Study on the Joining of Titanium and Aluminum Dissimilar Alloys by Friction Stir Welding

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Abstract: Titanium alloy TC1 and Aluminum alloy LF6 were butt jointed and lap jointed by friction stir welding (FSW), and the influence of process parameters on formation of weld surface, cross-section morphology and strength were studied. The results show that, Titanium and Aluminum dissimilar alloy is difficult to be butt joined by FSW, and some defects such as cracks and grooves are easy to occur. When the tool rotation rate is 950 r/min and the welding speed is 118 mm/min, the tensile strength of the butt joint is 131MPa which is the highest . FSW is suitable for lap joining of TC1 Titanium alloy and LF6 Aluminum alloy dissimilar materials, an excellent surface appearance is easy to obtain, but the shear strength of the lap welding joint is not high. At the welding speed of 60 mm/min and the tool rotation rate of 1500 r/min, the lap joint has the largest shear strength of 48 MPa. At the welding speed of 150 mm/min and the tool rotation rate of 1500 r/min, crack like a groove occurs on the interface and the shear strength is zero.

Keywords: Joining of Ti/Al dissimilar alloys, friction stir welding, butt welding, lap welding.

1. INTRODUCTION

Aluminum alloys are widely used in automotive, aerospace and ship industries as high strength-to-weight ratio materials. Titanium alloys are also attractive in these fields due to their lower density, high specific strength and excellent corrosion-resistance. With the increasing demand for lightweight components, their application is becoming more extensive [1-3]. In some special locations, the complementary characteristics of Ti and Al are required, such as increased strength, lowered weight and cost. Therefore, the joining of Al alloys and Ti alloys is an emergent problem to be solved in industrial application. However, it is sufficiently difficult to obtain sound dissimilar welds of these two kinds of alloys because of the great differences in their performance, including crystal microstructure, melting point, heat conductivity and coefficient of linear expansion, etc. [4,5]. Using traditional fusion welding method, Al element is severely lost at the temperature below the melting point of Ti. Composition of the weld metal is asymmetric and the laminated Ti/Al intermatellics such as Ti_3Al, TiAl and TiAl3 can be easily formed. So it is difficult to weld the Ti/Al compound structure by means of fusion welding [6].

To solve this problem, special welding methods have been reported for joining these two materials such as pressure welding [7], diffusion bonding [8,9], vacuum brazing [10], laser welding-brazing [11,12], liquid phase diffusion welding [13] and friction welding [14]. These studies showed that the key issue encountered in welding Al alloy to Ti alloys is the formation of interfacial intermetallic phases [15], which depends on the process related temperature-time cycles. Friction stir welding (FSW), a solid-state welding process patented by The Welding Institute (TWI) in 1991, is a potential candidate for the joining of dissimilar materials due to its advantageous lower processing temperature over conventional fusion welding [16]. There are several studies on the FSW of Ti/Al dissimilar alloys at present in the world. Dressler [17] joined titanium alloy TiAl6V4 and aluminium alloy 2024-T3 successfully and investigated microstructure, hardness and tensile strength of the butt joint. It was found the ultimate tensile strength of the joint can reach 73% of 2024-T3 base material strength. Chen [18] studied lap joining of Al–Si alloy and pure titanium by FSW and the maximum failure load of joints reached 62% of Al–Si alloy base metal with the joints fractured at the interface.

In this paper, dissimilar metals of Ti alloy TC1 and Al alloy LF6 were butt jointed and lap jointed by FSW and and the influence of process parameters on formation of weld surface, morphology of weld cross- section and tensile strength were studied in order to provide the theoretical guidance for obtaining an optimal process parameters and improved mechanical properties of the welded joint.

2. EXPERIMENTAL

TC1 Ti alloy and LF6 Al alloy plates with thickness of 2 mm were used in the present study, and the chemical compositions and mechanical properties are separately listed in Tables **1** and **2**. The plates are cut and machined into rectangular welding samples, which is 250 mm long and 100 mm wide. The surfaces of the welding samples were ground with grit paper to remove the oxide film and then cleaned by ethanol before welding. The welding tests are carried out on the homemade clamp using friction stir welding machine

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which is modified from milling machine, the tool rotation rate changes from 600 r/min to 1180 r/min, welding speed changes from 95 mm/min to 190 mm/min, the tilt angle of the stir head is 2°.

Table 1. Composition and Mechanical Property of LF6

Composition (Wt%)						Mechanical property	
Mn	Mg	Si	Cu	Fe	Zn	σb(MPa)	δ(%)
0.6	5.8	0.3	0.1	0.3	0.15	320	15

Table 2. Composition and Mechanical Property of TC1

Composition (Wt%)							Mechanical Property	
Al	Mn	Fe	Si	C	O	N	σb(MPa)	δ(%)
2.0	1.8	0.1	0.15	0.1	0.15	0.05	650	20

During butt welding, titanium alloy is placed on the advancing side, aluminum alloy is placed on the retreating side, the offset of the pin which is the distance of the edge of the pin and the seam of titanium and aluminum alloy is 0.5 mm. A tool with a concaved shoulder of 15 mm in diameter and a cone-threaded pin of 5 mm in diameter and 1.85 mm in length was used. During lap welding, LF6 Al alloy and TC1 Ti alloy were placed at the advancing side (AS) and the retreating side (RS) of the tool pin, the aluminum alloy plate is placed over the titanium plate (see Fig. **1**). A tool with a concaved shoulder of 15 mm in diameter and a cone-threaded pin of 4 mm in diameter and 2.1 mm in length was used.

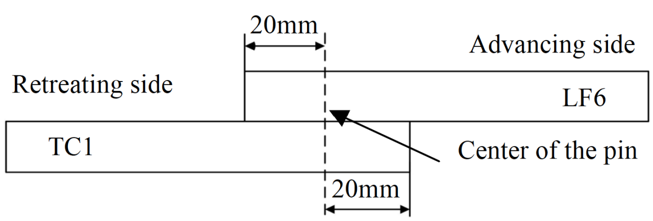

Fig. (1). Sketch map of relative position between Ti alloy and Al alloy of lap welding.

Microstructure and interface characteristic analysis were performed on the cross section perpendicular to the welding direction. A solution of 2 mL HF acid, 4 mL HNO_3 acid and 94 mL distilled water was used as the etchant of the specimen. Microstructure and element distribution of the weld were observed by optical microscope (OM, 4XB-TV) and scanning electron microscope (SEM, Quata200) equipped with an energy dispersive X-ray spectroscopy (EDS) system. The mechanical properties of the joint are measured by tensile tests which are carried out at room temperature at a crosshead speed of 3 mm/min using a tensile testing machine. The tensile strength of the butt joints and shear strength of the lap joints are evaluated using three tensile specimens cut from the same joint on electronic almighty testing machine (WDW-50) which is controlled by computer. The shape of the test specimen is rectangular and the width of each specimen is 12.5 mm.

3. RESULTS AND DISCUSSION

3.1. Influence of Process Parameters on Morphology of Surface and Cross Section of Butt Joints

When the tool rotation rate (n) is 1180r/min, and welding speed (v) changes from 95mm/min to 190mm/min, the longitudinal cracks always occur at the side of titanium alloy after welding, as shown in Fig. (**2**). For the FSW of titanium/aluminum dissimilar materials, the reasons of generating cracks is related to the intermetallic compound formed in the weld. Ti and Al are active element, according to Ti-A1 duality phase diagram, Ti and Al can form TiAl, Ti_3Al, Al_3Ti and other intermetallic compounds. During FSW, the frictional heat between the stir head and workpiece make the weld temperature rise, at the same time, Ti and Al element in the weld zone are mixed under the action of the stir head and experience severe plastic deformation, combination of both make Ti and Al form Ti-Al intermetallic compounds at solid state. A large number of brittle intermetallic compounds makes the weld brittle, the weld crazes under the action of welding stress at last. The higher the rotation speed is, the more frictional heat between the stir head and workpiece generates, more intermetallic compounds form in the weld, and greater possibility the weld crazes. So the weld crazes easily at the tool rotation rate of 1180r/min.

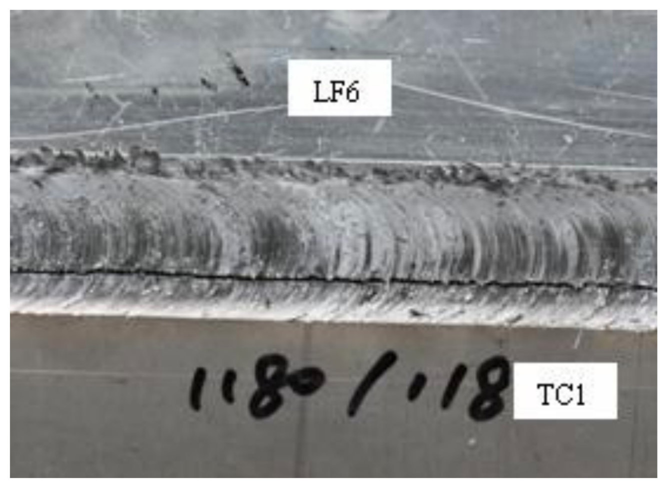

Fig. (2). Surface morphology of butt joint of 1180r/min.

When the tool rotation rate reduces to 600r/min, and welding speed changes in the range of 95 mm/min and 190 mm/min, the formation of weld surface is rough, both sides of the weld have more excessive flash, and grooves occur in the weld, as shown in Fig. (**3**). The reason is that, too low rotation speed results in less heat generated by friction in per unit length of the weld, the temperature of weld zone is too low, A1/Ti can't be jointed in plastic state, and the macro-defect like groove in the weld occurs.

A large number of technological experimentions show that, when rotation speed is 750r/min and 950r/min, the welding speed is 118mm/min and 150mm/min, a good formation of weld surface can be obtained, as shown in Figs. (**4**, **5**). When the welding speed increases to 190mm/min, the grooves appear in the weld for the heat is not enough as well.

Metallographic specimens were intercepted on the weld sample at the tool rotation rate of 750r/min and 950r/min,

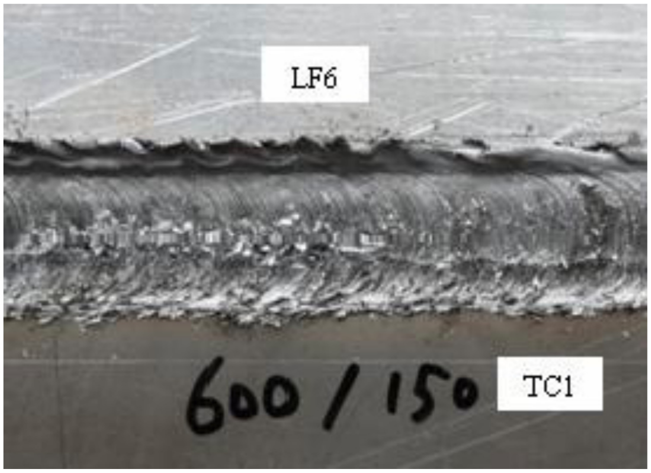

Fig. (3). Surface morphology of butt joint of 600r/min.

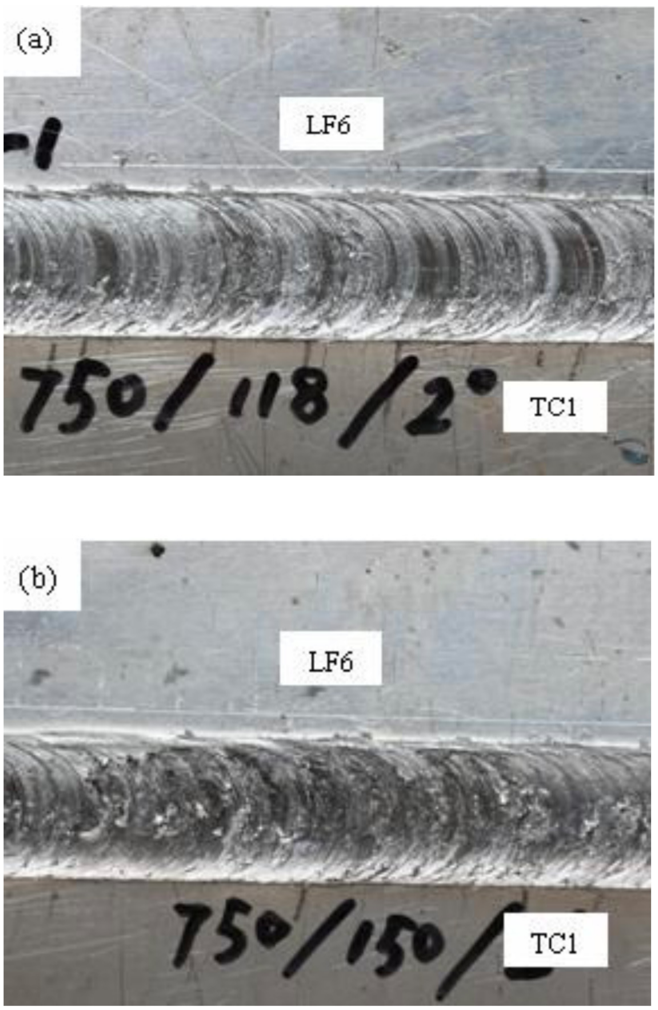

Fig. (4). Surface morphology of butt joint of 750r/min: (**a**) v=118mm/min; (**b**) v=150mm/min.

welding speed of 118 mm/min and 150 mm/min, then observe the morphology of cross-section of welded joint, as shown in Fig. (**6**). We can see from the figure, when the tool rotation rate is 750r/min and welding speed is 118 mm/min (Fig. **6a**), there is a part of titanium in the weld zone, but the titanium/aluminum interface is clear and perpendicular to the surface of the base material. It indicates that titanium and aluminum alloy don't sufficiently stir and mix during FSW. When the welding speed increase to 150mm/min (Fig. **6b**), the cracks will appear at the titanium/aluminum interface below the shoulder. When the tool rotation rate is 950r/min and the welding speed is 118 mm/min (Fig. **6c**), interface bonding of titanium and aluminum in the cross-section of weld joint is well and only a little of titanium transfer into the weld. When the welding speed increase to 150 mm/min (Fig. **6d**), there is a lot of titanium near by the titanium alloy base metal, as a result, more titanium/aluminum intermetallic compounds was created in the weld, it will decreases the tensile strength.

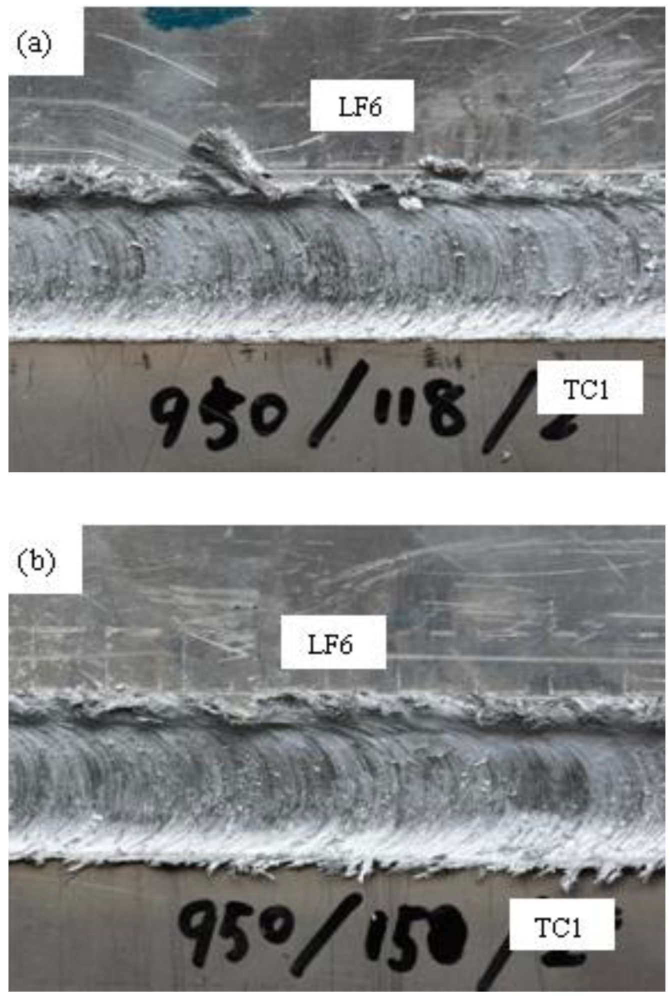

Fig. (5). Surface morphology of butt joint of 950r/min: (**a**) v=118mm/min; (**b**) v=150mm/min.

3.2. Tensile Strength of the Butt Welding Joints

The weld joints of four group parameters (the tool rotation rate is 750 r/min or 900 r/min, welding speed is 118 mm/min or 150 mm/min) were made into standard tensile specimens, then the strength of these weld joints were tested. Three tensile specimens were cut from each parameter and the average of the strength of the three specimens was regard as the tensile strength of weld joints, the results are seen in Table **3**.

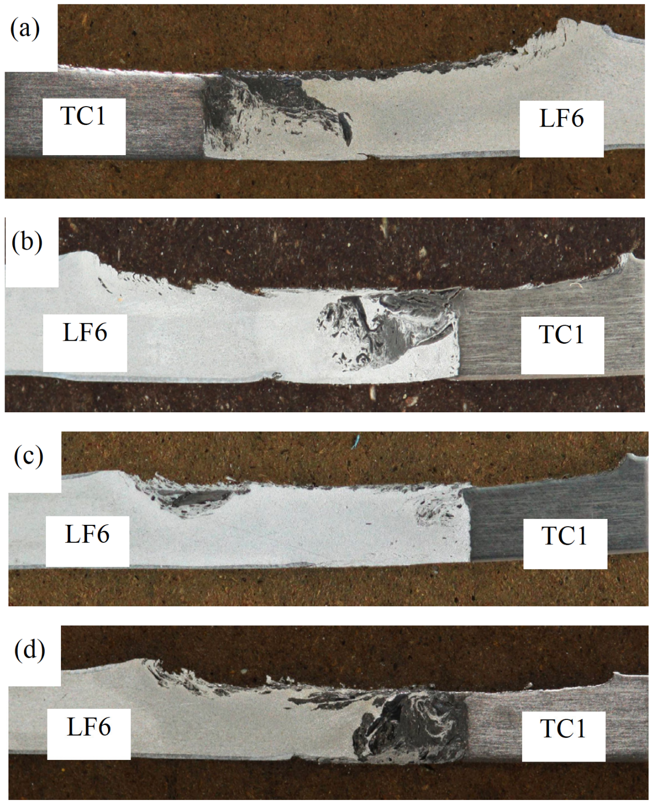

Fig. (6). The macroscopic morphology of cross section of butt joint: (**a**) n=750r/min, v=118mm/min; (**b**) n=750r/min,v=150mm/min; (**c**) n=950r/min,v=118mm/min; (**d**) n=950r/min,v=150mm/min.

Table 3. Tensile Strength of Butt Joint Ti/Al Alloy Dissimilar Materials

Sample Number	Rotational Speed (r/min)	Welding Speed (mm/min)	Average Tensile Strength (MPa)
1	750	118	-
2	750	150	16.4
3	950	118	131.1
4	950	150	96.4

It can be seen from Table **3** that the tensile strength is the lowest when the tool rotation rate is 750 r/min and welding speed is 118 mm/min, two specimens fractured when they were clamped in the tensile testing machine, indicating that Titanium/aluminum combine badly at these parameters, it is consistent with the morphology observed from weld cross-section. When rotational speed is 950r/min and welding speed is 118 mm/min, the strength of joint is is 131MPa which is the highest, but it is still far below the strength(314MPa) of LF6 aluminum alloy base material and the strength(600MPa) of TC1 titanium alloy base material. So about the FSW of Titanium and Aluminum dissimilar materials, further measures (such as the design of stir head, add the middle materials etc.) are took to improve the strength of joint and then it is possible to carry out the applications of engineering.

3.3. Surface and Cross Section of Lap Joints at Different Parameters

The friction stir welded Ti/Al lap joints at the parameters listed in Table **4** all have an excellent surface appearance, a typical surface appearance as seen in Fig. (**7**). It can be seen from Fig. (**7**) that the surface is smooth and without any defects. But the interface macrograph of the lap joint cross-section at different parameters has very difference as shown in Fig. (**8**). It can be seen from Fig. (**8**) that, at the welding speed of 60 mm/min and the tool rotation rate of 1500 r/min, the stir zone (SZ) of weld contains a large amount of Ti particles and the cross-section morphology of the lap joint is good (see Fig. **8a**). The SZ reveals a mixture of f Al alloy and titanium pushed away from the titanium surface by the stirring action of the tool pin. When the welding speed increases to 95 mm/min and 118 mm/min, the cross-section morphology is also good but the amount of Ti particles in the stir zone of weld decreases (see Fig. **8b**). This may be because the welding heat input reduces and the plastic flow ability of Ti alloy decreases when the welding speed increases. When the welding speed increases to 150 mm/min, crack occurs on the interface between Ti alloy and Al alloy (see Fig. **8c**). When the welding speed is 95 mm/min and the tool rotation rate decrseas to 950 r/min and 600 r/min, the tip of tool pin nearly does not touch the surface of lower Ti alloy plate because lower tool rotation rate effectively avoids serious softening of Al. It can be seen from Fig. (**8d**, **e**) that Al alloy and Ti alloy are joined tightly but there is little Ti in the SZ.

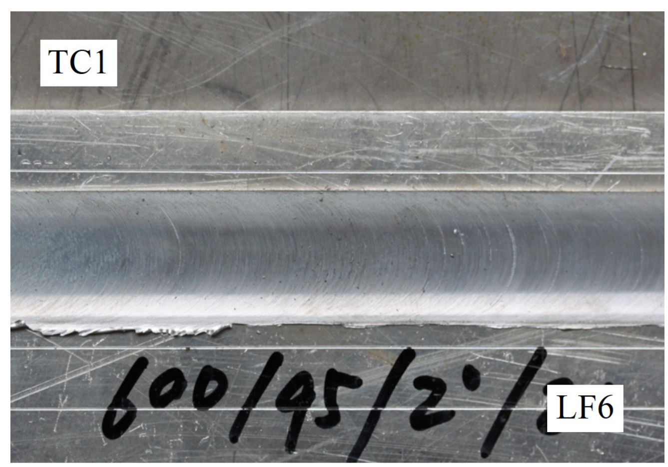

Fig. (7). Surface morphology of of Ti/Al dissimilar alloys lap joint.

Table 4. Lap Welding Parameters

Weld Sample No.	1	2	3	4	5	6
Tool Rotation Rate/n (r/min)	1500	1500	1500	1500	950	600
Welding Speed/v (mm/min)	60	95	118	150	95	95

3.4. Shear Strength of the Lap Welding Joints

Table **5** shows the shear strength of the lap joints welded at parameters listed in Table **4**. It can be seen from Table **5** that the shear strength decreases with the increasing of the welding speed when the tool rotation rate is fixed at 1500

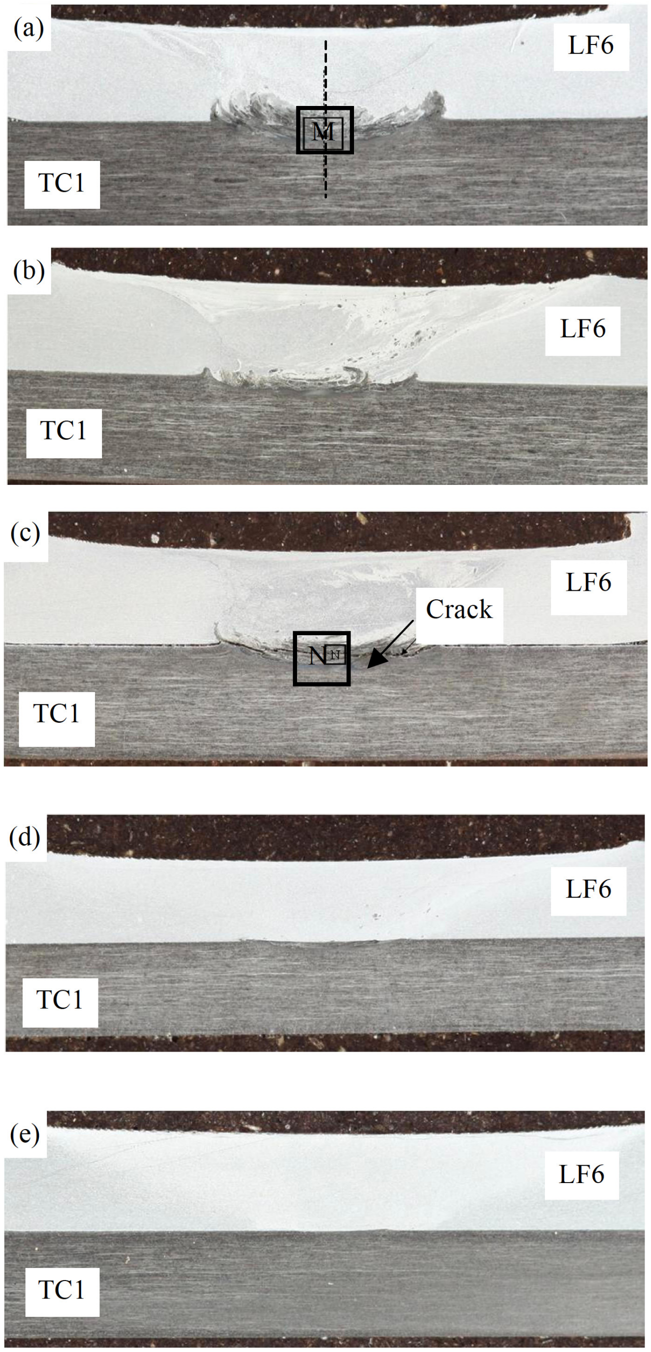

Fig. (8). The macroscopic morphology of cross section of lap joint of Ti/Al dissimilar alloys: (**a**) n=1500r/min, v=60mm/min; (**b**) n=1500r/min, v=118mm/min; (**c**) n=1500r/min, v=150mm/min; (**d**) n=950r/min, v=95mm/min; (**e**) n=600r/min, v=95mm/min.

r/min. The shear strength of the joint welded at the tool rotation rate of 1500 r/min and welding speed of 150mm/min is zero which has crack on the interface. When the welding speed is 95 mm/min and the tool rotation rates are 950 r/min and 600 r/min, the shear strength of the welded joints are relatively larger than the joint welded at the tool rotation rate of 1500 r/min and welding speed of 95 mm/min. This may be because there is less amount of intermetallic compound on the interface between Al alloy and Ti alloy since there is little Ti in the SZ (see Fig. **8d**, **e**).

Table 5. Shear Strength of the Lap Joints

Weld Sample No.	1	2	3	4	5	6
Tool Rotation Rate/n (r/min)	1500	1500	1500	1500	950	600
Welding Speed/v (mm/min)	60	95	118	150	95	95
Shear strength/P (MPa)	48	36	32	0	41	44

4. CONCLUSIONS

(1) Weld surface of friction stir welded butt joint of Titanium and Aluminum dissimilar metals easily appears longitudinal cracks if the tool rotation rate of stir head is too high, the weld surface is rough and occurs grooves if the tool rotation rate of stir head is too low.

(2) When the tool rotation rate is 750r/min and 950r/min, the welding speed is 118mm/min and 150mm/min, a good formation of butt weld surface can be obtained. When the tool rotation rate is 750r/min, the welding speed is 118mm/min and 150mm/min, the interface bonding of titanium and aluminum in the weld cross-section of butt joint is bad which results in a low strength joint.

(3) When the tool rotation rate is 950r/min and welding speed is 118mm/min, the strength of the butt joint of Titanium and Aluminum dissimilar metals is 131MPa which is the highest.

(4) FSW is suitable for lap joining of TC1 Ti alloy and LF6 Al alloy dissimilar materials, an excellent surface appearance is easy to obtain. But the interface macrograph of the lap joint cross-section at different parameters has very difference. When the welding speed increases or the tool rotation rate decrseas, the amount of Ti particles which is stirred into the stir zone by the forcr of tool pin decreases. When the welding speed increases to 150 mm/min crack like a groove occurs on the interface.

(5) The shear strength of the lap joints decreases with the increasing of the welding speed. In this paper, the shear strength of the joint welded at the tool rotation rate of 1500 r/min and welding speed of 60mm/min is the largest of 48 MPa and that of the joint at the tool rotation rate of 1500 r/min and welding speed of 150mm/min is zero.

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CONFLICT OF INTEREST

All authors do not have conflicts of interest to declare.

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