

THE EFFECT OF POST HEAT TREATMENT ON THE FATIGUE BEHAVIOR OF FRICTION STIR WELDED ALUMINUM 6013 ALLOY FOR USE IN AEROSPACE STRUCTURES

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Abstract

Aluminum alloys are widely used on aircraft structures especially on the fuselage and wing fairings. During the joining of these structures, the traditional technique riveting is used. But riveting increases the structural weight of the aircraft and rivet holes form stress concentration for the fatigue cracks. An alternative joining technique is welding. In traditional welding techniques metal is heated till the melting point for this reason the mechanical behavior of the material deteriorates. And also the weldability of high strength materials is low. In recent years Friction Stir Welding (FSW) has been used as an alternative joining technique. In this study Aluminum 6013 sheet joined by using FSW technique. Fatigue specimens were machined from the welded plate in the dimension of $A_0 = 12.5$ mm, $l_0 = 200$ mm and fatigue tests were performed. Vickers microhardness values were taken at 1 mm increments from base metal to base metal across the weld, on the weld cross-sections. The intermetallic particles and the grain structure of the welded sheet were examined via optical and scanning electron microscopy.

Key words: Friction Stir Welding, Fatigue and Tensile Tests, Microstructural Evaluation, Al 6013-T6, Aircraft Structures

1. INTRODUCTION

Friction stir welding (FSW) is a solid state welding method which was invented by The Welding Institute (TWI) in England in 1991. FSW is a low heat input solid state welding technique where the bonding takes place below the melting point of the alloys for this reason its suitable for low melting point metals, such as Al and Mg (Prado et al. 2001). FSW has spread out quickly since its development in 1991 and has found applications in a wide variety of industries, as aerospace, railway, maritime, automotive and others (Gibson et al. 2013). There is a wide area on using this technology and it is considered the main advance on joining technology during the last decade. The first idea of FSW is that, after the weld edges are fastened, a nonconsumable rotating tool is forced between the edges and moved along the weld nugget. The material is then necessarily forced out around the tool before being forged by the pin shoulder. During FSW metals are welded in the solid state as a result of the heat produced by the friction and flow of metal by the stirring effect of a pin tool (Rosado et al. 2010).

Frictional heat is produced both internally by viscous dispersion and at the interfaces between the pin and pin shoulder and the material of the work pieces. The tool has two basic roles; one is to heat the work piece and the other is to provide the material flow. The heat generated into the work piece affects the quality of the welding process (Rosado 2010; Hattel 2012). FSW is also an efficient intend to refining grain size or forged aluminum and magnesium based alloys by means of dynamic recrystallization (Casaline et al. 2014).

FSW is appearing as a suitable alternative technology with high efficiency account of high welding speeds. Since the joint can be acquired under the melting temperature, the process is suitable for joining a number of materials that are difficult to be welded by conventional fusion welding methods. In addition to welding friction stir welding process has been improving as possible metal working methods for metallic components. The basic principle of FSW is easy and very simple. The rotating pin shoulder and the pin of a nonconsumable tool heat and plasticize the metal and a solid state joining is performed. Because of thermal and mechanical deformation in weld zone during FSW, the weld zone has different microstructural characteristics and mechanical properties (Tra et al. 2012). For improving and widening the application of FSW, it is important to develop and clarify mechanical and microstructural characteristics of the joining technique.

FSW is an effective solid state joining technique meant for joining similar or dissimilar high strength aluminum alloys which are often difficult to weld with traditional welding techniques. Some of the advantages of the FSW are; improved mechanical properties of the welds, reduced porosity and distortion, without hot cracking, lower

residual stresses, and favorable environmental characteristics (Hattel et al 2012). During welding, the material is heated by friction to a temperature at which it turns in to more plastic.

On commercial transport airlines joints generally used are riveted, bolted and bonded joints. When compared with these techniques, FSW technology in light weight structures for the aerospace industry is seen as better joint integrity in which reliability and damage tolerance are the main expectation (Prater et al 2014; Wang et al 2013).

In order to obtain weight reduction, it is important to select lighter materials. The aerospace industry uses primarily aluminum alloys. The selection of lightweight and strong materials continues to be a guiding consideration in design of aerospace vehicles ((Prater 2014). While FSW is believed a fully developed process for many aluminum alloys such as 2000, 6000 and 7000series, there is also considerable interest in improving the process. Because the FSW process is affected by many variables and parameters, such as the tool design, tool contact conditions and material thermo-mechanical properties, there are a number of subjects that need to be studied numerically and experimentally. One of the main subjects that need to be studied is determining the effect of post welding heat treatment conditions on the welding process (Gibson et al 2013).

During the FSW process an enormous amount of residual stress would remain in the weld zone because of stirring effect and plastic deformation. This residual stress has a harmful effect on the mechanical properties of the friction stir welded structures. In order to improve the metallurgical properties and reduce the residual stress, post weld heat treatment was implemented on the welded materials (Wang 2013). Throughout the welding process, frictional heat on account of the thermal cycle changes in the crosswise direction of the weld. The highest temperature is observed in the weld nugget that brings out an adjustment in the precipitate distribution present in the raw material and also caused by stirring of the plasticized material. These changes in the heat and temperature distribution in FSW, affects the microstructure and the strength of the welded joints (Elangovan et al 2008).

In this study, the mechanical and microstructural elevation of friction stir welded Al 6013-T6 aluminum alloy, the base material and the post heat treated specimens were studied in order to provide more knowledge for the practical FSW of aeronautical structures. The influences of heat treatment on intermetallic surfaces and mechanical properties of friction stir welded joints are also investigated.

2. EXPERIMENTAL

The material that has been used in this study was 6013-T6 aluminum alloy with dimensions of 3,6mm x 1100mm x 400mm (thickness, length, width). The chemical composition of base material is given in Table 1. This material is widely used in aerospace applications because of some preferred special features as high mechanical strength, high fatigue resistance, low sensibility to high temperature and good corrosion resistance.

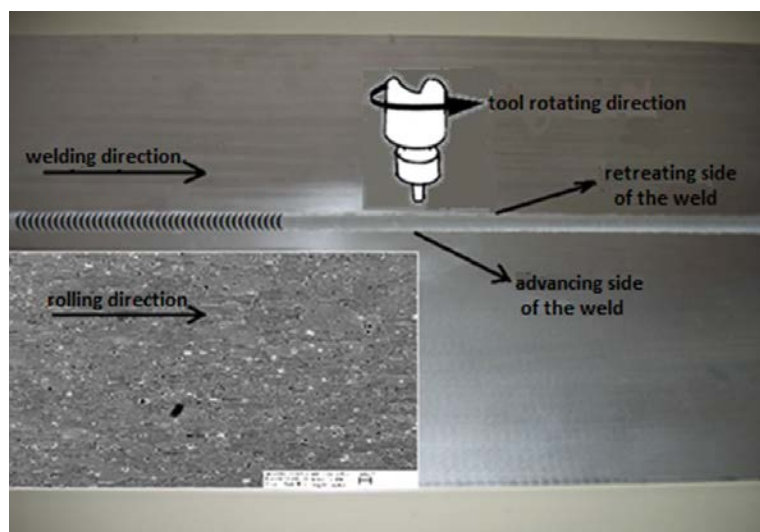


Figure 1. Welding direction.

Table 1. Chemical composition of the 6013 base material (Mishra & Mahoney 2007).

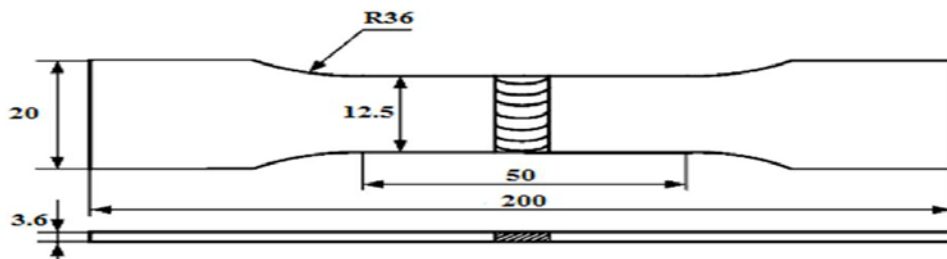
Element	Mg	Si	Cu	Mn	Fe	Cr	Zn	Ti	Al
Wt (pct)	0.90	0.72	0.95	0.36	0.27	0.03	0.07	0.02	bal

The material studied was friction stir welded by Germany Aerospace Center (DLR). Welding was carried out at a welding speed of 1000 mm/min and a rotational speed of 1200 rpm (Figure 1). Pin and shoulder diameters were 6 mm and 18 mm, respectively. Welding was carried out perpendicular to the primary rolling direction.

For the temperature measurements, two thermocouples were plug into at a depth of 2 mm (half thickness) on the base material and one on the shoulder. The thermocouples were located at distance of 6 mm and 15 mm from the joint center line at both advancing and retreating sides.

Some specimens were post weld heat treated by Nabertherm 1340 and Reta 1350 furnaces. The alloy was solution heat treated at 550 °C for a soaking time of 6 hours. Specimens were placed in an induction furnace and heated from room temperature at a rate of 50 °C per hour. After soaking time the specimens were removed and water quenched at room temperature. Artificial aging treatment was carried out at 175 °C for a time of 12 hours. After the specimens removed and cooled to the room temperature, it has been waited for the secondary artificial aging treatment for three weeks.

After having the base materials welded; hardness profile, tensile tests and fatigue tests of base materials (BM), welded joints (FSW) and post weld heat treated joints (PHT) have been performed in order to make a mechanical characterization. Fatigue and tensile tests have been performed by computer controlled Instron 8500 Servo Hydraulic Universal Test Machine which has 200 KN static and 100 KN dynamic load capacity. Standard fatigue and tensile tests were carried out and all specimens were been prepared in accordance with ASTM E 466 and ASTM E 8M standards. The surfaces of the specimens were machined off and the specimen dimensions have been given in Fig. 2. Tensile tests were carried out at a speed of 1 mm/min and then 0.2% ultimate tensile strength and percentage of elongation were recorded. Fatigue tests were carried out in room conditions at a stress ratio of $R=0.1$ and at a frequency of 10Hz. Load was applied transverse to the welding direction. Constant amplitude fatigue tests were performed and the load applied was in sinusoidal curve. Almost all the experiments were maintained till the specimens have been broken.

**Figure 2. Fatigue and tensile specimen (dimensions are given in mm).**

Vickers microhardness testing performed on the weld cross-sections provided microhardness profiles that revealed the compensation of the normal degradation of 6013-T6 Al in the heat affected zone (HAZ), by using Buehler Digital Microhardness Tester MMT-3. The Vickers hardness values were taken at about 1 mm increments from base metal to base metal across the weld (more than 30 mm from each sides), at a depth of 1.5 mm from the surface of the welded sheet. Vickers micro-hardness was carried out with 100 gf load and 15s dwell time. It was also noticed that all the welds showed very high and erratic microhardness values in the weld

zone, in comparison to the base material. Microhardness measurements, tensile tests and fatigue tests were carried out 3 months after welding.

In addition to mechanical characterization, extensive microstructural investigations have been performed by optical and scanning electron microscopy. Standard metallographic techniques were applied to prepare samples for optical microscopy (OM) and Zeiss Supra 50VP FEG attached with Oxford Instrument EDX-7430T scanning electron microscopy (SEM). The samples were mechanically polished. During polishing firstly sandpaper and then diamond was used. After polishing, etching was carried out in 0.5% aqueous solution of hydrofluoric acid.

3. RESULTS AND DISCUSSION

A Vickers microhardness testing machine Buehler Digital Microhardness Tester MMT-3 was used to measure the hardness across the weld cross section of the FSW joints; the measured values are obtained and the diagram drawn in Figure 3. The base metal in the condition T6 showed average hardness value of 135 HV, but in the as-welded joint the hardness was average 100 HV in the FSW zone and 85 HV in the HAZ and the average hardness value of PHT joint was 125 HV. The weld zone is considerably softer than the BM. This softening is observed within about 13 to 15 mm of both sides of the weld centerline ($x = 0$). Similar results with respect to the shape of the microhardness curves were reported by previous studies (Tesch et al 2007). The HAZ is soft and it behaves in a ductile manner during mechanical loading. And also it was observed that after post weld heat treatment hardness values increase about to base materials values.

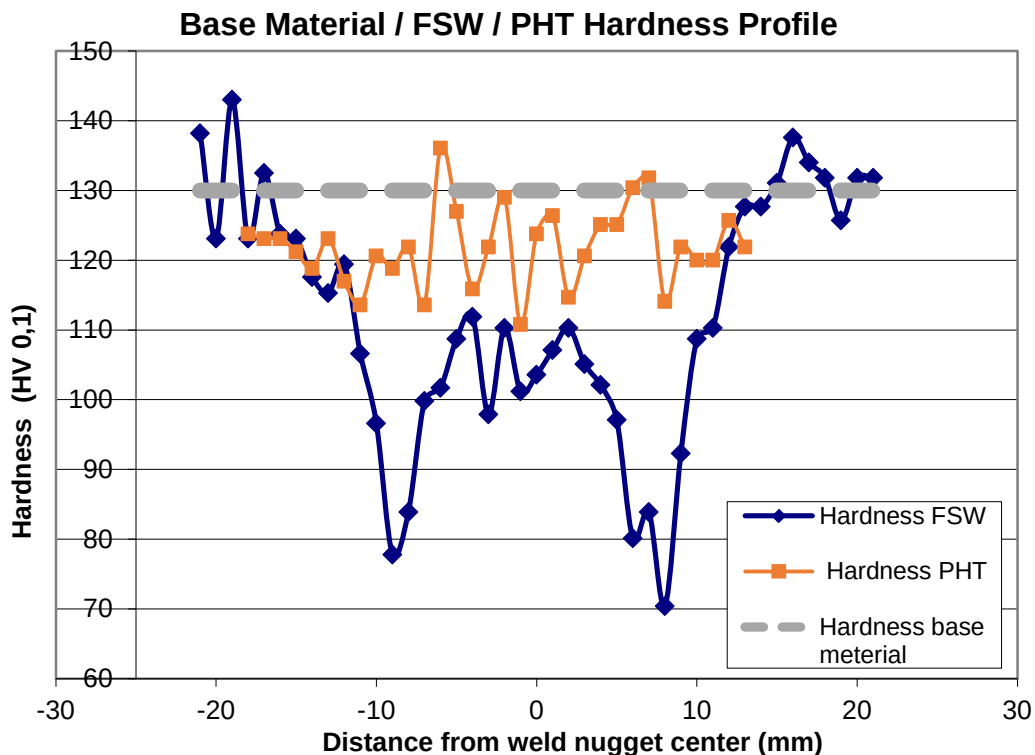


Figure 3. Hardness profiles of base, welded and post weld heat treated materials.

The 0.2% offset yield strength; ultimate tensile strength and percentage of joint efficiency were recorded. The ratio between the tensile strength of a welded joint and the tensile strength of unwelded base metal is known as the joint efficiency (Elangovan et al 2008). The tensile tests in the T6 condition showed that fracture always occurred in the HAZ. Failure took place approximately as a 45 degree shear surface and was accompanied with some necking (Liu et al 2003). The average tensile properties of our material are given in Table 2 which has been composed of from different specimens. Compared to the base material, specimens tested transverse to the weld exhibit reduced strength and ductility. The unwelded base metal showed a yield strength and tensile strength of 330 MPa and 375 MPa, respectively. However, the yield strength and tensile strength of the as-

welded (FSW) joints were 207 MPa and 281 MPa, respectively. This indicates a 25–35% reduction in strength for the FSW joints. And also the yield strength and tensile strength of the post weld heat treated (PHT) joints were 300 MPa and 245 MPa, respectively. This also indicates a 20% reduction in strength towards the base material and increment in strength towards the FSW joints.

Table 2. Tensile test results of base and friction stir welded AA 6013 T6 sheets.

Material	Young's Modulus [MPa]	Stress at 0.2% Yield Strength [MPa]	Stress at Max. Load (ultimate tensile strength) [MPa]	Changing in the strenght [%]	Joint Efficiency $\sigma_{\max\text{FSW}} / \sigma_{\max\text{Base}}$ [%]
6013-T6 Base	31804	330	375		
6013-T6 FSW	32453	207	281	64	75
6013-T6 FSWPHT		245	300	75	80

S-N fatigue test were performed at constant load amplitude, constant frequency of 10 Hz and constant stress ratio $R=0.1$. Load was applied in transverse direction. Constant amplitude fatigue crack growth tests were performed on a servo-hydraulic machine. The load direction in the S-N tests was perpendicular to the weld direction. The maximum stress levels used were taken as a function of the yield stress for base, welded and post weld heat treated materials. Characteristic fatigue crack growth (S-N) curves plotted over the number of fatigue cycles are shown in Figure 4 for base, welded and post weld heat treated specimens.

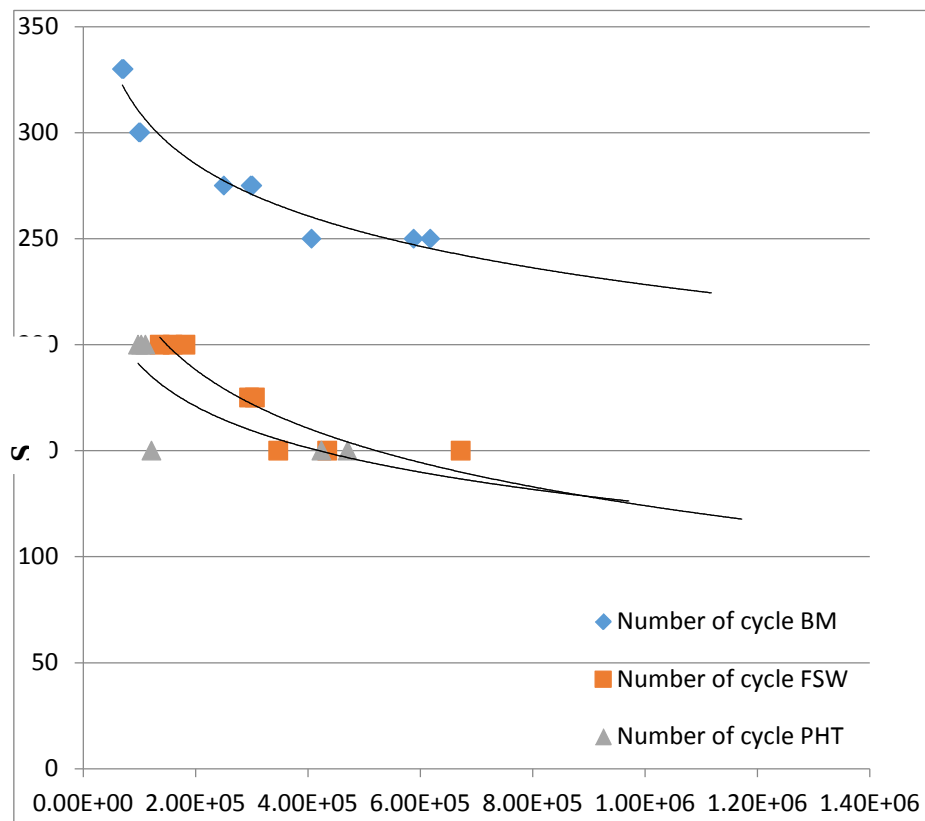


Figure 4. Fatigue life results of base, welded and post weld heat treated specimens.

In literature several papers have been inspected about the fatigue life of friction stir welded materials. Especially results of fatigue tests of notched and un-notched friction stir welded specimens of different kind of aluminum alloys and also 6xxx series can be found (Moreire et al2008).

The microstructural evaluation of the Al 6013-T6, has been investigated. SEM images of the base material are shown in Figure 5. As it can be seen in the Figure 5.a, the base material is determined by a recrystallized microstructure with equiaxed grains. EDX images have been taken from different parts of Figure 5.b. The chemical compositions were approximately same to each other in this EDX results and one of the points taken was spectrum 2 that was shown on Figure 5.c. The EDX results invariably identify Mg_2Si as the predominant precipitate in all the joint variations (Prado et al 2001). As reported from the previous studies, the major precipitate in 6000 series Al-Mg-Si alloy system is Mg_2Si . The formation and distribution of these precipitates depend on solution treatment and aging treatment (Wang et al 2013).

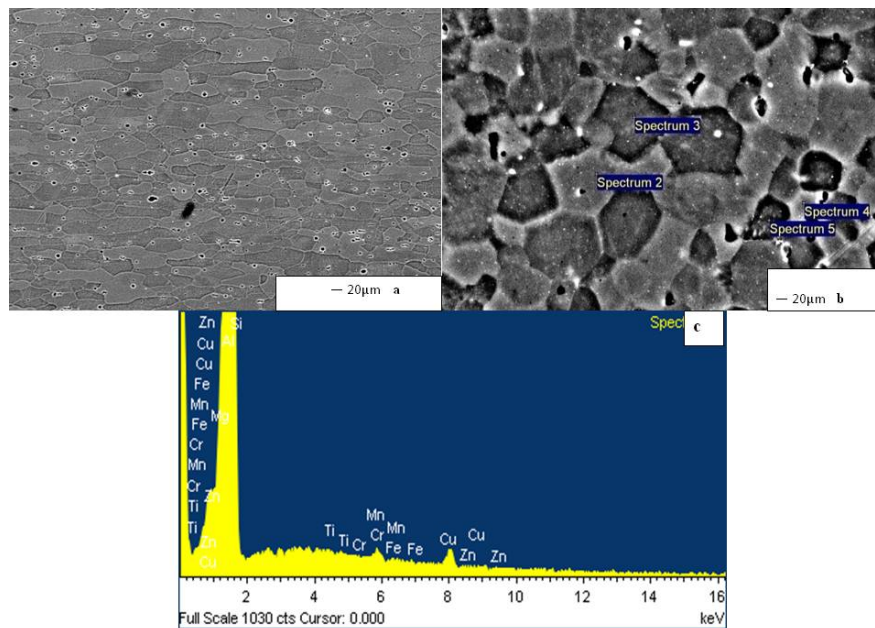


Figure 5. (a) SEM images of the base material (b) SEM images of the base material (c) EDX results for AA6013-T6.

The joining of AA6013 T-6 to itself was successfully welded by friction stir welding. The microstructure of FSW joints can be separated to four zones; first base material; second heat affected zone (HAZ); third thermo-mechanical affected zone (TMAZ); and fourth weld nugget (Figure 6).

On un-notched specimens, the starting and the growth of the cracks have been formed in the edges of the specimens where the stress concentration is higher than the other parts. In Figure 7 the starting of the crack seen on the left corner and the growth of crack can seen clearly.

When the Figure 8 is analyzed it is seen that the plane in which the fatigue stress moved on is perpendicular to the stress axis and ductile rupture zone is positioning 45 ° angle to the same axis. In ductile metals under tensile stress the expected fracture plane is at 45 ° to the same axis. Figure 8 shows advancing of crack face in the circular form.

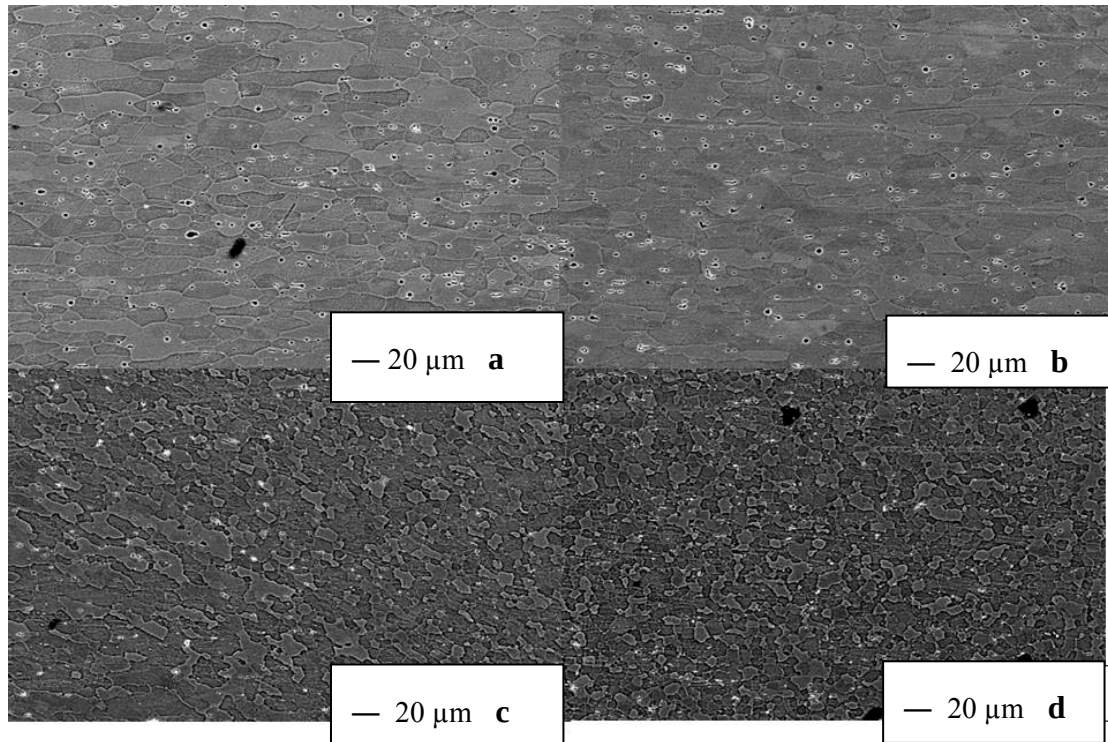


Figure 6. Optical microstructures (SEM images) of FSW joint of 6013 T-6: (a) base material; (b) heat affected zone (HAZ); (c) thermo-mechanical affected zone (TMAZ); and (d) weld nugget.

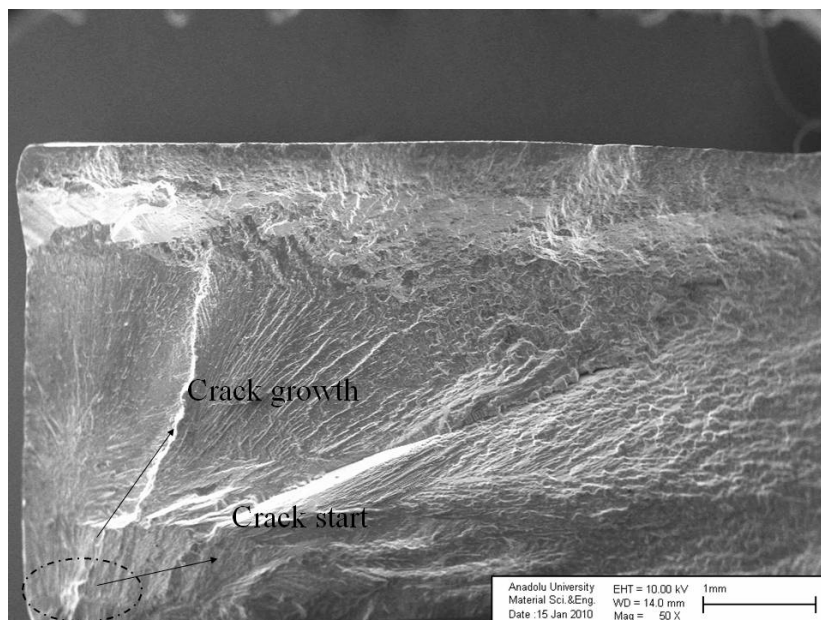


Figure 7. Crack start and crack growth.

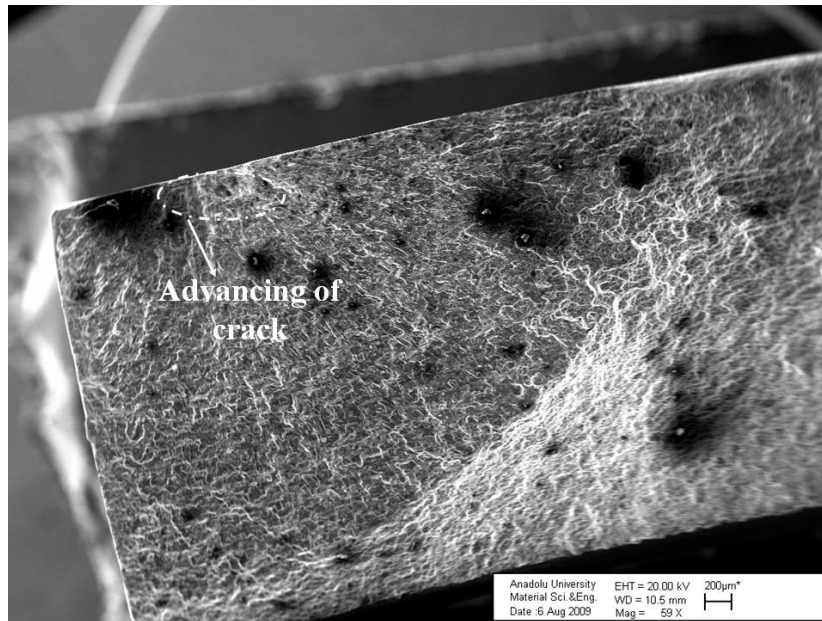


Figure 8. Advancing and movement of crack face.

In Figure 9 the final breaking zone and the boundary between the end regions of fatigue is shown in further detail.

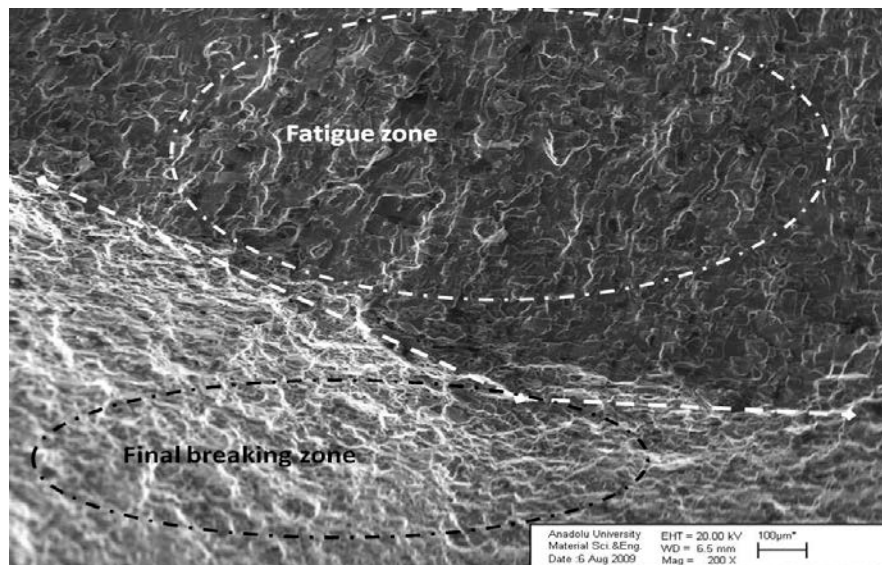


Figure 9. The boundary between the end regions of fatigue.

All figures show dimpled fracture surfaces and dimples forms the half of the gaps that are associated with intermetallic particles (Figure 10). This, despite the changes in the microstructure associated with FSW, it shows that ductile fracture is dominated in all regions. Ductile fracture in one of the spaces at the break during the formation of gaps, with large (coarse) grain intermetallic particles are formed. Some of the important parameters in ductile fracture are the size of the intermetallic particles, the distance and the volumetric ratio.

Ductile fracture under tensile loading during the pores of materials usually occurs before necking. However, if the necking occurs at relatively earlier stage, with the result that the pore formation is more pronounced and prolonged pits will appear larger. In this manner at an early stage necking occurs is a measure of ductility of

material wells containing significantly larger fracture surfaces show that the material is more ductile (Zhao et al 2014).

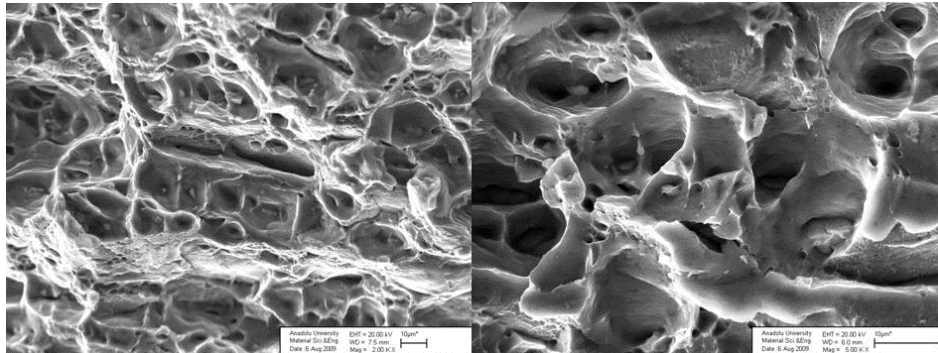
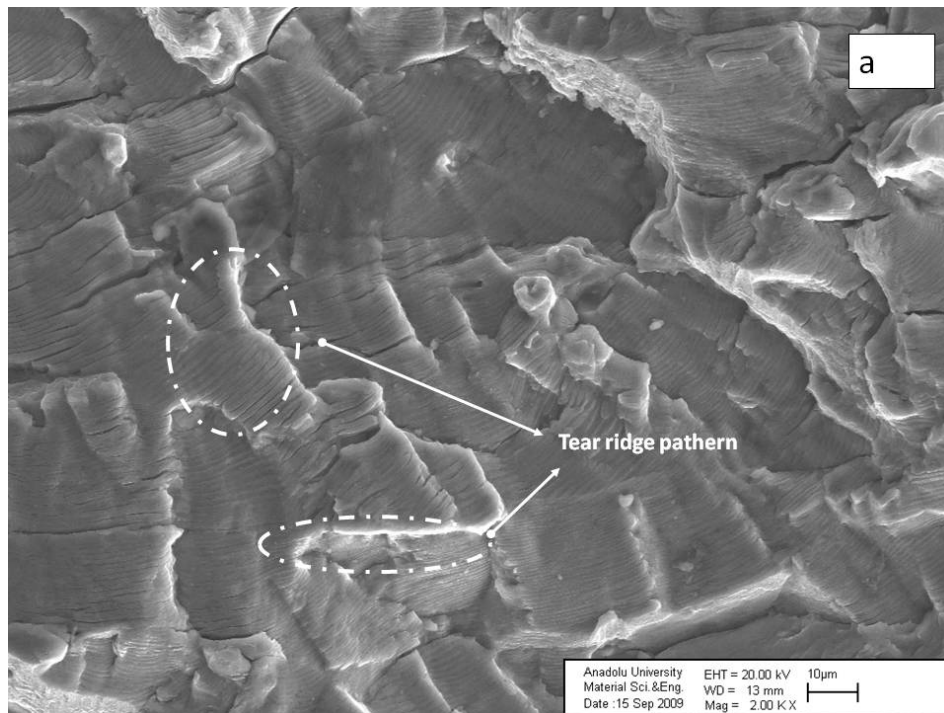


Figure 10. Dimpled fracture surfaces.

From Figure 11.a and Figure 11.b images it is observed that along the main crack propagation direction is the same but with a small angular difference advancing numerous fatigue cracks formed by the merger of the tear sets (tear ridge pathern).



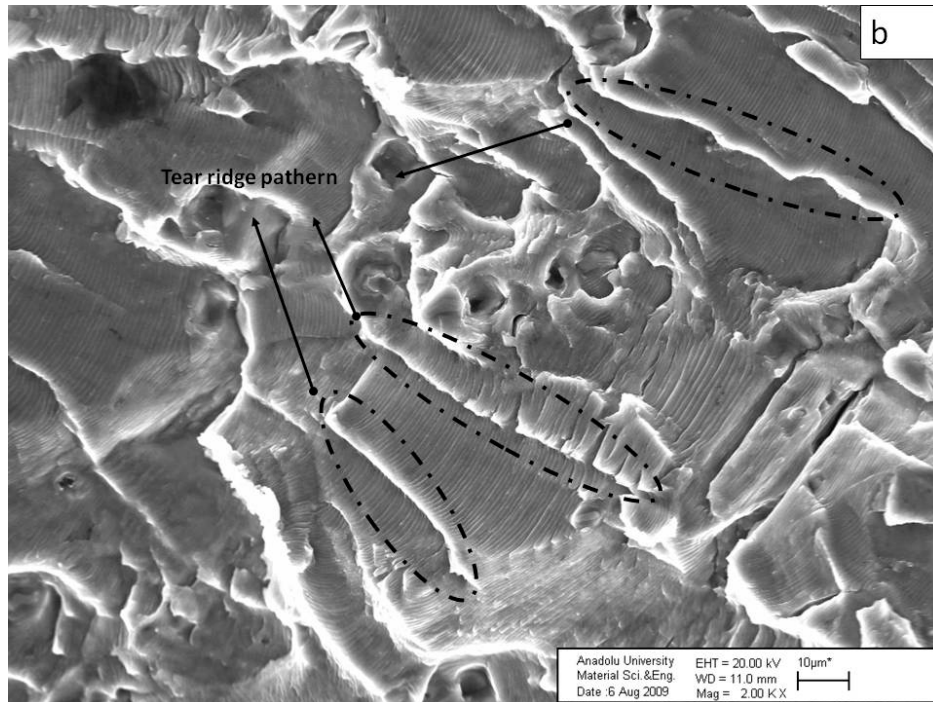


Figure 11. (a)(b) Tear ridge pathern

4. CONCLUSIONS

The joining of AA6013-T6 to itself was successfully carried out using a friction stir welding technique. The fatigue, tensile, microstructure, microhardness and EDX analysis of friction stir welded AA6013-T6 have been studied in the present work. The following conclusions have been obtained:

- The microstructure of the welding zone in the friction stir welded AA6013 T-6 was divided into four zones are base material, heat affected zone (HAZ), thermo-mechanical affected zone (TMAZ) and weld nugget.
- EDX measurements clearly show that both the parent material and the weld region consist of relatively homogenous distributions of the fine and coarse Mg_2Si particles.
- The base material exhibits average hardness value of 130 HV while the weld nugget has an average hardness of 100 HV. The average hardness values in the TMAZ are slightly lower than in the weld nugget. The hardness value of the post weld heat treated material is almost near to the base material 125 HV and this is shows post weld heat treatment provides higher strength.
- The reasons for the better tensile properties of post weld heat treated to the as welded materials are; smaller grain size, the lack of a precipitate free zone, higher dislocation density, and finer strengthening Mg_2Si precipitates.
- Joints exhibited a joint efficiency of 64-75 % and after post weld heat treatment the efficiency increases to 75-80 %.
- Friction stir welding results in a dynamically recrystallized grain structure in the weld nugget with smaller grain size than in the BM. Such dynamically recrystallized grains are equiaxed compared to the elongated grains observed in the rolled BM.
- Fine equiaxed grains in the FSW region implies that dynamic recrystallization has taken place during friction stir welding due to plastic deformation.
- The results of the fatigue tests point out that with higher strength, post heat treated AA6013-T6 friction stir welded material has lower fatigue strength than the friction stir welded material. This was an unexpected result. Generally materials with higher strength also have higher fatigue strength. In friction stir welding process there are different variations in grain size across the thickness of the material throughout the welding zones. Below the side of the stirred, fine grained structure is the fibroid region where the grain size is inhomogeneous. The

reduction in fatigue strength of post weld heat treated specimens was related to internal gaps (pores) causing crack initiation.

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