Final Draft
of the original manuscript:

Huang, Y.; Lv, Z.; Wan, L.; Shen, J.; dos Santos, J.F.:

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In: Materials Letters (2017) Elsevier

DOI: 10.1016/j.matlet.2017.07.081

A new method of hybrid friction stir welding assisted by friction surfacing for joining dissimilar Ti/Al alloy

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Abstract

A new method of friction surfacing assisted hybrid friction stir welding (FS-HFSW) technique was developed to improve the joint efficiency and avoid the pin abrasion for joining of dissimilar Ti/Al joints. The FSW tool with enlarged head and concave end-face was designed to broaden the lap width and promote material flow. The maximum tensile load reached 12.2 kN, representing 85.3% of the parent Al alloy, with a ductile fracture locating at the heat affected zone of base Al. The excellent bonding of Ti and Al was based on the combined effects of nanoscale $TiAl_3$ IMCs layer and complex mechanical inter-locking.

Key words: Welding; Friction surfacing; Ti/Al alloys; Interfaces; Microstructure

1. Introduction

As the potential application, the jointing of aluminum (low cost, low weight) to titanium (corrosive properties, strength) become increasingly attractive in aviation and automobile industry. Due to the mismatch in physical properties and metallurgical conflict, the welding of Ti/Al alloys is still an arduous task [1-3]. The core problem lies in the control of brittle intermetallic compounds (IMCs) formed at Ti/Al interface [4-6]. Friction stir welding (FSW), as a revolutionary solid-state technology, is famous for its low heat-input [7-9]. During the FSW process, the maximum failure load can reach 62% of Al base metal and $TiAl_3$ phase is the only reaction product [10]. Lots of methods have been tried to minimize the thickness this $TiAl_3$ layer. By shifting the pin towards aluminum side, the $TiAl_3$ phase could be restricted to 1 μm in maximum during friction stir butt welding [11]. By applying FSW lap jointing, a thin (<250 nm) interlayer can be achieved if the pin was set close to but not penetrating the lap interface [12]. High-quality as their work, however, the issues of tool abrasion, when the probe or shoulder inserted into the Ti base metal, were not further discussed.

In the present research work, two vital points were taken into consideration: to minimize the thickness of IMCs layer and to avoid the abrasion of pin. Friction surfacing (FS), which was investigated mainly for producing homogeneous fine grained coating [13-14], has been employed as a supplementary means to assist the joining of Al to Ti for the process of FSW, and the new method was described as friction surfacing assisted hybrid friction stir welding (FS-HFSW).

2. Experimental procedure

The surface of TC4 titanium was roughed by a crawler equipped with 60-grit abrasive paper. A consumable 6082-T6 aluminum rod with diameter of 20mm was used to fabricate the Al-coating onto the TC4 surface by FS, as illustrated in Fig.1a. The FS parameters included traverse speed of 90 mm/min, downward force of 3 kN and rotational speed of 1800 r/min. Then, a taper shaped pin together with enlarged head (with diameter of 8 mm) and concave end-face was applied to realize the FSW process. Control the pin to plunge into the Al-coating layer, but not touch the titanium surface, as shown in Fig.1b. Thus, the welding of Al to Ti transformed into the joining of Al-coating to Al-plate (2A12 Al, 3mm thickness), while the latter is easy to realize and free from abrasion of the pin. Samples for analysis were prepared by standard mechanical and metallographic procedures. Optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscope (TEM) were used.

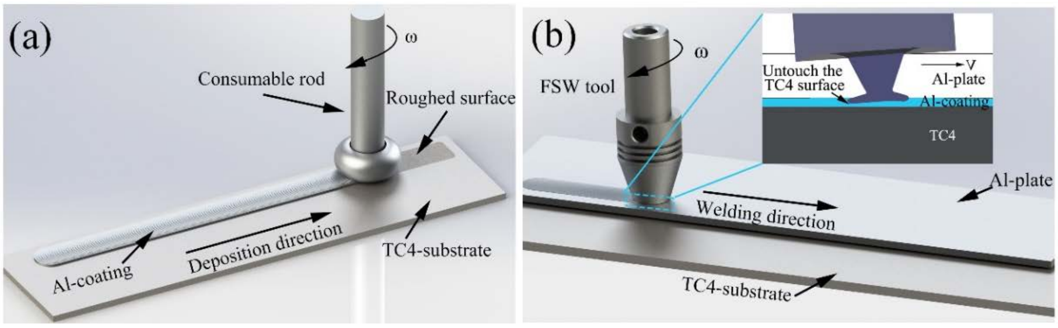

Fig. 1. The FS-HFSW process: (a) friction surfacing; (b) friction stir lap welding.

3. Results and discussions

The macro-view of Al-coating over TC4 substrate fabricated by FS was showed in Fig.2a. Since no bulk melting takes place during the FS process, solid-state Al-coating affiliated with homogeneous surface wave was attained. The average thickness of deposition layer was measured to be 0.23mm, and non-defect was perceived at the Ti/Al interface, as depicted by the cross-section morphology in Fig. 2b. A typical optical image of the etched cross section through FS-HFSW joint was exhibited in Fig. 2c. The as wleded FS-HFSW joint revealed to be made up of 5 compositions: up weld nugget zone (UWNZ), down weld nugget zone (DWNZ), interficial zone (IZ), thermomechanically affected zone (TMAZ) and heat affected zone (HAZ). By applying the enlarged head tool, the efficient bonding width was increased to a great extent when compared to conventional FSW lap joint, as marked with blue lines (IZ'). Because the end-face of the pin was fabricated into a concave shape, the coating meterial at IZ flow whirly from retreating side (RS) to advancing side (AS), thus leading to the gathering of coating materials at AS of IZ. Moreover, this gathering phenomena generated a local high pressure, which urged a upward flow behavior and mixed with Al-plate materials to form a hybrid structure at DWNZ, as depiced in Fig. 2c.

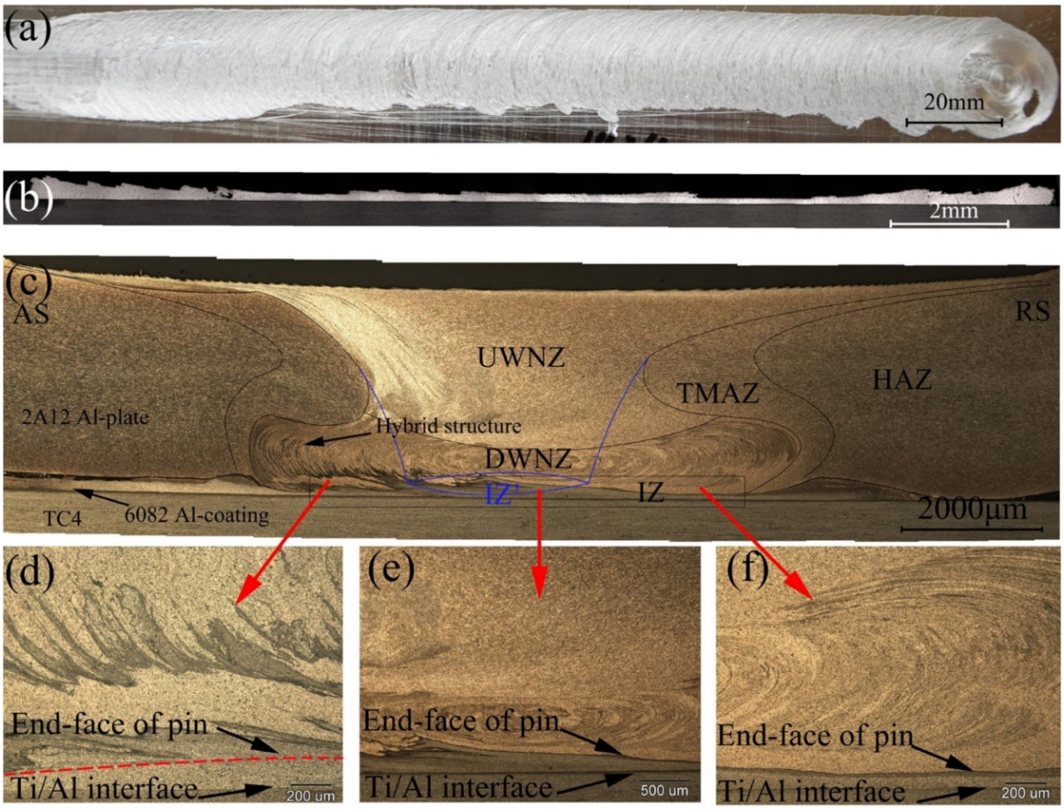

Fig. 2. (a) the macro-view of Al-coating and (b) cross-section morphology; (c) macrostructure of FS-HFSW joint, (d-f) distance between the pin and Ti/Al interface.

Due to no touch of the pin to titanium surface, there always exist a safe distance between the end-face of pin and the Ti/Al interface, as shown in Fig. 2d-f. So that, free from directly stirring Ti material, the FSW tool abrasion was successfully avoided.

The tensile test showed that joints bonded with parameters of ω/v =6~12 failed at the Al-coating/Al-plate interface, and the fracture load reached a relatively high value by ranging from 9.1~10.8 kN. When ω/v =20, the highest tensile load reached 12.2 kN, about 85.3% of the 2A12 Al alloy and the fracture was located at the HAZ of Al-plate, as shown in Fig. 3a-b. No sample failured at the Ti/Al interface, and all the tested joints showed excellent elongation. By adopting the hybrid solid-state FS-HFSW technology, a dramatically improvement of mechanical properties of the Ti/Al joints were achieved.

The corelation between mechanical properties and microstructure can be explained as follow: 1) a layer of lamellar structure with nanoscale was formed at the Ti/Al interface, which was identified by diffraction patterns to be $TiAl_3$, as shown in Fig. 3c. $TiAl_3$ phase was proved to form prior to the formation of any other titanium aluminide and was the only reaction product during both FSW and FS [15,16]. In this experiment, the friction heat was weakeded when conduct through the "safe distance" and the temperature was insufficient for this $TiAl_3$ layer to grow thick, resulting in the $TiAl_3$ layer with thickness of nanoscale. This nanoscale-IMCs layer might have acted as an adhesion-promoting agent, and also a proof of high quality metallurgical bonding at the Ti/Al interface, which was also reported by Dressler [11]. 2) the roughed surface of TC4 can provide interspace to accommodate the softened material to form a mechanical interlocking, as shown in Fig. 3d. 3) the mixing of Al-plate and Al-coating at the IZ led to a synergetic mechanism of metallurgical bonding and mechanical inter-locking, which could heighten the joint's performance, as shown in Fig. 3e. 4) the enlarged efficient bonding width at IZ also promoted the ultimate tensile strength of the joint.

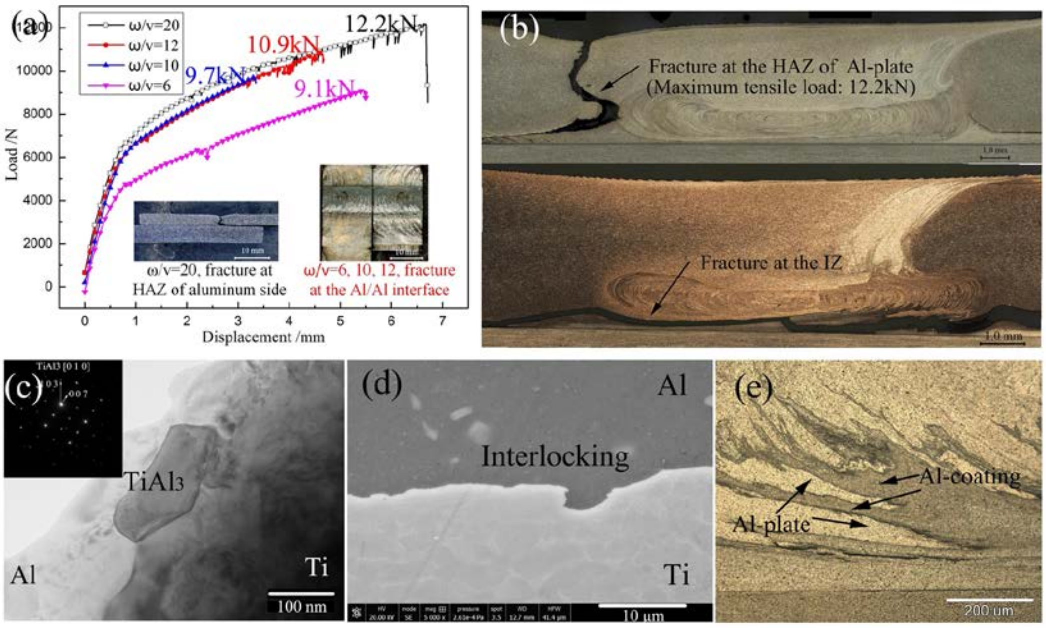

Fig. 3. (a) force-displacement curves at different parameters; (b) two kinds of fracture modes; the interfacial behavior of (c) nanoscale $TiAl_3$ IMCs layer (d) inter-locking, and (e) materials mixing at the Al-coating/Al-plate interface.

Fig. 4 showed the $TiAl_3$ IMCs at the interface and EDS results. Fig. 4d-f displayed the EDS results of the local region corresponding to the marked blue symbol d-f in Fig. 4a. At point d, the content of Al material (wt%) accounted for 42.2% and 44.3% for Ti, which was confirmed to be $TiAl_3$ by the diffraction patterns in Fig. 4b. At point e, the mass fraction of Ti comes to 4.6%, 46 times of that in 6082 aluminum base material, as showed in Fig. 4e, which declared the migration behavior of Ti atom from the substrate into the coating layer. The mass content of Al at point f was only 6.1%, the same as that in TC4 titanium base material, which indicated that almost no diffusion of Al into titanium substrate occured.

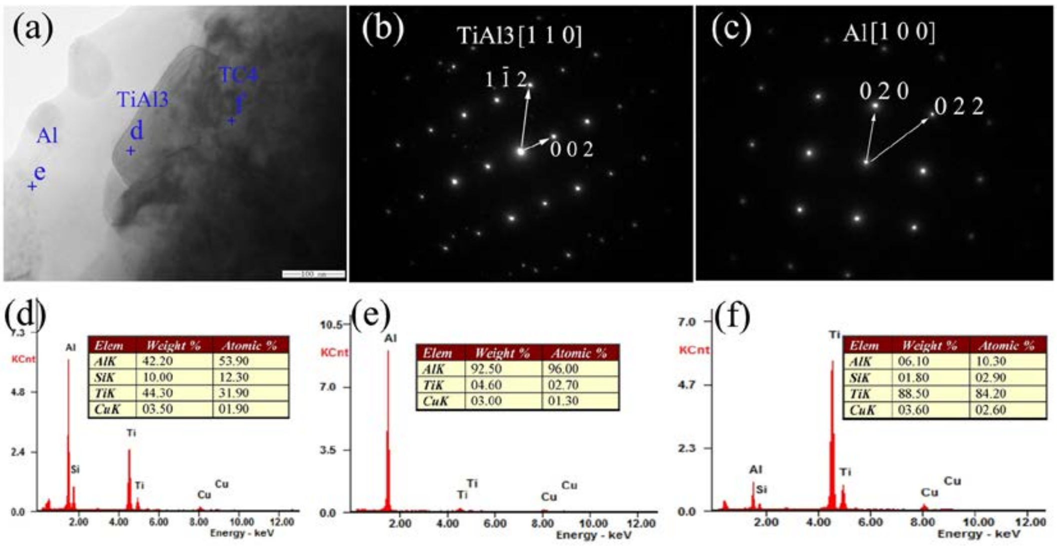

Fig. 4. (a) $TiAl_3$ IMCs, (b) diffraction patterns of point d and (c) of point e; EDS results of (d) point d, (e) point e and (f) point f.

4. Conclusion

In this study, hybrid FS-HFSW joints of high quality were perceived. The highest tensile load reached 12.2kN (85.3% of the Al base material) and the tool abrasion was avoided. The bonding mechanism of the Ti/Al interface lay in the combined contribution of metallurgical reaction with nanoscale $TiAl_3$ IMCs and mechanical inter-locking with Ti/Al interface and Al-plate/Al-coating interface. The interdiffusion behavior of Ti and Al was perceived to be the migration of Ti to the coating layer, while little evidence was found to prove the diffusion of Al to the substrate.

Acknowledgements

This work was jointly supported by the National Natural Science Foundation of China (No. 51575132) and the Fund of National Engineering and Research Center for Commercial Aircraft Manufacturing (No. COMAC-SFGS-2016-33214).

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