Effect of Flash Trap Profiles on Joint Integrity of Friction Welded Titanium Tube to Stainless Steel Tube Plate by External Tool Process

C. Maxwell Rejil [1], C. Sharan [1], S. Muthukumaran [1,*] and M. Vasudevan [2]

[1] *Department of Metallurgical and Materials Engineering, National Institute of Technology, Tiruchirappalli-620015, India*

[2] *Advanced Welding Processes and Modeling Section, Materials Technology Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, India*

**Corresponding author. Tel. +91-9442069381; Fax No. +91-431 2500133.*

E-mail address: *pondymuthu@gmail.com*

Abstract

Friction Welding of Tube to Tube Plate using an External Tool, an innovative welding process was used to join titanium tube and stainless steel tube plate with copper as an interlayer. Among various process parameters, flash trap profile of the tube significantly influences joint integrity. Various flash trap profiles like Vertical Slots, Holes, Zig-Zag holes, and Petals were made on the titanium tube and welded to the stainless steel tube plate. The micrographic studies revealed defect free joints. Microhardness survey was presented across and along the interface. The XRD pattern was analyzed for identifying the phases formed at the interface. A novel test procedure named “Plunge Shear Test” was developed to determine fracture load of the welded joints. The highest shear fracture load observed was 31.58 kN on sample having petals as flash trap profile. The sheared surfaces were further characterized and analyzed in this work.

Keywords: FWTPET**,** flash trap**,** plunge shear test, petals

1. Introduction

Commercially Pure titanium (CP-Ti Grade 2) is the workhorse for industrial applications due to its excellent ductility, formability and high strength to weight ratio. The presence of very low interstitials in CP-Ti will enhance erosion and corrosion resistance [1]. Stainless steel (304L) with its low carbon content and enhanced Cr-Ni ratio are extensively used in chemical, textile and processing industries for its high strength and excellent corrosion resistance. Increase in manufacturing cost and demand for superior corrosion resistant materials resulted in the need for forming a bimetallic system. One such example is the use of SS-Ti bimetallic joints in the spent fuel reprocessing unit of nuclear power plants. In these plants, boiling nitric acid carries the spent nuclear fuel from a Titanium dissolver vessel through Stainless Steel pipes to other processing units [2-4]. The SS-Ti transition joint operates in a highly corrosive environment and hence a leak proof joint is very essential.

Joining of Stainless Steel tube to Titanium tube plate or vice-versa by conventional fusion or solid state welding processes for stringent applications is extremely difficult. In Fusion welding, due to melting of base materials, enormous strain is induced at the interface which leads to distortion. Difference in thermal expansion and thermal conductivity are the prime reasons for such a phenomenon to occur during welding of dissimilar materials [5]. Among Solid state welding processes the most probable ones for welding tube to tube plate configuration are pressure welding, friction welding, explosive welding, diffusion bonding, ultrasonic welding and laser forming [4]. Though explosive welding can be used for joining tube to tube plate [4, 6] the usage of explosives always create safety issues in industries. Friction Welding of Tube to Tube Plate using an external tool (FWTPET) is an eco-friendly solid state welding process that has been successfully used to weld dissimilar metals of tube to tube plate configuration. This process was invented and patented by one of the present authors [7]. FWTPET process can be done by two methods, clearance method and interference method. The parameters that generally influence this process are: tool rotational speed, plunge rate, plunge depth, axial load, and flash trap profile. Among these parameters, flash trap profile has more influence on the joint strength. FWTPET process by interference method was used to join copper tube to aluminum plate to get a high quality defect free joints [8].

Welding of the titanium-stainless steel dissimilar combination leads to the formation of intermetallics irrespective of the welding process used. The formation of brittle hard intermetallic phases are detrimental to the joint properties. The concept of adopting an interlayer between the two metals was introduced to reduce the detrimental effects of intermetallics at the interface. Kundu et al. [9-11] successfully joined CP-Ti with stainless steel using copper as an interlayer by diffusion bonding. Nickel, silver, Gold and Platinum can also be used as interlayers but the cost of these metals hinder their usage. Copper as an interlayer also improves the bond strength by increasing the flowability at the contact area [12].

In this study, an effort was made to improve the joint integrity of Friction welded titanium tube to stainless steel tube plate by clearance method. The flash trap profiles found to influence more on the material flow during plunge stage of FWTPET process. Hence an elaborate work was done by varying the flash trap profiles such as vertical slots, Zig-Zag holes, Continuous holes, and Petals representation. From this study, the flash trap profile that is preferable for improving the joint integrity can be determined.

2. Materials and Methods

The materials used in this experimental study are commercially pure Titanium (CP-Ti Grade-2) and 304L austenitic stainless steel. The interlayer used for joining these dissimilar materials was pure copper foil of 100μm thickness. The chemical composition of the CP-Ti (in wt. %) as indicated in the supplier's test certificate was 0.18 % Fe, and 99.77 % Ti. For stainless steel the material composition (in wt. %) was 0.018 % C, 0.335 % Si, 1.436 % Mn, 0.006 % S, 0.032 % P, 18.253 % Cr, 8.211 % Ni, 0.323 % Mo, 0.422 % Cu, 0.003 % Co, 0.014 % Ti, 0.055 % V, 0.030 % W and 70.590 % Fe. The as- received rolled stainless steel plates were sheared into 50 × 50 mm pieces by shear cutting machine and a hole of 19 mm diameter was drilled on the center of the plate. CP-Ti tube of height 30mm having outer diameter of 19mm and inner diameter of 14mm was used for characterization purpose. A 30mm tube, where top half is hollow and the remaining half is solid was used for Plunge Shear Test. Varying flash trap profiles such as Vertical slots, Zig-Zag holes, Holes, and Petals were made on the circumference of the tube as explained below [Fig. 1]:

i) Vertical Slots (VS) – slots of 2 mm width and 7mm depth separated by equal angles (≈ 60°) were made on the circumference of the tube.

ii) Zig-Zag holes (ZZ) - equal number of holes were drilled as per holes profile but between two holes a depth of 0.5 mm was maintained to form a Zig-Zag pattern.

iii) Holes - 2 mm diameter holes were made separated by equal angles (≈ 60°) on the circumference of the tube at a depth of 3.5 mm from the surface.

iv) Petals - suitable slots of width 1.5 mm were made to a depth of 10 mm separated by equal angles (≈ 60°) and were formed into petals.

Fig. 1 Flash trap profiles

The backing block used to hold the workpiece was made of EN-8 steel. The backing block was designed so that the workpiece is totally constrained during welding. Sand paper and acetone was used to clean the surface of plate, tube and copper foil before tube was interference fitted to the tube plate with interlayer in the middle. FWTPET process was carried out in a 4-axis Friction Stir Welder machine manufactured by BiSS-ITW. The assembled workpiece with the tube, tube-plate and interlayer was fixed to the backing block. A projection of 2 mm was provided to the tube. The backing block was then fixed to the machine table. A custom software was used to weld FWTPET samples in the existing FSW machine. The process parameters were decided after a series of trial welds. The following process parameters, rotational speed of 900 rpm, plunge rate of 1.5 mm/min and plunge depth of 2 mm were kept constant for the entire study. The external tool used for welding was made of tungsten alloy which acts as the non-deformable rigid one during the entire welding process.

After welding, the welded samples were cut along its cross-section using an abrasive cutting machine. The samples were mounted using hot mounting technique for polishing and microhardness analysis. For microstructural analysis standard metallographic polishing techniques were followed.

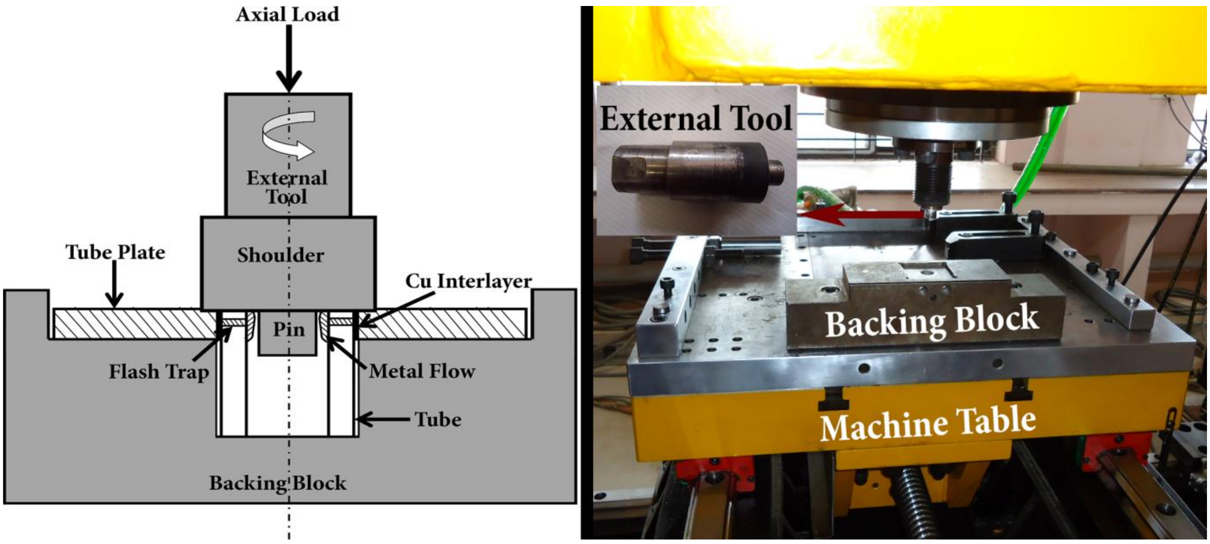

Fig. 2 FWTPET Schematics and Process Setup

The dissimilar materials were etched seperately and the optical micrographs obtained were stitched together for clarity. The titanium side was etched with an aqueous solution containing 3 mL HNO_3, 3 mL HCl, 8 mL HF and 37 mL water. A solution of 5 mL HNO_3, 10 mL glycerol and 15 mL HCl was used for etching the austenitic steel side. The macrograph of the welded sample was captured using a stereo microscope. The microhardness of the welded sample was measured across and along the interface using a load of 500g with dwell time of 15 seconds. Distance between two indentation was 0.25 mm. The X-Ray Diffraction analysis (RIGAKU) was carried out on the welded samples to identify the phases formed due to welding. The operating voltage was 30 kV from the copper target with the following parameters - scan rate: 2 degree per minute, step width: 0.05 degree and scan range: 20° to 95°.

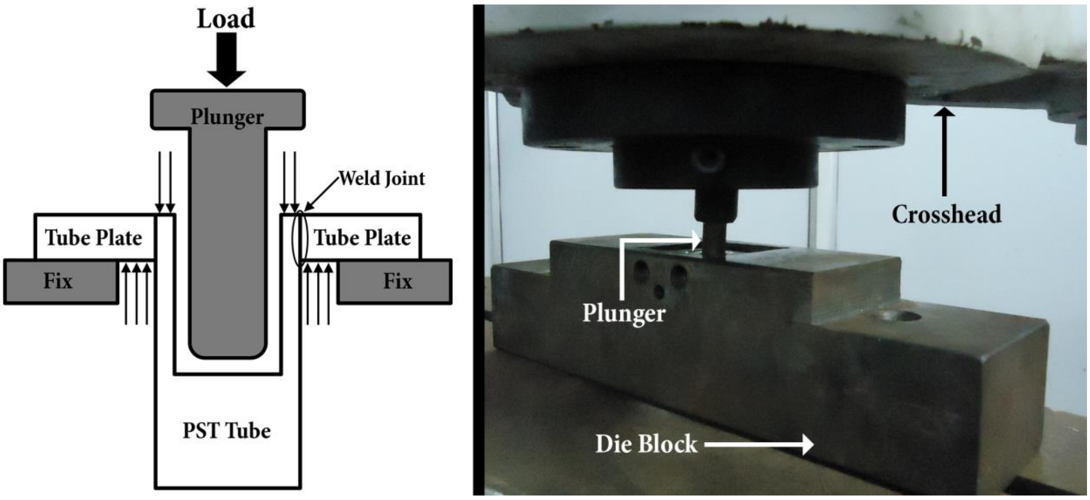

Fig. 3 PST Schematics and Experimental Setup

Plunge shear test was carried out on a Universal Testing Machine with cross head speed of 3 mm/min. A specially designed plunger was used to test the joint intergrity of the welded samples. The fractured samples were examined on both Ti and SS sides for surface morphology studies. Fractography was done on a S-3000H type Scanning Electron Microscope (SEM) manufactured by HITACHI.

3. Results and Discussion

3.1 Microstructural Analysis

The micrographs are presented in etched [Fig 5 (e-h)] and unetched [Fig 5 (a-d)] condition. It is evident from the micrographs that the joint interfaces are free from defects. Since the welding parameters are kept constant, the amount of heat input will be same in all the varying flash trap profiles. During welding, the rotating external tool is lowered with a defined plunge rate. Due to the 2 mm projection in the titanium tube, the rotating external tool will first touch titanium tube and produces frictional heat. This frictional heat along with the axial and rotational forces plasticizes the tube material forcing the metal to flow downwards. When the plunge depth increases, the heated tool touches the stainless steel plate. The plate surface is easily plasticized due to the combined action of tool heat, rotation speed and axial force. The constraints provided by the backing block, force the plasticized materials to flow towards the center. The tool pin acts as an anvil which drives the material away from the center. These opposing forces, force the plasticized materials to fill the flash trap. The high temperature developed at the surface of the plate completely dissolve the copper interlayer, bringing the naked Ti and SS to come in contact forming intermetallics.

But as the temperature decreases when we move down the plate-tube interface, copper is only partially dissolved as shown in Fig.4 (a).

The titanium tube experiences phase transformation from α phase (hcp) to β phase (bcc). This transition from α to β phase is evident from the Widmanstätten bands shown in Fig. 4 (b). The microstructure shows Widmanstätten bands which contains α phase with needles of β phase. This band formation can also be attributed to the presence of copper interlayer since copper acts as a β stabilizer which promotes the formation of Widmanstätten bands. Due to more open space in the bcc structure of titanium (β phase), it can readily accept copper in its lattice, thus promoting the formation of Ti-Cu intermetallics [11]. The regions closer to the tool shoulder experiencing high temperatures, form Widmanstätten bands and as we move away from the interface fine grain microstructure is seen. This typical variation of microstructure is as shown in Fig.4 (b). On the other hand, stainless steel does not show any microstructural change and this is evident from the identical annealing twins Fig 5 (e-h). This type of twins in stainless steel is typical representation of austenite phase in the matrix.

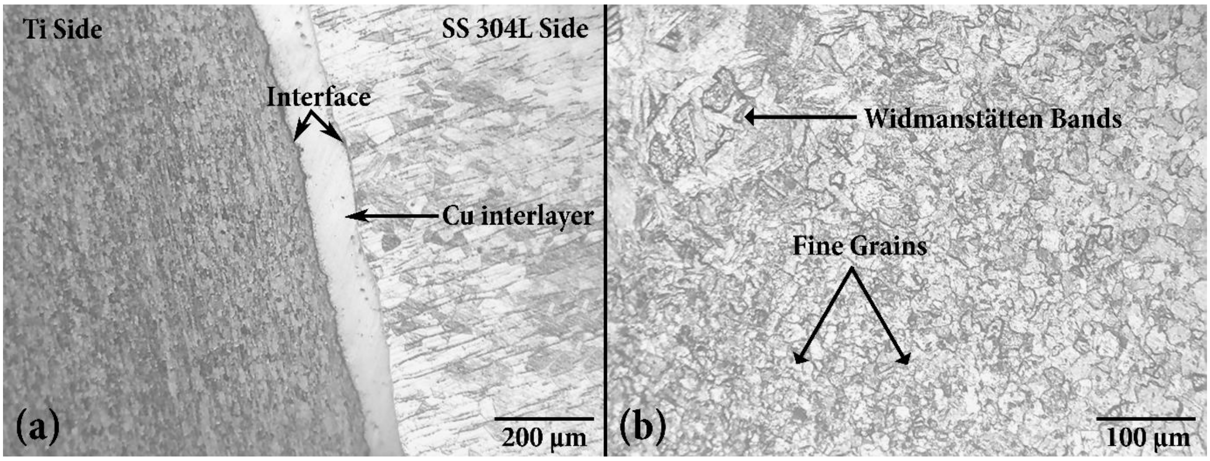

Fig. 4 Micrograph showing (a) Partially Dissolved Copper at the interface, (b) Phase Transformation in Ti Tube

In case of Vertical slots and holes profiles, the titanium side showed the formation of Widmanstätten bands closer to the interface of the weld joint [Fig. 5-e, h]. These bands indicate that these welds have been subjected to temperatures more than 882^0 C. In case of petal profile, the weld interface is subjected to a lower temperature when compared to other welds since the titanium petals takes away most of the heat. Due to low thermal conductivity of titanium and very short welding time (~40 sec) in FWTPET, only minimal heat flows along the joint interface. The temperature at the joint interface is not high enough to form Widmanstätten bands. Instead coarse grain microstructure was observed at the interface which is evident from the microstructure shown in Fig. 5-h.

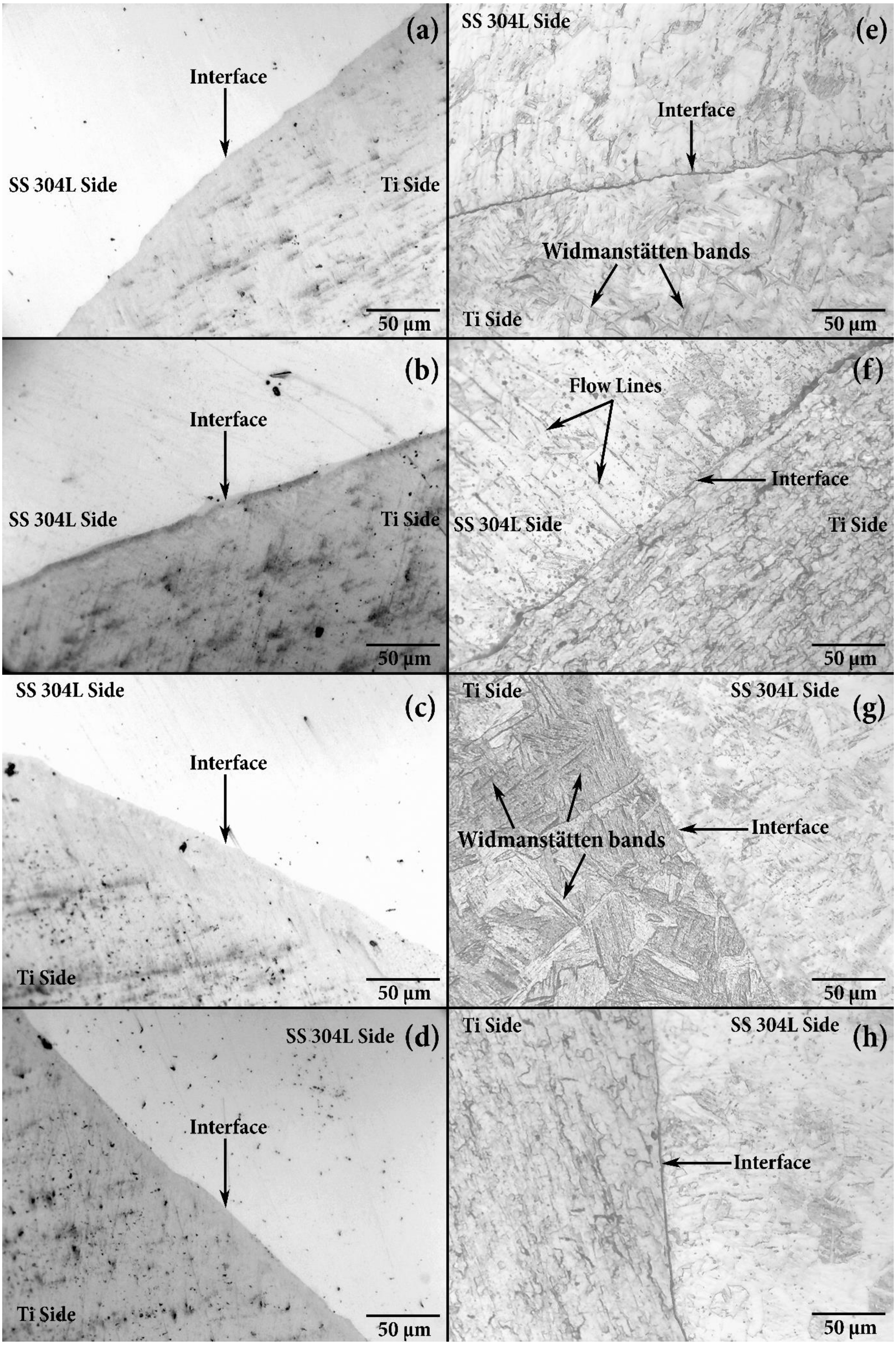

Fig. 5 (a-d) Unetched Micrographs, (e-h) Etched Micrographs

3.2 Microhardness Survey

The microhardness survey was carried out across at three different locations for repeatability and the average value is presented in Fig. 5(a). Across the interface, the peak hardness of 288 HV was observed for vertical slots whereas petal profile had the lowest hardness of 182 HV. This variation in peak hardness in VS and Petals are due to the formation of hard and soft intermetallics at the interface. Titanium tube experiences an increase in hardness after welding than as received material (as received Titanium sample was ~156 HV). This increase in hardness is due to phase transformation occurring during welding. Since stainless steel was not affected by the frictional heat generated during welding, there is no significant variation in microhardness.

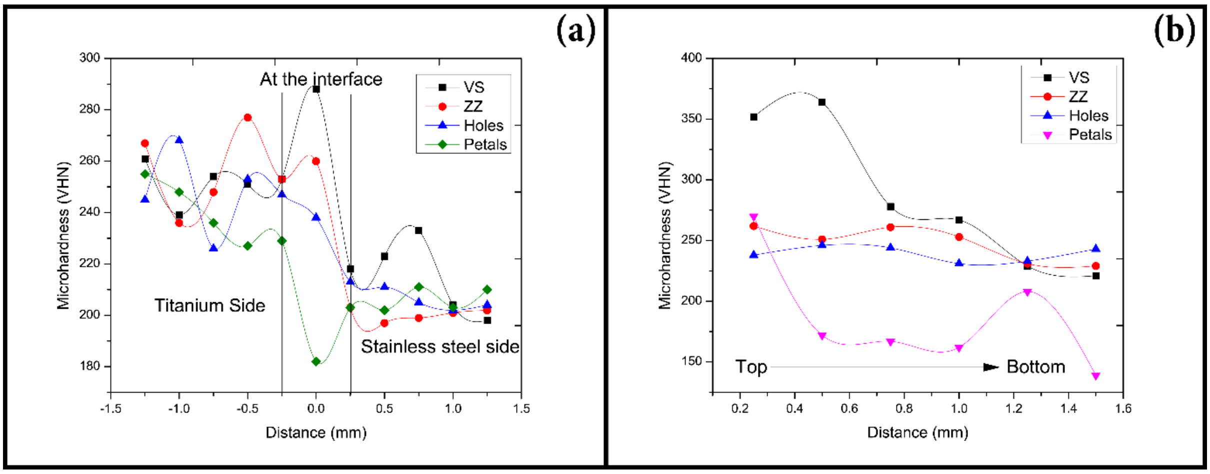

Fig. 6 Microhardness Survey (a) Across the interface, (b) Along the interface

In order to find out the variation of hardness along the interface an elaborate survey was done from top to bottom region of the interface as shown in Fig 5(b). As top region experiences high heat input favoring the formation of intermetallics such as Fe_2Ti and $TiFe_2$, peak hardness values were observed in this region. Vertical slots had the highest hardness of 364 HV. A very low hardness of 139 HV was observed in petal profile due to the presence of soft Ti-Cu phases at this region.

3.3 X-Ray Diffraction (XRD) Analysis

The formation of intermetallics in the interface zone and adjacent matrix has been confirmed by XRD plot as shown in Fig. 7. The XRD pattern has been analyzed for all the varying flash trap profiles to bring out variation in peak intensity and formation of intermetallics. The XRD analysis indicates the presence of Fe_2Ti, Ni_3Ti, β-Ti, $TiFe_2$, Cu_3Ti_2,

Cr_2Ti, Cu_4Ti_2, and $CuTi_2$. The formation of Fe_2Ti, $TiFe_2$, Ni_3Ti, and Cr_2Ti indicates that at some places along the interface the copper interlayer was completely dissolved leading to the diffusion of stainless steel into Titanium. The β-Ti formation confirms the phase transformation phenomenon occurring in CP-Ti due to the high heat input generated by the external tool.

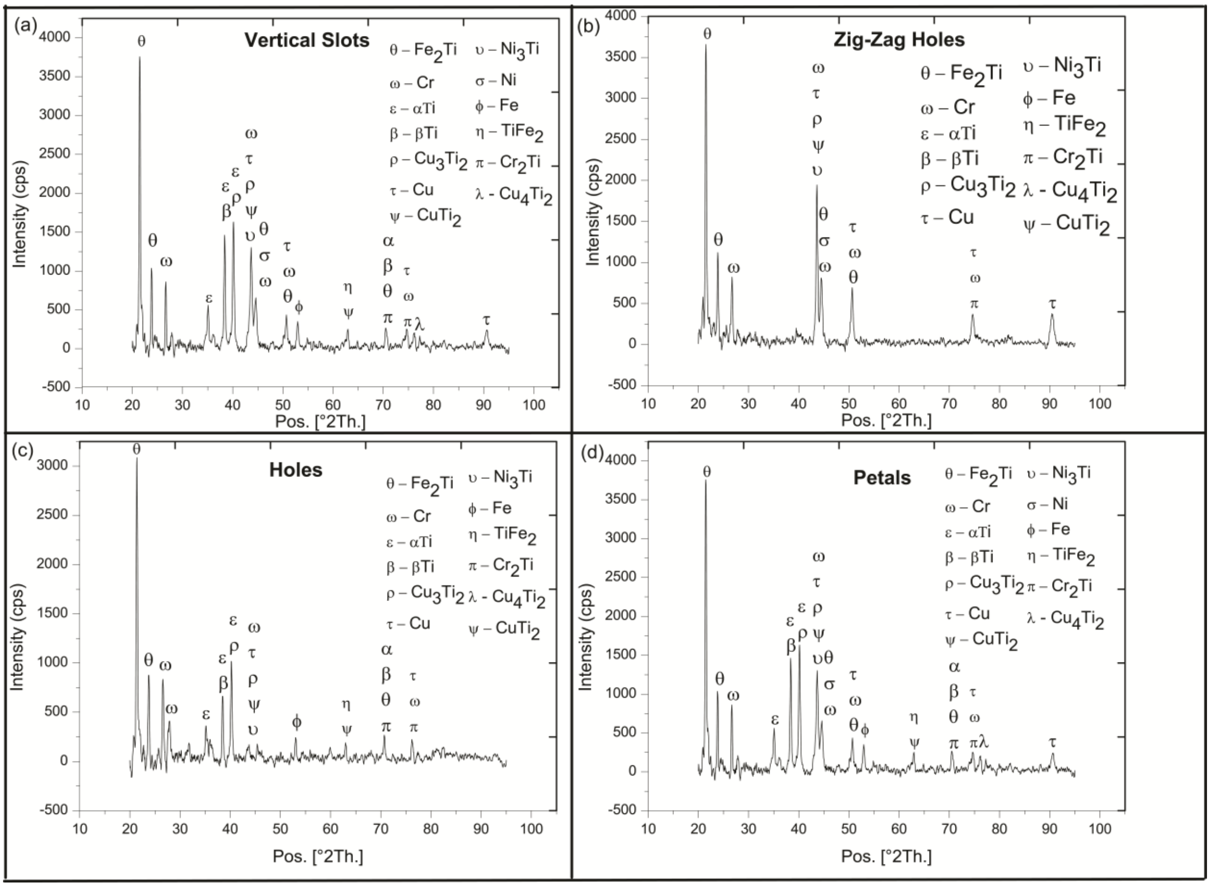

Fig. 7 XRD Plot (a) Vertical Slots, (b) Zig-Zag, (c) Holes, (d) Petals

3.4 Plunge Shear Test (PST)

In order to determine the integrity of joints, PST procedure was designed for tube to tube plate configuration. PST consists of a plunger and a die block. PST is carried out using a regular UTM where the crosshead speed was kept constant for all the tests. The test is designed such that the entire load is taken by the weld joint. PST was performed on three samples welded with the same parameters for repeatability. The fracture load observed after complete shear was noted and is presented in Fig.8. Petal profile took the highest fracture load of 31.58 kN followed by holes and Zig-Zag holes profile. Vertical slots profile recorded the lowest shear fracture load of 15.5 kN.

The huge difference in fracture load can be explained by simple visual examination using a stereo microscope [Fig. 9]. In vertical slots profile, cap formation of plate material over the tube was observed. Due to this cap formation, when this profile was subjected to PST it fractured very easily without offering much resistance to the shear load.

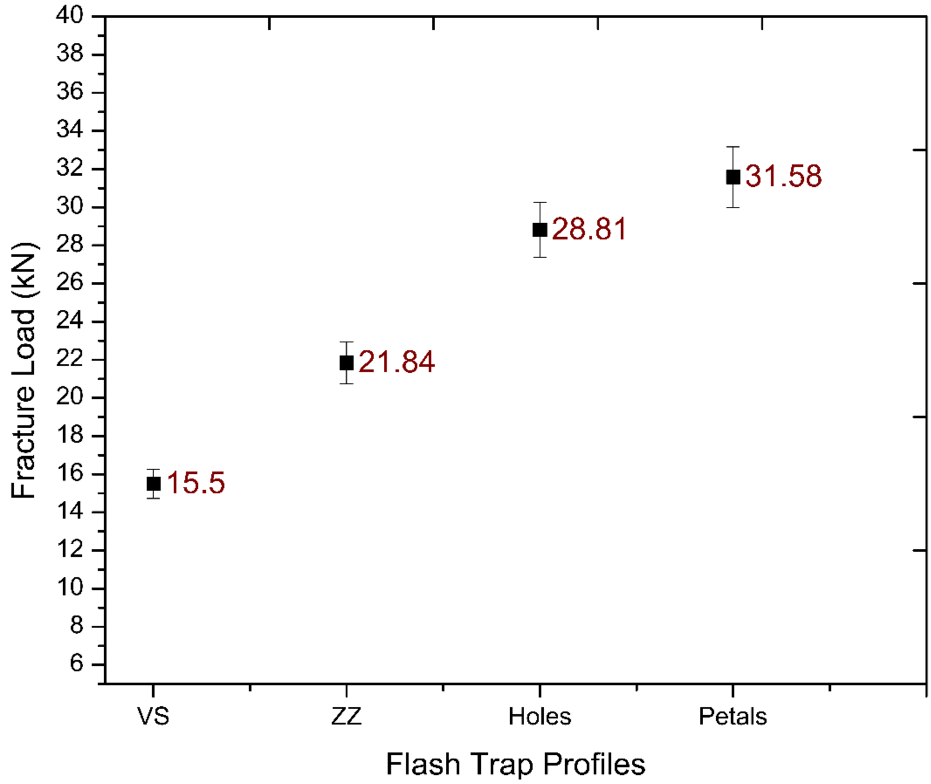

Fig. 8 Shear Fracture Load of different flash traps

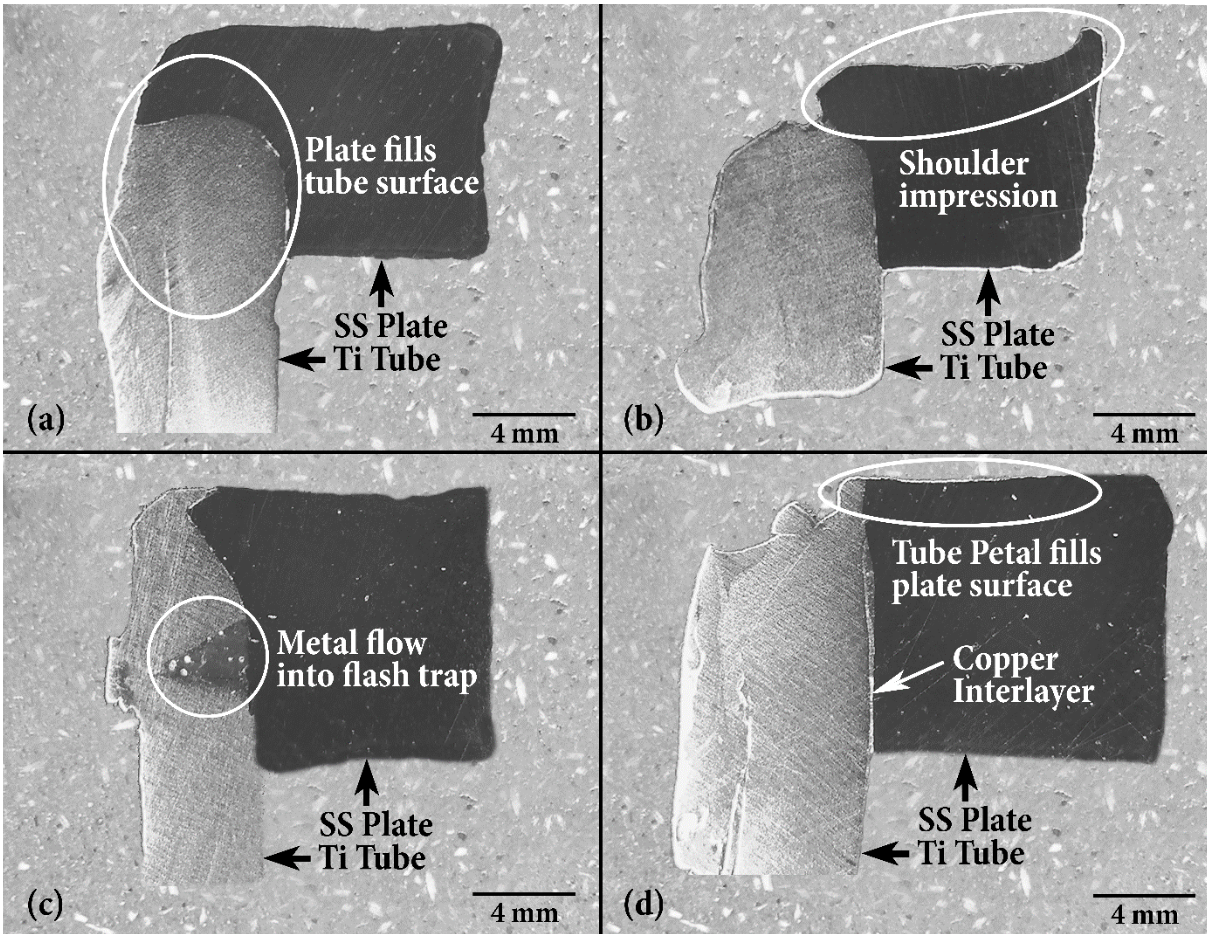

Fig. 9 Macrograph of (a) Vertical Slots, (b) Zig-Zag Holes, (c) Holes, (d) Petals

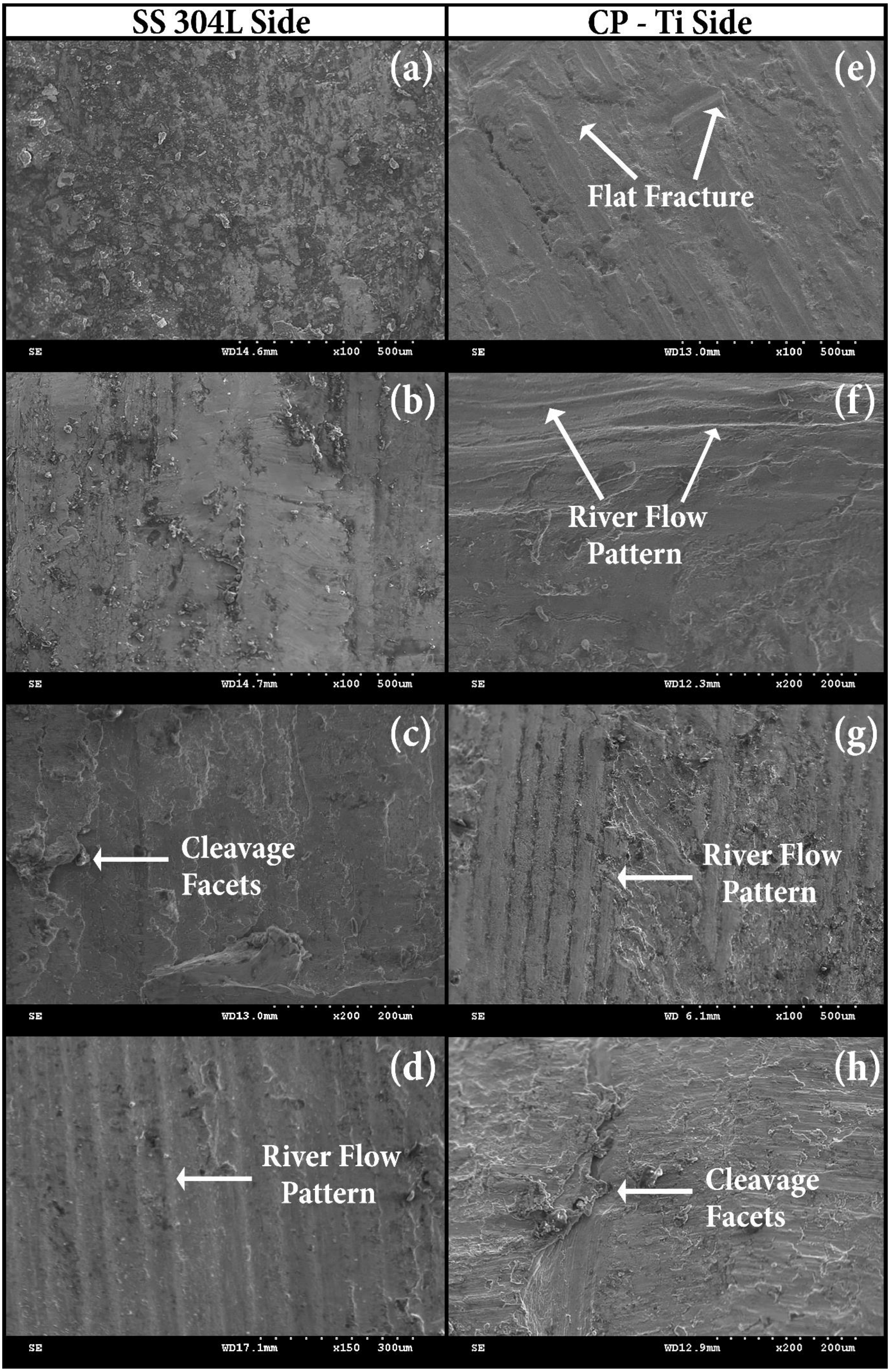

Fig. 10 Fractograph of (a,e) Vertical Slots, (b,f) Zig-Zag Holes, (c,g) Holes, (d,h) Petals

The Zig-Zag profile showed impression of the tool shoulder on the plate surface and improper filling of the Zig-Zag holes. This type of welded samples when loaded in PST resisted better compared to vertical slots specimen. The holes profile showed complete filling of holes which fractured at a load of 28.81 kN during PST. This high fracture load is due to the formation of interlocking mechanism between hole and tube. The petal profile withstood even higher fracture load, due to the gripping mechanism of titanium tube petals filling the stainless steel plate surface. The presence of Ti-Cu soft intermetallics at the interface was also a contributing factor for its high fracture load.

Fractography was performed on either side of the fractured samples which is shown in Fig. 10. The flat surface fracture [Fig. 10-e] on titanium side of vertical slots explains the way in which fracture occurred due to PST. The presence of partial river flow pattern [Fig. 10-f] was observed on fractured sample in titanium side of Zig-Zag profile. Cleavage facets and completely dominated river pattern [Fig. 10, c-h] was observed in both holes and petal shaped profiles. This phenomenon of facet formation and river flow pattern influence the joint to slide in shear mode [13].

4. Conclusions

In this study, FWTPET process was successfully employed to weld titanium tube to stainless steel tube plate by adopting copper as an interlayer. An elaborate discussion on the effect of flash trap profiles and its influence on joint integrity have been discussed. They are briefly concluded below:

- The optical micrographs show defect free joints in all flash trap profiles. Due to frictional heat input on the surface of tube and tube plate during welding, phase transformation phenomenon has been observed on the titanium tube. The phase transformation was confirmed through microstructure and XRD analysis.
- Microhardness survey done across and along the interface showed peak hardness at the interface which is attributed to regions where copper interlayer is completely dissolved. Low hardness values were attributed to partial dissolution of copper at the interface. Highest hardness of 364 HV was observed in Vertical Slots profile and lowest hardness of 139 HV was observed in Petals profile.
- XRD pattern analysis gives a clear picture on various phases and intermetallic compounds formed during FWTPET process. The area where high heat input was experienced favors the formation of Ti-Fe intermetallics due to complete dissolution

of copper in the matrix. Low heat input areas have formed Cu-Ti intermetallic systems.

- A new test procedure called “Plunge Shear Test” was proposed to determine the fracture shear load of the welded joints. Petals profile showed the highest fracture load of 31.58 kN and Verticals Slots profiles showed the lowest fracture load of 15.5 kN. The effect of flash trap on joint integrity was attributed to material flow pattern and intermetallic formation.
- The macrographic observation of the welded region provided the necessary information on material flow due to flash trap profiles. Scanning Electron Micrographs of the fracture surface of Titanium and stainless steel revealed change in fracture pattern for different flash trap profiles. The presence of flat fracture appearance, cleavage facets and river flow pattern was observed. This type of fracture appearance is an indication that the weld joints fractured in shear mode during PST.

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