CHAPTER1
INTRODUCTION

1.1 GENERAL

Welding is the process of joining materials by heating them to suitable temperatures such that they coalesce into one material. In our day to day life we make use of welded products directly or indirectly. During the recent years, various developments have been occurring in the field of material processing. Welding is one of the vital metal fabrication processes that have wide variety of industrial applications. Vehicles we drive, bridges we travel on and the buildings we live in, all use welded products in one or the other way. Welding processes can be broadly divided into fusion welding process and solid state welding process. Fusion welding processes are well established and are extensively used around the world because of its capability to produce high quality joints with much ease as well as low setup and labour cost. But fusion welding is characterized by certain drawbacks such as loss of strength in the heat affected zone, porosity or cracks in the weld, extreme sensitivity to surface condition and cleaning, prone to stress corrosion cracking in marine environment etc.. Solid state welding is devoid of many of the above drawbacks and it gives better results while welding high strength aluminium alloys compared to fusion welding.

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1.2 SOLID STATE WELDING

Solid state processes produce coalescence of the faying surfaces at temperatures below the melting point of the base metal being joined, without the addition filler metal. Pressure may or may not be applied. These processes involve either the use of deformation or of diffusion and limited deformation in order to produce high-quality joints between both similar and dissimilar materials. Some of the major advantages of the solid state processes are mentioned below.

- It is capable of joining dissimilar materials with much ease
- Filler material not needed
- Shielding gases not required
- Less influence on metallurgical properties of the welded materials
- Environment friendly

1.3 FRICTION WELDING (FRW)

Friction welding is one of many solid state welding processes. In simplest form, it involves two axially aligned parts. While one part is rotated, the other stationary part is advanced to make pressure contact. Axial force then increases to generate the frictional heat necessary for welding at the abutting surfaces in order to form a solid-state joint. Fig. 1.1 shows a simple FRW process

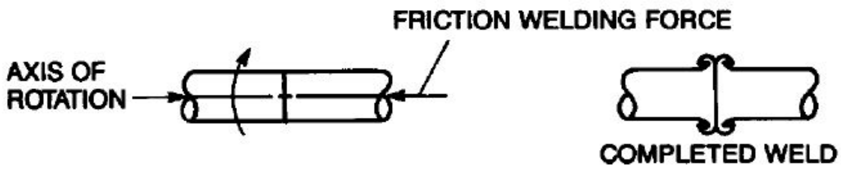


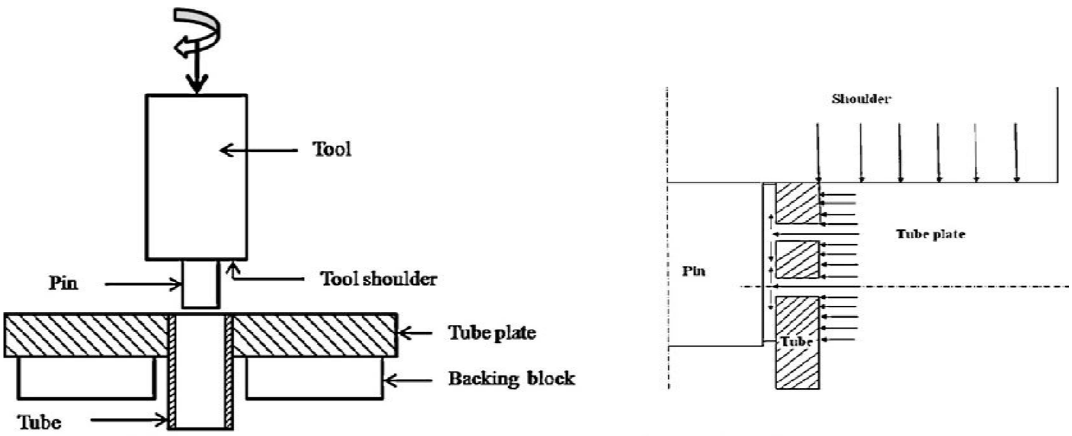
Figure. 1.1 Friction welding process

Friction welding can be used successfully to join a much broader spectrum of different ferrous and non-ferrous alloys than fusion welding. This method, however, have a few drawbacks. For example, friction welding lacks versatility. Hence, there is a need to develop highly efficient joining methods for a specific application such as tube to tube plate joints, which can achieve higher strength and quality than the fusion welding process.

1.4 FRICTION WELDING OF TUBE TO TUBE PLATE USING AN EXTERNAL TOOL (FWTPET)

Friction welding of tube to tube plate using an external tool (FWTPET) was invented in the year 2006 by Dr.S.Muthukumaran. FWTPET is an innovative joining process which is capable of producing high quality leak proof joints. Further, it is an energy efficient, environment friendly and versatile process when compared to traditional welding techniques. Some of the welding parameters that determine the quality of welds produced by FWTPET include tool rotational speed, shoulder diameter and clearance between pin and tube. Significant improvement in metallurgical and mechanical properties of FWTPET process depends on the efficient control of its process parameters. FWTPET process is capable of welding tube to tube plate of either similar or dissimilar metals. Weld joints produced by FWTPET process exhibits enhancement in mechanical and metallurgical properties and better repeatability.

FWTPET can be done by two methods clearance method and interference method.In clearance method tube is placed in the backing block and plate assembly and the rotating external tool is plunged into the tube hole(shown in Fig.1.2).The heat produced by the contact of the tool shoulder initially with the tube and finally with the plate surface makes the material to plastic state. Plastic flow of plate material occurs towards the tube axis (shown in Fig.1.3) through the flash trap holes provided on the tube circumference. The tool pin blocks this plastic metal flow, exerting pressure at the joint. Thus the pressure and heat produced at the weld joint together produce excellent metallurgical bonding.



(a) FWTPET set up

(b) Metal flow in tube to tube plate welding using an external tool

Figure. 1.2 (a) FWTPET (b) Plastic metal flow towards tube axis Clearance method

In interference method, the tube is heated in a furnace and interference fitted to the tool pin. This assembly is inserted into the tube plate – backing block assembly while in rotation (shown in Fig1.4). Surface faying between the tube and tube plate hole removes the surface oxides and causes surface heating. Materials become plastic state at the interface and a braking force is offered by the plate. At one point of time braking force exceeds the hoop stress in the tube fitted on the tool pin and the tube stops rotating and gets welded to the tube plate.

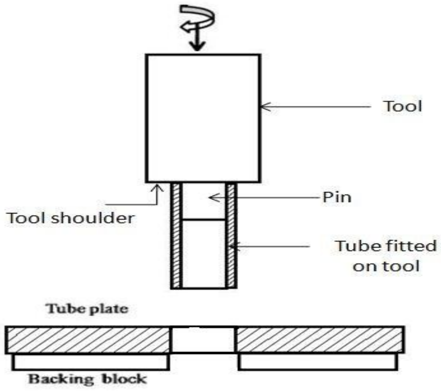


Figure. 1.3 FWTPET- interference method

The various advantages of FWTPET process are as follows.

- Simple Machinery.
- Dissimilar metals can be joined
- Low distortion of work piece.
- Good dimensional stability and repeatability.
- High joint strength.
- Absence of cracks.
- Lesser energy consumption
- No shielding gas required

1.5 APPLICATIONS OF FWTPET PROCESS

Tube to tube joints made by FWTPET finds application mainly in

- Heat exchangers
- Pressure vessels

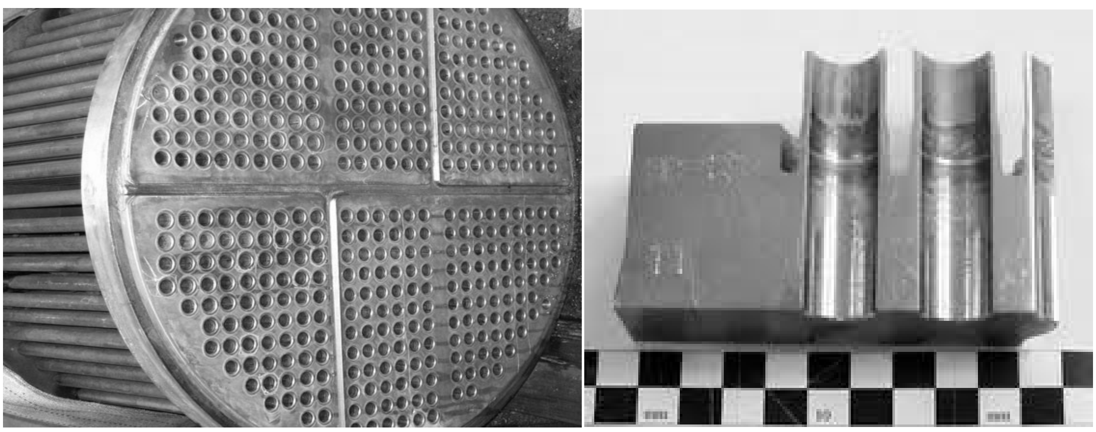


Figure. 1.4 Applications of tube to tube plate joints

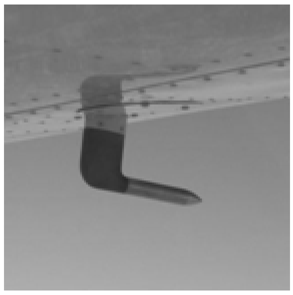
Joints made of dissimilar metals, for example copper and aluminium can be used as bimetallic strips which finds application in

- Refrigerator parts
- Electrical Transition Joints
- Bus bars in batteries

Joining of Titanium to Aluminum have wide applications in aircraft industry as both are used widely in the manufacturing of aeroplanes.

Bimetallic strip

Pipe faucets



Pitot tube in aircrafts

Figure 1.5 Applications of dissimilar FWTPET process

1.6 BASE MATERIAL PROPERTIES

1.6.1 Aluminium 6061-T651

It is the most widely used alloy in the 6xxx series. This standard structural alloy, one of the most versatile heat treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. It is easily weldable and can be joined by various commercial methods. It has excellent corrosion resistance to atmospheric conditions and good corrosion resistance to sea water. A unique feature is great extrudability, making it possible to produce in single shapes relatively complex architectural forms, as well as to design shapes that put the majority of the metal where it will most efficiently carry the highest tensile and compressive stresses. This feature is a particularly important advantage for architectural and structural members where stiffness criticality is important.

6061 is a precipitation hardening aluminium alloy, containing magnesium and silicon as its major alloying elements. It is commonly available in pre-tempered grades such as 6061-O (solutionized) and tempered grades such as 6061-T6 (solutionized and artificially aged) and 6061-T651 (solutionized, stress-relieved stretched and artificially aged).

T6 temper 6061 has an ultimate tensile strength of at least 42,000 psi (300 MPa) and yield strength of at least 35,000 psi (241 MPa). More typical values are 45,000 psi (310 MPa) and 40,000 psi (275 MPa), respectively. Shear strength of AA6061 T6 temper is about 207 Mpa. In thicknesses of 0.250 inch (6.35 mm) or less, it has elongation of 8% or more; in thicker sections, it has elongation of 10%. Its Vickers hardness value is 107. The typical value for thermal conductivity for 6061-T6 at 80°C is around 152 W/m K.

1.6.2 Applications of aluminium 6061 alloy

Aluminium alloy 6061 extrusions and plate find broad use in welded structural members such as truck and marine frames, railroad cars, and pipelines. It has an abundant industrial significance due to its wide applications in industries. Some are mentioned below.

1) Building and Construction Markets

- The structural members of wide-span roof structures for arenas and gymnasiums are usually 6061 extruded tube or beams.
- Bridges and other highway structures

2) Transportation Applications

6061-T6 is extensively used in Automobile, Van, Sport Utility Vehicle (SUV), Bus and Truck Applications such as:

- Space frame
- Door beams, seat tracks, racks, rails
- Hood, deck lids
- Wheel spacers

3) Aircraft and Aerospace Application

- 6061 is widely used for construction of aircraft structures, such as wings and fuselages

4) Marine Transportation

- Hull material
- Structural beam

5) Petroleum and Chemical Industry Components

- Pressure vessels
- Pipelines
- Cryogenic tankage

6) Packaging Applications

- Aluminium foil for food
- Aluminium can for beverages

1.6.3 Titanium Grade V(TiAl6V4)

Titanium and its alloys are used for aerospace, chemical, general engineering, and biomedical applications because they show an astonishing range of mechanical properties The unique high strength-to-weight ratio, easy formability, and fatigue resistance led to the introduction of titanium in aerospace applications like rocket engine parts, fuel tank, gas bottles, etc. It is also used in the airframe structures, such as landing-gear beams, hydraulic tubings, wing boxes, spacers, bolts, etc. Titanium alloys are used in fan-jet engines for which large front fans are required. The high specific strength of titanium along with the metallurgical stability at high temperatures and low creep rates make it favourable for jet engine components like blades and discs in the low and intermediate sections of compressors. The next important area of application of titanium alloys is chemical and general engineering. The outstanding corrosion resistance of titanium in many environments is the prime reason for its use in these industries. For low-stress applications, commercially pure (CP) titanium is generally used, and for high-strength applications Ti-6Al-4V or Ti-13Nb-13Zr alloys are used. In the petrochemical industries, CP titanium grades and Ta- or Pd-containing alloys are utilized for outstanding corrosion resistance. Titanium alloys are used in marine and offshore applications for their excellent corrosion resistance in seawater and in sour hydrocarbon atmospheres. Figure 1.6 illustrates typical applications of titanium alloys. In the field of biomedical applications, titanium is used for prosthetic devices for bone and joint implants, heart valves, and dental implants. These are made from CP titanium, Ti-6Al-4V, or recently developed alloys such as Ti-6Al-7Nb. In the automobile sector, titanium engine valves have been used by Toyota in Japan. Titanium products like springs are also used in racing cars and motorcycles. A more recent application of titanium is in architecture, a concept first used in Japan. The Guggenheim Museum in Bilbao, Spain, is the most spectacular titanium building. Besides these applications, titanium is also used in sports equipment, such as spikes for running shoes used by sprinters, tennis rackets, mountain crampons, ice axes, bicycle frames, etc. Titanium is also finding increasing use in jewelry and fashion industries.

TiAl6V4 has ultimate tensile strength of 950 MPa and yield tensile strength of about 880 Mpa. Modulus of elasticity is 113.8 Gpa and shear strength is about 550 MPa. Melting point is 1604 ºC and beta transus temperature is 980ºC. Annealing temperature of grade V Titanium is 700-780ºC. Density is 4.43 g/cc.

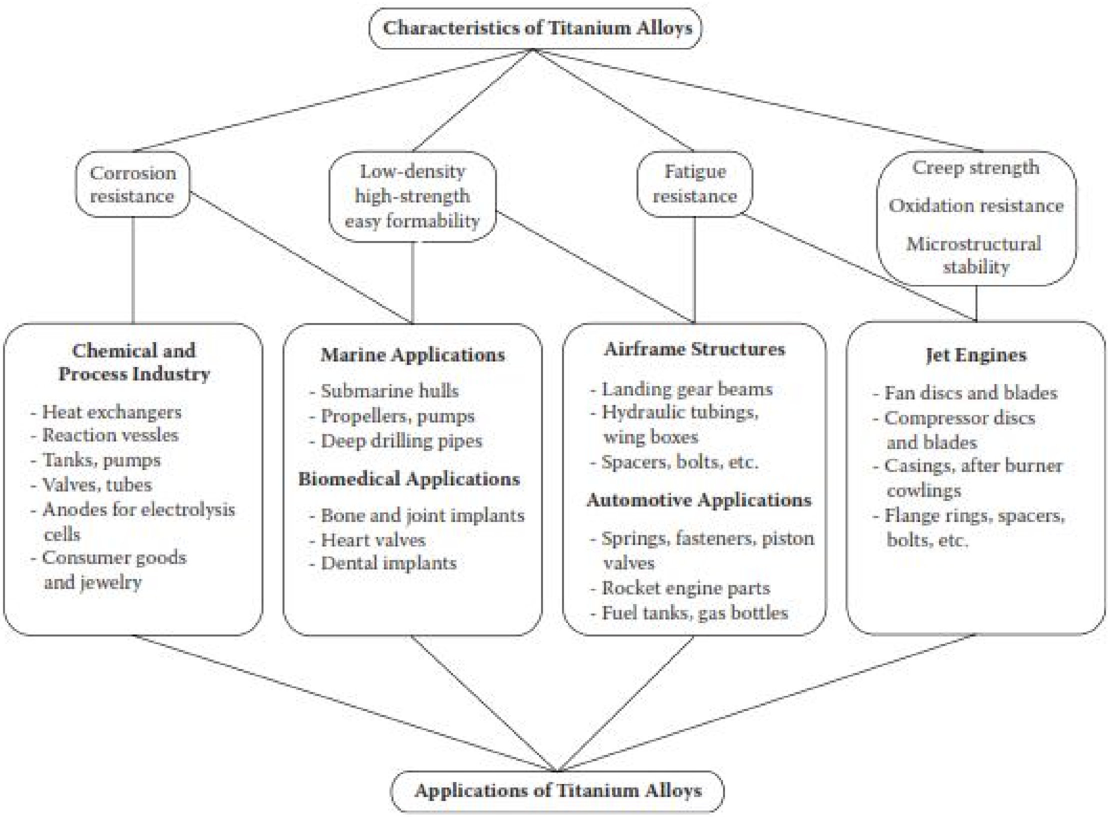


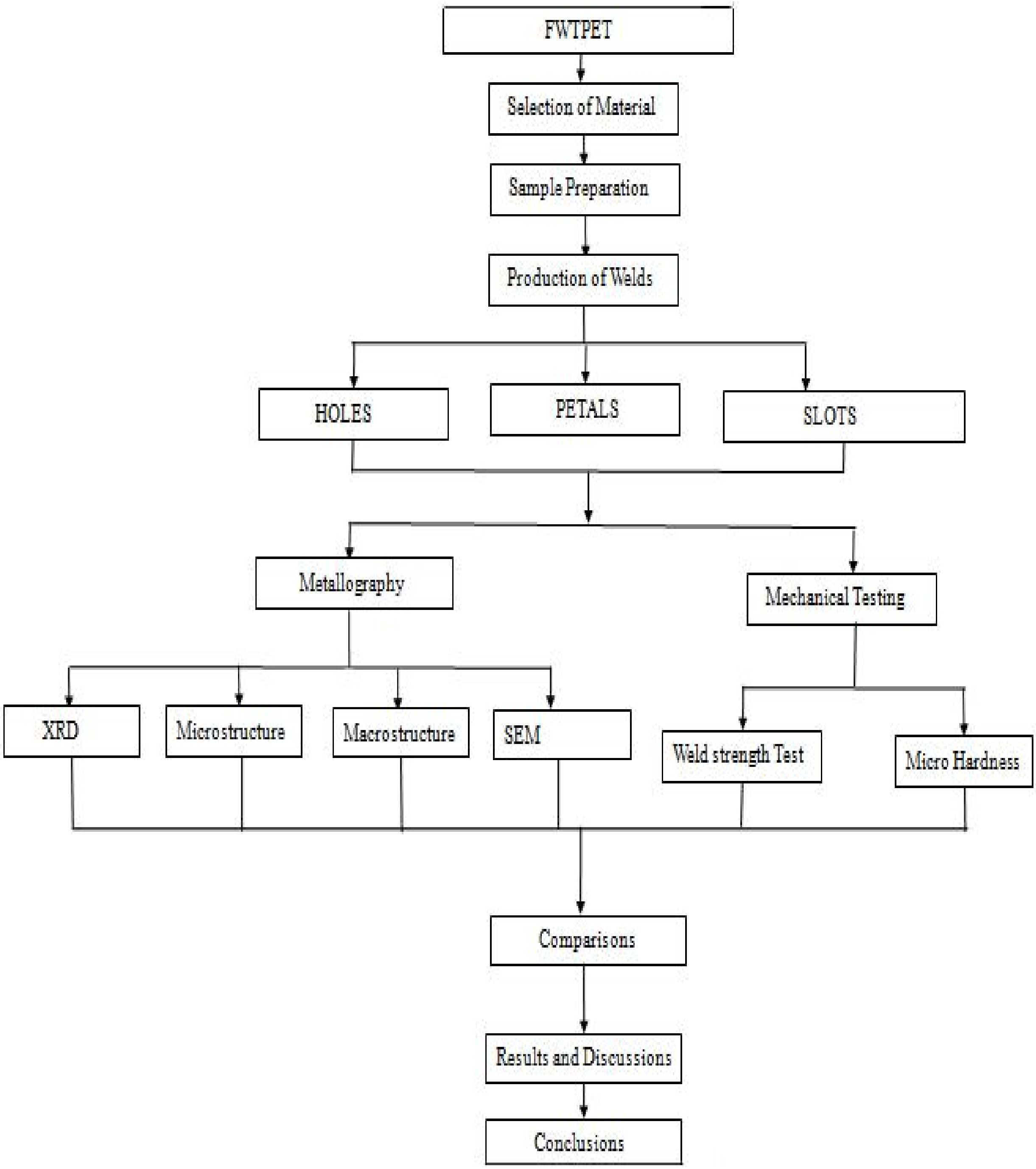
Figure 1.6 General characteristics and typical applications of Titanium alloys

1.7 OBJECTIVE

The major objectives of the present work are listed below

- To obtain dissimilar weld joint between TiAl6V4 tube to AA6061-T651 plate by FWTPET clearance method.
- To analyse the micro structure and mechanical properties of the joints produced.
- To study fracture surfaces and interface region using XRD and SEM analysis.
- Comparison of weld joint properties obtained by different tube profiles.

1.8 WORK PLAN FLOW CHART



CHAPTER 2
LITERATURE REVIEW

The process of friction welding of tube to tube plate using an external tool (FWTPET) was invented and patented by Mr.S.Muthukumaran (2006).The welding can be done in two methods namely clearance and interference method. Although interference method give better joints than clearance method, less research work has been done in this area. In the present work an attempt has been made to join stainless steel tube to mild steel tube plate by FWTPET process by clearance method.

2.1 SUMMARY

Bahrani et al. (1973) studied the possibility of welding tube to tube plate by explosive welding process which can be used for the purpose of plugging of heat exchangers in advanced gas-cooled reactor. Explosive welding occurs under the condition of high velocity oblique collision between two metal surfaces, which creates high velocity jet at collision point, but jet is trapped within the vertices before and behind the waves normally observed at interface of weld. It is found that the velocity of propagation of the weld should not be much greater than the sonic velocity. Krishnan et al. (1990) also studied explosive welding of tube to tube plate using an impactor and high detonation velocity explosive. In this study, two type of geometry has been used for welding by impactor method. They are Angular geometry and parallel geometry. The parallel geometry set-up and high detonation-velocity explosive material is found to be feasible but, the kinetic energy of the impacting tube and distortion of the tube-plate are the important factors which have to be considered to obtain a satisfactory weld. A stand-off distance of around one-half of the wall thickness of the tube has been reported as adequate.

Yu.S. Vorob'ev et al.(2002) in their research work used the process of explosion braze-welding to weld thin-walled tube plate and tubular elements in making heat exchangers. This process is simulated by the high velocity contact interaction of co-axial cylinders with a thin layer of high-strength amorphous solder of nickel group between them. The explosive charge is placed on the inner surface of one cylinder element, which begins to expand during explosion at a rate of 300-1000 m/s and interact with outer stationary cylindrical element with thin layer of solder. High level of pressure, temperature, strain, and the strain rate are induced in the contact zone.

Mumin Sahin (2009) joined copper and aluminium materials by friction welding. Tensile and microhardness tests were done on the joints.Micro and macrophotographs were examined. Tensile strength of the joint increased with friction pressure and friction time upto a certain value and then decreased. The maximum tensile strength obtained was 140 MPa.The hardness variation was higher in aluminium side than in copper side. Microstructural observations showed that a mixed layer of aluminium and copper that includes brittle intermetallic compounds are formed at the weld interface. Energy dispersive X-ray analysis was used to determine these compounds. EDX measurements clearly show that Cu–Al joints consist of some intermetallic compounds namely $CuAl_2$, CuAl and Cu_9Al_4 together with some Al and Cu (saturated solid solution of Al in copper). A grey layer was observed at the fracture surfaces of welded parts. It was considered that this layer decreased the strength of the joint.

S. SenthilKumaran and S. Muthukumaran(2010 a) performed FWTPET by clearance method and the process parameters are optimized. The material used was commercially pure aluminium. The prioritization of the process parameters has been done and ANOVA has been conducted to predict the statistical significance of the process parameters. Authors studied the percentage contributions of the process parameters and found that the tool rotation speed possess highest contribution (80.61%) followed by the shoulder diameter (9.46%) and the pin clearance (8.17%). The optimization of the process parameters has been carried out using GA. The optimized value of tool rotational speed, shoulder diameter, pin clearance and ultimate tensile strength was found to be 1030 rpm,30 mm, 1 mm and 70.87 MPa respectively. They also (2010 b) worked on the was the influence of backing block on the joint produced by FWTPET process. Authors carried out an experimental investigation of FWTPET (clearance method) on commercially pure Aluminium with and without backing block arrangement. The results revealed that by employing backing block, FWTPET is capable of producing defect free welds. Authors ensured this result by conduct of macro structural observation as well as tensile test.. Besides experimental investigation, numerical investigation has been conducted using Finite Element Analysis (FEA).From the experimental and numerical investigation of FWTPET process it is clear that the employment of backing block greatly enhances the quality of thejoints produced**.**

S. SenthilKumaran et al.(2010) also investigated the effect of tube preparation on joint strength in FWTPET process. Drilling of different size holes along the periphery of the tube, cutting vertical and horizontal slots on the tube were the various tube preparation methods followed in this study. It was found that drilling holes and cutting vertical slots on the tube results in defect free weld joint.But, drilling holes of 2 mm diameter found to possess maximum joint strength. S. SenthilKumaran, S. Muthukumaran et al. (2011) studied the eco-friendly aspects associated with the FWTPET process and a comparison between conventional TIG welding and FWTPET process was presented. The tensile strength of the sample welded by FWTPET process found to have superior value than that of the conventional TIG welding process. Welding time and manufacturing cost of the sample were found to be less in FWTPET process. Material utilization and corrosion resistance of the friction welded sample were higher when compared with TIG welding..

S. Muthukumaran et al. (2011) did friction welding of tube to tube plate using an external tool (FWTPET) was used to weld copper tubes with aluminum plates using interference method. Tubes were heated and interference fitted to the tool pin. Welding was successfully carried out. The weld microstructure shows line of stir zone (SZ), a narrow thermo mechanically affected zone and heat affected zone (HAZ). The welded samples were found to have satisfactory joint strength. Formation of AlCu intermetallic compound is observed along the joint interface and author confirms it by XRD analysis.. The study confirms that a high quality copper tube to aluminium tube plate joint can be achieved by FWPET process by interference method. It is also observed from joint strength results that the higher interference value and tool rotation speed produces the weld having better joint strength.

G.K. Balaji, S. Muthukumaran et al.(2011) successfully applied FWTPET process(clearance method) with filler plate and optimized it for joining commercially pure aluminum tube and tube plate. Taguchi L9 orthogonal array was used in this study, and the tool rotational speed is found to be the most influential process parameter in deciding the joint strength. Authors determined the optimum levels of process parameters through the Taguchi parametric design approach. The optimal values of process parameters, namely, tool rotational speed, tube projection, and plunge depth are found to be 710 rpm, 3 mm, and 1.5 mm respectively The percentage of contribution of each process parameter has been found by ANOVA, with the tool rotational speed leading with the highest contribution (46.98%), followed by plunge depth (30.71%) and tube projection (22.29%). The predicted optimal value of joint strength was found to be83.26 MPa. The results were confirmed by further experiments.

Ulrike Dressler et al. (2009) successfully joined Titanium alloy TiAl6V4 and aluminium alloy 2024-T3 by friction stir welding. Microstructure, hardness and tensile strength of the butt joint were investigated. They found that weld nugget exhibits a mixture of fine recrystallized grains of aluminium alloy and titanium particles. Hardness profile revealed a sharp decrease at titanium/aluminium interface and evidence of microstructural changes due to welding on the aluminium side. Highest local elongation occurred, as expected, on the aluminium side of the joint in the region, where the hardness minimum was localized. The ultimate tensile strength of the joint reached 73% of AA2024-T3 base material strength.

The fracture surface is situated at the interface between titanium and aluminium. However, there are some areas on the fracture surface, where the aluminium alloy was still bonded to titanium. It is assumed that these areas correspond with swirl-like structures observed on metallographic sections, which depict that one material was clutched into the other at least locally. The main objective of future research might be the increase in number and size of these clutched areas by optimization of welding parameters.

Yuhua Chen et al.(2011) made butt and lap joints of Titanium alloy TC1 and Aluminum alloy LF6 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. Maximum tensile strength obtained for butt joint was 131 MPa and maximum shear strength obtained for lap joint was 48 MPa. 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. The shear strength of the lap joints decreases with the increasing of the welding speed.

Yanni Wei et al. (2012) lap joined Aluminum 1060 and titanium alloy Ti–6Al–4V plates by friction stir welding. A cutting pin of rotary burr made of tungsten carbide was employed. The microstructures of the joining interface were observed by scanning electron microscopy. Joint strength was evaluated by a tensile shear test. During the welding process, the surface layer of the titanium plate was cut off by the pin, and intensively mixed with aluminum situated on the titanium plate. The microstructures analysis showed that a visible swirl-like mixed region existed at the interface. Aluminum 1060 and titanium alloy Ti–6Al–4V high strength lap joints were successfully obtained by FSW with cutting pin. There are many titanium scrapings distributed in aluminum near the interface. A swirl-like structure with lighter and darker parts was observed in the SEM micrograph of the interface region.The failure load of the joint reached 1910 N at the welding speed of 300 mm/min, which was approximately equal to that of 1060Al base metal, and the ultimate fracture happened in Al metal that underwent thermal cycle provided by the shoulder during FSLW.

Xiao-Long Gao et al. (2012) compared properties of the Ti6Al4V titanium alloy joints between pulsed Nd:YAG laser welding and traditional fusion welding. Ti6Al4V titanium alloy plates with a thickness of 0.8 mm were welded using pulsed Nd:YAG laser beam welding (LBW) and gas tungsten arc welding (TIG), respectively. Residual distortions, weld geometry, microstructure and mechanical properties of the joints produced with LBW and TIG welding were compared.. Compared with the TIG, the welded joint by LBW was found to have the characters of small overall residual distortion, fine microstructure, narrow heat-higher strength and ductility.

Yanbin Chen et al. (2008) developed a rectangular spot laser welding–brazing method to join butted Ti/Al dissimilar alloys. In order to evaluate effects of heat input on mechanical property of the joints, microstructure of the joints were characterized. TiAl3 intermetallic compounds (IMCs) were found at the joint interface in the case of low-heat input and TiAl3, TiAl, Ti5Si3, and Ti3Al IMCs were observed at high heat input. Results of tensile test showed that the joints fracture in the fusion zone under the condition of low-heat input and in the interfacial reaction layer or the fusion zone with a mass of porosities at high-heat input. Shuhai Chen et al (2010) also joined Ti/Al dissimilar alloys using laser welding–brazing process with automated wire feed. The microstructures of fusion welding and brazing zones were analysed in details by transmission electron microscope (TEM). It was found that microstructures of fusion welding zone consist of α-Al grains and ternary near-eutectic structure with α-Al, Si and Mg_2Si. Interfacial reaction layers of brazing joint were composed of α-Ti, nanosize granular $Ti_7Al_5Si_{12}$ and serration-shaped $TiAl_3$. For the first time, apparent stacking fault structure in intermetallic phase $TiAl_3$ was found when the thickness of the reaction layer was very thin (approximately less than 1 μm).

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CHAPTER 3

EXPERIMENT DETAILS

3.1 MATERIALS

3.1.1 Work piece - Aluminium 6061-T651 plates of 6 mm thickness and Titanium Grade V(TiAl6V4) tubes of 19 mm outer diameter are chosen for the present study. The chemical composition is listed in Table 3.1 and Table 3.2.

Table.3.1 Chemical composition of AA 6061-T651

Element	Mg	Si	Fe	Cu	Cr	Mn	Ti	Zn	Al
Wt%	0.70	0.43	0.497	0.164	0.148	0.0971	0.0495	0.0042	Remaining

Table 3.2 Chemical composition of TiAl6V4

Element	C	Fe	O	N	Al	H	V	Y	Ti
Wt%	0.08	0.03	0.2	0.05	5.5-6.75	0.015	3.5-4.5	0.005	Remaining

3.1.2 Tool - Material used for FWTPET of TiAl6V4 to AA6061-T651 is Tungsten Heavy alloy. Chemical composition is listed in Table 3.2.

Table.3.3 Chemical composition of tool material

Element	W	Ni	Co	Fe	O
Wt%	90.5	5.3	0.2	3.4	0.07

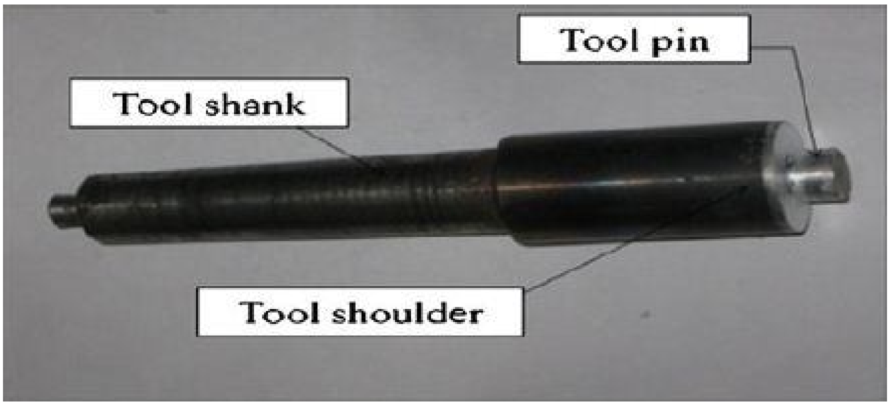


Fig.3.1 External tool

The dimensions of tool used is given in table 3.3. The dimension of the tool is a parameter influencing the joint strength in FWTPET process. In this study tool dimensions are kept constant and tool rotation speed is kept constant.

Table 3.4 Dimensions of the tool used

Shoulder diameter	29mm
Pin diameter	12.5mm
Pin length	10mm
Pin profile	Cylindrical

3.2 EXPERIMENTAL SET UP

The FWTPET machine developed in house is shown in Fig. 3.1. It is a modified milling machine which consists of vertical tool holder, table for holding plate assembly and support strucalture. Separate fixtures are specially designed for this process.

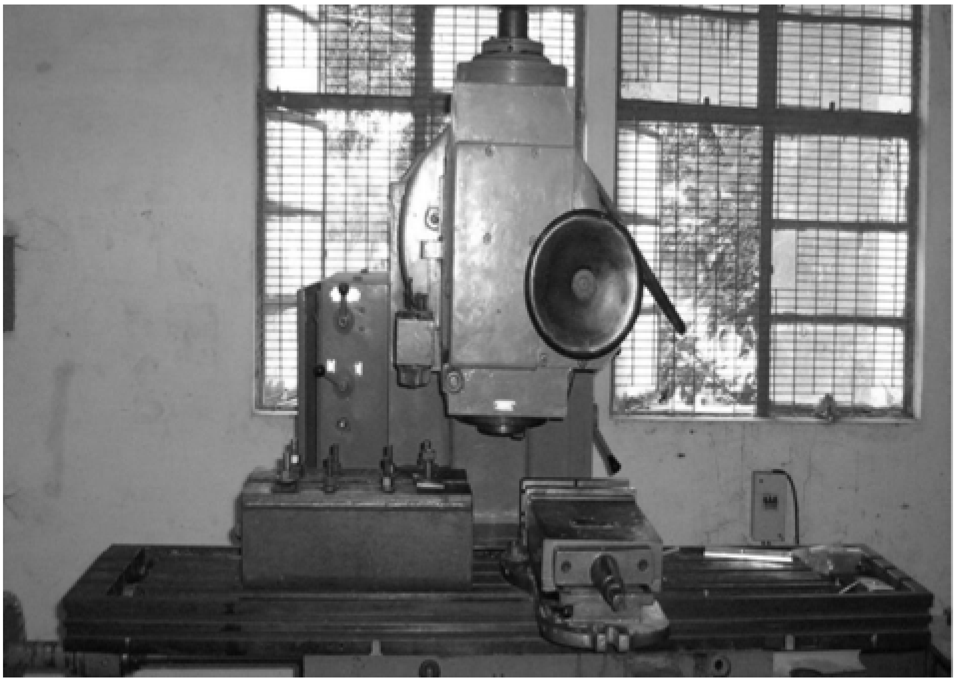


Figure 3.2 Modified milling machine for FWTPET

3.3 STEPS IN FWTPET

3.3.1 Sample preparation

The 6mm thickness aluminium 6061-T651 rolled plate is made into required size and edges are made flat. The work piece length and width are 50mm each. A hole of 19mm diameter is drilled at the centre of the plate to accommodate TiAl6V4 tube. Outer diameter and inner diameter of the tube is 19mm and 14mm respectively. Tube length is 20mm for normal sample and for shear test sample, tube length is increased to 35mm where the first 20mm is hollow and the remaining 15mm is solid part. Both the tube and plate are prescribed to clean with acetone to remove all the debris like grease, dirt etc. samples are kept in lap configuration as shown in Figure 3.3

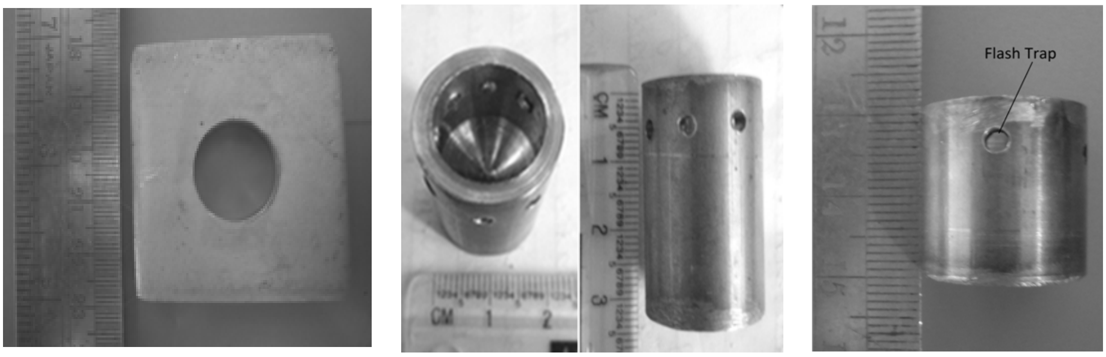


Plate **Tube(shear test sample)** **Tube(normal sample)**

Figure 3.3 Sample preparation

3.3.2 Assembly

The tube plate with hole drilled (same diameter as that of tube) on it is placed on a specially prepared mild Steel backing block(shown in Fig.3.4) and clamped tightly in the vice on the machine table. The backing block will have hole drilled on it. The depth of the hole will be proportionate to the length of the tube used. The backing block gives more support for the plate to have less residual stresses and distortion. The experimental and numerical investigation of FWTPET process revealed that the employment of backing block greatly enhances the quality of the joints produced. Tube to be welded are inserted in to the tube plate and the tool is fixed on the spindle of the machine.

(a) **(b)**

Fig.3.4 (a) Backing block (b) Assembly of tool, tube and plate

3.3.3 Alignment

Whole assembly with the backing block is placed under the tool and clamped tightly in vice in such a way that the pin centre coincides with the centre of the hole. If it centers did not coincide, while performing shear test the stress might not act symmetrically all through the weld and the strength values that obtain are absurd.

3.3.4 Welding:

The basic requirements to achieve a FWTPET weld are temperature & pressure high enough for forging.

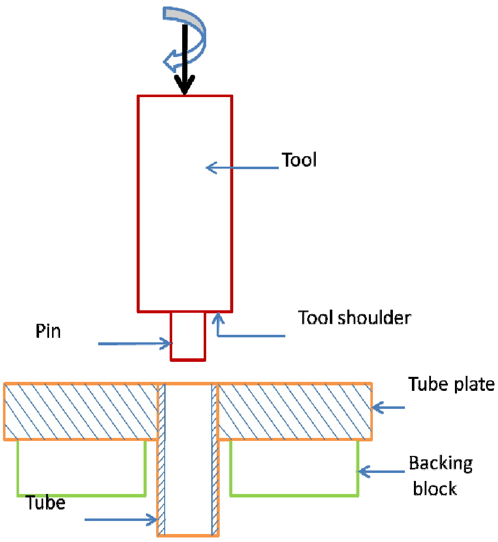


Figure 3.5 Schematic illustration of FWTPWET process

Figure 3.5 shows schematic representation of FWTPET process. The tube is fitted in the plate on the backing plate as shown in figure. Tool is fixed in the spindle and lowered under rotation. After the shoulder of the tool plunges into the plate surface, it is withdrawn after pre-determined time while in rotation.

3.4 Welding parameters

The different parameters identified in FWTPET clearance method which influence joint strength, are mentioned below.

- Tool rotation speed
- Shoulder diameter
- Pin length.
- Projection

In the present study, all these parameters are kept constant and tube profile is varied to get a defect free weld of reasonable shear strength. This work is a feasibility study of Aluminium to Titanium welding using FWTPET. All the welds are made with same tool rotation speed of 1120 rpm.

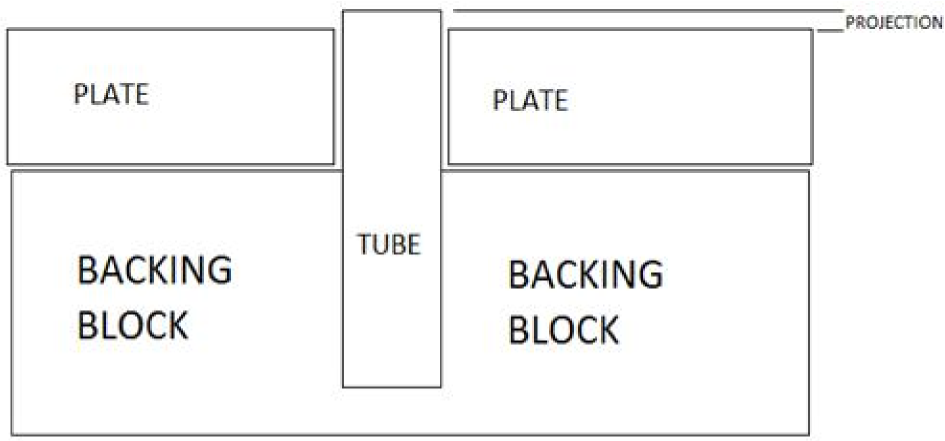
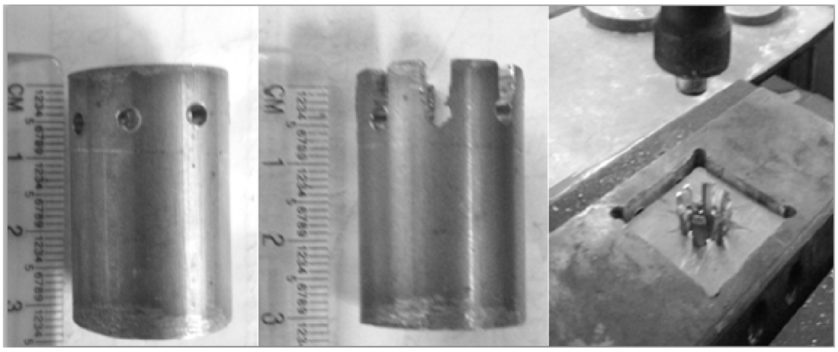


Figure 3.6 Schematic illustration of projection given to the tube

Here different projection is given for different tube profiles.

3.5 Tube profiles

Three different tube profiles are used for welding Aluminium plate to Titanium tube. They are –tube with holes, tube with slots and tube with petals. Number of holes , slots, and petals for a tube is 8 and it is made constant for all welds.



(a) (b) (c)

Figure 3.7 (a)Holes (b) Slots (c) Petals

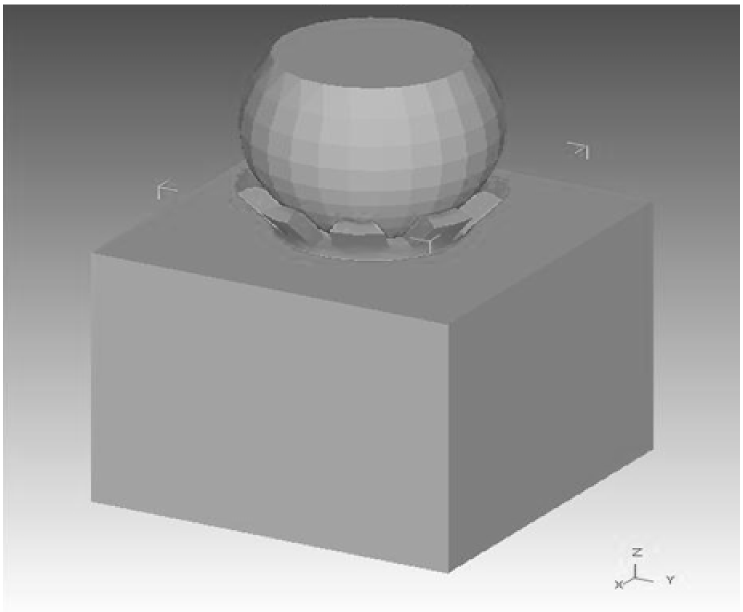


Figure 3.8 Petaling done using an oval tool

Petals are made using an oval shaped tool as shown in fig.3.8 and pressure is applied using UTM. First slots are made on the tube and then using the above mentioned method these slots are opened-up to form petal like structure on the surface of the plate.

3.6 Metallographic studies

The weld joints are sectioned in the transverse direction and samples are prepared and polished with emery sheet of different grades, further polishing has been done using alumina polishing and diamond polishing with 1μm diamond paste. Microstructures and macrostructures are taken using optical microscope. For observation of weld microstructures of AA 6061-T651 plate, specimens are etched with is 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 is 10-15 seconds. For observation of weld microstructures of TiAl6V4 tube, specimens are etched with Kroll's reagent (192ml H2O, 5ml HNO3, 3ml HCl, 2ml HF) for a etchant time of 25-30 seconds.

3.7 Microhardness measurement

The Vickers microhardness test was performed on the cross-section of the FWTPET samples perpendicular to the welding direction using a 300 g load for 10 seconds to obtain the hardness profiles across different weld regions. Measurements are taken at a span of 0.5 mm for the comparison of hardness at different regions of the welded joint. Diamond pyramid indenter having 136 degrees apex angle is used.

3.8 Shear test

The shear specimens are then tested by using a tensile testing machine at a monotonic displacement rate of 0.01 mm/s. The load and displacement are simultaneously recorded during the test. The shear strength is obtained by averaging the strengths of three individual specimens, which are welded with identical welding parameters.

3.9 Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX)

The scanning electron microscopy (SEM) and Energy Dispersive X ray (EDX) analysis are performed so as to have an insight into the phases occurring during welding at the interface. The observations are carried out using 200kV field effect scanning electron microscope(SEM-JEOL JSM 5410LV microscopy) coupled to EDS(Energy dispersive X ray Spectography) analysis has used in examinations. The software allowed piloting of the beam, scanning along a surface or a line to obtain X ray cartography or concentration profiles by elements respectively.

3.10 X-Ray diffraction analysis

XRD analysis had been done at the weld interface of Aluminium-Titanium dissimilar welds. XRD analysis helps to find out the different compounds formed at the interface. The amount of different compounds formed can be found out from the peaks obtained in the XRD plot. A small sized sample containing weld interface was given for test and results were obtained. Scan speed is 10º/min and step width is 0.02º.

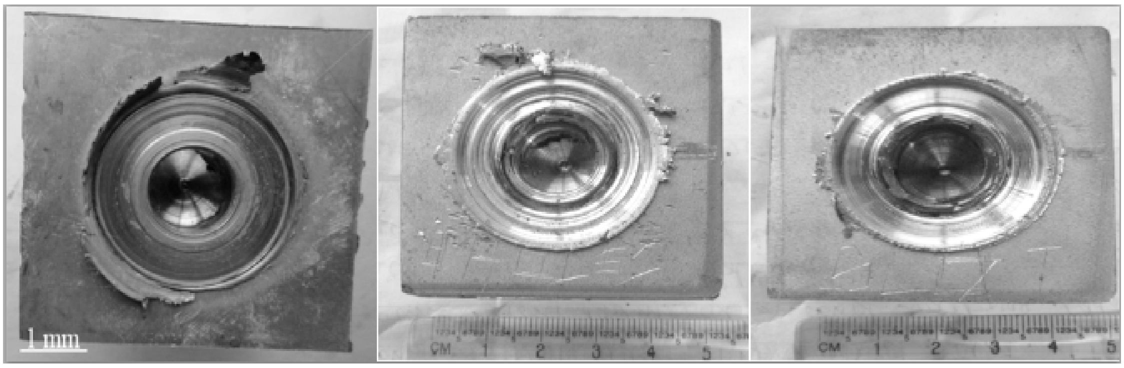
CHAPTER 4

RESULTS AND DISCUSSIONS

In the present work, feasibility of FWTPET of dissimilar materials (AA6061-T651 plate and TiAl6V4 tube) and properties of these joints are investigated. Tube profiles are varied to study its effect on the weld strength.

4.1 METALLOGRAPHIC ANALYSIS

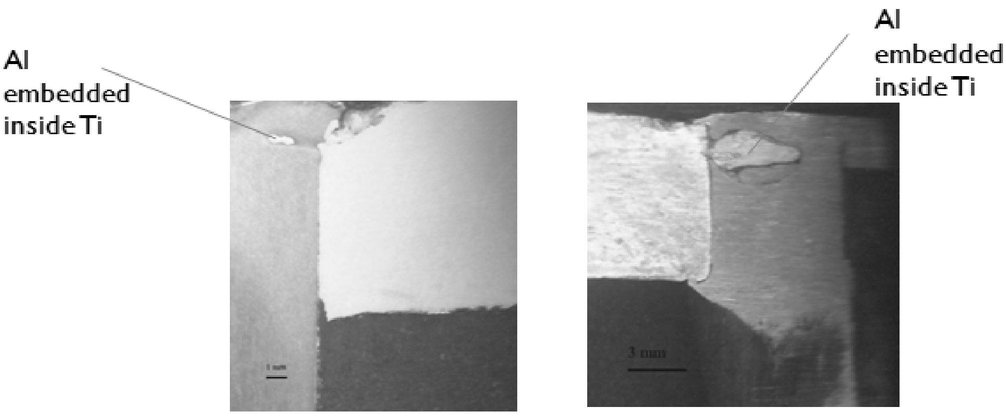
4.1.1 Macrostructure analysis



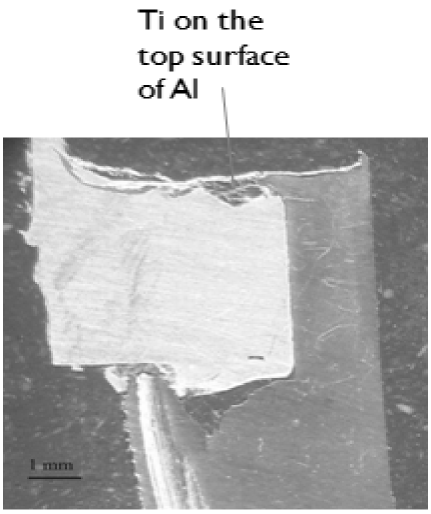
(a) (b) (c)

Figure 4.1 Top view of FWTPET with (a) Petals (b) Holes (c) Slots

Figure 4.1 shows top view of the welds made by FWTPET with three different tube profiles –petals, holes and slots. Plate welded with tube having petals is found to have Titanium deposited on the surface of the plate were shoulder came in contact with the plate. This can be clearly seen in the macrostructure of the welds.



(a) (b)

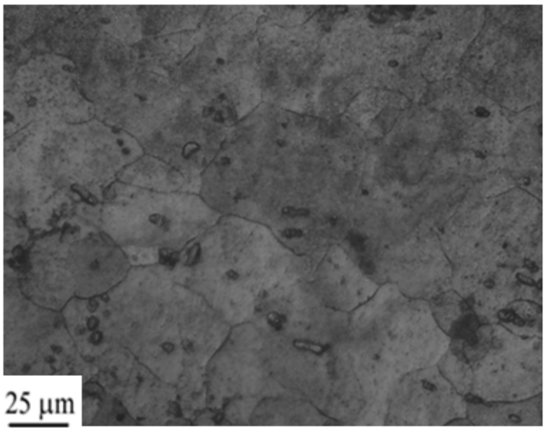


(c)

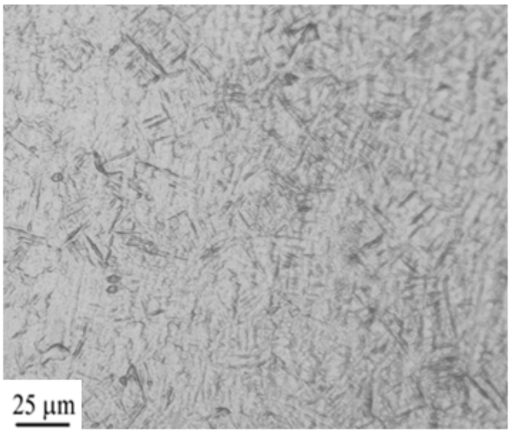
Figure 4.2 Macrostructures of FWTPET with (a) Holes (b) Slots (c) Petals

From the macrostructures, we can distinguish between the three different profiles. For tube with holes and slots we can see aluminium embedded in the titanium tube at the top. For tube with petals , we can see a covering of Titanium on the top surface of the Aluminium plate. This is expected to give additional mechanical interlocking which will eventually increase the weld strength.

4.1.2 Microstructure Analysis



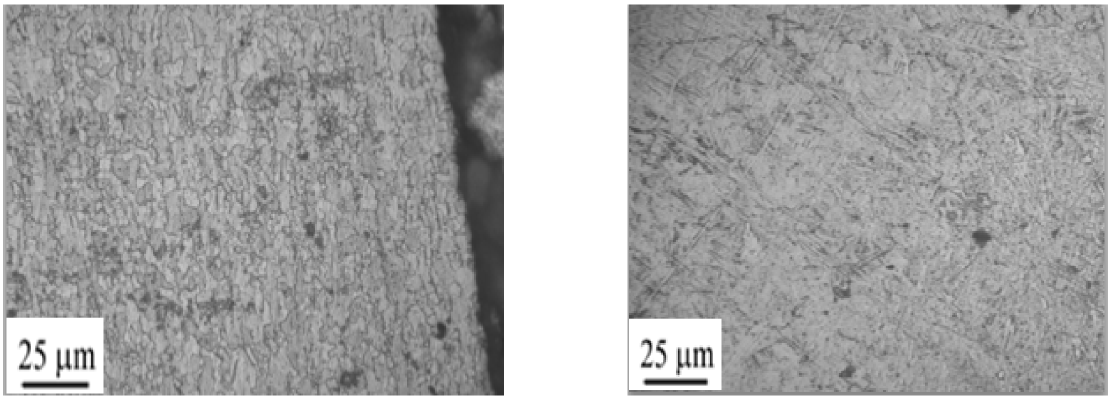
(a)



(b)

Figure 4.3 Microstructures of base material (a) AA6061-T651 (b) TiAl6V4

Fig.4.3 shows the microstructure of the base materials. Grains are clearly visible along with grain boundaries for AA6061-T651. Microstructure of TiAl6V4 is called “Basket Weave” structure. Grade V Titanium(TiAl6V4) has both alpha and beta phases. The dark lines in the microstructure is the beta phase and the light region is the alpha phase.



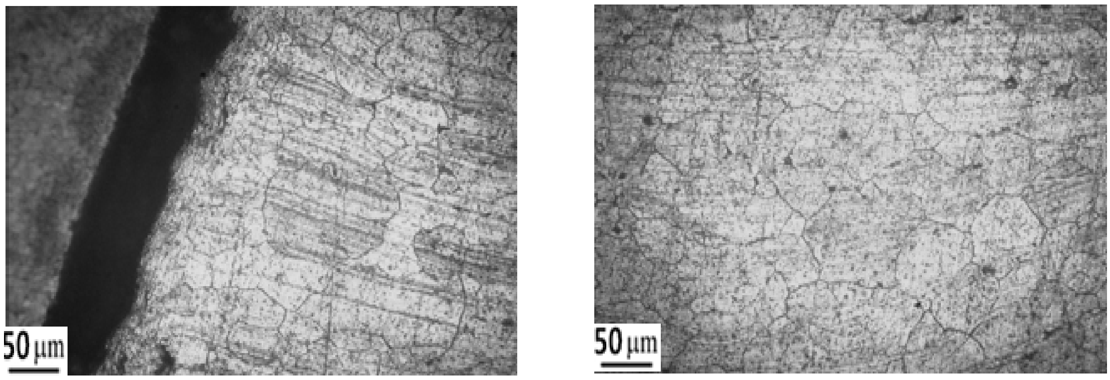
(a) **(b)**

Figure 4.4 Microstructure of TiAl6V4 (a)at the interface(b) away from the interface

It can be clearly seen that microstructure of TiAl6V4 tube at the interface and away from the interface are different. Away from interface , Titanium tube has a microstructure similar to that of base material. At the interface, change in microstructure can be due to high heat generated at the interface during welding process.

Figure 4.5 Change in microstructure of TiAl6V4

Figure 4.5 shows change in microstructure of Titanium tube .Annealing temperature of Titanium is in the range of 700-780ºC. If Titanium is heated to that high temperature and air cooled, it can result in microstructural changes . Annealing and air cooling of TiAl6V4 result in the formation of equiaxed alpha (light) phase with intergranular retained beta phase (dark)



(a) **(b)**

Figure 4.6 Microstructure of AA6061-T651 (a)at the interface(b) away from the interface

AA6061-T651 plate did not show much change in microstructure at the interface and away from the interface. It looked similar to that of the base material microstructure.

4.2 MICROHARDNESS

Micro hardness value was measured along the Al-TI joints and indentations were made with a spacing of 0.5mm.

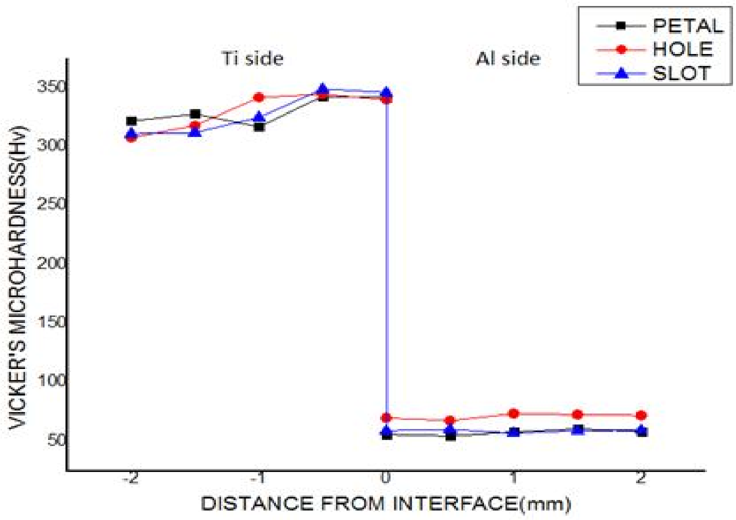
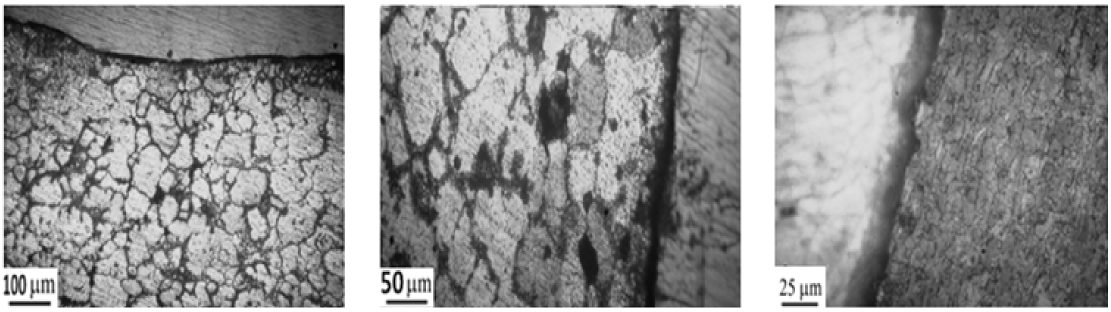


Figure 4.7 Hardness profile across the interface

For all the three tube profiles there is not much variation in the hardness profile. Titanium side is having very high hardness, close to base material hardness of around 349 Hv. Interface region is having higher hardness compared to nearby areas, which can be attributed to the change in microstructure of the Titanium alloy at the interface. Alpha phase is brittle and hard compared to beta phase which is ductile.

There is reduction in hardness at the Aluminium side which can be due to an overaging effect caused by high heat input generated during the welding process. This loss in hardness can be retrieved by the employing various post weld heat treatment processes.

Aging is carried out on the welded sample at a temperature of 160 ºC for 18 hours (K. Elangovan et al. (2007) and hardness was measured (Fig.4.9). There is substantial increase in hardness on the Aluminium side but post weld heat treatment did not have much effct on Titanium.



(a) **(b)** **(c)**

Figure 4.8 Microstructure of the heat treated sample (a) Al at the top interface (b) Al at the interface (c) Ti at the interface

Microstructure of the AA6061-T651 after post weld heat treatment is similar to that of the as welded condtion. Increase in hardness is due to the precipitation of Mg_2Si which will not be visible in the microstructure. Titanium alloy will not be affected by the aging process because annealing temperature of Titanium is in the range of 700-780ºC.

Aluminium alloy hardness increased to the range of 100 Hv which is near the base metal hardnesss of the AA6061-T651 material.

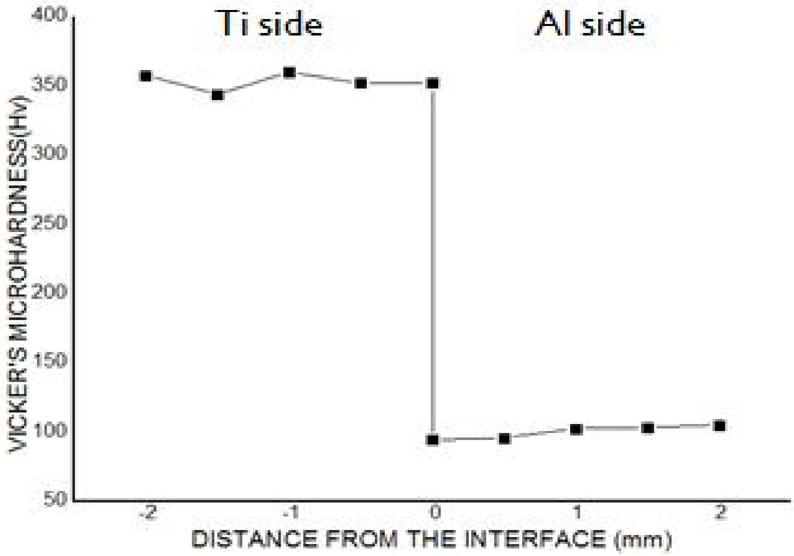


Figure 4.9 Hardness profile across the interface of aged sample

4.3 WELD STRENGTH

Weld strength was measured in the UTM using a plunger by applying compressive load. Shearing will take place along the interface of the welded sample and shear strength is calculated by dividing the load with the resisting area. The shear strength values for different tube profiles are given in the table

Table 4.1 Shear strength for different tube profiles

Sl.no.	Tube Profile	Shear strength (MPa)
1	Holes	75.3
2	Slots	104.71
3	Petals	117.27

From the bar graphs (Figure 4.10), it is clear that tube with petals are having high shear strength compared to other to profiles. So it can be suggested as a better method to join the Al tube plate to Ti tube. Further investigation such as XRD and SEM analysis is done on the weld made with this profile .

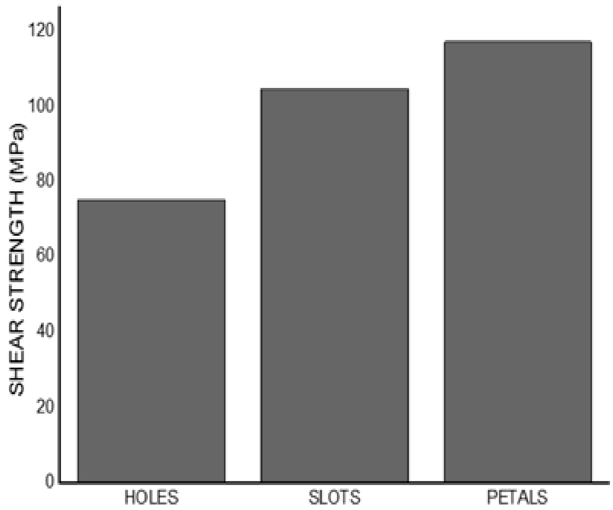


Figure 4.10 Weld strength for different tube profiles

4.4 X-Ray Diffraction Analysis

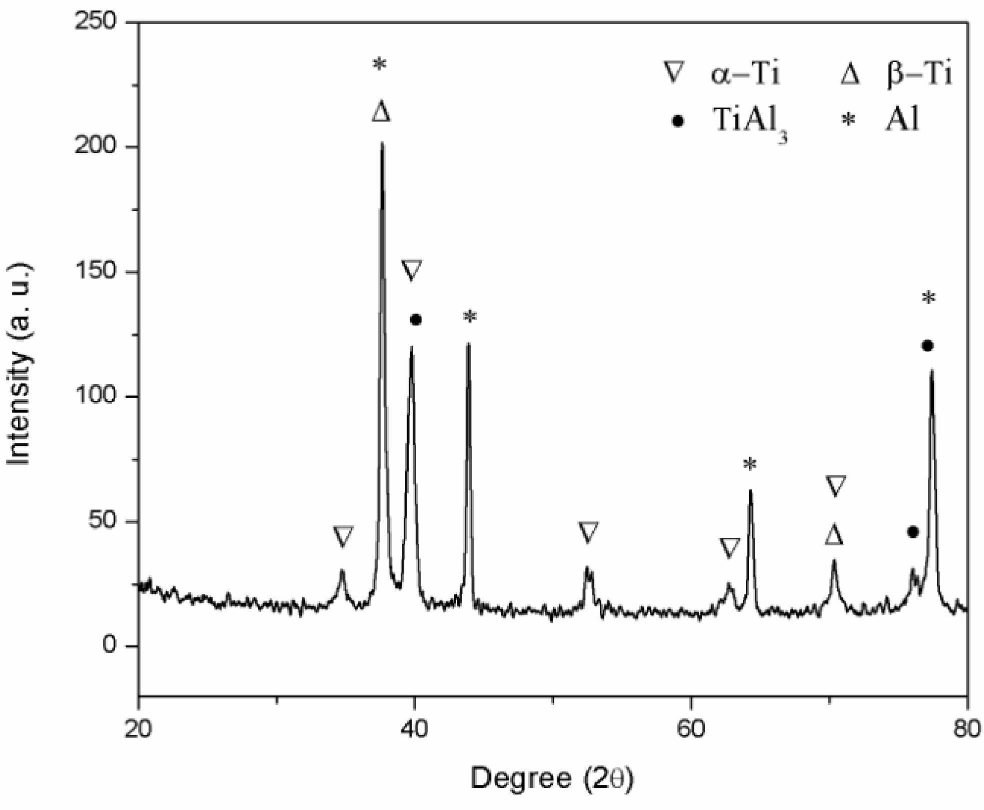


Figure. 4.11 XRD plot of Ti-Al weld interface

Figure 4.11 shows the XRD plot at the weld interface for welds made with Tube with petals . XRD is done to analyse phase composition. From the XRD plot, we can see different phases but all of the phases except $TiAl_3$, are present in the base material. Formation of intermetallic compounds are detrimental to weld joint strength. Unlike fusion welding, where a large number of intermetallic compounds like TiAl, Ti_3Al, $TiAl_3$ etc.. are formed, in FWTPET only $TiAl_3$ is formed at the interface . Hence formation of intermatallic compounds is hampered by this process. Reason for reduction in intermetallic compounds can be due to less heat generation in the interface region compared to other traditional welding processes**.**

4.5 SEM Analysis

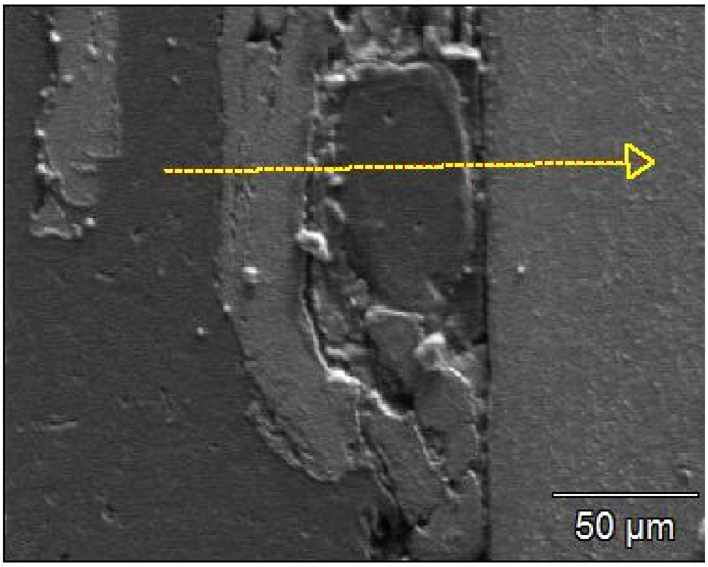


Figure. 4.12 Line scan across Ti-Al interface

Figure 4.12 shows SEM micrograph of Titanium particles which entirely entrapped Al at the weld interface. It can be seen that thick mixed layers are formed on the interface. EDS Line scanning analysis along the dotted line (Fig.4.12) are shown in Fig.4.13.

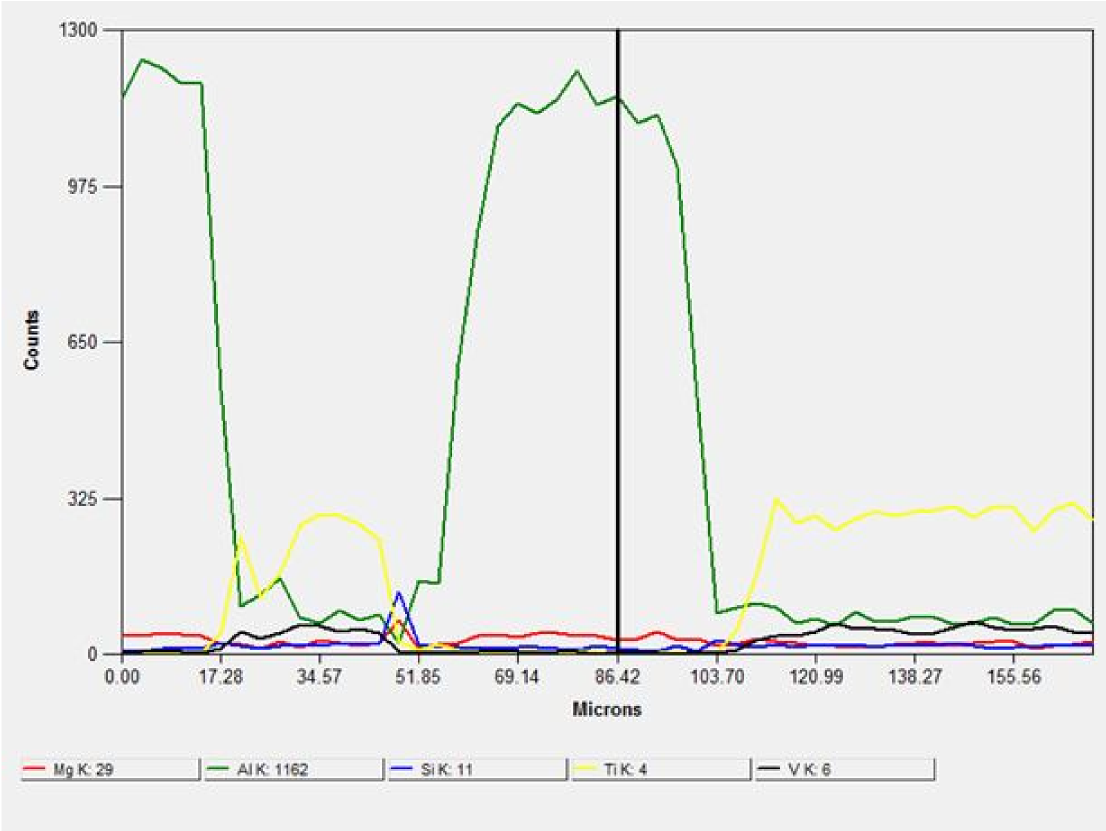
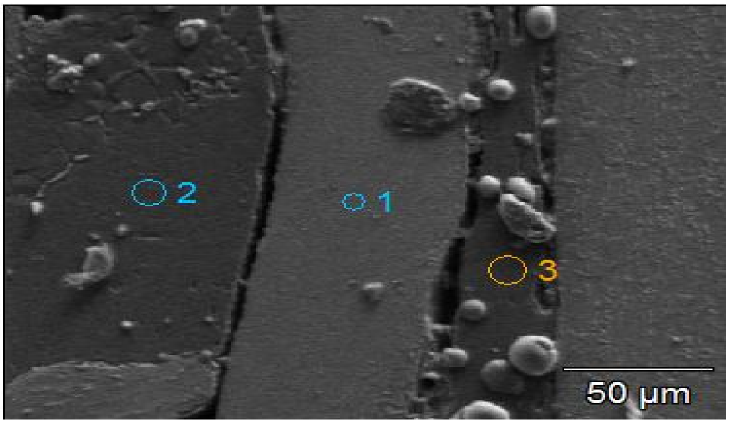


Figure 4.13 EDS plot showing the composition along the line scan



	Mg-K	Al-K	Si-K	Ti-K	V-K
(1)_pt1	0.00	12.63	0.36	83.19	3.82
(1)_pt2	0.80	92.61	0.00	0.18	0.00
(1)_pt3	1.29	15.49	0.46	75.07	6.34

Figure 4.14 SEM image at the interface along with the composition at various points

EDS analysis was performed at various points near the weld interface. EDS patterns and element contents are shown in Fig. 4.15 at the zone 3 shown in the SEM micrograph.

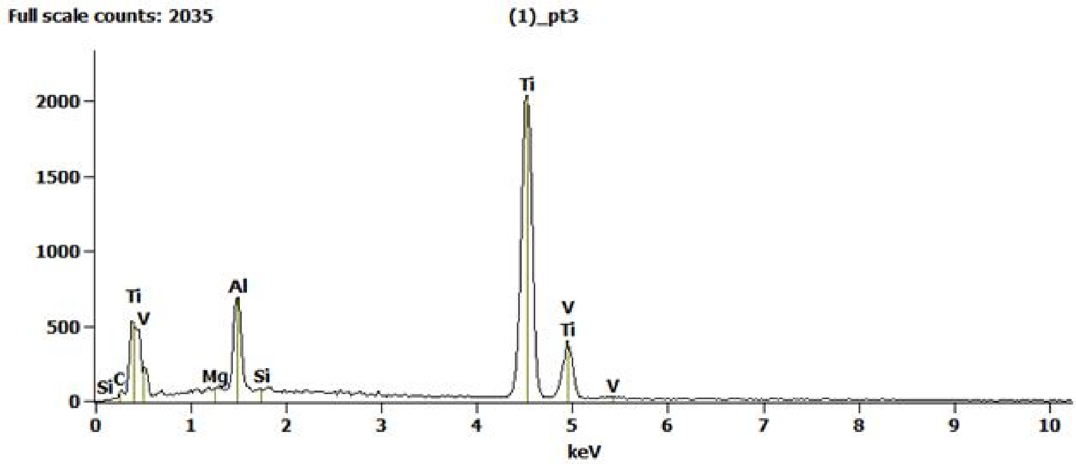


Figure 4.15 EDS patterns at zone 3

4.6 FRACTOGRAPHY

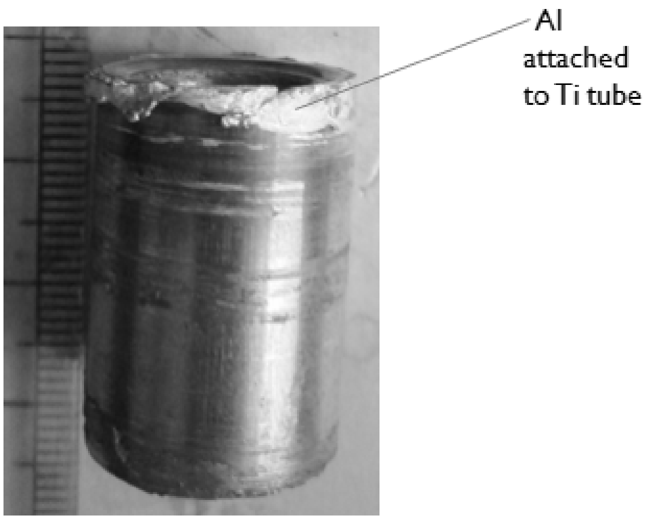


Figure 4.16 Titanium tube after shear test

Figure 4.16 shows fracture surface of Titanium tube. From the figure we can clearly see some areas on the fracture surface, were the aluminum alloy is still bonded to Titanium. These Aluminum particles bonded to the Titanium demonstrate that the welding connection is very strong at these zones.

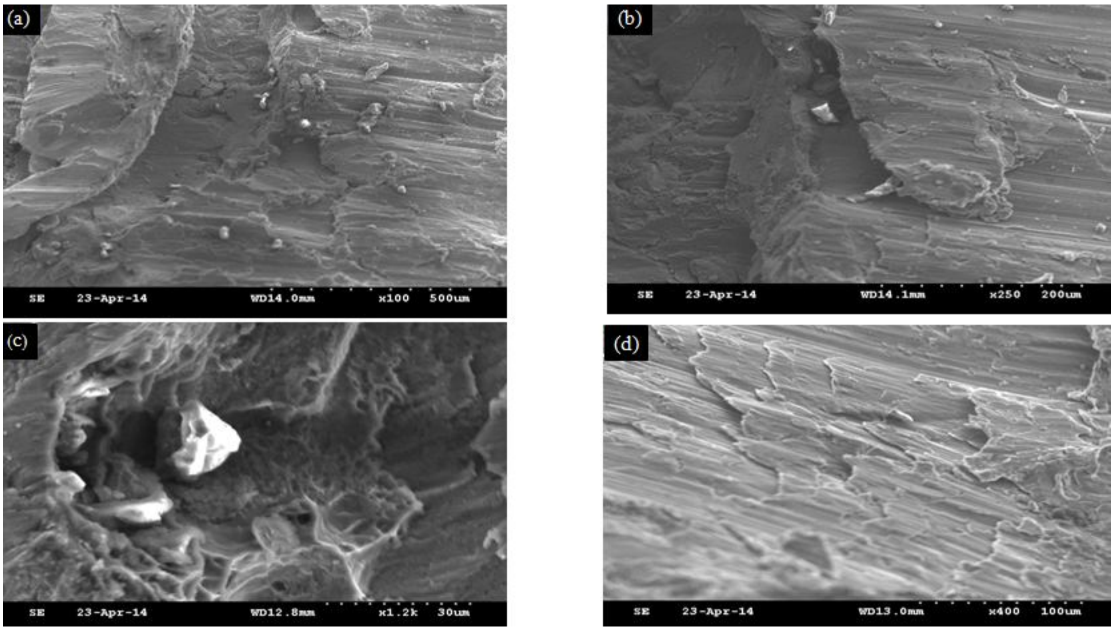


Figure 4.17 SEM images of the fracture surface on the Aluminum plate

SEM images of the fracture surface on the Aluminum plate shows cleavage facets which is an indication shear fracture. Some Titanium particles embedded in the Aluminium matrix are also visible in the SEM images (Fig.4.17 c)

CHAPTER-5
CONCLUSIONS AND FUTURE SCOPE

5.1 CONCLUSIONS

1) FWTPET-clearance method has been established to join 6mm thick Aluminum (AA6061-T651) tube plate to Titanium (TiAl6V4) 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) Microhardness for the Aluminum side drastically reduced after welding due to overaging which was recovered after post weld heat treatment .
5) XRD analysis showed formation of $TiAl_3$ at the interface. Intermetallic compounds at the interface were less compared to traditional fusion welding processes due to reduction in heat generation during the welding process.
6) Fracture surface showed cleavage facets which is an indication of shear fracture.

5.2 FUTURE SCOPE

1) Optimization of welding parameters, like tool rotation speed and shoulder diameter, to improve the weld strength.
2) FWTPET – clearance method can be applied to make joints between steel tube and aluminium, steel tube and magnesium plates etc.
3) Experiments can be done to compare TIG welded tube to plate joints to FWTPET
4) Experiments can be done to establish the process in large diameter tubes.

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