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Recent developments and challenges in welding of magnesium to titanium alloys

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Abstract. Joining of Mg/Ti hybrid structures by welding for automotive and aerospace applications has attracted great attention in recent years due mainly to its potential benefit of energy saving and emission reduction. However, joining them has been hampered with many difficulties due to their physical and metallurgical incompatibilities. Different joining processes have been employed to join Mg/Ti, and in most cases in order to get a metallurgical bonding between them was the use of an intermediate element at the interface or mutual diffusion of alloying elements from the base materials. The formation of a reaction product (in the form of solid solution or intermetallic compound) along the interface between the Mg and Ti is responsible for formation of a metallurgical bond. However, the interfacial bonding achieved and the joints performance depend significantly on the newly formed reaction product(s). Thus, a thorough understanding of the interaction between the selected intermediate elements with the base metals along with the influence of the associated welding parameters are essential. This review is timely as it presents on the current paradigm and progress in welding and joining of Mg/Ti alloys. The factors governing the welding of several important techniques are deliberated along with their joining mechanisms. Some opportunities to improve the welding of Mg/Ti for different welding techniques are also identified.

Keywords: Mg alloy; Ti alloy; Mg/Ti dissimilar welding; intermetallic compound (IMCs); properties

1. Introduction

The growing demand for energy conservation and exhaust gas reduction has made light weight an important design parameter in automobile development (Auwal *et al.* 2018b, Avedesian and

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Baker 1999, Baqer *et al*. 2018, Manladan *et al*. 2017a, Mordike and Ebert 2001). Magnesium (Mg) has been described as a green engineering material and one of the most promising material in the 21st century (Mordike and Ebert 2001). It has unique properties such as low density, formability, good recyclability and high specific strength. In recent years, particular attention is given to the use of Mg components in automotive and aerospace sector in order to reduce exhaust gas emissions and to improve fuel efficiency (Kulekci 2008, Manladan *et al*. 2016, Mordike and Ebert 2001). However, Mg has relatively poor corrosion resistance and poor strength at moderate temperatures, thus restricting its application (Mordike and Ebert 2001). In contrast, titanium (Ti) has excellent corrosion resistance and biocompatibility, high strength to weight ratio coupled with low thermal conductivity (Schutz and Watkins 1998). It is commonly used in aerospace, automotive, chemical, biomaterial, petrochemical and aviation industries. Nevertheless, titanium is more costly than most commonly used engineering materials because of its expensive manufacturing process, which restrict its application to complex structures or functions where its use is crucial for the required performance (Lütjering and Williams 2007). Therefore, some applications are in favor of one of the materials than the other. The advancement in dissimilar joining technology has created the opportunity to combine both metals and to exploit their advantages for industry applications.

Recently, the application of both Mg and Ti alloys is rapidly increasing, particularly in automotive and aerospace manufacturing sectors. In particular, Mg/Ti parts are of great interest, not only for improve performance but also to reduce the cost of the entire structure (Gao *et al*. 2011, Tan *et al*. 2016a, 2017, Xu *et al*. 2014a). However, the significant differences in the physical properties and limited mutual solubility between both metals make joining them together very difficult. Many researchers have used different joining processes to join Mg/Ti, and the main factor for getting a metallurgical bond between Mg and Ti in all of those studies was the use of an interlayer or mutual diffusion of alloying elements from the base metal. The formation of a reaction product in the form of solid solution or intermetallic compound (IMC) along the interface between the Mg and Ti is responsible for formation of a metallurgical bond between them. However, the interfacial bonding achieved and the joints performance depend significantly on the newly formed reaction product. Hence, joining Mg/Ti alloys requires a careful selection of welding techniques and intermediate material to overcome the above mentioned problems.

Fusion welding technologies based on arc welding (Cao *et al*. 2014, Xu *et al*. 2014a, b, 2016, 2017) and laser beam welding (Auwal *et al*. 2019a, b, Gao *et al*. 2011, 2012, Tan *et al*. 2016a, b, 2017, 2018a, b, Zang *et al*. 2018, Zhang *et al*. 2018a, b, c) have been used to examine the weldability of Mg/Ti parts. However, the tendency of developing weld defects such as poor gap bridging, void, spatter and porosity must be considered due to rapid solidification of the weldment.

In comparison, solid-state joining techniques have also been attempted to join Mg/Ti which include friction stir welding (Aonuma and Nakata 2009, 2010, 2012, Tanabe and Watanabe 2008), diffusion bonding (Atieh 2013, Atieh and Khan 2013, 2014a, b, c, d, Jiangtao *et al*. 2006), and ultrasonic welding (Ren *et al*. 2017, Zhao *et al*. 2017). Most of these techniques can eliminate the weldability issues associated with joining of Mg to Ti, because during the solid-state bonding the parent metals remain in solid state. Nevertheless, the process conditions may make certain joining methods unbefitting; for example, the processing head during FSW imposed size and shape limitation, which make it difficult to apply. Similarly, diffusion bonding is applicable to only certain geometries and the bonds are characterized by rather low strength. Thus, diffusion bonding is not classified as a mass production process. Consequently, developing an alternative joining process that is more efficient, user friendly and low cost have become requisite for the realization of Mg/Ti hybrid structures in transportation industries.

This paper presents a comprehensive review on the microstructural development at the interface of the joints made by different welding techniques for joining Mg/Ti sheets with the intention of assessing the potential of each technique as well as challenges, and identifying areas for further research.

2. Challenges in joining Mg/Ti alloys

Joining dissimilar materials has been controlled by compositional gradients and microstructural variations, which resulted in changes in chemical, physical and mechanical properties across the joint (Manladan *et al*. 2017b). In particular, the main challenge in joining Mg/Ti alloys comes from their large differences in physical properties and early zero intersolubility (Gao *et al*. 2011). The comparison of the room temperature physical properties of some commonly used engineering metals are given in Table 1. It can be observed that huge property differences exists between magnesium and titanium. For instance, Mg has a melting point of 649℃ while that of Ti is 1678℃. This wide discrepancy in melting temperature makes it extremely difficult to melt the base materials at the same time as required in fusion-based welding techniques (Gao *et al*. 2011). Furthermore, the large differences in the thermal conductivity and thermal expansion coefficient of Mg (78 $Wm^{-1}k^{-1}$ and 25.8 × $10^{-6}k^{-1}$, respectively) as compared to Ti (17 $Wm^{-1}k^{-1}$ and 9.24 × $10^{-6}k^{-1}$, respectively) clearly indicates that there would be issues with heat dissipation and welding residual stress could easily be developed in the joint (Gao *et al*. 2012, Zhang *et al*. 2018c).

Although the welding process itself is a non-equilibrium process, phase diagram has always been an effective tool to forecast the reactions formed during welding process and serve as a reference to examine the feasibility of achieving a metallurgical bonding between the metals. Fig. 1 shows the binary phase diagram for Mg/Ti which indicates extensive miscibility gap exist in the solid and liquid states. The maximum solid solubility of titanium in Mg is 0.12 at.% while that of magnesium in Ti is nil (Gao *et al*. 2012, Villars *et al*. 1995). Therefore, Mg and Ti is immiscible (neither the formation IMC nor atomic diffusion occurs between them after solidification), thereby presenting another difficulty in joining them together. Thus, the solution for getting a metallurgical bond between Mg and Ti is the use of an interlayer or mutual diffusion of alloying elements from the base metal. The formation of a reaction product, either in the form of solid solution or IMC, along the interface between the Mg and Ti is responsible for formation of a metallurgical bond between them. However, the interfacial bonding achieved and the joint’s performance depend significantly on the newly formed reaction product(s). Generally, choosing a suitable interlayer for joining Mg alloys to Ti largely depends on the interlayer composition that provides excellent wetting and bonding without generating thick layers of hard and brittle IMCs at the joint interface.

Intermetallic compounds are solid phases comprising at least two metallic elements, with one or more non-metallic elements, whose crystal structure varies from the other constituents. Formation of thick, brittle IMCs between Mg and Ti can cause significant deterioration of mechanical properties. Therefore, when choosing the joining process, minimization of the thickness of any brittle IMCs that might form along the interfaces of the Mg-interlayer-Ti joint and also minimization of intermixing between the Mg and Ti in the liquid-state are the main factors that must be considered. If melting of the Ti and intermixing with liquid Mg occur during the welding process, weld cracking and porosity formation are inevitable at the interface because of the rapid vaporization of the Mg and zero intersolubility between Mg and Ti (Gao *et al*. 2012).

Table 1 Room temperature physical properties of Mg, Ti, Al and Fe (Baqer *et al*. 2018)

Properties	Unit	Ti	Mg	Al	Fe
Ionization energy	eV	6.8	7.6	6	7.8
Specific heat	$Jkg^{-1}K^{-1}$	519	1360	1080	795
Latent heat of fusion	kJ/kg	419	368	398	272
Melting temperature	°C	1678	649	660	1536
Boiling temperature	°C	3285	1091	2520	2860
Viscosity	$kgm^{-1}s^{-1}$	0.0052	0.00125	0.0013	0.0055
Surface tension	Nm^{-1}	1.65	0.559	0.914	1.872
Thermal conductivity	$Wm^{-1}K^{-1}$	22	78	238	38
Thermal diffusivity	m^2s^{-1}	2.15×10^{-6}	3.73×10^{-5}	3.65×10^{-5}	6.80×10^{-6}
Coefficient of thermal expansion	1/K	9.24×10^{-6}	25.8×10^{-6}	24×10^{-6}	10×10^{-6}
Density	kgm^{-3}	4500	1590	2385	7015
Elastic modulus	N/m^3	10.3×10^{10}	4.47×10^{10}	7.06×10^{10}	21×10^{10}
Electrical resistivity	$\mu\Omega$m	5.5	0.275	0.2425	1.386

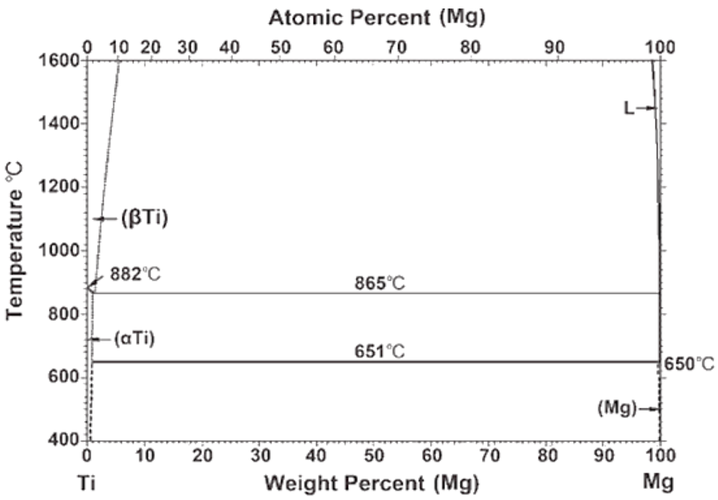

Fig. 1 Mg/Ti binary phase diagram (Villars *et al*. 1995)

3. Joining of Mg/Ti alloys

The flexibility in the production of components was enhanced by the incorporation of joining technology in the manufacturing process. However, careful selection of the joining techniques for the dissimilar parts is essential (Atieh 2013). Different joining processes have been employed to join Mg/Ti sheets, and they can be categorized as solid-state methods such as diffusion bonding, friction stir welding, and fusion-based processes, including arc welding and laser welding. To improve metallurgical compatibility and joint formation, these processes are used in combination with interlayers/filler metals such as Al, Zn, Ni and Cu. In this section, the potential of these methods for joining Mg/Ti are reviewed.

3.1 Fusion-based welding processes

Fusion welding has been described as the mostly commonly used welding methods in manufacturing (Sun and Ion 1995). Thus, considerable number of researchers concentrated on joining of dissimilar metals using this method despite their obvious difficulties while joining Mg/Ti, such as coarsening of the grains, voids development and cracks formation at the welding temperature (Gao *et al*. 2012). Fusion welding involves joining the surface of the materials through melting and solidification to produce the bonding (Atieh 2013). A filler material can also be added to strengthen the weld region and compensate for the differences in chemical composition of the base metals. Generally, the major fusion processes are gas welding, arc welding and high energy beam welding (electron beam welding and laser beam welding). Amongst these processes, arc welding (Cao *et al*. 2014, Xu *et al*. 2014a, b, 2016, 2017) and laser beam welding (Auwal *et al*. 2019a, b, Gao *et al*. 2011, 2012, Tan *et al*. 2016a, b, 2017, 2018a, b, Zang *et al*. 2018, Zhang *et al*. 2018a, b, c) have been investigated for joining Mg/Ti alloys. The various fusion based welding methods are distinguished from each other by the method used to generate the heat.

3.1.1 Arc welding

Arc welding belongs to the group of fusion-based welding methods that use an electric arc to generate the heat that melt and joint the materials. Previous studies showed that the widely used arc welding techniques to produce Mg/Ti welds are metal inert gas (MIG) (Cao *et al*. 2014) and tungsten inert gas (TIG) (Xu *et al*. 2014a, b, 2016, 2017). The success in this joining technique in producing a metallurgical bond between Mg and Ti was the use of alloying element from the parent metals, filler metal or coating layers. Both being gas shielded arc welding processes, TIG uses non-consumable tungsten electrodes while MIG employs consumable electrodes (wires) during welding.

Cold metal transfer (CMT) welding which is a modified MIG welding, has introduced a new way to join dissimilar metals having large difference in their melting point such as Mg/Ti (Cao *et al*. 2014) and Mg alloy/steel (Cao *et al*. 2013, 2016). The CMT welding employs a new technique of droplet detachment based on short circuit welding, which reduced thermal input and resulted in low distortion and high precision. Cao *et al*. (2014) joined pure Ti (TA2) to AZ31B (3 wt.% Al) under different configurations by CMT technique using AZ61 filler (6 wt.% Al). The authors observed welding and brazing joints at the Mg and Ti sides, respectively as shown in Fig. 2. The analysis of the interface characteristics showed that of both joints configurations, the brazing interfaces which determines the joint quality composed of Ti_3Al and $Mg_{17}Al_{12}$ phases resulting from diffusion of the Al elements from the molten magnesium base metal whereas the filler wire aggregated at the liquid/solid interface and reacted with titanium substrate. This interfacial reaction was in good agreement with Al-Mg-Ti ternary system (Eustathopoulos *et al*. 1999).

Although sound Mg/Ti welds were achieved using CMT welding, the joint tensile strength was low. To enhance the tensile strength of the joints during CMT welding, the local melting of titanium substrate is crucial. Nevertheless, the low melting point of the Mg based filler wire (649℃) caused the arc temperature to slightly melt the titanium sheet. Future research should concentrate on offsetting the filler wire towards the Ti sheet to address this problem.

More recently, Xiong *et al*. (2018) demonstrated that gas metal arc welding (GMAW)-based additive manufacturing could be a promising joining method capable of utilizing materials and energies for manufacturing complex metallic components. In this research, the authors used a laser vision system to investigate the surface roughness on the side face of multi-layer single-pass low

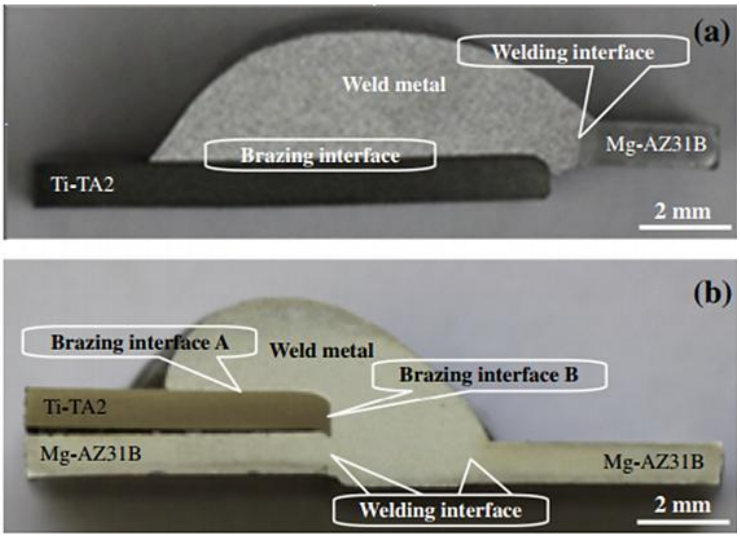

Fig. 2 Mg/Ti welded-brazed joints under different configurations: (a) Mg-Ti and (b) Ti-Mg (Cao *et al*. 2014)

carbon steel parts. They showed that process parameters such as the interlayer temperature, wire feed speed and travel speed have an impact on determining the surface condition of the thin-walled parts. This assessment approach could also provide further insight on the influence of process parameters on the surface roughness of Mg/Ti joint.

Prior studies reported that Bypass Current MIG (BC-MIG) could improve joint performance because of the stable, steady droplet transfer and low heat input (Miao *et al*. 2014). However, no research on the usage of BC-MIG technique in Mg/Ti joining has been reported and this would be a possible endeavor to pursue.

On the other hand, TIG welding is more favorable than MIG welding, since the TIG arc is stable even at low currents, making joining of thin parts promising. It offers additional benefits such as flexibility, high efficiency, good joint quality and has the potential to join dissimilar metals such as Mg/Ti. Xu *et al*. (2014a) studied the TIG lap welded TA2 to AZ31B dissimilar metal joints using AZ31B Mg based filler. Their results showed that a welded–brazed joint was formed and that metallurgical bonding was achieved at the joint interface due to the formation of coarse-grained fusion zone with precipitated phase of $Mg_{17}Al_{12}$ and a distributed Mg/Ti solid solution. Under optimum process parameters a joint with maximum shear strength of 193.5 Nmm^{-2} was achieved. However, excessive grain coarsening was observed at the fusion zone due to the large differences in thermal properties of the base metals.

Conversely, applying vibration during the solidification of welding pool could refine the microstructure and enhance the mechanical resistance of the welding parts. Thus, the Mg/Ti joints characteristics was improved using dynamic grain refining method via ultrasonic assisted TIG (U-TIG) welding-brazing technique. The application of ultrasonic power into the molten material and subsequent solidification stage, nucleation and cooling rates of molten material were improved, which resulted in remarkable refinement of columnar α-Mg grains into equiaxed grains. This has also improved the joint strength from 193 Nmm^{-2} to 228 Nmm^{-2} (Xu *et al*. 2014b). These studies suggested that the microstructure of metals is not only influenced by nucleation stage but also affected by the subsequent growth state (Xu *et al*. 2014a, b).

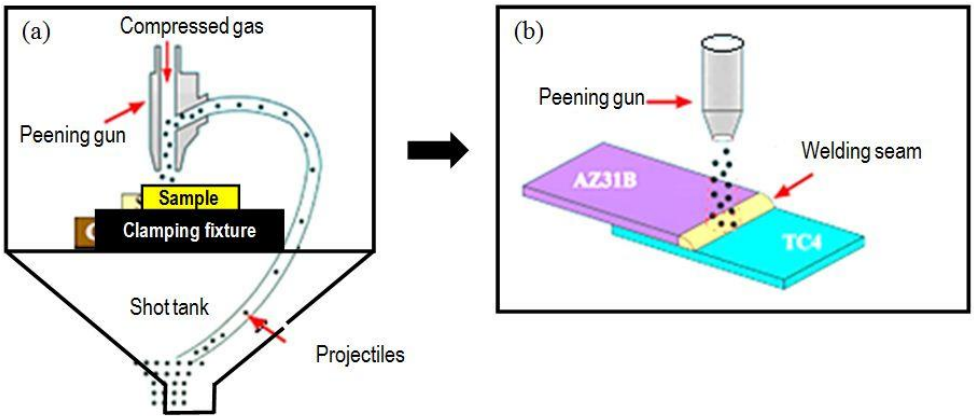

Fig. 3 Schematic of HESP assisted TIG process (Xu *et al*. 2017)

Xu *et al*. (2017) has further improved the joint performance by using high-energy shot-peening (HESP) treatment as shown in Fig. 3. The addition of the HESP treatment eliminated the weld defects and introduced high compressive residual stress and surface strain strengthening. As shown in Figs. 4(a) and (b), many defects could be seen for the TIG welded joint without HESP treatment. However, these defects were reduced significantly through plastic deformation of the surface layer induced by HESP (Figs. 4(b), (c), (e) and (f)), which resulted in tensile strength improvement from 190 to 241 MPa.

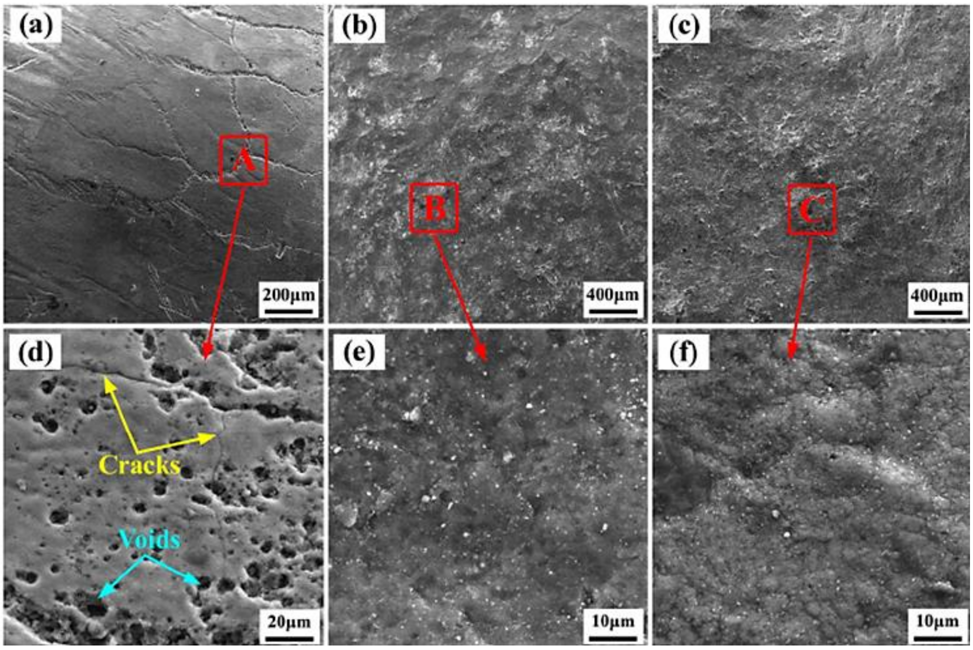

Fig. 4 Surface appearance of HESP assisted TIG welded brazed Mg/Ti joints: (a) to (c) at peening time of 0 s, 60 s and 180 s; (d) to (f) ammplifed images of zone A, B and C (Xu *et al*. 2017)

Table 2 Comparison of the Mg/Ti alloys joints maximum tensile shear strength produced by arc welding techniques

Techniques	Materials	Joint design	Transition material	Max. tensile shear strength	Failure location	Ref.
CMT welding	AZ31B/TA2	Lap (Mg on top)	Al from AZ61 filler	2.10 kN	Interface	Cao *et al.* (2014)
TIG welding-brazing	1 mm AZ31B/ 1 mm TA2	Lap (Mg on top)	Al from Mg base metal and filler wire	193.5 N/mm	Mg Fusion zone	Xu *et al.* (2014a)
TIG welding-brazing	1 mm AZ31B/ 1 mm TA2	Lap (Mg on top)	Al from Mg base metal and filler wire	228 N/mm	Mg base metal	Xu *et al.* (2014b)
TIG welding-brazing	1 mm AZ31B/ 1 mm TC4	Lap (Mg on top)	Al from Mg base metal and filler wire	190 N/mm^2	Interface	Xu *et al.* (2016)
TIG welding-brazing	1mm AZ31B/ 1 mm TC4	Lap (Mg on top)	Al from Mg base metal and filler wire	241 N/mm^2	Mg base metal	Xu *et al.* (2017)

Although the feasibility of employing various techniques to enhance joint performance of Mg/Ti joints have been explored, in most cases the joint strength is still considered low. Therefore, more research efforts are still needed to improve the joint mechanical resistance. Based on the existing literature, the joint performance depends largely on the surface and microstructure evolution. Although some degree of success has been achieved with ultrasonic and HESP assisted TIG welding techniques, other surface strengthening technology should be explored.

Table 2 compares the tensile-shear strength of Mg/Ti joints produced by arc welding techniques. During the arc welding of Mg/Ti alloys, several authors observed that a welded–brazed joint was formed. Addition of suitable interlayer could improve the adhesion and the nucleation of magnesium on the Ti substrate. However, the reaction that occurs at the interface have not been fully understood. Both MIG and TIG seem to have some issues with the use of low welding speed and high heat input which resulted in severe defects in the weldment such as voids, high residual stresses and distortion.

3.1.2 Laser beam welding

Laser beam welding presents a viable option for welding dissimilar metals such as Mg/Ti because of its high specific heat input (Auwal *et al.* 2018a, Baqer *et al.* 2018, Gao *et al.* 2009, 2011). Some of the major benefits of laser welding over arc welding include high welding speed, less distortion and no slag or spatter etc. In general, laser welding of metals involves the formation of a melt-pool and subsequent rapid solidification resulted from alteration of properties and the microstructure of the welded metal. Thus, understanding and predicting relationships between the laser welding process parameters (laser power, welding speed) and melt-pool characteristics such as geometry, thermodynamics, fluid dynamics, microstructure and porosity are necessary in controlling as well as improving laser welding (Fotovvati *et al.* 2018). Although several experimental studies have been conducted on melt-pool characterization in laser welding, direct experimental observation of melt-pool characteristics remains a challenge because of the high temperatures in the melt-pool and the difficulty of monitoring the metal vapor in the keyhole (Fotovvati *et al.* 2018, Mann *et al.* 2018). Thus, in order to circumvent this issue, intermediate element, filler metal or coating layers have been used as a bridge to promote the metallurgical

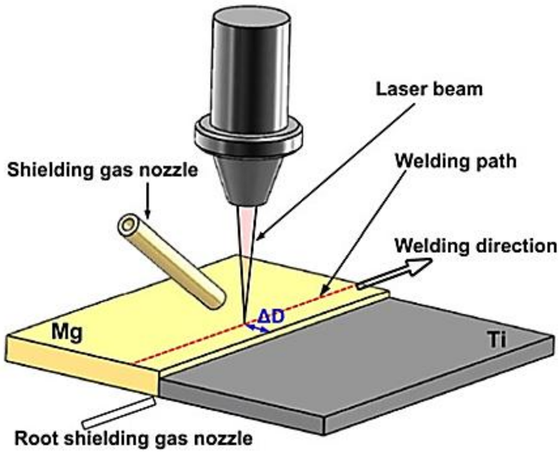

Fig. 5 Illustration of fiber keyhole laser welding experimental set-up (Gao *et al*. 2012)

bonding of Mg/Ti joint.

Gao *et al*. (2011, 2012) butt joined AZ31B to Ti-6Al-4V using AZ31 brazing filler or melting of thicker magnesium base metal to compensate excessive vaporization of Mg. The typical illustration of the fiber keyhole welding is shown in Fig. 5. The results showed that beam offset (ΔD) played an essential part in the process stability and weld characterizations by altering the power-density at the initial interface. Fig. 6 shows that a good joint was obtained when the offset was 0.3-0.4 mm which resulted in an ultimate tensile strength of 266 MPa (Gao *et al*. 2012). The interfacial reaction layer of this joint comprised of α-Mg and Mg-Al eutectic, whereas the poor joint surface composed of only *α*-Mg (Gao *et al*. 2011). The formation of $Mg_{17}Al_{12}$ IMC layer was associated with Al in Ti-6Al-4V reaction with magnesium base metal. The thickness of the IMC layer was found to increase with temperature and diffusion at the interface, which are determined by the laser offset.

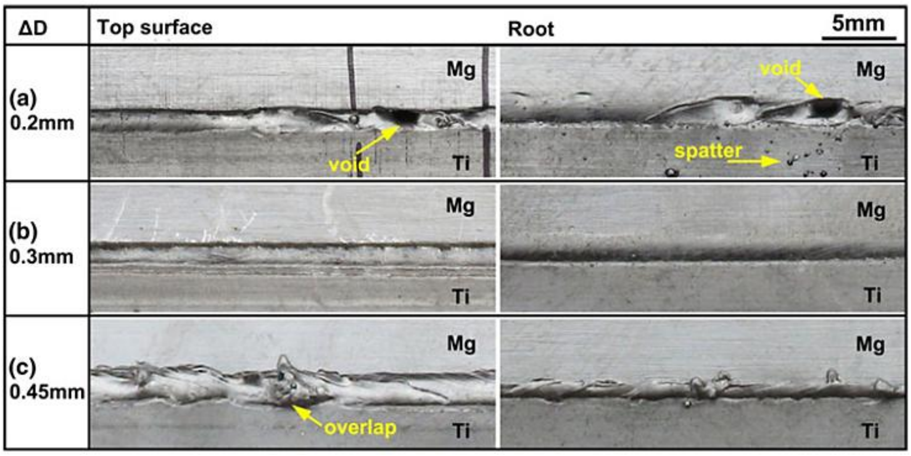

Fig. 6 Mg/Ti joints appearances at (a) Δ*D* = 0.2 mm, (b) Δ*D* = 0.3 mm, and (c) Δ*D* = 0.45 mm (Gao *et al*., 2012)

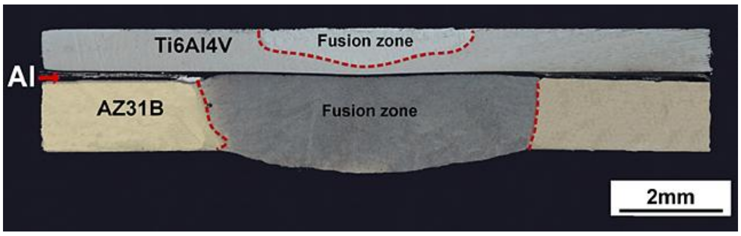

Fig. 7 Cross-section of laser conduction welded Mg/Ti joint (Zang *et al*. 2018)

On the other hand, compared with introducing the Al alloying element from the filler material, addition of the Al in the form of foil is easier. Therefore, the interfacial characteristics and mechanical properties of AZ31B/Ti-6Al-4V lap joints using Al foil interlayer was examined (Zang *et al*. 2018) using laser conduction welding technique. During the laser heat conduction process, the laser beam irradiated on the titanium substrate and subsequently the energy was transferred via conduction to the adjoining layers (the aluminum and magnesium), causing them to melt.

Thus, Mg, Al and Ti were mixed from the fusion zone to liquid/solid as typically shown in Fig. 7. The analysis of the interface characteristics revealed that ultra-thin $TiAl_3$ layer formed at the liquid/solid interface. The $TiAl_3$ IMC layer thickness changed a little and Mg-Al became denser with the increasing Al interlayer thickness. This was attributed to the fact that the diffusion between liquid/solid interfaces was restricted under the rapid heating and cooling; the melting of Al occurred due to the heat conduction from Ti and would dissolved into the fusion zone preferentially because of the gravity-effect and $TiAl_3$ phase forming temperature was lower. The joint quality showed that the interlayer thickness influenced the joint performance (Fig. 8).

To further improve the flexibility of introducing the intermediate element, electrodeposition was also explored. In another study Zhang *et al*. (2018a) welded AZ31B to Ni plated-Ti-6Al-4V alloys using laser heat conduction welding method. The effect of the Ni electrodeposition on the joint formation under different heat input was investigated. Under optimum joining parameters, Ti_2Ni reaction layer and Ti solid solution were formed at the braze interface. Moreover, the thickness of the reaction products increased with the increase in heat input. The analysis of the Ni coating diffusion mechanism revealed that the diffusion of electrodeposited Ni was influenced by

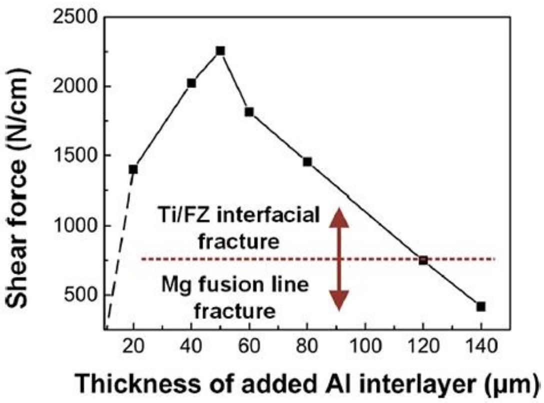

Fig. 8 Effect of Al foil thickness on the tensile-shear force of laser welded Mg/Ti joints (Zang *et al*. 2018)

bidirectional mechanism to Mg and Ti sides, which resulted in the variation of reaction layer thickness as shown in Fig. 9. Nevertheless, low tensile strength of 144 N/mm was achieved, which was attributed to the magnesium molten pool instability under the action of gravity.

Laser beam can be a preferred method for welding Mg/Ti because of the more precise heat input and limited deformation (Atabaki *et al*. 2014, Auwal *et al*. 2018a); however, the tendency of developing weld defects such as poor gap bridging ability, void, spatter and porosity must be considered due to rapid solidification of the weldment. Filler wire could minimized the weld defects greatly, but imposed additional complications in the joining process. In particular, improving the stability of the keyhole is the main concern for laser welding in keyhole mode compared to unsteady welding process for laser heat conduction welding technique. Table 3 compares the joint performance of keyhole and conduction Mg/Ti laser welding techniques.

In general, joining Mg/Ti by laser welding is still at its infancy stage. Contrary to poor gap bridging ability, high precession in work piece fit-up and edge preparations requires by laser welding process, the arc welding processes have an excellent gap bridging ability (Ascari *et al*. 2012, Le Guen *et al*. 2011, Shenghai *et al*. 2013). However, their low energy density resulted in

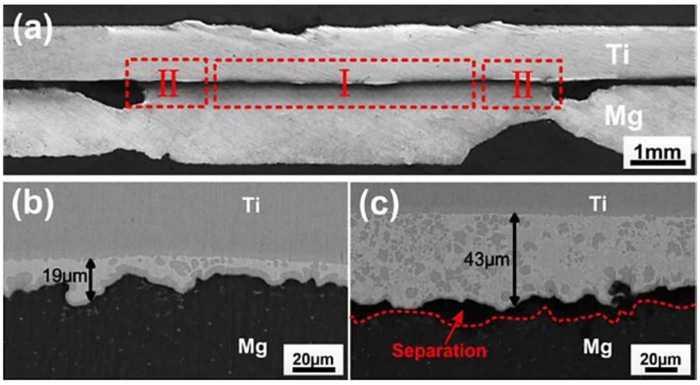

Fig. 9 Laser conduction welded Mg/Ti: (a) optical micrograph; (b) SEM micrograph of the zone I in (a); and (c) SEM micrograph of the zone II in (a) (Zang *et al*. 2018)

Table 3 Comparison of the Mg/Ti alloys joints maximum tensile shear strength produced by conduction laser welding techniques

Techniques	Materials	Joint design	Transition material	Maximum tensile shear strength	Failure location	Ref.
Keyhole laser welding	3 mm AZ31/ 2 mm Ti-6Al-4V	Butt (Offset towards Mg)	Al from Ti base metal	266 MPa	Interfacial	Gao *et al.* (2011, 2012)
Laser heat conduction	1.5 mm AZ31B/ 1.5 mm Ti-6Al-4V	Lap (Ti on top)	Al foil (0.05 mm thick)	2230 N/cm	Interfacial	Zang *et al.* (2018)
Laser heat conduction	1 mm AZ31B/ 1 mm Ti-6Al-4V	Lap (Ti on top)	Ni coating (20 μm thick)	144 N/mm	Interfacial and weld appearance of Mg side	Zhang *et al.* (2018a)

thermal distortion of joint. Therefore, hybridization of laser and arc welding could compliments their advantages and compensates their shortcomings (Acherjee 2018, Sathiya *et al*. 2013).

Several researchers (Liu and Qi 2009, 2010, Liu *et al*. 2010, Liu and Shan 2009, Qi and Liu 2010, 2011, Qi and Song 2010) employed laser-hybrid techniques to join AZ31B and Q235 steel (having similar immiscible characteristics with Mg/Ti) in the lap configuration using different interlayers (Ni, Cu, Sn and Cu-Zn). 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 joint shear strength could reach a significantly high value or even surpasses Mg alloy base metal. The high joint shear strength obtained was associated with better wettability and deeper penetration in the weld. However, no study available in the literature on the use of laser-hybrid welding in Mg/Ti joining and this would be an area for further research.

To address the problems associated with laser welding of Mg/Ti alloys, considerable number of researchers have recently attempted an alternative laser welding method known as laser-welding brazing (LWB). Brazing of metals differs from fusion welding in that brazing temperatures are generally lower than the melting points of the base metals. Hence, brazing can be an alternative welding technique for joining dissimilar materials having large difference in melting point such as Mg/Ti (Auwal *et al*. 2019a, b, Tan *et al*. 2016a, b, 2017), Ti/steel (Chen *et al*. 2014) and Ti/Al (Chen *et al*. 2009, 2018, 2019) and Al/steel (Dharmendra *et al*. 2011, Li *et al*. 2018). In addition, the IMC thickness could be minimized by fast heating and cooling rates. If IMCs could be limited below the critical thickness of 10 μm, an acceptable mechanical properties may be obtained (Auwal *et al*. 2018b, Kreimeyer *et al*. 2005). With the high specific heat input of the laser beam, high welding speeds and cooling rates could be realized with least heating of the base materials. Therefore, the use of LWB technologies for joining Mg/Ti will be of great benefit to the industry because of the combined features of laser welding and brazing (Nasiri 2013).

Typically, in LWB, the upper magnesium is irradiated by the laser beam causing it to melt and to wet the bottom titanium sheet. In addition, an intermediate element which could interact with or have significant solubility in both materials could be used to achieve better interfacial reaction (Tan *et al*. 2016a). In addition, to enhance the flexibility of controlling the interfacial reaction, the use of filler wire containing high Al has been suggested. Tan and co-workers studied the interfacial characteristics of LWB lap welded AZ31/Ti-6Al-4V joints using magnesium filler metal. The results showed that compared with mechanical bonding when using magnesium filler metal having low Al contents (AZ31), a thin interfacial reaction layer whose thickness varied slightly with heat-input was observed when using magnesium filler metal having low Al contents (AZ91). The analysis of the brazed interface by TEM bright field image (Figs. 10(a) and (b)) and HAADF micrograph (Fig. 10(c)) with corresponding SADP (Fig. 10(d)) show that a thin interfacial reaction layer indexed as Ti_3Al phase was formed, which improved the joint performance from 25.5 to 2057 N (Tan *et al*. 2016a). The outcome of this study proved that Al played an indispensable role in Mg/Ti joint formation and by varying the content of interlayer elements is an effective way to regulate interfacial reaction. However, the restricted contents of Al to be added into the magnesium filler metal without erosion of the parent metals poses another challenge.

Elements such as nickel and copper are commonly used to enhance the weld properties (Amer *et al*. 2010). In addition, these elements can react with Ti and Mg, and thus interfacial bonding could be achieved. In addition, the Ni-Cu binary phase diagram belongs to an isomorphous system i.e., they have complete liquid and solid-solubility; hence a reasonably good homogeneous microstructure with good corrosion resistance can be expected (Yue *et al*. 2010).

Based on these considerations, Ni (Tan *et al*. 2017, 2018a, b), Cu (Zhang *et al*. 2018b, c) and

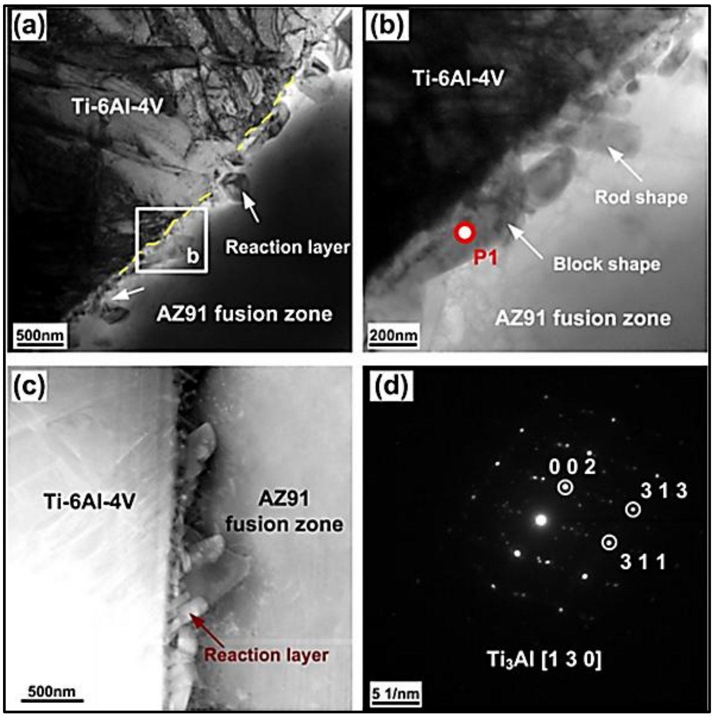

Fig. 10 TEM images of Mg/Ti joint interface: (a) Interface bright field image; (b) Higher magnification of (a); (c) HAADF image of (a) and (d) SAED of the interface (Tan *et al*. 2016a)

Cu-Ni (Auwal *et al*. 2019a, b) electrodeposited layer were investigated as a bridge to promote the interfacial reaction by laser welding-brazing technique. The effect of the electroplated coatings addition on the interfacial reaction and joint performance were systematically studied. It was revealed that the electroplated coatings enhanced the wettability of the brazing filler and took part in the microstructure development. The actual interfacial products was depended on the welding heat-input and interlayer elements contents.

Tan *et al*. (2018b) found that for AZ31B/Ni coated Ti-6Al-4V lap joints, interfacial bonding was achieved by the Ti_3Al IMC formed at direct irradiation zone whereas Ti-Al-Ni ternary IMC and Ti_3Al phase were formed at the middle zone while Ti-Ni IMC was observed at the weld toe zone. With increasing Ni thickness, the Mg-Al-Ni IMC grew bigger and changes from granular into dendritic shape. In addition, the Ti-Ni formed at the weld toe region grew thicker and transformed to Ti_2Ni phase when the thickness of the Ni exceeded 5.8 μm. The interface characteristics was explained using thermodynamic analysis based on enthalpy of formation and chemical potential. Similarly, the thickness of the interfacial IMC layer increased with increase in heat input (Tan *et al*. 2017). Under optimum welding parameters and Ni content, the joints produced peak shear tensile load of 2430 N, having joint efficiency of 90% compared to AZ31 alloy (Tan *et al*. 2018b). In comparison, the LWB characteristics of AZ31B/Ti-6Al-4V butt joints with and without Ni coating revealed that with increasing heat input the interfacial reaction products transformed from Ti_3Al phase to mixed layer of Ti_3Al + Ti_2Ni, to Ti_3Al. Furthermore, Ti_2Ni phases evolved at high heat-input on titanium surface (Tan *et al*. 2018a). This interfacial reaction formed was verified by TEM analysis as shown in Fig. 11 for the joint welded at 1500 W.

Two type of phases were observed from the bright field micrographs in Fig. 11(a) indexed as Ti_2Ni and Ti_3Al according to the SAED analysis (Figs. 11(b)-(c)). In contrast, no obvious IMC was formed at Mg/bare Ti joints interface. However, atomic diffusion of Al from the brazing alloy to titanium occurred, which resulted in the formation of thin Ti_3Al (Tan *et al*. 2016a). Fig. 12 shows the tensile-shear loads of both direct and Ni coated joints under different heat input. It can be observed that in both cases, the joint performance increased initially with heat input and then decreased with further increase of heat. The optimum fracture load of 3900 N was obtained with Ni coating i.e., about three times higher than that of un-coated joint. Moreover, the thickness of the IMCs shown in Fig. 13 also increased with heat-input, suggesting that suitable heat-input could improve the joint interfacial bonding.

On the other hand, LWB of AZ31B to Cu-plated Ti-6Al-4V using AZ92 brazing filler was investigated by Zhang *et al*. (2018b, c). The results indicated that only Ti_3Al phase was produced at the direct irradiation zone and grew with increasing Cu thickness. With increasing Cu contents, the IMC evolved from Ti_3Al to Ti_3Al/Ti_2Cu to Ti_3Al/Ti_2Cu + $AlCu_2Ti$ at the middle zone, while Ti_2Cu was developed at the weld toe zone. The interface characteristics were explained using thermodynamic analysis based on enthalpy of formation and chemical potential. The analysis of the role of Cu coating on joint formation showed that the Cu coating protected the Ti surface from oxidation. In addition, the Cu element supported mutual diffusion of Al and Ti atoms, which

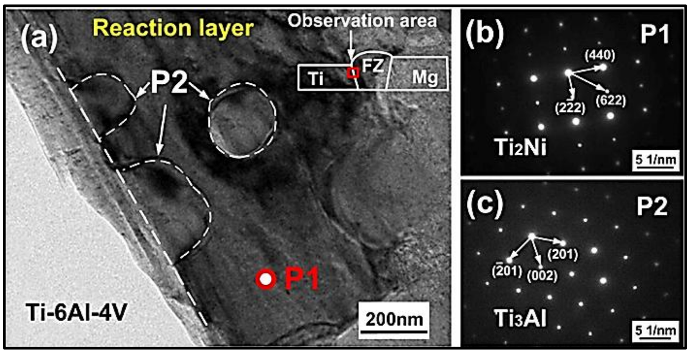

Fig. 11 TEM images of Mg/Ti butt joint interface: (a) Interface bright field image; (b)-(c) SAED of the interface phases formed (Tan *et al*. 2018a)

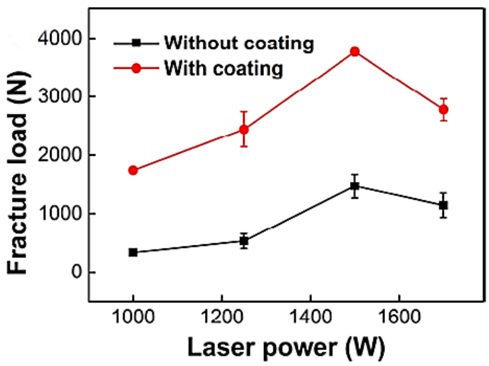

Fig. 12 The variation of tensile-shear performance with heat input (Tan *et al*. 2018a)

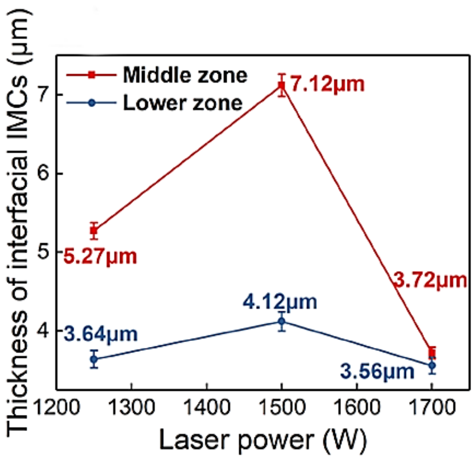

Fig. 13 The variation of thickness of the IMCs layer with heat input (Tan *et al*. 2018a)

resulted in the growth of Ti-Al IMC at both direct and middle regions. Compared to Mg/bare Ti joint where only Ti_3Al phase was formed upon cooling (Tan *et al*. 2016a), Ti-Cu mixed IMC was observed at the interface with addition of Cu, which contributed in enhancing the quality of the joint. Under optimum welding conditions, the tensile-shear load reached a maximum value of 2314 N (Zhang *et al*. 2018c). Nevertheless, the joints performance obtained were lower than that of Ni-plated joint as discussed earlier. This could be associated with formation of denser Mg-Cu eutectic structure in the fusion zone.

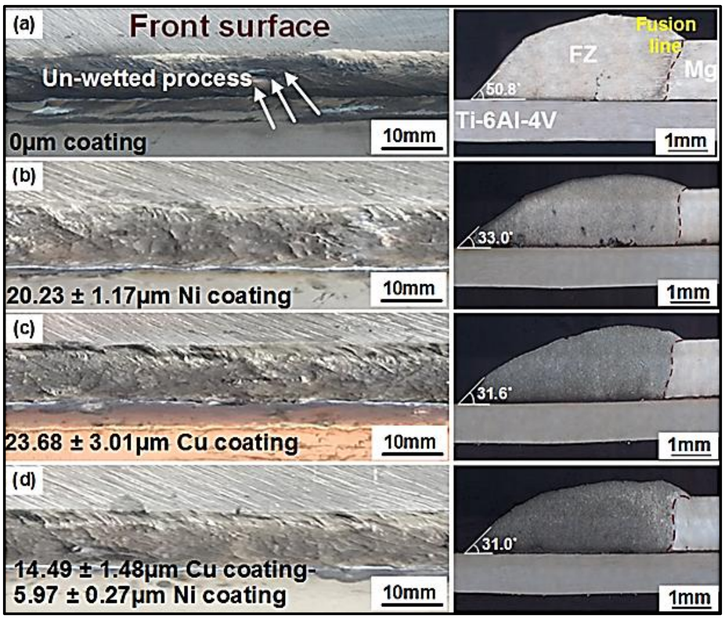

Fig. 14 Mg/Ti joint interface appearances: (a) Un-coated; (b) Ni plated; (c) Cu plated; and (d) Cu-Ni plated (Auwal *et al*. 2019a)

In another study, LWB characteristics of AZ31B to Cu-Ni-plated Ti-6Al-4V using AZ92 brazing filler was also investigated under different coating layer arrangements. The preliminary results showed that obtaining a sound joint largely depends on the pre-existing copper-nickel layer. The analysis of the microstructure development showed that both the coating arrangements and heat-input influenced the layer formation. However, under optimum joining conditions, a mixed reaction layer composed of Ti_2Ni and Ti_3Al was observed at the braze interface for both coating layer configurations, which grew with increase in heat input (Auwal *et al*. 2019b). In addition, the effect of the Cu, Ni and Cu-Ni coatings on LWB Mg/Ti lap joints was also examined under similar welding and electrodeposition conditions. The results showed that the addition of the coating layers improved the joints appearances, signifying that the presence of the coating enhanced the spreadability of brazing alloy on the titanium surface as shown in Fig. 14.

The different coating condition resulted in the obvious differences in the brazed side of the joint. The Mg/Ni-Cu coated Ti joint sustained superior mechanical performance (Fig. 15). The higher joint performance was attributed to the Al and Ti mutual diffusion enhancement by the Cu atoms and the Ti-Ni IMC formation at the brazed interface. Furthermore, the thickness of the mixed interfacial layer was less than the critical thickness of 10 μm (Kreimeyer *et al*. 2005) which was beneficial to the joint's mechanical resistance.

Table 4 compares the performance of LWB Mg/Ti joints. Good tensile-shear strength was achieved which could be attributed to the suppression of IMCs by this welding technique. However, the formation mechanism of the interfacial reaction is not clear and would need further investigation.

In addition, the poor wetting, if not carefully controlled, could deteriorate the weld appearance and process stability. Therefore, the wetting of brazing alloy and interfacial reaction products formation can be controlled by adjusting the welding parameters such as heating mode, heat-input, initial temperature of the parent metals and laser configuration (Haboudou *et al*. 2003, Laukant *et al*. 2005, Li *et al*. 2018, Mei *et al*. 2013, Takemoto *et al*. 2009). In addition, eliminating the non-

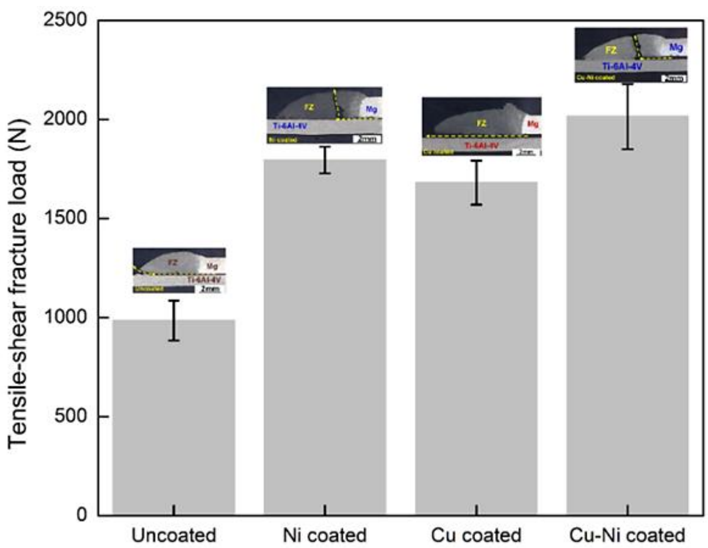

Fig. 15 Comparison of tensile-shear load and fracture location under various coating conditions (Auwal *et al*. 2019a)

Table 4 Comparison of the Mg/Ti alloys joints maximum tensile shear strength produced by laser welding-brazing techniques

Materials	Joint design	Transition material	Maximum tensile shear strength	Failure location	Ref.
1.5 mm AZ31/ 1.5 mm Ti-6Al-4V	Lap (Mg on top)	Al from AZ91 filler metal	2057 N	Fusion zone	Tan *et al*. (2016a, b)
1.5 mm AZ31/ 1 mm Ti-6Al-4V	Lap (Mg on top)	Ni coating	2430 N/cm	Fusion zone	Tan *et al*. (2017, 2018b)
1.5 mm AZ31/ 1 mm Ti-6Al-4V	Butt	Ni coating	3900 N	Mg base metal	Tan *et al*. (2018a)
1.5 mm AZ31/ 1 mm Ti-6Al-4V	Lap (Mg on top)	Cu coating	2314 N	Interface	Zhang *et al*. (2018b, c)
1.5 mm AZ31/ 1 mm Ti-6Al-4V	Lap (Mg on top)	Cu-Ni coating	2020 N	Fusion zone	Auwal *et al*. (2019a, b)

homogeneity of the interfacial reaction using suitable welding groove could increase the length of interface and improve joint performance (Li *et al*. 2017, Sun *et al*. 2016, Zhang *et al*. 2013). However, the influence of most of the process parameters mentioned on weld morphology and joint performance are not fully understood and require more study.

3.2 Solid state joining processes

Fusion welding is prone to generate micro-voids, porosity in welds and thermal distortion. Therefore many alternative methods have been explored based on solid state welding techniques to address the complications faced in fusion welding methods. Solid state joining processes produce coalescence at a temperature below the melting point temperature of joining materials without addition of any filler material. Bonding is realized by the introduction of diffusion and/or thermal, electrical, or mechanical energy. Some of commonly used solid-state welding techniques are ultrasonic welding, cold welding, diffusion bonding, friction welding and friction stir welding. Based on these options, the friction stir welding (FSW) (Aonuma and Nakata 2009, 2010, 2012, Tanabe and Watanabe 2008), diffusion bonding (Atieh 2013, Atieh and Khan 2013, 2014a, b, c, d, Jiangtao *et al*. 2006) and ultrasonic welding (Ren *et al*. 2017, Zhao *et al*. 2017) have been investigated for joining Mg/Ti alloys. Although the formation of defects such as surface voids and cracks are often eliminated because the parent metals stay in the solid-state, but the service conditions may make certain methods unsuitable since most of the welding processes are applicable to only certain geometries. Generally, in solid-state bonding, the joint performance is influenced by the intimate contact between the dissimilar metals and the microstructure, particularly the IMC formation (Chen and Nakata 2010).

3.2.1 Friction Stir Welding (FSW)

FSW is a solid-state welding method that operates by generating frictional heat between a rotating tool and the work-piece. The welds are created by the combined action of frictional heating and plastic deformation due to the rotating tool. Compared to traditional fusion welding,

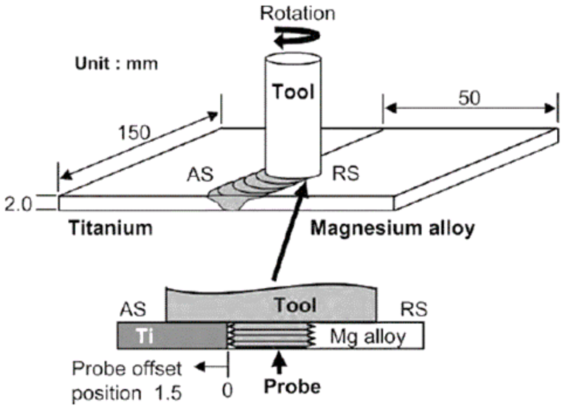

Fig. 16 A schematic illustration of the FSW process (Aonuma and Nakata 2010)

FSW offers some unique advantages over conventional welding such as absence of flux or filler, fewer or no defects, enhanced mechanical properties and very high heat efficiency. However, FSW is best use for long and straight welds. In addition, developing economically buyable tools which would allow the process to contest against the fusion-based welding methods remain a challenge (DebRoy and Bhadeshia 2010).

A typical schematic illustration of FSW is shown in Fig. 16. In general, a probe is inserted in Mg alloy side and slightly offset into Ti sheet side to ensure direct contact between them (Fukumoto *et al*. 2004, Watanabe *et al*. 2005). The main issue when joining Mg/Ti by FSW is the differences in deformation behaviors and physical properties such as thermal conductivity contribute to the asymmetry in both heat generation and material flow. Thus, application of this technique to join Mg/Ti alloys obviously poses a unique set of difficulties.

There is not much work done in studying the FSW of Mg/Ti alloys. However, Tanabe and Watanabe (2008) examined the effect of rotating tool on the butt joint quality of AZ31B Mg alloy to commercially pure Ti (CP-Ti) produced by FSW technique. The results showed that the probe geometry significantly influence the joint strength. Compared to cylindrical probe, the probe with thread showed 79% higher tensile strength because the area with plastic flow of Mg was enlarged owing to the diffusion of Ti into the Mg. Furthermore, the downward plastic flow reduced the likelihood of the occurrence of voids near the weld interface. Although the activities occurring at the joint interface have not been fully explored, the preliminary analysis of the joint interface showed that the Al contained in the magnesium diffused into the Ti side. Moreover, Ti fragments were scattered in the Mg matrix resulting in a reduction in the joint performance.

In another research, Aonuma and Nakata (2009) examined the performance of TA2/Mg-Al-Zn (AZ31B, AZ61A, AZ91D) joints produced by FSW technique. The interfacial characterization showed that Ti-Al IMC layer identified as $TiAl_3$ was observed at the Ti interface. This is contrary to the observation made by Tan *et al*. (2016a) who found that increasing the Al content of the Mg-Al-Zn base metal resulted in metallurgical bonding and improved the joint performance. These authors also observed that with the increasing Al element content in the Mg base metal, the thickness of the Ti-Al IMC increased, whereas the tensile strength decreased as shown in Fig. 17. This could be associated with slow cooling rate of FSW process which resulted in larger content of diffusible Al.

Based on this study, Al was considered as a necessary alloying element in magnesium base

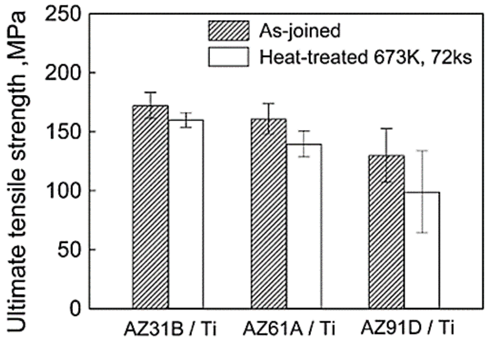

Fig. 17 Ultimate tensile strength of TA2/Mg-Al-Zn joints with increasing Al content (Aonuma and Nakata 2009)

metal for effective Mg/Ti joining. Thus, regulating the precipitation of Al is the main factor for realizing interfacial bonding, which certainly increases the difficulty of attaining optimal welds (Aonuma and Nakata 2009). Therefore, the authors explored the feasibility of regulating the precipitation of Al when Mg–Al–Ca (AMCa602 and AM60) alloys joint with TA2. For AM60/TA2 joints, it is surmised that the strong affinities between Ca and Al will affect the microstructure of the joint interface. A thick $TiAl_3$ IMC layer was also observed at the interface because the Al element in the matrix was in solid solution condition and easy to diffuse at elevated temperature, whereas, a thin layer containing Ca and Ti-Al layer were observed for AMCa602/TA2 joint. Because of the high affinity of Ca and Al (Yamamoto *et al*. 2007), the Al content in the sold-solution of AMCa602 matrix was reduced by Al_2Ca compound formation. The Al_2Ca compound was able to suppress the formation of $TiAl_3$ at the AMCa602/Ti joint interface and resulted in higher joint strength of 225 MPa compared to only 138 MPa for AM60/Ti joint.

Aonuma and Nakata (2012) also investigated the performance of ZK60/TA2 joints produced using FSW. Their results showed that a thin layer rich in Zn and Zr was evolved at the joint interface, which improved the tensile-shear strength (237 MPa). The fracture occurred primarily in the stir zone of magnesium alloy and partially at the interface. In contrast, no reaction layer was observed when pure Mg was joined to TA2 which resulted in poor tensile strength (135 MPa).

Joining Mg to Ti by FSW process is still at its infancy. In general, the content of the alloying element of the parent metals affected the interfacial microstructure and the dissimilar joint performance. The prior research results have shown that the joints tensile strength increased with the increase in mutual solubility of alloying elements present in the parent metals (Lakshminarayanan *et al*. 2015). Under optimum processing conditions, joint performance is still low compared to Mg alloy base metal. To increase the joints mechanical resistance, the benefits of using friction stir spot welding (FSSW) which is a variant to FSW should be explored because of its green welding processes, minimal thermal deformation as well as ability to produce joints with good mechanical properties (Uematsu *et al*. 2012). Furthermore, since the joint strength is determined by the Ti interface, the use of hybrid heat source during the FSW could be explored. Joo (2013) reported that joints with higher strength, sufficient material flow and tool wear reduction could be obtained using hybrid gas tungsten arc welding (GTA) assisted friction stir welding.

In FSW, the geometry of the tools including its size and shape limitation can influence the properties of the joints produced. Thus, the process is best used with long and straight welds. In addition, keeping the interlayer at the interface between the Ti and Mg alloy is very difficult due to the stirring action of the pin and material flow with high plasticity along the interface. In addition, FSW is currently employed mainly for joining Al alloy. Thus, expanding its scope to incorporate harder alloys such as titanium will certainly require the development of reliable, wear resistant and economically buyable tools, although the tool associated concerns could be avoided using certain ingenious configurations.

3.2.2 Diffusion bonding

Diffusion bonding depends on the combination of micro-deformation at the bonding interface and the inter-diffusion of atoms between the materials being joined (Freer, 1982). Interestingly, diffusion bonding has the benefit of producing perfect welds with no fusion zone and the absence of heat affected zone. However, the process is economical only when close dimensional tolerances, expensive materials or special material properties are involved. Even then, not all metals can be easily or effectively be bonded using this method.

Transient liquid phase (TLP) bonding which is a variant of diffusion bonding, is an alternative method for joining Mg/Ti alloys (Atieh and Khan 2013, 2014a, b, c, d, Jiangtao *et al*. 2006). Generally, diffusion is the driving force for TLP bonding. Through isothermal solidification followed by solid-state homogenization, joints with microstructure characteristics and mechanical properties comparable to the parent materials could be achieved (Atieh 2013). TLP bonding relies on generating a liquid phase between the counteracting interfaces. The liquid may form because the melting point of the interlayer has been exceeded or because reaction with the parent metal results in a low melting point liquid eutectic formation (MacDonald and Eagar 1992). The liquid phase formation depends largely on interlayer type employed. Therefore, the interlayer must be carefully selected to reduce bonding time, increase wetting and reduce intermetallic formation within the joint. Interlayers can be introduced in the form of foils or coatings using electrodeposition, evaporation or sputter techniques directly onto the bonding metals (Illingworth *et al*. 2007, MacDonald and Eagar 1992).

Selection of the optimum parameters such as bonding time, bonding temperature and bonding pressure as well as interlayer characteristics is extremely vital to achieve high quality welds (Atieh and Khan 2013, Jiangtao *et al*. 2006). For instance, Jiangtao *et al*. (2006) studied the TPL bonding behavior of AZ31B to Ti-6Al-4V alloys using a pure Al interlayer. Bonding temperature was observed to have great effect on the kinetic factors of AZ31B/Al/Ti-6Al-4V interfacial reaction, which in turn determines the composition and distribution of the reaction product. When the bonding temperature was lower than 450℃, no liquid phase was produced and bonding of AZ31B and Ti-6Al-4V was not realized. The joint with maximum shear strength of 72.4 MPa, was achieved after bonding at 470℃ for 180 min. The joints were bonded by the formation of $Mg_{17}Al_{12}$ and Ti_3Al phases at the interface. In another study, Atieh and Khan (2013) used Ni foil as interlayer to study the effect of bonding temperature, bonding time and interlayer contents on TPL bonding of AZ31 and Ti-6Al-4V. Their results indicated that increasing the time from 5 to 60 minutes greatly affected the microstructure and the bond strength of the joint. They reported that the shear strength of the joints reached a maximum value of 39 MPa for a bonding time of 20 minutes at 540℃. However, the joint strength decreased with an increased in bonding time to 60 min. due to the formation of hard intermetallic within the joint during isothermal solidification. The long thermal cycle of diffusion welding/brazing process promotes the formation of brittle intermetallic compounds along the interface of dissimilar joints. In contrast to the traditional TPL process, the microstructural characterization of the joints revealed that the bonding mechanism involves Ni-Mg eutectic formation at the Mg-interface with solid-state diffusion and bond formation at the Ti-interface, thus, it was characterized as "semi-solid TPL bonding". Considerable increase in the joint performance to 57 MPa was observed when Ni-Cu sandwich foils where employed (Atieh and Khan 2014d). The limited increased in shear strength observed was attributed to the fact the foils thickness produced a large volume of thick IMCs. These IMCs reduce the direct contact area and, hence, affected the bond strength. To enhance the flexibility of adding intermediate element, electrodeposition was employed (Atieh and Khan 2014b, c). For instance, electrodeposition of thin (12 μm) coats improved the flow and uniformity of the liquid, which enhanced the joint strength to 61 MPa at optimum TPL bonding parameters (Atieh and Khan 2014c). To further investigate the effect intermediate elements, the authors used an electroplated Ni coating having nickel and copper of nanoparticles dispersion. Results showed that different nanoparticles were observed in different compounds at the interface. The maximum joint performance of 69 MPa was achieved with copper nanoparticles (Atieh and Khan 2014a). The addition of nano-sized copper dispersion in Ni coating facilitates the bonding process through shorter diffusion distances. However, the bond strength could be severely affected by the IMCs formation and agglomeration of the nanoparticles. Therefore, careful selection of the type and application of nanoparticle dispersion is crucial.

In general, selection and optimization of the TPL bonding process parameters (bonding temperature, bonding time, applied pressure and surface roughness) played a significant role in getting a sound joint. Beside process parameters, the joint strength and the microstructural developments is influenced by the interlayer material. More work is required to improve the joints performance such as exploring the use of various dispersion strengthened coatings. It is perceived that the use of appropriate surface treatments of the Ti alloy in order to achieve either pure or composite coatings will enhance bonding at the Ti/interlayer interface before the TLP bonding step to join Ti-alloy to the AZ31 alloy. Therefore, use of different coating techniques (e.g., vapor phase coating or sputter coating) which could enhance the metallurgical bond on the Ti surface can be used to better control interlayer thicknesses and increase diffusion at the Ti/coat interface. Furthermore, the benefits of using different interlayer materials that forms eutectic phase with Mg either in a pure form like Sn, Ag or as alloys such as Al-Cu, Ag-Sn should be explored. To further understand the reliability of the bond, focus should be given to corrosion behavior, fracture toughness and fatigue performance of the welded joint.

3.2.3 Ultrasonic Spot Welding (USW)

In principle, ultrasonic spot welding (USW) is a solid-phase welding process that has been described by a low energy input and a short welding time. In this process, the material to be joined is held together under moderate pressure and a high-frequency ultrasonic vibration is applied locally on the joint. Due to the combined effect of the pressure and ultrasonic vibrations, the surface asperities, contaminants and oxides between the overlapping surfaces get removed and the pure metallic surfaces come into contact with each other, resulting in a metallurgical bond (Zhao *et al*. 2017, Jun and Yong 2019).

Ren *et al*. (2017) examined the weld strength and microstructure at the joint interface of ultrasonically welded AZ31B and Ti6Al4V alloys. The results showed that grain refinement occurred on the Mg interface. Unlike during FSW (Aonuma and Nakata 2009, 2010) and laser welding (Tan *et al*. 2016a, b) where Ti-Al IMC layer was produced at the interface, neither transition layer nor IMC layer was observed during USW probably because of the very low heat input compared to other welding techniques. The authors reported that the joint performance depends greatly on the welding time and under optimum welding condition, a mean tensile-shear load of 3.8 kN was achieved. The mechanism involve during USW joining is still not well understood and there have been very limited work in joining Mg alloys to Ti using USW, thus leaving a wide area of spectrum for future research.

4. Conclusions

The growing demand to join Mg and Ti especially for applications in the automotive and aerospace industries in order to realize light weight structures, versatililty in production and tailoring of properties, have provided the impetus for the continued research to improve available welding/joining techniques as well as for the development of hibrid reliable joining technology. The main criteria to achieve a good metallurgical bonding using any welding processes when joining Mg to Ti is to manage the big differences between their physical properties and limited solubility with each other. Besides this, the formation of intermatellic phases or intermediate phases in the joints is very much related to the compositions of the interlayer or fillers adopted during the joining process. This reaction product (in the form of solid solution or intermetallic compound) along the interface between the Mg and Ti is responsible for formation of a metallurgical bond between them. Thus, careful selection of welding techniques and intermediate materials cannot be overemphasised.

This comprehensive review has considered the various methods and presents the current state of understanding pertaining to the joining of Mg/Ti. Although, the conventional fusion welding technologies have been adopted by many researchers, the development of high strength Mg/Ti joint remains a challenge due to issues such as coarsening of the grain size, voids and cracks formation at the weldment. On the other hand, solid state welding methods such as FSW and diffusion bonding have shown to be viable but these methods are yet to be fully exploited for use in mass production industries. There are many oppurtunities for more research associated with the above mention welding techniques and this has been deliberated in this review.

Acknowledgments

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