

# Laser Welding of Titanium Grade 2 and Aluminium AA 3105-O Using a New AlScZr Filler Metal

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## Abstract

In this study, a pulsed Nd:YAG laser welding method is implemented to join Ti-G2 (1 mm thick) to AA3105-O (0.5 mm thick) via a ring of spots filled with AlScZr alloy (0.15 mm thick). The filler material improved the weld's microstructure and mechanical properties by reducing the undesirable intermetallic compounds (IMCs) such as TiAl<sub>2</sub> and TiAl<sub>3</sub> in the aluminium re-solidified zone near the titanium/aluminium interface. The joints having AlScZr filler were mostly failed at Al heat affected zone (HAZ) during the tensile shear test. The addition of zirconium to binary Al–Sc system formed a substitutional solid-solution in which 50 wt% Zr+10 wt% Ti replaced Al<sub>3</sub>(Sc,Zr,Ti). Scandium had a strengthening effect by solid-solution and precipitation hardening effect due to the formation of Al<sub>3</sub>(Sc,Zr) particles. The joint strength rose from 86% (of the base Al strip) for autogenously laser weld to 102% with filler metal. Hardness increased steadily at the Ti/Al interaction zone, and the maximum hardness was reduced from 650 HV to 570 HV when filler metal was utilized.

**Keywords** Laser spot welding · Titanium · Aluminium alloy · Filler metal · Microstructure · Mechanical properties

## Introduction

Owing to their light weight, high strength, excellent conductivity, and outstanding corrosion resistance, titanium and aluminum alloys are in high demand in aerospace, automotive, and smart structures [1]. When welded to titanium grade 2 (G2) tubing, the AA3105-O is a promising candidate for airplane cabin blade cooling fins.

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Welding these alloys has already been tested by a number of researchers [2–10]. The differences in lattice structures and thermophysical properties of Al and Ti alloys have presented a big challenge in assigning a suitable technique for joining them together. From the Ti/Al equilibrium diagram, it is possible to realize that solidified Al does not allow much Ti dissolution, although a Ti-rich solid-solution of up to 12 at.% Al is possible at 327 °C [2]. In conventional fusion welding, negative mixing enthalpies [3] causes an initial dissolution of Ti. After that, different IMCs such as Al<sub>3</sub>Ti, AlTi, and AlTi<sub>3</sub> form.

These days, laser technology is widely used in the welding/brazing of metals. It delivers many benefits over traditional joining methods, such as high precision, high speed, excellent versatility, and low distortion [4]. Chen et al.[5] studied the mechanism for joining Al to Ti utilizing the CO<sub>2</sub> laser technique using filler of AlSi12. The brazing region includes  $\alpha$ -Ti nano-size particles, Ti<sub>7</sub>Al<sub>5</sub>Si<sub>12</sub>, and TiAl<sub>3</sub>, and  $\alpha$ -Al and ternary formed  $\alpha$ -Al, Si, or Mg<sub>2</sub>Si. They reported that Ti<sub>7</sub>Al<sub>5</sub>Si<sub>12</sub> formation diminishes Ti dissolution and thereby restricts TiAl<sub>3</sub> growth. They [6] also tested the welding of Al to Ti alloys with AlSi12 filler wire using a continuous-wave laser welding/brazing technique. They found that the Ti content had more effect on the diffusion of Si than temperature. They also discovered that when Ti is melted, Si diffuses into the melt and the Ti-filler interface.

Chen et al. [11–13] investigated the impact of heat on the microstructure and mechanical properties of the Ti/Al interface during laser welding-brazing with AlSi12 filler. Lower heat inputs are expected to cause Ti dissolution in the filler metal, resulting in thin IMC layers and eventual FZ fracture. Increased heat input causes IMC thickness to increase, which, when combined with porosities, causes the interface to fracture.

Chen et al. [14] observed that the growth of  $TiAl_3$  could happen during the interfacial reaction at the solid/liquid Ti/Al laser welding-brazing interface since the formation of  $Ti_7Al_5Si_{12}$  and segregation of Si atoms hinders the dissolution of Ti alloy. Nevertheless, the process reliability and weld appearance are curtailed by some laser welding-brazing problems such as the spreading and poor wetting operation. In comparison, laser keyhole welding offers excellent versatility and controllability. The high welding speed of laser welding can reduce metallurgical reaction time and consequently suppresses the formation of IMCs.

Tomashchuk et al. [15] observed a transformation interface rich in Al<sub>3</sub>Ti with a thickness of 90-300  $\mu$ m as a result of focusing the laser beam on the Ti6Al4V/AA5754 interface. As the laser beam moved toward the AA5754 side, the TiAl precipitates thinned (by 20  $\mu$ m) at the interface, resulting in maximum output in joint power.

Chen et al. [16] examined the mechanical properties and fracturing activity of the Ti/Al joint and how they were affected by an overlap configuration's processing parameters in a multimode laser penetration weld. By increasing the laser power and slowing down the welding speed, they were able to strengthen the joint. However, weld spattering and keyhole instability resulted in a subsequent loss of strength. They also discovered that the joint and the Ti-side of the weld at the interface had two fracture modes. When the fracture occurred on the Ti-side of the weld, the joint strength increased to 184 MPa. According to Chelladurai et al. [17], the heat-affected zone (HAZ) joint fracture is caused by the thickness of the IMCs and the microstructure, which was softened by beam energy impact. Rapid cooling of the FZ could result in in-situ reactions and the formation of certain hard-ceramic particles, resulting in increased microscale hardness.

Majumdar et al. [18] reported that during  $CO_2$  laser welding of Ti-6Al-4 V to AlMg0.9Si, Al content below 20 at.% the Ti/Al mixing zone and crack-free welding was not achievable at any welding parameters. They discovered that inserting an Nb plate between Ti and Al sheets keeps 11 at.% of the Al in the FZ and results in a crack-free joint.

To eliminate IMC formation in a welded area, Vaidya et al. [19] modified the Ti/ Al interface area to reduce the extent of the Al and Ti interfaces and the length of TiAl<sub>3</sub>. They found that joint modification has doubled the resistance to fatigue crack propagation. However, tensile strength improved slightly. For enhancing the tensile properties, the requirement for new techniques in joining Ti to Al is crucial.

Shehab et al. [20] welded 1 mm thick Ti to 0.5 thick Al strips using a pulsed Nd:YAG laser instrument. The microstructural investigations showed that precipitation of TiAl3 IMCs in the Al FZ near the connection was the reason for most joint failures under shear loading. Joint strength rose to 86% of the base Al strip.

Since all IMCs are brittle and hard, a high-strength/tough Ti/Al joint requires minimum IMC formation [20, 21]. To minimize the formation of IMCs, previous authors [20] used Al-12Si-2.5 Mg filler. By forming a  $Ti_3$ (Al-Si) eutectic composition, Si reduces Ti dissolution in TiAl<sub>3</sub>, resulting in hardness relaxation at the Ti/Al interaction zone. The fast dissolution of Si and Mg in the Al re-solidified zone near the Ti/Al interface increases joint strength to 98% of the Al base metal, a 14% improvement over autogenous welding. However, Mg's existence in the weld microstructure may limit the usage of the joint in a corrosive environment.

In the current study, a tactile seam tracking system using a high-energy laser instrument is implemented for pulsed welding of Ti-G2 to AA3105-O. Utilization of the AlScZr filler with a ring-like spot-weld procedure was the new idea to achieve a high-strength joint. The study continued by looking at the effect of Al-0.2Sc-0.36Zr filler on microstructural improvements as well as the mechanical properties of the new joint obtained.

#### **Materials and Methods**

A 1 mm thick Ti-G2 was lap-joined to a 0.5 mm thick AA3105-O using Nd: YAG laser welding utilizing a 0.15 thick AlScZr filler metal. Tables 1 and 2, and 3 list the chemical composition and mechanical and physical properties of base (BMs) and filler metal. The Ti-G2 sheet locates on top of the AA3105-O sheet with a 5 mm wide overlap. Both BM sheets were in dimensions area of  $40 \times 5 \text{ mm}^2$ . Before welding, the sheets were cleaned from grease using acetone and then polished with emery papers, followed by further cleaning with 6-10% NaOH alkaline solution for 5 min. Finally, the sheets were rinsed with distilled water and 30% HNO<sub>3</sub> + 3% H<sub>2</sub>SO<sub>4</sub> acid solution for 3 min. Ti-G2 sheets were etched with 20% HNO<sub>3</sub> + 5% HF

Material	%wt										
	C	Mn	Sc	Zn	0	Mg	Cu	Fe	Zr	Al	Ti
AA 3105-0	-	0.51	-	0.06	-	0.50	0.09	0.61	-	Bal.	-
Ti (G2)	0.08	-	-	-	0.20	-	-	0.08	-	-	Bal.
Al-0.2Sc- 0.36Zr Filler metal	-	-	0.20	0.04	-	2.50	-	0.20	0.36	Bal.	-

Table 1 Chemical composition of base and filler metals used in the study [22]

 Table 2
 Mechanical properties of the base metals [22]

Material	Mechanical Properties								
	YS (MPa)	SS (MPa)	TS (MPa)	Elongation (%)	Hardness (HV)				
AA 3105-0	55	82	122	24	45				
Ti (G2)	275	-	344	28	125				

\* YS: Yield strength, SS: shear strength and TS: tensile strength

 Table 3 Physical properties of the base metals [22]

Property	ASTM Ti (G2)	Al 3105-O
Thermal Conductivity (W•m <sup>-1</sup> •K <sup>-1</sup> )	16.4	173
Density $(g \cdot cm^{-3})$	4.5	2.7
Melting point (°C)	1665	660
Boiling point (°C)	3535	2327
Thermal expansion coefficient ( $\mu m \cdot K \cdot m^{-1}$ )	9.4	23.6

acid solution for 5 min, then wiped and rinsed with ethanol and distilled water for 10 min before welding. Figure 1 illustrates a schematic representation of the joint design and welding procedure performed in this research.

Nd: YAG laser equipment (Model IQL-10) welded the samples. The machine's average power was 400 W, which generated 1-1000 Hz frequency standard square-shape pulses with a period of 2-20 ms and 0-40 J energy. The optical focusing system's focal length was 75 mm, generating spots of ~250  $\mu$ m in size. The clamping mechanism was moved under a 0.05 mm laser head by a movable XYZ table, which set precision. During welding, a commercially pure Argon (99.99% purity) was used as a shielding gas to cover the welding area. Gas was blown at a rate of 20 L•min<sup>-1</sup> through a coaxial nozzle.

A Universal Testing Machine type SANTAM model STM-20 with a 5 mm•min<sup>-1</sup> crosshead speed measured the tensile shear results. Three measurements determined each data point. The microstructure and fracture zone of the resulting joints were investigated using an optical microscope and a scanning electron microscope (SEM) model TESCAN MIRA 3



Fig. 1 Schematic illustration of laser welding Setup geometry of Ti/Al strips

(Czech) supplied with energy dispersive X-ray spectrometry (EDS) to determine the chemical composition of the joint. Microhardness test, using BUEHLER model MMT1, USA, was employed to evaluate the hardness values of the various locations in the joint, including BM, HAZ, and FZ. An applied load of 25 g and a dwell time of 25 s were applied.

# **Results and Discussion**

A high-quality Ti/Al joint was achieved using a seam welding on a ring-like path (that leads to a laser-spot-like shape). Table 4 presented the best welding parameters obtained from the pre-test experiments.

### Weld Appearance

Figure 2 presents the top view of Ti/Al welds with and without the application of filler metal. It can be seen from this figure that the diameter of the weld nugget in Fig. 2a is slightly larger than that of Fig. 2b for the same welding conditions, which indicates that filler metal consumed part of the welding energy during melting. More than two pulses are applied at the same location before the laser power supply is turned off to prevent the creation of weld craters at the final pulse area.

Figure 3 shows a cross-sectional view of the welds which have been sectioned along the indicated lines in Fig. 2. The single-pulse weld boundary is shown in Fig. 2a, while Fig. 2b presents multiple overlapped pulses weld boundaries. Weld penetration is deeper without using filler due to the heat dispersion by filler metal.

Table 4 Laser	welding paramete	IS							
Sample No.	Al-0.2Sc-0.362 filler thick (mn	Zr Pulse energy 1) (J)	Pulse duration (ms)	Welding speed (mm•s <sup>-1</sup> )	Peak power (kW)	Pulse fre- quency (HZ)	Gas flow rate (1•min <sup>-1</sup> )	Overlapping factor (%)	Average energy input (J·mm <sup>-1</sup> )
1	None 11		9	4	1.83	20	20	76	55
2	0.15 11		9	4	1.83	20	20	76	55



Fig. 2 Top view of Ti/Al welds: (a) without filler, (b) with using Al-0.2Sc-0.36Zr filler metal



Fig. 3 A cross-sectional view of the welds along the indicated lines in Fig. 2 as (a) section "Introduction" and (b) section "Materials and Methods"

#### Weld Microstructure

Figure 4a presents the SEM image of zone A in Fig. 3a. Based on the equilibrium phase diagram of the binary Ti/Al alloy [23] and EDS point scan analysis, the different IMCs formed at the Ti/Al interface were marked in Fig. 4b. The weld zone contains mainly  $Ti_3Al$  and TiAl at the Ti side,  $TiAl_2$ ,  $TiAl_3$  at the Ti/Al interface region, and Al at the FZ at the Ti/Al interface. Cracks are visible near the boundary of the Al FZ, as illustrated in Fig. 4a. The crack could be a result of brittle TiAl<sub>3</sub> IMCs formation, where the high thermal gradient between the FZ and solidified alloy can produce high residual stresses. As the brittle  $TiAl_3$  cannot withstand this thermal strain, cracks form at the welded samples' connection region [3].

A view with more magnification of zone A in Fig. 3a is presented in Fig. 5, where the distribution of the elements Al, Ti, Mn and Fe over the specified area are easily recognized with different colors. It can be seen from Fig. 5c and d that the light yellow and light blue colors for respectively Ti and Al distributions at the Ti/Al interface refer to IMC areas. Figure 5d and e refer to the uniform distribution of the elements Mn and Fe respectively.

Figures 6 and 7 show the equilibrium phase diagram of binary alloys: Al-Sc, Ti-Sc; Al-Zr; Ti-Zr; systems. Based on Figs. 6 and 7, the following points can be inferred:



Fig. 4 Microstructures of zone A of Fig. 3a and adjacent regions. A magnified view of Fig. (a) is presented in (b)



Fig. 5 EPMA mapping analysis of Al, Ti, Mn and Fe elemets of zone A in Fig. 3a

- 1. [0 to 0.4 wt% Sc] can dissolve in Al forming Al–Sc solid-solution ( $\alpha$  Al), otherwise  $\alpha$  Al + Al<sub>3</sub>Sc are formed above 0.4 Sc wt% as presented in Fig. 6a.
- 2. [0 to 3 wt% Sc] can dissolve in Ti forming Ti–Sc solid solution ( $\alpha$  Ti), Fig. 6b.



Fig. 6 Binary phase diagrams for (a) Al–Sc alloy, (b) Ti-Sc alloys [23]

- [0 to 0.14 wt% Zr] from Al-rich side, can dissolve in Al forming Al–Zr solid solution (α Al), otherwise Al3Zr is formed above 0.14 Sc wt%. as shown in Fig. 7a.
- 4. [0 to 49 wt% Zr] can dissolve in Ti forming Ti–Zr solid solution ( $\alpha$  Ti), Fig. 7b.



Fig. 7 Binary phase diagrams for (a) Al-Zr alloy, (b) Ti-Zr alloys [23]



Fig. 8 High magnification SEM images of the zones of Fig. 3b; a: zone B, b: zone C, c: zone D

Based on the analysis results and weight percentages of Al, Ti, Sc, and Zr from the EDS scan of Fig. 8a and b, and c presented in Table 5, the  $Ti_xAl_y$  phases were predicted. One of the modification effects of Sc in Al occurs at hyper eutectic concentrations above 0.4 wt%, where Al3Sc is formed. The addition of 0.15 Zr wt% reducing the Sc concentration to above 0.18 wt% with keeping its modification effects where zirconium addition to binary Al–Sc alloy forms a substitutional solid solution in Al3Sc in which 50 wt% Zr + 10 wt% Ti can be dissolved in Al<sub>3</sub>(Sc,Zr,Ti) [12].

Figure	#	Ti	Al	Sc	Zr	Ti <sub>x</sub> Al <sub>y</sub> Phase	Comments
8a	А	74	7	0.1	1.6	(Ti –Al)solid solution(α Ti)	Ti/Al solid solution
	В	41	56	0.1	0.65	TiAl <sub>2</sub>	IMP-TiAl <sub>2</sub>
	С	81	16	0.1	1.5	Ti <sub>3</sub> Al	IMP-Ti <sub>3</sub> Al
	D	49	47	0.11	1.8	TiAl	IMP-TiAl
	Е	62	34.5	0.1	1.4	TiAl	IMP-TiAl
	F	0.22	95	0.13	2.3	-	αAl(Sc,Zr,Ti)solid solution+IMPAl3Zr
	G	17	77	0.17	2.3	TiAl <sub>3</sub> (Sc,Zr,Ti)	IMP-TiAl <sub>3</sub> (Sc,Zr,Ti)
8b	А	30	66	0.13	2.2	TiAl <sub>3</sub> (Sc,Zr,Ti)	IMP-TiAl <sub>3</sub> (Sc,Zr,Ti)
	В	62	35	0	1.7	TiAl	IMP-TiAl
8c	С	30.8	65	0.15	2	TiAl <sub>3</sub> (Sc,Zr,Ti)	IMP-TiAl <sub>3</sub> (Sc,Zr,Ti)
	D	31.8	64	0.15	2.3	TiAl <sub>3</sub> (Sc,Zr,Ti)	IMP-TiA <sub>13</sub> (Sc,Zr,Ti)
	Е	74	23	0.12	1.77	Ti <sub>3</sub> Al	IMP-Ti <sub>3</sub> Al

Table 5 Weight% of Al, Ti Sc and Zr obtained from EDS of surfaces shown in Fig. 8a, b and c

The AlScZr filler is casted with 0.36 wt% Zr, 0.2 wt% Sc in Al base, where the additional amount 0.26 Zr wt% may form Al<sub>3</sub>Zr in the casted filler according to the Al-Zr phase diagram. During welding, the Zr in the Al<sub>3</sub>Zr phase is dissolved in Ti/Al molten metal forming Ti-Zr solid solution  $\alpha$  Ti, where a high temperature (above 2000 °C) is reached and thus a better connection between Ti and Al may be achieved [24, 25].

Figure 8 shows high magnification weld cross-sections SEM images for the zones of Fig. 3b. It can be seen from these figures that the interface between the mixed molten metal and the melted Al was 'fluffy' with some swirls where Al melted but not mixed with melted Ti, and this is due to the high difference in melting temperature between Ti and Al where Ti is solidified while Al is still in the liquid state [11].

Different IMCs [Ti<sub>3</sub>Al, TiAl, and TiAl<sub>3</sub>(Sc,Zr,Ti)] were presented in Fig. 8a. It can be seen from this figure that TiAl<sub>3</sub>(Sc,Zr,Ti) that formed at point G are highly distributed in the Ti/Al weld zone, and this could be related to the high dispersity of Al3(Sc) in the Ti/Al melted volume where the wt% of Sc at point G =  $(0.17 \times 100) / 77 = 0.22$ wt% Sc in binary Al-Sc system, which is above the range (0.18 wt.%Sc) for the modification effect of Sc in Al, which occurred in the presence of 50 wt% Zr with respect to Sc (i.e., 0.1wt.% Zr). In the point F,  $\alpha$  Al(Sc,Zr,Ti) solid solution + IMP Al<sub>3</sub>Zr are formed (Table 5), and these phases (Al<sub>3</sub>Zr) can always exist in the Al FZ in the absence of Ti (Fig. 6). Point A in Fig. 8b has the same phase Ti Al3(Sc, Zr, Ti) of point G Fig. 8a where wt% of Sc = (0.13 × 100) / 66=0.2wt.% Sc in binary Al-Sc system at which the modification effect of Sc in Al occurred in the presence of 50 wt% Zr with respect to Sc (i.e., 0.1 wt%). Figure 8c shows how particles of TiAl<sub>3</sub>(Sc,Zr,Ti) phase (at points C and D, Table 5) are distributed in Al FZ close to Ti/Al interface, which are the zones of weakness, as a result of a high gradient in mechanical and thermophysical properties, as observed in the previous work [19, 20].

Table 6         Effect of AlScZr filler           metal on mechanical properties         of the joint	Sample code	Shear force at yield- ing point (N)	Shear force (N)	Length exten- sion (mm)
	Without Filler	55	264	1.66
	With Filler	80	300	4.75

#### **Mechanical Behavior**

#### Shear Strength of the Joint

Table 6 represents shear force at the yielding point, shear strength, and length extension of the samples with and without using filler metal. Figure 9 shows shear force as a function of extension curves with images of fused areas at the bottom of the Ti sheet at the Ti/Al contacted surfaces. Despite that the area of fusion without using filler (3.77 mm<sup>2</sup>) is larger than that area of fusion with using filler (3.6 mm<sup>2</sup>), Fig. 9; Table 6 show that the weld with AlScZr filler metal has a higher fracture shear force (300 N) and a higher extension value than the autogenous weld. This result could be related to the modification consequence on the composition of the weld metal by Sc and Zr, which leads to the highest atomic percent strength values when added to Al and to decrease the hardness gradient between the aluminum FZ and Ti/Al zone as illustrated in Fig. 12, which decreases the opportunity of initiation crack under thermal stress [19].

The strengthening is achieved by solid solution and precipitation hardening of  $Al_3(Sc, Zr)$  particles, which impedes the dislocation cell structure [26, 27]. The modification effect of Sc and Zr for Al was the primary motivation to choose such elements since the cracks in autogenous weld joint located in Al near Ti/Al interface and thus fractured, as observed in the previous works [16, 20, 21, 26].



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The effect of filler metal existence on fracture behavior is shown in Fig. 10. When autogenous weld was performed, the fracture occurred at the FZ, as presented in Fig. 10a. Further fracture details were detected by the SEM examination, as shown in Fig. 10c. It was observed that the fractured area occurred between the Al weld zone and the Ti/Al interaction area. The fracture zone featured a cleavage fracture characterized by a river pattern band with some dimples. The cleavage fracture is contributed to the formation of Ti/Al IMCs (like TiAl<sub>3</sub> as detected in EDS analysis of point A) at the Ti/Al interaction zone. It is believed that the presence of a river-like pattern is an indication of a crack that moves along the grains through crystallographic planes that form a series of plateaus and joining ledge. The presence of small dimples is an indication of the ductile fracture of Ti in some areas. While the sample's rupture using filler metal occurred at Al HAZ-base metal (Fig. 10b) with ductile fracture behavior characterized in SEM image by large dimples as shown in Fig. 10d.

The strength of the lap joint design is mainly affected by the area of the FZ and the strength of the welded sheets [27, 28]. Considering the shear forces of 264 and 300 N for the joints (without and with filler respectively) and also the fusion surface areas  $(3.77 \text{ mm}^2 \text{ and } 3.6 \text{ mm}^2)$  in Fig. 9, the values of shear strength of



Fig. 10 Images of the samples fractured under shear load (a,c) without filler, (b,d) with AlScZr filler



70 MPa and 83.3 MPa were calculated for the joint without and with AlScZr filler, respectively. Figure 11 compares the shear strength values for Ti-Al dissimilar weld joint with and without filler metal and Al base metal. In dissimilar metals Ti/Al joint, it is more logical to compare the value of the shear stress of the joints (with and without AlScZr filler), with the shear stress of the aluminium 82 MPa, (i.e., lower strength base-metal). Due to the addition of AlScZr filler metal, joint shear strength of up to 102% of the Al base metal shear strength was achieved, which was around 16% higher than that obtained by autogenous welding.

#### **Microhardness of the Joint**

Figure 12 shows Vickers hardness measurements of the Ti/Al welding joint with and without filler metal, covering BM, HAZ, and FZ. Ti and Al BMs had an average



Fig. 12 Vickers hardness measurements of the welding joint





hardness value of 120 HV and 43 HV, respectively. There is no discernible difference in HAZ hardness between the two metals, which may be attributable to the LBW process's low heat input [29], which limits the change in HAZ mechanical properties. At the Ti side, the microhardness increases at the FZ over the BM with an average hardness of 317 HV. This rise in hardness might be due to the existence of acicular alpha-martensite (Fig. 13), produced by thermal-cycling rapid laser welding [13]. A large increase in hardness was observed in the interaction zone, with a greater value than 650 HV. This increase in hardness is an impact of the Ti/Al IMCs developed in this region. While in the FZ at Al side, the hardness was approximately the same degree as the BM.

When filler metal was added, a significant improvement in the microhardness values at the Al FZ was observed compared with Al BM, and this could be assigned to the high cooling rate that modifies the grains size of Al, besides, the strengthening effect of Sc and Zr of filler metal. At the Ti/Al interaction zone, the hardness rising was steady, and the maximum hardness recorded in the interaction zone was lower than that without utilizing the filler metal. The observed fluctuations in the microhardness values in the interaction zone could be attributed to the local composition at each point (IMC formation at Ti/Al interface + strengthening filler effect (Sc and Zr that dissolved in Ti).

## Conclusions

In this paper, a pulsed Nd: YAG laser welding was employed for dissimilar joining of Ti-G2 and AA3105-O using AlScZr filler metal. The following conclusions can be drawn from this paper:

1. Most autogenous welding joint failures were caused by the formation of intermetallic compounds (IMCs) such as TiAl<sub>3</sub> and TiAl<sub>2</sub> at the Al re-solidified zone.

- 2. With using of AlScZr filler metal, the addition of zirconium to binary Al–Sc alloy formed a substitutional solid solution in Al<sub>3</sub>Sc in which Zr, Ti dissolved in Al<sub>3</sub>(Sc,Zr,Ti).
- 3. Sc has a strengthening effect by solid solution and precipitation hardening by forming Al<sub>3</sub>(Sc,Zr) particles, which pin the Ti/Al joint's dislocation cell structure
- 4. The relaxing effect of Ti(Al,Sc)<sub>3</sub> and the strengthening effect of AlScZr filler metal on the Al FZ and Al re-solidified zone (near Ti/Al interface) increase the joint strength from 86% for autogenously laser weld to 102% with filler metal.
- 5. The high cooling rate of laser welding that decreases Al grain size, and the strengthening effect of Sc and Zr in the filler metal, resulted in a substantial increase in Al FZ hardness.
- 6. The hardness increased steadily at the Ti/Al interaction zone, and the maximum hardness reported was lower than without the filler metal.

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**Data Availability** The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

# References

- Möller, F., Grden, M., Thomy, C., Vollertsen, F.: Combined laser beam welding and brazing process for aluminium titanium hybrid structures. Phys. Procedia. 12, 215–223 (2011). https://doi.org/10. 1016/j.phpro.2011.03.028
- Zhu, Z., Lee, K.Y., Wang, X.: Ultrasonic welding of dissimilar metals, AA6061 and Ti6Al4V. Int. J. Adv. Manuf. Technol. 59, 569–574 (2012). https://doi.org/10.1007/s00170-011-3534-9
- Palanivel, R., Dinaharan, I., Laubscher, R.F.: A comparative study on microstructure and mechanical properties between friction and laser beam welded titanium tubes. Optik (Stuttg) 177, 102–111 (2019). https://doi.org/10.1016/j.ijleo.2018.09.022
- Sohn, W.H., Bong, H.H., Hong, S.H.: Microstructure and bonding mechanism of Al/Ti bonded joint using Al–10Si–1Mg filler metal. Mater. Sci. Eng. A. 355, 231–240 (2003). https://doi.org/10.1016/ S0921-5093(03)00070-4
- Cao, R., Sun, J.H., Chen, J.H.: Mechanisms of joining aluminium A6061-T6 and titanium Ti–6Al– 4V alloys by cold metal transfer technology. Sci. Technol. Weld. Join. 18, 425–433 (2013). https:// doi.org/10.1179/1362171813Y.0000000118
- Chen, Y., Ni, Q., Ke, L.: Interface characteristic of friction stir welding lap joints of Ti/Al dissimilar alloys. Trans. Nonferrous Met. Soc. China 22, 299–304 (2012). https://doi.org/10.1016/S1003-6326(11)61174-6
- Baqer, Y.M., Ramesh, S., Yusof, F., Manladan, S.M.: Challenges and advances in laser welding of dissimilar light alloys: Al/Mg, Al/Ti, and Mg/Ti alloys. Int. J. Adv. Manuf. Technol. 95, 4353–4369 (2018). https://doi.org/10.1007/s00170-017-1565-6
- Casalino, G., D'Ostuni, S., Guglielmi, P., Leo, P., Mortello, M., Palumbo, G., Piccininni, A.: Mechanical and microstructure analysis of AA6061 and Ti6Al4V fiber laser butt weld. Optik (Stuttg). 148, 151–156 (2017). https://doi.org/10.1016/j.ijleo.2017.08.138
- Atabaki, M.M., Yazdian, N., Kovacevic, R.: Partial penetration laser-based welding of aluminum alloy (AA 5083-H32). Optik (Stuttg). 127, 6782–6804 (2016). https://doi.org/10.1016/j.ijleo.2016. 05.007

- Akbari, M., Saedodin, S., Panjehpour, A., Hassani, M., Afrand, M., Torkamany, M.J.: Numerical simulation and designing artificial neural network for estimating melt pool geometry and temperature distribution in laser welding of Ti6Al4V alloy. Optik (Stuttg). 127, 11161–11172 (2016). https://doi.org/10.1016/j.ijleo.2016.09.042
- Chen, S., Li, L., Chen, Y., Huang, J.: Joining mechanism of Ti/Al dissimilar alloys during laser welding-brazing process. J. Alloys Compd. 509, 891–898 (2011). https://doi.org/10.1016/j.jallcom. 2010.09.125
- CHEN, S., LI, L., CHEN, Y., LIU, D.: Si diffusion behavior during laser welding-brazing of Al alloy and Ti alloy with Al-12Si filler wire. Trans. Nonferrous Met. Soc. China. 20, 64–70 (2010). https://doi.org/10.1016/S1003-6326(09)60098-4
- Chen, Y., Chen, S., Li, L.: Effects of heat input on microstructure and mechanical property of Al/Ti joints by rectangular spot laser welding-brazing method. Int. J. Adv. Manuf. Technol. 44, 265–272 (2009). https://doi.org/10.1007/s00170-008-1837-2
- Chen, Y., Chen, S., Li, L.: Influence of interfacial reaction layer morphologies on crack initiation and propagation in Ti/Al joint by laser welding-brazing. Mater. Des. 31, 227–233 (2010). https:// doi.org/10.1016/j.matdes.2009.06.029
- Tomashchuk, I., Sallamand, P., Cicala, E., Peyre, P., Grevey, D.: Direct keyhole laser welding of aluminum alloy AA5754 to titanium alloy Ti6Al4V. J. Mater. Process. Technol. 217, 96–104 (2015). https://doi.org/10.1016/j.jmatprotec.2014.10.025
- Chen, S., Yang, D., Li, M., Zhang, Y., Huang, J., Yang, J., Zhao, X.: Laser penetration welding of an overlap titanium-on-aluminum configuration. Int. J. Adv. Manuf. Technol. 87, 3069–3079 (2016). https://doi.org/10.1007/s00170-016-8732-z
- Chelladurai, A.M., Gopal, K.A., Murugan, S., Venugopal, S., Jayakumar, T.: Energy transfer modes in pulsed laser seam welding. Mater. Manuf. Process. 30, 162–168 (2015). https://doi.org/10.1080/ 10426914.2014.965829
- Majumdar, B., Galun, R., Weisheit, A., Mordike, B.L.: Formation of a crack-free joint between Ti alloy and Al alloy by using a high-power CO2 laser. J. Mater. Sci. 32, 6191–6200 (1997). https:// doi.org/10.1023/A:1018620723793
- Vaidya, W.V., Horstmann, M., Ventzke, V., Petrovski, B., Koçak, M., Kocik, R., Tempus, G.: Improving interfacial properties of a laser beam welded dissimilar joint of aluminium AA6056 and titanium Ti6Al4V for aeronautical applications. J. Mater. Sci. 45, 6242–6254 (2010). https://doi.org/ 10.1007/s10853-010-4719-6
- Sadrnezhaad, S.K., Shehab, A., Mahmoud, A., Torkamany, M.J., Kokabi, A.H., Fakouri Hasanabadi, M.: Pulsed Nd: YAG laser dissimilar welding of Ti/Al3105 alloys. Sci. Iran. B. 27, 1982–1994 (2020). https://doi.org/10.24200/sci.2019.52217.2600
- Shehab, A.A., Sadrnezhaad, S.K., Torkamany, M.J., Fakouri Hasanabadi, M., Alali, M., Mahmoud, A.K., Abass, M.H., Kokabi, A.H.: Ring-like laser spot welding of Ti grade2 to AAl3105-O using AlSiMg filler metal. Optik (Stuttg). 206, 163630 (2020). https://doi.org/10.1016/j.ijleo.2019.163630
- 22. ASM: Handbook Volume 2: Properties and selection: nonferrous alloys and special-purpose materials. ASM International, Geauga County (1990)
- Okamoto, H., Schlesinger, M.E., Mueller, E.M. (eds.): ASM Handbook Volume 3; Alloy phase diagrams. ASM International, Geauga County (1992)
- Davydov, V., Rostova, T., Zakharov, V., Filatov, Y., Yelagin, V.: Scientific principles of making an alloying addition of scandium to aluminium alloys. Mater. Sci. Eng. A. 280, 30–36 (2000). https:// doi.org/10.1016/S0921-5093(99)00652-8
- Ahmad, Z.: The properties and application of scandium-reinforced aluminum. JOM. 55, 35–39 (2003). https://doi.org/10.1007/s11837-003-0224-6
- Totten, G.E., MacKenzie, D.S.: Handbook of Aluminum: vol. 1: Physical Metallurgy and Processes. CRC Press, Boca Raton (2003)
- 27. Ion, J.C.: Laser processing of engineering materials: principles, procedure and industrial application. Elsevier, Oxford (2005)
- Ready, J.F., Farson, D.F., Feeley, T.: LIA handbook of laser materials processing. Springer-Verlag, Berlin Heidelberg (2001)
- Shehab, A.A., Nawi, S.A., Al-Rubaiy, A.A., Hammoudi, Z., Hafedh, S.A., Abass, M.H., Alali, M.S., Ali, S.D.: CO2 laser spot welding of thin sheets AISI 321 austenitic stainless steel. Arch. Mater. Sci. Eng. 2, 68–77 (2020). https://doi.org/10.5604/01.3001.0014.6974

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