INVESTIGATION ON PROPERTIES OF THE WELDED JOINTS BY FRICTION STIR WELDING OF TITANIUM UNDER AIR AND WATER

Ethiraj Narasimhalu*, Sivabalan Thanapal, Vineth Kumar Jayakumar, Vikram Rajendran, Manikandan Chinna Thambi, Vignesh Sundaram, and Meikeerthy Selvaraj

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Abstract

Friction stir welding (FSW) is one of the green manufacturing technologies which is eco- friendly due to the absence of electrode, sparks and fumes. Underwater FSW is the advancement of FSW and it is called so because the process takes place under the water. Titanium is widely used in automobile, aeronautics, marine industries etc. It is observed from the past researchers work that the FSW of titanium is difficult and compared with other materials. The current work is to investigate the effect of process parameters on mechanical and metallurgical properties of the welded joints made conventionally and also under the water. After trial and error, the tool rotational speed of 400, 500, 600, 700, and 800 rpm at constant tool traversing speed of 60 mm/min and 0º angle of tool tilt. The mechanical and microstructural properties of the joints are compared between air and underwater process as well as with the base material. Within the experimental values, the quality characteristics of the joints made are better in under water FSW than air FSW in all process parameters used. Among the process parameters used, best results are achieved at 500 rpm of tool rotational speed and 60 mm/min traversing speed in underwater FSW.

Keywords: Friction stir welding, underwater friction stir welding, mechanical properties, microstructure, titanium

Introduction

Friction stir welding (FSW) is one of the latest welding methods used as a green manufacturing technology. It is a solid state welding process which is recently gaining importance in automobile, aerospace, marine and consumer electronics industries (Zahari *et al*., 2016). Joining process takes place by the heat generated by the friction produced between the rotating tool and the workpiece material without melting but plasticizing the material. Since no electrode is used in this process, fumes or arcs are not produced causing no harm to the persons handling it. Titanium metal is recently very widely used due to its low density, high strength, good fatigue life, non magneticcharcteristics and excellent corrosion resistant to sea water (Litvin and Smith, 1971).

Department of Mechanical Engineering, Dr.M.G.R Educational and Research Institute, Maduravoyal, Chennai-600 095, India. E-mail: ethiraj.mech@drmgrdu.ac.in
* *Corresponding author*

Researchers in the past performed FSW using metals or alloys (Dudzik and Czechowski, 2010; Buffa *et al*., 2013; Polezhayeva *et al*., 2015; Kundu and Singh, 2016; da Silva *et al*., 2017; Fei and Wu, 2018), different grades of same materials (Zahari *et al*., 2016) or different materials (Niu *et al*., 2019) and plastics (Ethiraj *et al*., 2017). Also, few attempts have been made on studying the FSW of composite (Sheikh-Ahmad *et al*., 2019), carbon doped high-entropy alloy (Shaysultanov *et al*., 2018) and cermet/SC45 steel (Avettand-Fènoëla *et al*., 2019). Recently, the wider use of titanium and its alloys due to their excellent properties especially like light weight and higher strength attracted the researchers to study the joints made by FSW process (Lee *et al*., 2005; Hui-Jie and Li, 2010; Lauro, 2012; Liu and Fujii, 2018; Mashinini *et al*., 2018; Fall *et al*., 2019).

Lee *et al*. (2005) stated that the welding of titanium using traditional fusion welding process caused problems like distortion, large residual stresses and brittle structure formation. In order to avoid the occurrence of these problems, solid state welding processes like FSW are more useful techniques.

Hui-Jie and Li (2010) have studied the FSW of 2 mm thick titanium alloy sheet using specially designed welding system with liquid cooling and concluded that the joints with tensile strength 92% that of base metal and the fracture has occurred in stir zone (SZ) since it is the weakest part of the joint.

In order to have uniform distribution of temperature during FSW of 2.5 mm thick Ti-6Al-4V alloy, which is not possible when using the conventional type of tools, stationary shoulder tool was used by Lauro (2012). It was found that thermo mechanically affected zone (TMAZ) is absent due to the welding temperature exceeding α- β transformation temperature (Lauro, 2012, Liu and Fujii, 2018; Mashinini *et al*., 2018, Fall *et al*., 2019). In contrast to this, Liu and Fujii (2018) have expressed that the microstructural development during FSW of β type Ti alloy is mainly due to discontinuous dynamic recrystallization in TMAZ where as it is due to continuous dynamic recrystallization in SZ.Similarly, the different zones (TMAZ, SZ and Heat affected zone (HAZ)) are identified in the joints made in FSW of Ti alloy and observed that the hardness is higher in SZ under all welding parameters due to the formation of finer grain structures by Mashinini *et al*. (2018).

Researchers have extended their investigation on FSW of aluminium alloys (Zhao *et al*., 2014; Heirani *et al*., 2017), magnesium alloy (Liu *et al*., 2019) and different metals (Mofid *et al*., 2012; Zhang *et al*., 2014) by performing the process under water or other liquid medium. Zhao *et al*. (2014) and Heirani *et al*. (2017) have observed higher tensile properties in under water FSW (UWFSW) of Al alloy when compared to the welding in air. But, Liu *et al*. (2019) have obtained lower shear strength and higher percentage elongation in under water FSW of lap joint of magnesium alloy. The inter metallic compound formation is suppressed due to the lesser peak temperature available during under water FSW of Al and Mg alloy (Mofid *et al*., 2012) and similar result was achieved by Zhang *et al*. (2014) in case of FSW of Al-Cu in under water condition.

Ma *et al*. (2018) have experimented FSW of Ti alloy with rapid cooling using liquid nitrogen and concluded the following results when compared to that of air cooled FSW: (i) better uniform distribution of microhardness; (ii) non existence of TMAZ and (iii) higher fatigue life of the joint made in rapid cooling condition than that of the joint made of air cooling. Wu *et al*. (2019) have investigated the microstructure evolution of the joint produced by the underwater FSW of Ti alloy and found that the ultra fine grained structure is formed in underwater condition due to the dominated continuous dynamic recrystallization (CDRX). It is observed from the survey of literature that the FSW of titanium is very much limited (Ma *et al*., 2018, Wu *et al*., 2019) when compared to FSW of aluminium alloy. Hence, the objective of this research paper is to investigate the effect of rotational speed of the tool on the microstructure and mechanical properties of the joints made in air and underwater FSW of 1mm thick Titanium sheet material.

Materials and Methods

Experimental Procedures

The sheet material used for the present study is 1mm thickness Titanium grade 1. The material is supplied by M/S. Manhar Metal Supply Cooperation, Mumbai, India. The plates are cut to the size of 100×80 mm from the bought standard size sheet of 900×1,200 mm and are cleaned to remove the dirt, oil and grease. The composition of

Table 1. Composition of Titanium

Elements	C	Fe	Ti	TOI
Specified weight %	0.08 max	0.20 max	Remainder	0.40 max
Observed weight %	0.001	0.004	Remainder (99.85)	0.113

Table 2. Important Tensile Properties of Titanium

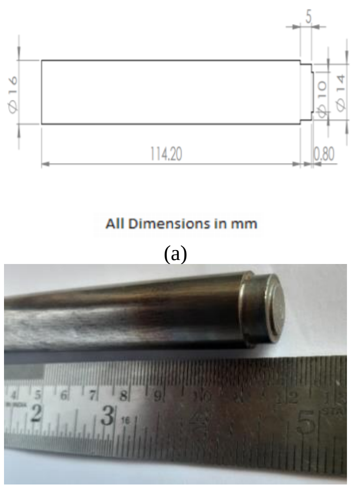
Test Parameters	Observed Values
Yield Strength (MPa)	288
Ultimate Tensile Strength (MPa)	311
Elongation % in 50mm GL	34.5

the material and important tensile properties are shown in the Tables 1 and 2 respectively.A specially fabricated setup for underwater friction stir welding was used and is shown in Figure 1.

The tool for both air and underwater FSW is made of high carbon high chromium tool steel (HCHCr), shown in Figure 2, which is hardened to 50-55 HRc. The dimensions of the tool are as follows: Clamping diameter is 16 mm; Shoulder diameter is 14 mm; Pin diameter is 10 mm and pin length is 0.8 mm. The welding process is carried out in a LITZ MV -800 make computer numerical controlled (CNC) Vertical machining center. The important specifications of machine are as follows: 10 HP Spindle motor, Maximum Spindle speed of 10,000 rpm, Maximum feed rate of 20,000 mm/min and Work table area of 850×450 mm. Figure 3 shows the air and underwater FSW process in progress.

The welding processes are carried out both in air and underwater using the following parameters: Tool rotational speeds of 400, 500, 600, 700, and 800 rpm and Traversing tool speeds of 30, 40, 50, and 60 mm/min.

Figure 1. Setup for underwater FSW



(a)

(b)

Figure 2. (a) Dimensions of the tool; (b) Actual Tool for FSW and UWFSW

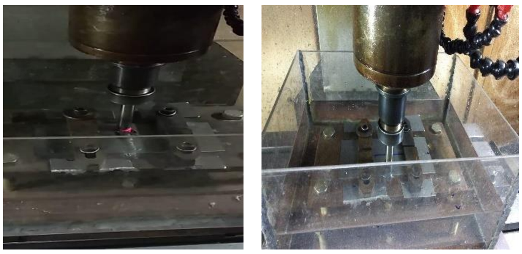
Testing Procedures

For tensile testing, both the sheet material as received, and welded material is cut according to the ASTME - E8 standard by water jet cutting process using S3015 waterjet cutting machine at M/S.ALIND-Water jet cutting services and the cutting is made perpendicular to the welded direction as shown in the Figure 4. The tensile testing was carried out in TE JINAN/WDW 100 Universal testing machine at M/S. Microlab. To study the microstructure, the images are taken in scanning electron microscope (SEM)-TESCAN VEGA 3.

Results and Discussion

The FSW of Titanium metal in both air and underwater was carried out and the major challenge was encountered during the process done in air (room temperature) in getting a good welded joints. This may be attributed to the reason that the high specific strength at room and higher temperatures and lower thermal conductivity of the titanium material. Thus the welded joints made at lower traversing speeds (30, 40, and 50 mm/min) and higher tool rotational speeds (800 and higher rpm) are either with poor joint strength so that it may be broken by hand force itself or over heating which burns the material. The various defects observed in the welded joints made under the above process parameters are incomplete filling, blow holes and burning marks are shown in Figure 5.

Better welded joints are obtained at tool rotational speed of range 400-700 rpm at a constant tool traversing speed of 60 mm/min. The successful



(a) Air (b) Underwater

Figure 3. FSW process

Figure 4. Specimen cut for tensile testing

welded joints produced in air using the above mentioned parameters are shown in Figure 6.

The successful and defective welded joints produced underwater condition using the same process parameters as that of under air process are shown in Figure 7.

In underwater welding condition, the joints are successfully made at 400,500, and 600 rpm but poor weld was observed at 700 rpm at constant tool traversing speed of 60 mm/min. The reason for formation of poor welded joint is due to the low thermal conductivity characteristic of titanium which retain the frictional heat generated by the high rotational speed of the tool and rapid cooling by the surrounding water not allowing the material in the welded region to become plastically flow and the material is splashed out of the weld region due to the higher rotational speed. The success of the welding underwater at 600 rpm as against the welding in air is may be due to the rapid cooling of material in the welding region by the surrounding water. Also, FSW in air produce non uniform microstructure and uneven microhardness distribution is observed in stir zone, whereas in case of rapid cooling, the stir zone with uniform microstructure and microhardness is produced. The same was reported by Ma *et al*. (2018) in their study on FSW of 2 mm thick Ti -6 Al-4V alloy. In general, in all cases, the welds formed are not smooth and tool travel marks are visible to the naked eye.

Figure 5. Defective welded joints made in air at lower tool traversing speed and higher tool rotational speeds

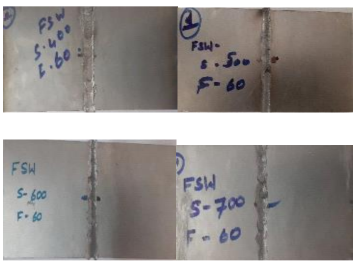
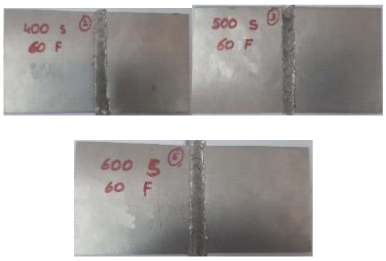


Figure 6. Successful welded joints made in air

Microstructural Properties of the Joint

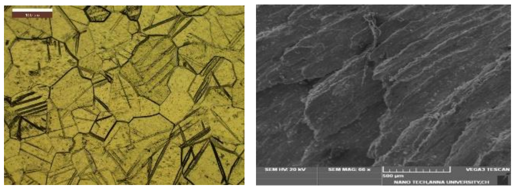
The optical microscopic image and SEM image of the base metal (BM) is shown Figure 8. It is observed from the image that the equiaxed grains of average ASTME grain size number 4.5 are distributed in a different angle orientations.



a) Successful welded joints

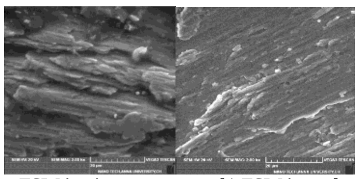
b) Defective welded joints

Figure 7. Joints made by underwater FSW

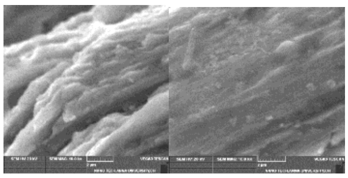


(a) (b)

Figure 8. Image of BM (a) Optical microscopy (b) SEM



a) FSW in air **b) FSW in underwater**



c) FSW in air **d) FSW in underwater**

Figure 9. SEM images of welded joints (a, b) at 400 rpm, 60 mm/min and 2,000X in air and water respectively (c, d) at 500 rpm, 60 mm/min and 10,000X in air and water respectively

Figure 9(a-d) shows the few SEM images of welded joints made in air and underwater. It is seen from the images that the grains are elongated due to the stirring action of the rotating tool during the process. Also, the distribution of the elongated grains is smooth and uniform in underwater FSW when compared with that of FSW in air. Similar type of microstructure was observed by Ma *et al.* (2018) in their study. The non uniform distribution of grains in joints welded in air is may be due to the irregular thermal gradient because of the low thermal conductivity of the titanium material.

Tensile Properties of the Joints

The Stress Strain diagram obtained from the tensile testing of BM and the few welded joints produced by FSW in air and underwater is shown in Figure 10(a-c). The observed values of yield strength, ultimate tensile strength and Percentage elongation during tensile testing of welded joints made in air or under water condition using different process parameters are shown in the Figures 11(a-c) respectively.

The Yield strength and the ultimate tensile strength of the joints made in air is only maximum of 16.32% and 16.07% of the BM respectively in the experimented process parameters. But in case of FSW underwater, the values obtained are 60.07% and 62.06% of the BM respectively. The reason for such a low strength characteristics may be attributed to the following: (i) the low thermal conductivity of the titanium causes temperature gradient in the stir zone which produces thermal stresses; (ii) the high strength property at room and higher temperatures of titanium may prevent the tool from plasticizing the material in the stir zone and (iii) there is a possibility of influence of thickness of sheet material which may not be able to bear the loads applied. The higher strength values in Underwater FSW than in air may be due to the uniform distribution of elongated grains and hence the corresponding micro hardness values are uniform. This favours the joints to bear higher loads and also the strain to be uniform during deformation. Within the experimented parameters, the best results are obtained at rotational speed of 500 rpm and traversing speed of 60 mm/min. Similar results are reported by Lauro (2012) in FSW of Ti-6Al-4V.

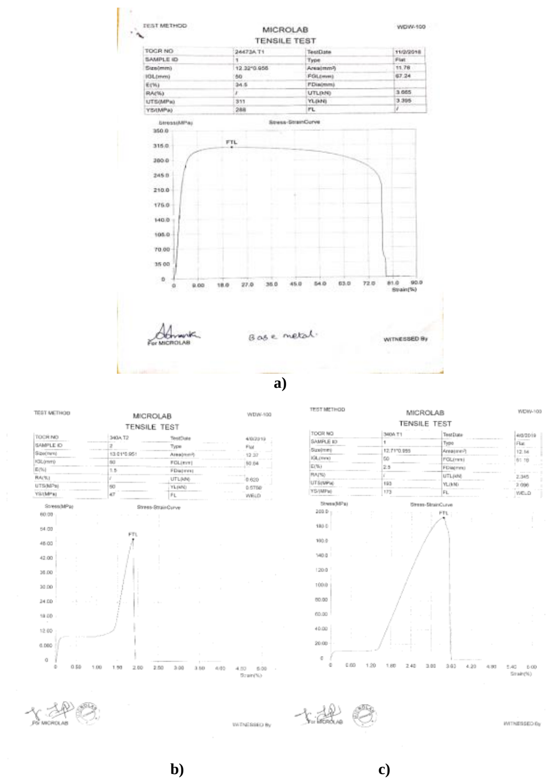


Figure 10. **(a-c) Stress Strain diagram of the a) BM; b) Joint at 400 rpm in air and c) Joint at 500 rpm in water**

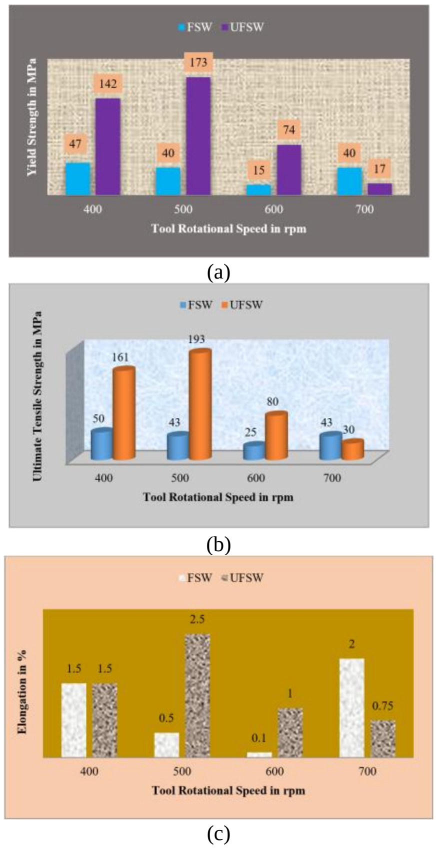


Figure 11. **Effect of Tool rotational speed at constant traversing speed of 60 mm/min on (a) Yield Strength; (b) Ultimate Tensile Strength; and (c) % Elongation**

The % elongation is only maximum of 5.8% and 7.25% of BM in air and underwater respectively. Same situation was encountered by Ma *et al*. (2018) during investigation on FSW of Ti alloy and it was stated that material slip system is associated with the elongation during deformation. Titanium exhibit two allotrophic forms i.eα- Titanium and β - Titanium with hexagonal close packed (HCP) structure and body centered cubic (BCC) structure respectively. These two phases have different material slip systems and the non-uniform deformation of the welded joint due to the different α to β phase ratio in FSW than BM produce very less elongation (Ma *et al*., 2018). In all cases, the location of the fracture is in the weld region due to the brittleness of the material which also reflect in the % elongation results.

Conclusions

FSW under air and water is performed in Titanium metal at different process parameters. The following conclusions are arrived from the experimentation:

- Successful welding in both air and under water in certain process parameters and failed in higher tool rotational speeds and lower traversing speeds.
- The observed maximum value of tensile strength, UTS and % elongation of the welded joints produced in air is 16.32%, 16.07% and 5.8% of base metal.
- The measured maximum value of tensile strength, UTS and % elongation of the welded joints made in underwater is 60.07%, 62.06%, and 7.25% of base metal.
- Microstructure analysis revealed that the grains are elongated and are uniformly distributed.
- The surface quality of the stir zone is very poor even though there are no noticeable welding defects.

Further investigation is under progress by (i) Pre heating the sheet metal and (ii) Use of specially designed stationary shoulder tool.

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