Joining of Ti-6AL-4V to AISI 304 Stainless Steel using Laser Spot Welding with Circular Technique

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Abstract

In this research, dissimilar laser spot welding of the Ti-6Al-4V and AISI 304 (stainless steel) was investigated. The joining of 0.7 and 0.5 mm thickness plates with using a copper interlayer of 0.2 and 0.3 mm in thickness was performed by LSW. A 400-W Nd: YAG laser pulse welding machine was used to obtain coaxial spot welds of 4 mm in diameter with circular technique. Visual inspection and metallographic examination were used for all samples. If no crack was identified, micro-Vickers hardness test, tensile test, and scanning electron microscopy (SEM) were performed on the samples. The result indicated that with a copper interlayer and 10.7 J heat input on peak power of 1.5 kW, welding frequency 15 Hz, and welding time of 7 ms, leading to an ultimate strength of 160 MPa. In addition the result indicated that applying the circular technique by creating adjacent spot welds can produce a good joint.

Keywords: Laser Spot Welding, Ti-6Al-4V, AISI 304, Circular Technique.

1. Introduction

Titanium is the most popular metal in the industry. This metal is resistant to corrosion and 40% lighter than steel. Tensile strength of titanium (900 – 1100 MPa) is higher than that of steel. On the other hand, it is biocompatible and nontoxic and retains its toughness even at sub-zero temperatures [1]. The Ti-6Al-4V is the most popular alloy of the titanium. The titanium alloys have been classified under three groups of alpha, alpha-beta, and beta alloys [1]. AISI 304 stainless steel contains chromium and nickel at 18% and 8%, respectively, and serves as more than 50% of the global steel consumption [2]. Joint of dissimilar metals and alloys are more needs in such industries as chemical industries, power plants, pharmaceutical factories, and food industries [3]. Fusion welding of the mentioned two alloys is more difficult due to the formation of brittle intermetallic phases. The main problem at joining the titanium alloy to the stainless-steel alloy is the formation of the brittle phase of Fe/Ti. This phase is brittle and due to weld cracking [4]. Tomaschuk et al. [3] welded two plates of Ti-6Al-4V and AISI 316L with a thickness of 2 mm using a copper interlayer of 0.5 mm in thickness by EBW and LBW they result indicated that the hardness and tensile strength of the weld was 400 HV and 359 MPa, respectively, with the TiFe and Ti-Cr phases identified in the weld zone.

The Gao and et al. [5] used the Mg interlayer for two plates of the Ti-6Al-4V and AISI 304. The LBW of plates shows that formation of the Al_{17}-Mg_{12} intermetallic compound in the weld metal. Abeer A. Shehab et al. [6] investigated the joint of grade-II titanium plates of 1 mm thickness to AA13105-O aluminum alloy by laser pulse welding machine. The intermetallic compounds $TiAl_3$ and TiAl were formed at the welded zone. Moradi et al. [7] welded Ti-6Al-4V by 400-W laser welding machine. Their result shows that the best quality joint was obtained with 12 J pulse energy، 6 ms pulsing time, and 2 kW peak power. Titanium has a good weldability toward a number of metals such as zirconium, niobium, molybdenum, tantalum, vanadium, and hafnium. Metals like silver, copper, and nickel can be good choices for the interlayer between the titanium and stainless steel [7].

2. Materials and Methods

The Ti-6Al-4V and AISI 304 stainless steel plates with the thickness of 0.7 and 0.5 mm were used as base metals. The copper and silver foils with purity of 99.9% with thickness of 0.2 and 0.3 mm were used as interlayer. Chemical composition of the metallic materials (Table. 1. to Table. 3.) was determined by OES method. The samples were prepared according to subsize mentioned of the the AWS C1.1 standard, with the dimensions reported in Table. 4.

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Table. 1. Chemical composition (wt.%) of the AISI 304.

Fe	Cu	Mo	Ni	Cr	Mn	Si	C
Base	0.300	0.160	8.230	18.170	0.940	0.450	0.050

Table. 2. Chemical composition (wt.%) of the Ti-6Al-4V.

Ti	Mn	Fe	Cu	V	Al
Base	0.010	0.130	0.010	4.040	6.500

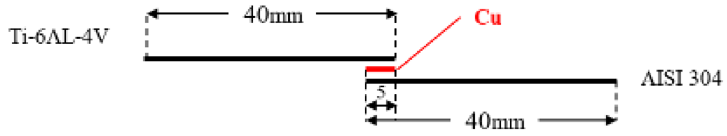


Fig. 1. Specimen preparation.

The samples before welding were assembled by proper fixture, as demonstrated in Fig. 1. The welding was performed via circular spot laser welding to form coaxial spot welds of 4 mm in diameter (Fig. 2.) [5, 8]. The welding was done by a 400-W Nd:YAG laser pulse welding machine (specifications are given in Table. 5. Table. 6. and Table. 7. present the welding conditions of the samples. The 12 samples included 6 samples with a copper interlayer and 6 samples with a silver interlayer were welded.

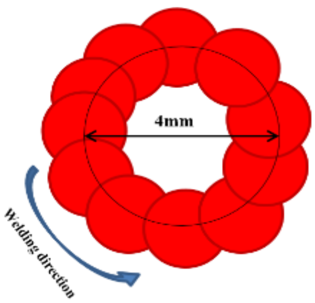


Fig. 2. The circular technique.

Table. 3. Chemical composition of (wt.%) copper.

Cu: 99.9	Co: 0.01
Ag > 99.9	-------

Table. 4. Specimen dimensions.

Alloy	Specimen Dimensions (mm)
AISI 304	40*5*0.50
Ti-6Al-4V	40*5*0.7
Cu	5*5*0.2
Ag	5*5*0.3

Investigating the samples 1 through 12, it was observed that when the AISI 304 is exposed to laser, the most appropriate weld penetration and Joint are obtained with an exposure time of 7 ms. On the other hand, when Ti-6Al-4V was exposed to the laser, the best weld penetration was achieved with an exposure time of 5 ms.

Table. 5. The pulsed laser welding machines specification.

Type	400 watt
Power input	Max. 10 Kw
Average power	400 watt
Pulse peak power	7 Kw
Wavelength	1064 nm
Pulse width	0.25–20 ms (adjustable)
Frequency	1–200 Hz
Beam diameter	0.3 to 0.6 mm
Bulb	Xenon ×2
Power source	380V 3-Phase
Cooling system	Chiller with water cooler

Considering the above mentioned observations, experiments were designed and conducted on samples 13 through 20. The welding conditions for different samples are reported in Table. 8.

Table. 6. Fixed parameters in the welding operation.

Frequency	15 Hz
Ar0067on pressure	2 bar
Current	150 A
Travel speed	4.6 mm/s
Welding cycle duration	2.7 s
Number of weld spots in a cycle	41 spots
Diameter of concentric circles	4 mm
Travel direction	Left to right
Weld point diameter	0.8 mm

Table. 7. Variables in the welding operation.

Top (exposed) metal	Stainless Steel/Titanium
Interlayer	Copper or Silver
Pulse width	3-5-7 ms

After welding, the samples were studied by VT and optical microscopy (OM) with OLYMPUS microscope. Then, defect-free samples had their surfaces prepared for further analyses. This was done by polishing them with 3 µm of an alumina suspension and etching with 85 ml of H_2O, 5 ml of

Table. 8. Welding Parameters.

Specimen Number	Top (Exposed) Metal	Interlayer Metal	I (A)	t (m.s.)	P_{Ar} (bar)	f (Hz)	E (j)	M (Kw)	Q (w)
1	Titanium	Copper	150	5	2	15	8	1.6	120
2	Stainless Steel	Copper	150	5	2	15	8	1.6	120
3	Titanium	Copper	150	3	2	15	5.3	1.7	80
4	Stainless Steel	Copper	150	3	2	15	5.3	1.7	80
5	Titanium	Copper	150	7	2	15	10.7	1.5	161
6	Stainless Steel	Copper	150	7	2	15	10.7	1.5	161
7	Titanium	Silver	150	7	2	15	10.7	1.5	161
8	Stainless Steel	Silver	150	7	2	15	10.7	1.5	161
9	Titanium	Silver	150	5	2	15	8	1.6	120
10	Stainless Steel	Silver	150	5	2	15	8	1.6	120
11	Titanium	Silver	150	3	2	15	5.3	1.7	80
12	Stainless Steel	Silver	150	3	2	15	5.3	1.7	80
13	Stainless Steel	Copper	150	7	2	15	10.7	1.5	161
14	Stainless Steel	Copper	150	7	2	15	10.7	1.5	161
15	Stainless Steel	Silver	150	7	2	15	10.7	1.5	161
16	Stainless Steel	Silver	150	7	2	15	10.7	1.5	161
17	Titanium	Copper	150	5	2	15	8	1.6	120
18	Titanium	Copper	150	5	2	15	8	1.6	120
19	Titanium	Silver	150	5	2	15	8	1.6	120
20	Titanium	Silver	150	5	2	15	8	1.6	120

HF, and 10 ml of HNO_3. Phase analysis was performed by SEM (MIRA3-VEGA\TESCAN-XMU) with 15 kV voltage. The Vickers hardness test was performed on the crack-free samples according to ASTM E384 standard test procedure under a loading force of 100 g and 15 s time. Tensile tests were performed on a universal tensile testing machine as the ASTM E8M (2016a) standard.

3. Results and Discussion

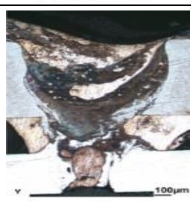
According to the images shown at the Table. 9., samples 1, 2, 5, 6, and 7 exhibited a better weld penetration than the other samples. The welding conditions of these samples are mentioned in Table. 10. Table. 9. present the weld sections of the samples 13 to 20. SEM images of the sample 13 are shown in Fig. 3. Fig. 4. shows the Map Scan images of the weld metal in sample 13.

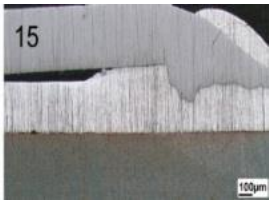
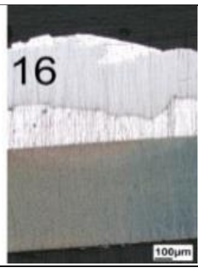
Investigation of Fig. 3. (SEM) and point analysis (EDS) of the percent weights at Points A, B, and C on the sample 13, it is evident that the titanium is the dominant element at Point A, where iron and copper are present at almost the same dosage. In this zone, there exists $FeTi_2$ phase. The dominant elements at Point B are the iron and titanium, and this point further includes FeTi compound.

At Point C, the dominant element along the grain boundary is the copper, and the dominant phase is TiCu. The grain size at Points A and B ranges between 2 and 3 microns. According to the results of tensile testing, the rupture started at the weld/titanium section in both tests, indicating the brittleness of this zone. Fig. 4. shows map scans of different metals in standalone and composite forms.

Based on the images shown in Table. 9., the best weld penetration was obtained for samples 13, 14, and 18 Table. 11. Investigating the copper and silver as the interlayer, it was figured out that both metals exhibit a cubic structure with center-facing sides (FCC) with pretty close heat transfer coefficients (429 and 399 W/m°K for copper and silver, respectively) [9]. The heat transfer coefficients of AISI 304 and Ti-6Al-4V are 14 and 6.7 W/m°K, respectively [1, 5]. Therefore, since (1) heat conductivity of the titanium plate is almost 40% higher than that of the stainless steel, and (2) the titanium plate is 40% thicker than the stainless steel, it can be concluded that the heat transfer will be improved if the AISI 304 plate is placed on the top and exposed to laser. Moreover, the lower heat conductivity of the Ti-6Al-4V plate caused to fail if it is exposed to the laser. An increase in the number of weld spots increases the preheating temperature of the Ti-6Al-4V plate, making the area around the initial weld spot susceptible to atomic penetration Table. 12. Based on the OM images shown in Table. 9., when AISI 304 is the upper base metal, better weld mixing and penetration are obtained. When the AISI 304 is exposed to the welding laser, the best results were obtained with a laser beam retention time of 7 ms. However, when the Ti-6Al-4V was exposed to the welding laser, the best output was achieved with a laser beam retention time of 5 ms. The welding parameters of the samples 13 and 18 are presented in Table. 14. The weld zone hardness profile is demonstrated in Fig. 5. According to Fig. 6. and Fig. 7., results of tensile tests on samples 13 and 18, and parameters of the mechanical tests (Table. 14.), the copper interlayer provided for better weld strength and mixing, as compared to the silver interlayer.

Table. 9. Cross-sections of welded specimens No. 1 to 6.

Specimen Number	Welding conditions			Microscopy images	Conclusion
	Top metal	Interlayer	Duration (ms)		
1	Titanium	Copper	5		Appropriate diffusion
2	Stainless Steel	Copper	5		Appropriate diffusion+2 holes
3	Titanium	Copper	3		Lack of diffusion
4	Stainless Steel	Copper	3		Lack of diffusion
5	Titanium	Copper	7		Appropriate diffusion
6	Stainless Steel	Copper	7		Appropriate diffusion+2 holes
7	Titanium	Silver	7		Appropriate diffusion
8	Stainless Steel	Silver	7		Lack of diffusion

Specimen Number	Welding conditions			Microscopy images	Conclusion
	Top metal	Interlayer	Duration (ms)		
9	Titanium	Silver	5		
10	Stainless Steel	Silver	5		Lack of diffusion
11	Titanium	Silver	3		Lack of diffusion
12	Stainless Steel	Silver	3		Lack of diffusion
13	Stainless Steel	Copper	7		Appropriate diffusion
14	Stainless Steel	Copper	7		Appropriate diffusion+ holes
15	Stainless Steel	Silver	7		Lack of diffusion
16	Stainless Steel	Silver	5		Lack of diffusion

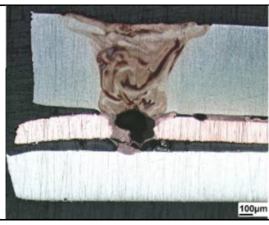
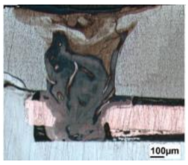
Specimen Number	Welding conditions			Microscopy images	Conclusion
	Top metal	**Interlayer**	**Duration (ms)**		
17	**Titanium**	**Copper**	**5**		**Negligible diffusion**
18	**Titanium**	**Copper**	**5**	 	**Appropriate diffusion**
19	**Titanium**	**Silver**	**5**		**Lack of diffusion**
20	**Titanium**	**Silver**	**5**		**Lack of diffusion**

Table. 10. Specifications of the accepted specimens.

Specimen Number	Top metal	Interlayer	t(ms)	E(j)	Conclusion
1	Titanium	Copper	5	8	Appropriate diffusion
2	Stainless Steel	Copper	5	8	Appropriate diffusion+ 2 holes
5	Titanium	Copper	7	10.7	Appropriate diffusion
6	Stainless Steel	Copper	7	10.7	Appropriate diffusion+ 2 holes
7	Titanium	Silver	7	10.7	Appropriate diffusion

Table. 11. Welding parameters of Specimens No. 7, 8, and 10.

Specimen Number	Top metal	Interlayer Metal	t (ms)	I (A)	f (Hz)	P_{Ar} (Bar)	E (j)
13	Stainless Steel	Copper	7	150	15	2	10.7
14	Stainless Steel	Copper	7	150	15	2	10.7
18	Titanium	Copper	5	150	15	2	8

Table. 12. Atomic percentage of different points in the HAZ.

Atomic percentage / point	Al	Ti	Cr	Fe	Ni	Cu	V	Present Phase
A	2.2	45.75	3.06	24.70	3.64	20.65	--	($FeTi_2$) 75%
B	3.72	36.22	12.39	40.85	1.30	4.95	0.75	(FeTi) 80%
C	6.63	28.70	6.29	14.24	0.78	42.80	0.57	(TiCu) 85%

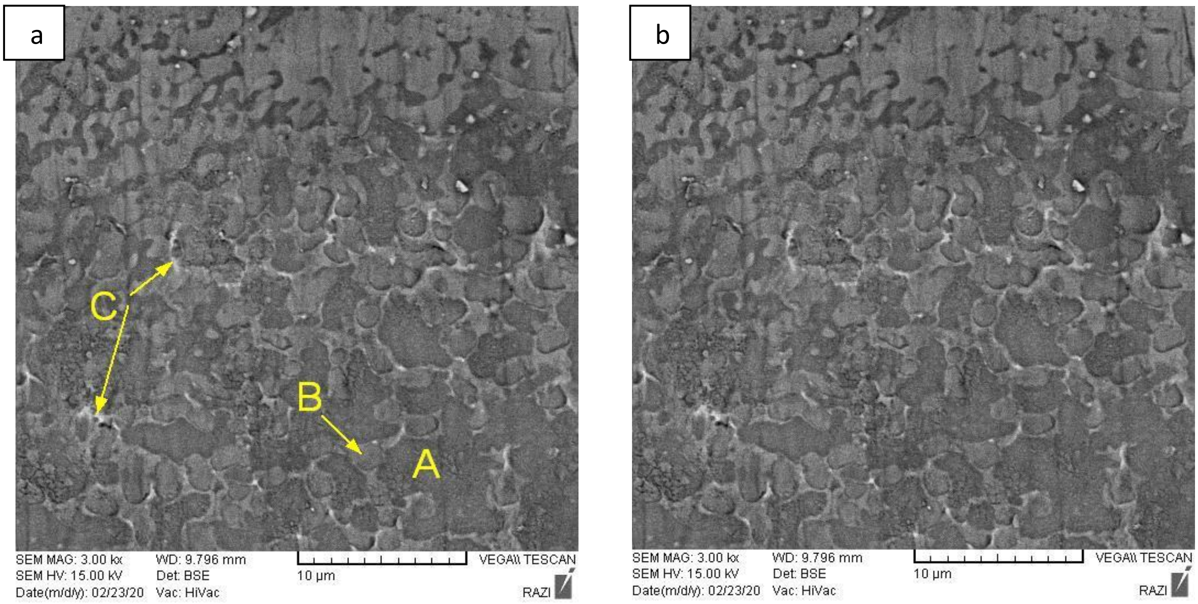


Fig. 3. SEM images of specimen 13–HAZ.

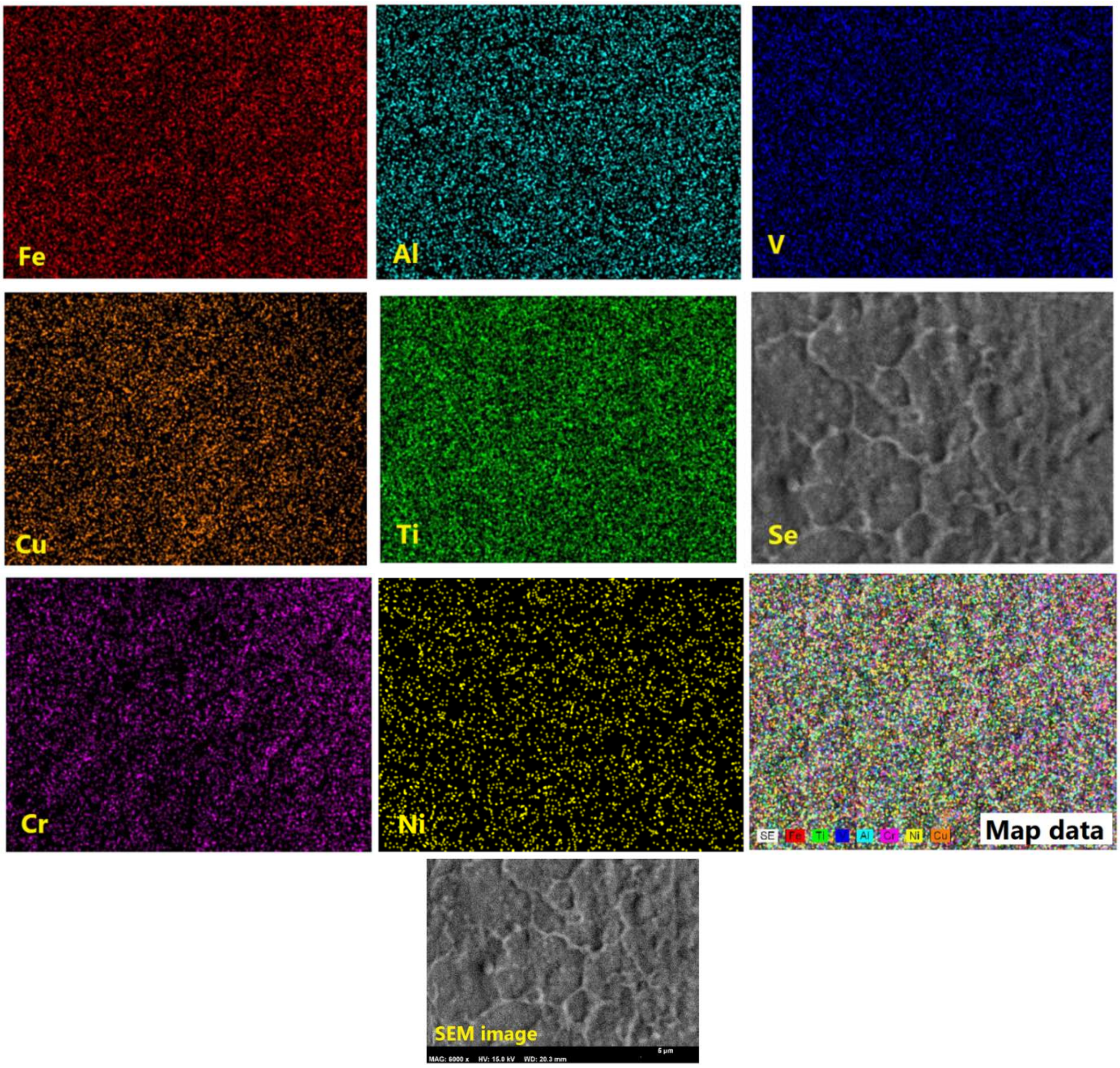


Fig. 4. Map scan analysis results of the HAZ in specimen no. 7.

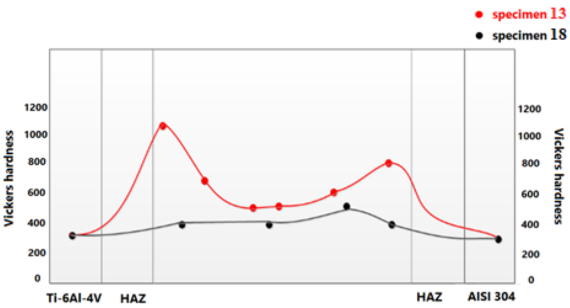
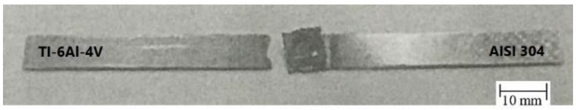


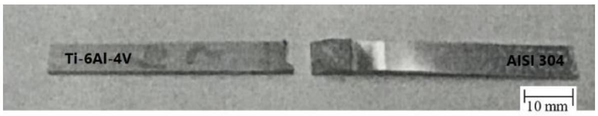
Fig. 5. Hardness profile in the HAZ of specimens no. 7 and 10.

Table. 14. Mechanical test results..

Top metal	AISI 304	Titanium
Specimen Number	13	18
Interlayer metal	Copper	Copper
Duration (ms)	7	5
f (Hz)	15	15
P_{Ar} (bar)	2	2
Q (w)	161	120
M (Kw)	1.5	1.6
E (j)	10.7	8
HAZ hardness	504	388
Shear strength	160	96
Tensile Fracture Position	Weld/Titanium	Weld/Titanium



Tensile specimen fracture (Weld/Titanium)
Fig. 6. Tensile test results for specimen No. 10.



Tensile specimen fracture (Weld/Titanium)
Fig. 7. Tensile test results for specimen No. 7.

When the AISI 304 is exposed to the welding laser, the hardness and strength of the weld were higher than the case when Ti-6Al-4V was exposed to the welding laser. The most appropriate phase in sample 13 is represented by areas containing $FeTi_2$ (e.g., Point A). These areas enjoy high levels of hardness and shear strength (504 HV and 160 Mpa, respectively). This is thanks to the better heat conductivity of the stainless steel (upper metal).

In sample 18, where the best case is the one whereTi-6Al-4V is the upper metal, the hardness and shear strength were measured at 388 HV and 96 MPa, respectively. These findings root in the lower heat conductivity of the titanium, as compared to stainless steel, and the larger thickness of the titanium plate. According to Table. 14. and Fig. 6. and Fig. 7., in samples 13 and 18, the rupture started form the weld/titanium interface. Based on Fig. 5., the weld-affected zone exhibited a hardness of 1000 HV in the titanium side. In the AISI 304 side, the hardness was measured at 700 HV and both samples ruptured from the weld/titanium interface.

4. Conclusion

In the present research, investigating dissimilar laser spot welding of Ti-6Al-4V to AISI 304, the following conclusions were drawn:

1. Joining Ti-6Al-4V to AISI 304 by means of laser spot welding is difficult without an interlayer metal and circular technique. The weld exhibits better mechanical properties with a copper interlayer rather than a silver interlayer.
2. Laser spot welding of the mentioned alloys in single-pass or even multi-pass mode may not end up with favorable results. However, applying the circular technique by creating adjacent spot welds can produce a good joint.
3. Focusing on the joint of two dissimilar metals with different heat transfer coefficients, the use of circular laser spot welding tends to preheat the base metal, making the joint feasible.
4. When AISI 304 was exposed to laser, the resultant joint was of adequate weld penetration, and symmetric microstructure.
5. As far as laser spot welding of Ti-6Al-4V and AISI 304 is concerned, the use of a copper interlayer of 0.2 mm in thickness leads to a better weld quality than a silver interlayer with a thickness of 0.3 mm.

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