Effect of Flash Trap Profile on Joint Strength of Friction Welded Ti-6Al-4V Tube and AA6061 Tube-Plate Using an External Tool

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***Abstract*—**Using a patented process - Friction welding of tube to tube-plate using an external tool (FWTPET), Ti-6Al-4V tube and AA6061-T651 tube-plate were welded together. In this present work, a study was done to investigate the effect of flash trap profiles (Holes, Slots and Petals) on the joint strength. After welding, the joint strength of the specimen was measured using a novel in-house developed test procedure named "Plunge Shear Test". Fractography of the sheared surfaces was studied. Since Titanium and Aluminium dissimilar welds are prone to form Titanium aluminides, XRD analysis was done at the joint interface to study the effect of intermetallics on the joint strength.

***Keywords*—**AA6061-T651, FWTPET, Solid State Welding, Ti-6Al-4V.

I. Introduction

Highest performance, concurrent weight and cost reduction has become more and more important in aviation industry. There are different approaches to meet these demands. It is well known, for example, that welding of skin-stringer joints is progressively replacing riveted fuselage structures. Another very effective possibility is the implementation of hybrid structures; components made of different materials can be tailored for local needs. There is a rising need for a welding method to join dissimilar materials, such as Titanium (Ti) and Aluminium (Al). However, joining of Al alloys to Ti alloys is difficult due to the formation of excessive intermetallic compounds at interface by traditional fusion welding method [1]. Excessive intermetallic compounds at the interface will make the joint brittle thereby reducing the weld strength.

Friction welding of tube to tube-plate using an external tool (FWTPET) is an innovative process that has been used successfully to join tube with tube-plate of different materials and has potential industrial applications [2]. Unlike FSW process, in FWTPET the pin acts as an anvil and does not cause any stirring action [3]. This leads to lesser heat generation at interface and in turn leads to lesser intermetallic formation when compared to Friction Stir Welding (FSW) process [4].

In the present study, an effort was made to weld Ti-6Al-4V tube with AA6061-T651 tube-plate using FWTPET process and thereby study the effect of flash trap profiles (Holes, Slots and Petals) on the joint strength of these welds.

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II. Experimental Details

A. Materials

Aluminium alloy (AA6061-T651) plates of 6 mm thickness and Titanium Grade V (Ti-6Al-4V) tubes of 19 mm outer diameter were used. T651 designation denotes that, after tempering of the Aluminium alloy, a 1% to 3% stretching was done to the material to get rid of residual stresses. The base material composition of AA6061 is (all in wt. %) Mg-0.70%, Si-0.43%, Fe-0.497%, Cu-0.164%, Cr-0.148%, Mn-0.045%, Ti-0.0495%, Zn-0.0042%, Al-Balance. The chemical composition of Ti-6Al-4V is, (all in wt. %) C-0.08%, Fe-0.03%, O-0.2%, N-0.05%, Al-5.5-6.75%, H-0.015, V-3.5-4.5, Y-0.005%, Ti-Balance. The external tool used for welding was made of Tungsten Heavy alloy (Fig. 1) having 29mm shoulder diameter and 12.5mm pin diameter. Chemical composition of the external tool is listed in Table I.

Fig. 1 External Tool Used in FWTPET

TABLE I

CHEMICAL COMPOSITION OF TOOL MATERIAL

Element	W	Ni	Co	Fe	O
Wt %	90.5	5.3	0.2	3.4	0.007

B. Sample Preparation

AA6061-T651 plate of 6mm thickness was cut into 50x50mm plates and a hole of 19mm diameter was drilled at the center of these plates to accommodate Ti-6Al-4V tube. Tube outer diameter and inner diameter was 19mm and 14mm respectively and its length was 20mm for metallographic studies. A 35mm tube, where the first 20mm is hollow and the remaining 15mm is solid was used for Plunge Shear Test (PST). Three different tube profiles were used, they were – holes, slots and petals (Fig. 2). Number of holes, slots and petals for a tube was made 8 for all welds.

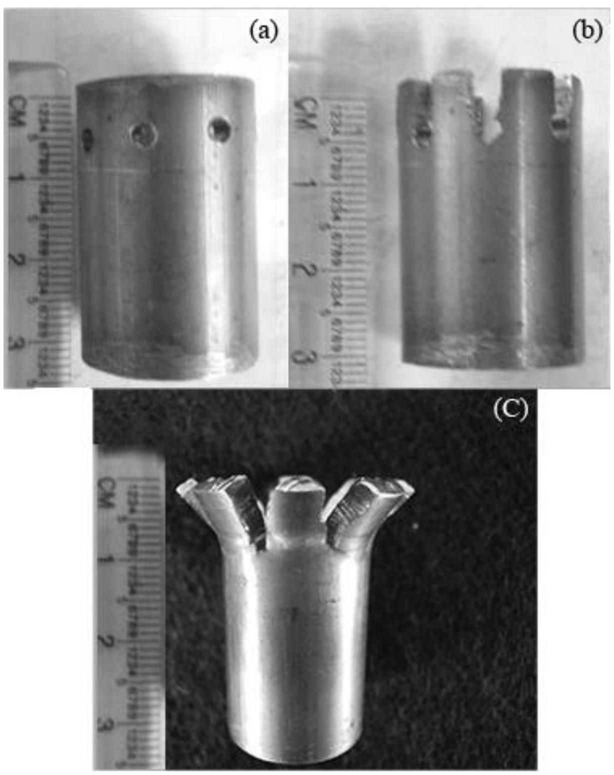

Fig. 2 (a) Holes, (b) Slots, (c) Petals

C. Welding

The welding was done in a 4-Axis Friction Stir Welding machine (Fig. 3). This fully automated machine has a pre-programmed FWTPET module that was used to carry out the welds. Before welding, both the tube and plate were cleaned with Acetone to remove grease, dirt etc. The tube and plate were fitted to a custom-made backing block as shown in Fig. 3. The parameters used for welding were – tool rotational speed - 1120 rpm, plunge rate – 2mm/min, plunge depth - 2mm. These parameters were kept constant for all subsequent welds.

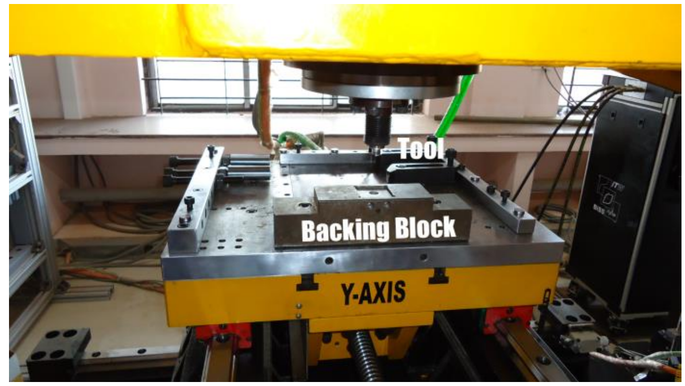

Fig. 3 FWTPET setup on FSW Machine

D. Plunge Shear Test

In order to evaluate the integrity of the welded joints, a novel testing procedure was used. With the help of a plunger (Fig. 4), a compressive load was applied on the inner diameter of the tube in an UTM until the joint breaks. Using the fracture load obtained, we then calculate the weld strength. Weld strength is calculated by dividing the Fracture load by the weld area.

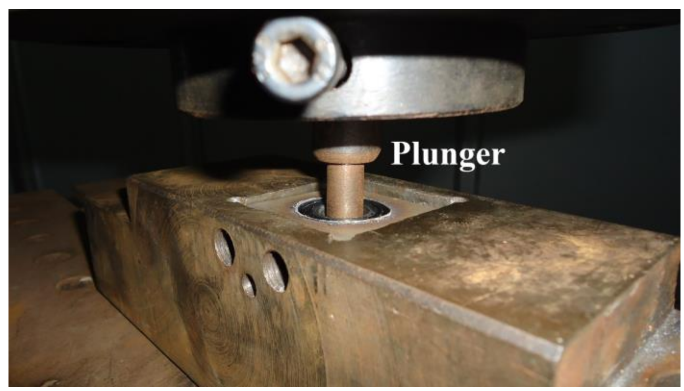

Fig. 4 Plunge Shear Test

E. Metallography

The welded sample was sectioned along the transverse direction, mounted and polished with emery sheet of different grades. Further alumina polishing and diamond polishing with 1µm diamond paste was done. In order to reveal the microstructures, AA6061-T651 plate specimens were etched with Poulton's reagent (30ml HCl, 40ml HNO_3, 2.5 mL HF, 12 g CrO_3, 42.5 mL H_2O). The etchant time used was 10-15 seconds. Ti-6Al-4V tube specimens were etched with Kroll's reagent (192ml H_2O, 5ml HNO_3, 3ml HCl, 2ml HF) for 25-30 seconds. Microstructures and macrostructures were taken using an optical microscope.

F. Scanning Electron Microscopy (SEM) and Energy-dispersive X-ray Spectroscopy (EDS)

SEM and EDS analysis were performed to quantify the elemental weight percentage at the joint interface. The observations were carried out in a 200kV field effect scanning electron microscope (SEM-JEOL JSM 5410LV microscopy) coupled with EDS. EDS line scan was also carried out along the weld interface.

G. X-Ray diffraction analysis

XRD analysis was done at the weld interface of Al-Ti dissimilar welds. XRD analysis helps to find out the formation of intermetallic at the weld interface. Scan speed was 10º/min and step width was 0.02º.

III. Results and Discussions

A. Macrostructure Analysis

The macrostructures, for all three different tube profiles revealed defect free joints. For tube with holes and slots profile, Aluminium is embedded in the Titanium region (Fig. 5 a,b). Plates welded with tube having petals are characterized by Titanium deposited on the surface of the Aluminium plates (Fig. 5 c).

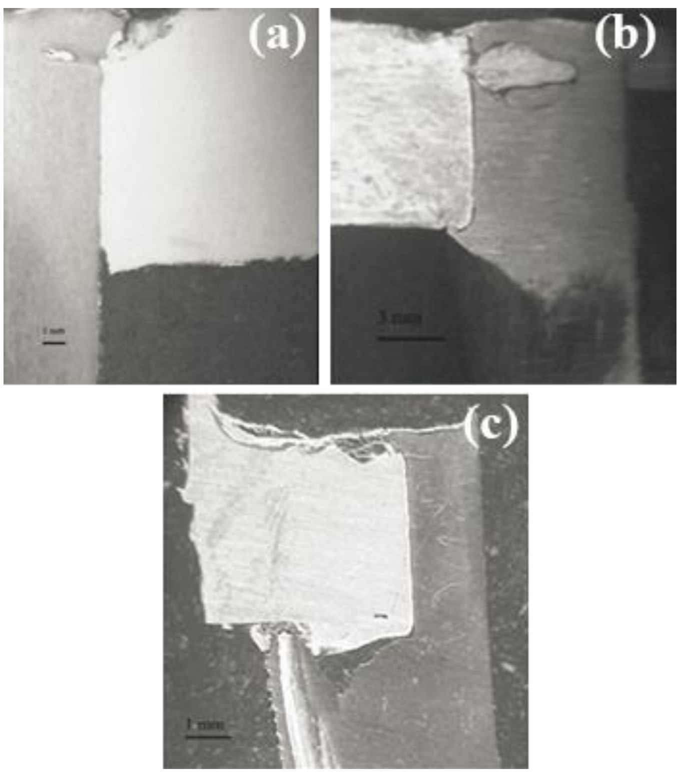

Fig. 5 (a) Holes, (b) Slots, (c) Petals

B. Microstructure Analysis

The microstructure of AA6061-T651 base metal is shown in Fig. 6. Optical micrographs of the base AA6061-T6 revealed the presence of Mg_2Si precipitates which strengthens the Al alloy [4]. Ti-6Al-4V is an α-β alloy that has a “Basket Weave” microstructure in which retained β lies between α platelets in a Widmanstätten structure, itself contains thinner secondary α platelets [5]. In Fig. 7, the dark lines in the microstructure are the β phase and the light region is α phase.

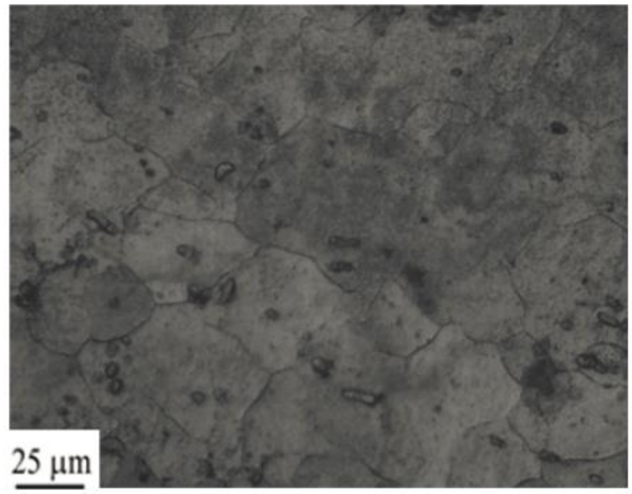

Fig. 6 Microstructure of base material AA6061-T651

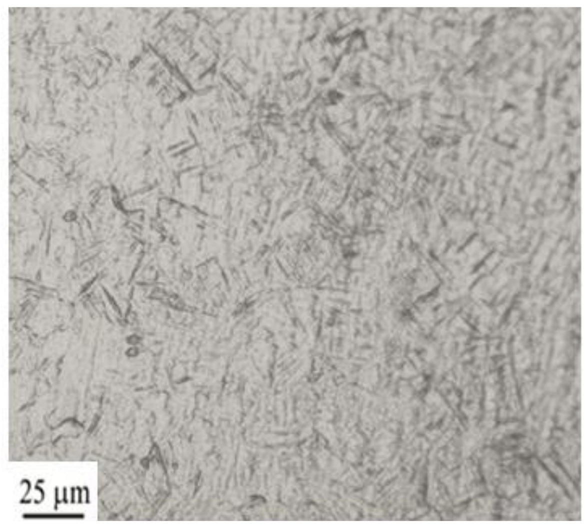

Fig. 7 Microstructure of base material Ti-6Al-4V

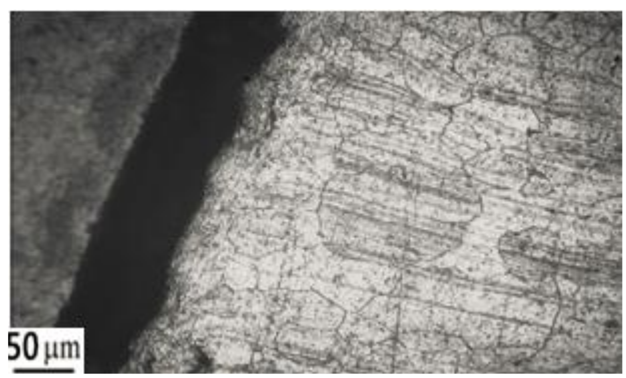

Fig. 8 Microstructure of AA6061-T651 at the interface

After welding, AA6061-T651 showed coarse grain structure at the weld interface with dissolution of Mg_2Si. In case of Ti-6Al-4V, the microstructure at the interface (Fig. 10) shows fine grain structure with equiaxed α phase with inter-granular retained β phase. When we move away from the interface, the microstructure resembles that of the base metal microstructure for both AA6061-T651 and Ti-6Al-4V.

Fig. 9 Microstructure of AA6061-T651 away from the interface

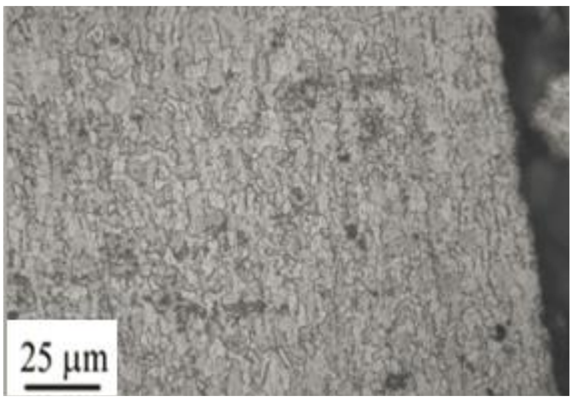

Fig. 10 Microstructure of Ti-6Al-4V at the interface

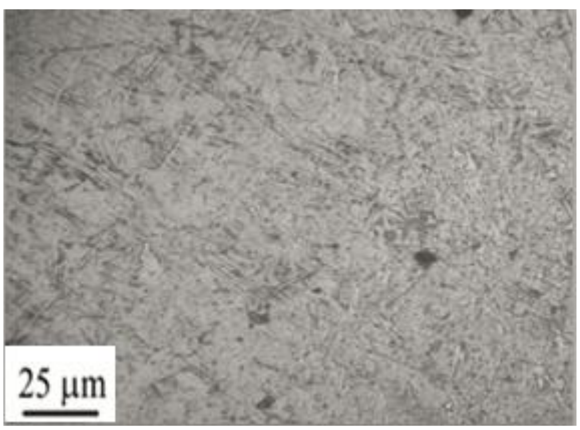

Fig. 11 Microstructure of Ti-6Al-4V away from the interface

C. Weld Strength

Weld strength was measured by using the shear fracture load obtained from PST. Shearing will take place along the interface of the welded sample. The shear strength values for different tube profiles are given in Table II. From the table, it is clear that tube with petals is having high shear strength compared to other to profiles. This is due to the increase in weld area when compared to other tube profiles.

TABLE II
SHEAR STRENGTH FOR DIFFERENT TUBE PROFILES

Tube Profile	Shear strength (MPa)
Holes	75.3
Slots	104.71
Petals	117.27

D. X-Ray Diffraction Analysis

XRD plot at the weld interface for welds made with Tube with petals is shown in Fig. 12. From the XRD plot, the presence of $TiAl_3$ intermetallic formation was observed. Formation of intermetallic compounds is detrimental to joint strength. Titanium aluminide has three major intermetallic compounds: γ TiAl, α Ti_3Al and $TiAl_3$. Although these intermetallics have very good mechanical and thermal properties, they have very low ductility [6]. Therefore, the presence of Titanium aluminides at the interface might decrease the joint strength.

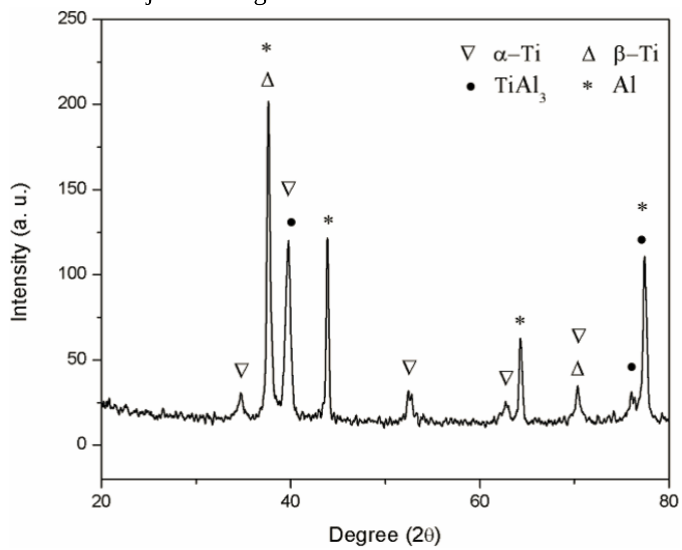

Fig. 12 XRD plot of Ti-Al weld interface

E. SEM Analysis

SEM micrograph (Fig. 13) shows the Titanium particles entirely entrapped in the Al matrix at the weld interface. It can be seen that thick mixed layers are formed on the interface. EDS Line Scanning analysis was done along the interface. EDS patterns and element contents are shown in Fig. 14.

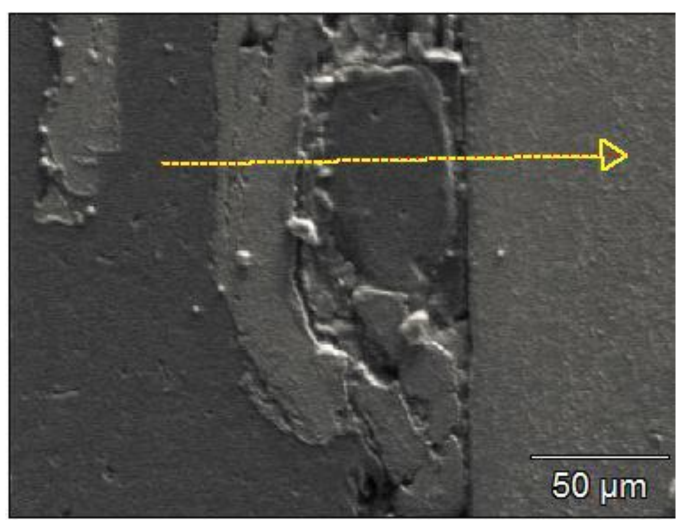

Fig. 13 SEM image of Ti-Al weld interface

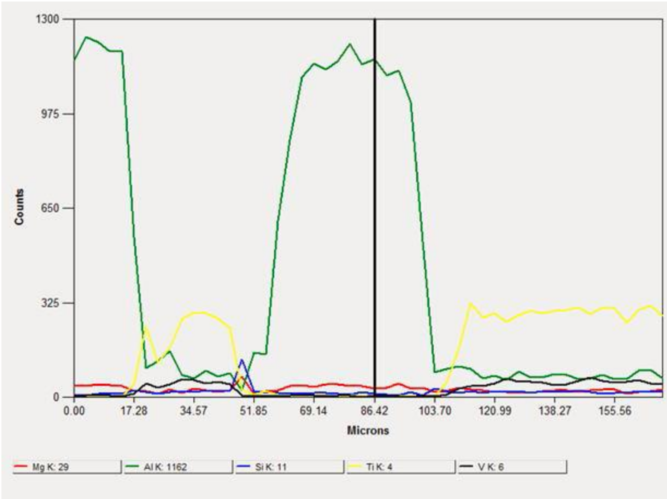

Fig. 14 EDS line scan along Ti-Al weld interface

F. Fractography

The SEM image (Fig. 15) shows fracture surface of Titanium tube for petal profile after the PST. From the image, we can clearly see some areas on the fracture surface where the aluminum alloy is still bonded to Titanium. SEM images of the fracture surface on the Aluminum plate shows cleavage facets, which is an indication shear fracture [7],[8]. Some Titanium particles embedded in the Aluminium matrix are also visible in the SEM images (Fig. 16 b).

Fig. 15 Titanium tube after PST

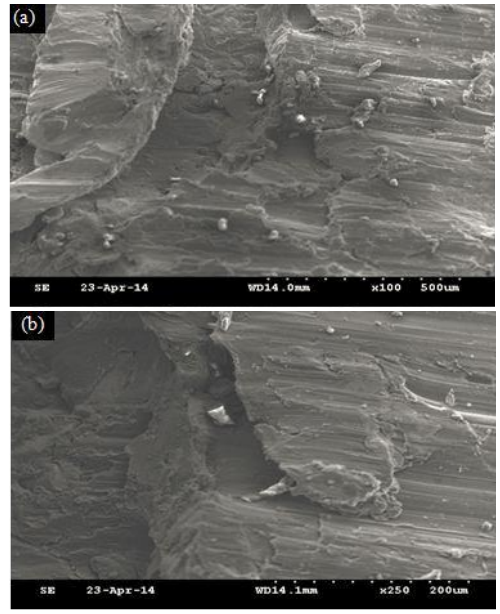

Fig. 16 (a),(b) SEM images of the fracture surface on the Aluminum plate

IV. CONCLUSIONS

1. FWTPET method has been established to join 6mm thick Aluminum (AA6061-T651) tube plate to Titanium (Ti-6Al-4V) tubes of 2.5mm wall thickness.

2. Three different tube profiles-hole, slot and petals, were used to study the feasibility of joining dissimilar materials (Al-Ti) using FWTPET and petal profile was found to have good strength.

3. Shear strength of the joint reached 60% of AA6061–T651 base material strength.

4. XRD analysis showed formation of $TiAl_3$ at the interface. Intermetallic compounds at the interface were less when compared to traditional fusion welding processes which is due to the reduction in heat generation during the welding process.

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