steel joints maximum tensile shear strength produced by laser-TIG process is shown in **Table 6**. In hybrid laser-TIG welding, excessive vaporization of the magnesium was observed due to the penetration of the laser

Techniques	Materials	Joint design	Transition material	Maximum tensile shear strength (MPa)	Failure mode	References
Laser-GTA	1.7 mm AZ31B/1.2 mm 304 steel	Lap (Mg on top)	No interlayer	90	Interfacial	[33]
Laser-TIG	1.7 mm AZ31B/1.2 mm Q235	Lap (Mg on top)	No interlayer	120	Interfacial	[36, 39, 96]
			Pure Cu foil (0.1 mm thick)	170	FZ	[38]
			Pure Ni foil (0.1 mm thick)	166		
			Pure Sn foil (0.1 mm thick)	117		
			Cu-Zn (H80)-0.1 mm thick	161		
			Cu-Zn (H62)-0.1 mm thick	157		
Laser-TIG	1.5 mm AZ31B/1.5 mm DP980	Lap (Mg on top)	Zn coating (10 to 15 μ m thick)	68	Interfacial	[89]
Laser-TIG	1.6 mm AZ31B/1.1 mm Q235	Butt (0.2 mm offset on steel)	Cu-Zn alloy (H62) 0.1 mm thick	203	Weld seam	[97]

Table 6.
Comparison of the magnesium alloys/steel joints maximum tensile shear strength produced by laser-TIG process.

Techniques	Materials	Joint design	Transition material	Maximum tensile strength	Failure mode	References
CMT Welding	1 mm AZ31B/ Mild steel	Lap (Mg on top)	HDG Zn coating (10 μm)	224 N/mm	Interfacial	[99, 101]
			Uncoated	258 N/mm	Mg HAZ	
Bypass current-MIG-welding	2.5 mm AZ31B/ 2 mm Q235, with 1.6 mm AZ31 filler	Lap (Mg on top)	Zn coating	133.02 MPa	weld metal	[135]
MIG spot welding	1.8 mm AZ31B/1.5 mm Q235 with 1.2 mm ER50-6 filler	Lap (Steel on top)	Pure Cu foil (0.1 mm)	3200 N	Interfacial	[72]
MIG spot welding	3 mm AZ31B/3 mm Q235, 1.6 mm Mg based filler	Butt (V groove)	Uncoated	160 MPa	Interfacial	[100]
			Pure Cu foil (0.1 mm)	185 MPa	weld metal	
CMT brazing	2 mm AZ31/1 mm steel with 1.2 mm AZ31 filler	Lap (Mg on top)	Zn coating (10 μm)	3100 N	Interfacial	[102]
			Zn-Fe (8 μm)	4100 N		
			Uncoated	7000 N	Weld metal	
			AlSi Coating (25–30 μm)	6000 N		

Table 7.
Comparison of the Mg alloys/steel joints maximum tensile shear strength produced by MIG welding brazing.

from upper magnesium plate and the interlayer into the bottom steel. Furthermore, the violent stirring of molten pool restricted metallurgical bonding adjacent to the steel interface, which limited the application of this welding technique. Despite the fast heating and cooling rate of the TIG-assisted laser process, the interfacial reaction was achieved through diffusion and combination of alloying elements from the BM. Based on the existing literature, the interfacial characteristics and the mechanism of wetting in Mg alloys to steel joints produced using TIG-assisted laser process with addition of interlayers were thoroughly investigated. The feasibility of using Cu, Ni, Sn, Zn, and Cu-Zn intermediate elements was also explored. The presence of interlayer was essential for successful joining Mg to steel. The selection of a suitable interlayer was essential for successful bonding. For instance, the Sn added joint shows comparatively lower value due to inhomogeneous compositions in the FZ. A comparison of the joints mechanical properties shows that excellent static strength has been achieved, even surpassing that of magnesium alloy base metal with insertion of Cu and Ni intermediate elements. The high joint shear strength obtained was associated with better wettability and deeper penetration in the weld. However, limited studies focused on corrosion behavior of the TIG-assisted laser magnesium to steel joints. Furthermore, no study has focused on the behavior of the joints under dynamic loading.

3.2.3 Arc welding

Arc welding involves joining the materials surface permanently using power supply to obtain an electric arc between the electrode mounted in a torch and a metal. Among the arc welding processes, so far only metal inert gas welding has been used for this material combination.

Metal inert gas (MIG) welding has been widely used in automobile industries due its inherent properties, such as high efficiency, lower cost, and excellent adoptability to material geometry [133, 134]. Therefore, obtaining a reliable Mg alloy to steel joint by MIG welding is essential. However, joining magnesium to steel by MIG is rarely reported, including AZ31B/Zn-coated steel [99, 101, 102, 135], AZ31B/Q235 with Cu interlayer [72, 100] and AZ31B/Aluminized steel [102]. Generally, the addition of suitable interlayer improves the spreadability and the nucleation of magnesium on the steels.

Cold metal transfer (CMT) modified gas metal arc welding of AZ31B Mg to galvanized and bare mild steel sheets showed that welded brazed joints formed in both joints [99, 101].

A comparison of the Mg alloys/steel joints maximum tensile shear strength produced by MIG welding brazing is shown in **Table 7**. Generally, the investigation on the Mg alloys/steel joints produced by MIG welding is still in its infancy. Therefore, more interlayers should be tested. Moreover, the behavior of the joints under dynamic loading should be studied.

4. Summary and outlook

As there is a desire in the aerospace, aircraft, and automotive industries to join magnesium alloys to steel in order to achieve lighter weight, versatile, and tailored properties in one composite part, and development of a welding technology for Mg alloys/steel with a strong metallurgical bond will expedite increased applications of magnesium alloys in these industries. The major challenge in welding of magnesium alloys to steel is the huge differences in physical properties and limited solubility that make the welding process difficult. Different joining processes have been used to join Mg alloys to steel sheets but metallurgical bonding can only be possible with insertion of intermediate interlayer elements or alloy or mutual diffusion of alloying elements from BM. The existence of intermetallic phases or solid solutions between Mg and the interlayer and also the interlayer and Fe is an indication that metallurgical bonding between Mg and Fe using the interlayer may be possible. Formation of thick, brittle intermetallic compounds along the interface between Mg and steel can cause significant deterioration of mechanical properties. Therefore, when choosing the interlayer and the joining process that will be used, minimization of the thickness of any brittle IMCs that might form at magnesium alloy-interlayer-steel joint interfaces and minimization of intermixing between the Mg and Fe in the liquid state are main factors that must be considered.

Solid-state bonding techniques based on FSW, USW, and diffusion and eutectic bonding have been used. Generally, the intimate contact between the dissimilar materials and the formation of IMC with insertion of the suitable interlayer played a significant role in controlling the joint performance of solid-state bonded magnesium alloys to steel.

Joining magnesium alloys to different grades of steels by fusion processes such as RSW, laser welding, and arc welding with and without insertion of interlayers were also reported. Despite the fast heating and cooling rate of the fusion process,

the interfacial reaction was achieved through diffusion and combination of alloying elements from the BM. The phase formation in the magnesium-interlayer-steel alloy system and the mechanism of wetting in magnesium-interlayer-steel alloy system were extensively investigated. The benefits of using Cu, Ni, Sn, Zn, and Cu-Zn interlayers were also explored. The addition of suitable interlayer improves the spreadability and the nucleation of magnesium on the steel substrate. Therefore, more interlayer materials that form the eutectic phase with Mg either in a pure form such as Ag and Al or as alloys such as Al-Cu and Ag-Sn should be investigated.

Currently, a great deal of research has been conducted on the interface characteristics and mechanical performance of Mg alloys to steel joints, particularly under static loading. Under optimized processing conditions, excellent static strength has been achieved, even surpassing that of Mg alloy base metal with insertion of Ag, Cu, and Ni intermediate elements. However, few experiments have been carried out on the corrosion behavior of the jointed parts and the joints performance under dynamic loading. Thus, cost-effective and reliable joining techniques for Mg/steel will still require further development. The need for the industries for more advanced materials to accommodate the huge demands for strong, rigid and light structures may be the powerful drivers for further development of the welding techniques of hybrid structures of Mg alloys to steel.

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