# Effect of Friction Stir Welding on Mechanical Properties of Dissimilar Aluminium Alloys

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## ABSTRACT
Friction stir welding is advance joining process for different similar and dissimilar metals. It is commonly used for joining of Aluminium alloys. In this study an attempt were made to join commercial structuralaluminium with 7039 aluminium alloy. A zig-zag pattern of hardness was found in weld nugget. Microstructural characterization and fractography of joints were examined using optical and scanning electron microscopes. Also, the effects of the welding parameters ontensile properties of friction stir welded joints were analyzed. The results showed that the optimum parameters to get a maximum of tensile strength were 635 rev/min, 12 mm/min and, where the maximum of tensile elongation was obtained at 635 rev/min, 8 mm/min after post weld heat treatment. All welds were failed outside of weld nugget in low strength alloy side. The tensile strength of welds was decreases after post weld heat treatment.

## Keywords
Friction stir welding, Mechanical Properties, 7039 Al alloy

## 1. INTRODUCTION
Friction-stir welding (FSW) is an autogenous solid-state welding process in which the material being welded is not melted and recast as in case of conventional fusion welding processes but plastically deformed, extruded and forged to form weld joint at temperatures below melting point [1-3]. In FSW a rotating tool with a shoulder and terminating into a specially designed pin, moves along the faying surfaces of two rigidly clamped plates placed on a backing plate as shown in Fig. 1. The pin is lowered into the plates so that shoulder makes firm contact with the top surface of the work-piece [4-5]. The pin diameter is slightly larger than the thickness of plates while its length is shorter than the thickness of the plates [6]. The localized heating produced by friction at the shoulder and to a lesser extent at the pin surface softens the material around the pin. This plasticized soft material is transported from the front of the tool to the trailing edge due to tool rotation and translation where it is forged into a monolithic joint [7].

As FSW is an energy efficient, environment friendly welding process so there have been widespread benefits resulting from the application of FSW in joining most of the aluminium alloys (because of high strength to weight ratio, durability etc.) for aerospace, shipbuilding, automotive, marine and railway industries because of the absence of parent metal melting and related problems such as brittle dendritic structure, porosity, distortion and residual stresses [8-10]. Aluminium alloy 7039 has good combination of strength and toughness at room temperature and at cryogenic temperature -1960C. Aluminium alloy 7039 is used for light weight transportable bridges, girders, armor plates, military vehicles, road tankers, railway transport systems and cryogenic pressure vessels [11]. The fusion welding of high strength precipitation hardening 7000 series aluminum alloys is unattractive because of loss of strength, solidification and liquation cracking. Friction stir welding can avoid most of these problems but suffer from severe softening in the heat affected zone (HAZ) and poor corrosion resistance. Hence to improve mechanical properties of weldments it is necessary to, overcome or minimize the HAZ softening and to control coarse columnar solidification structure in fusion welds, responsible for inferior weld mechanical properties and poor resistance to hot cracking [12-13]. Above mentioned problems are automatically overcome by FSW because of low temperature and narrower HAZ.

## 2. EXPERIMENTAL PROCTDURE
The friction stir butt welds between rolled plates of size 150mm x 50mm x 6mm of 7039 aluminium alloy and Commercial structural aluminiumwere obtained at two transverse speeds (8 and 12mm/min) and one rotational speed (635 rpm) employing single pass welding procedure. A specially designed and developed fixture was used to hold plates firmly in butt joint position during friction stir welding. The direction of welding was normal to the rolling direction. Quenched and tempered die steel tools with cylindrical threaded pin were used to fabricate the joints. The Electron dispersive X-ray (EDAX) analysis was undertaken to determine the composition of specific elements in the material being joined. The chemical compositions of the base metals are presented in Tables 1 and 2, respectively. Room temperature mechanical properties of the base metal are presented in Tables 3. Vertical Milling Machine (HMT, 5 H.P.) was used to fabricate FSW joints using optimized FSW parameters. FSW parameters were optimized by making welds at constant rotary speed of 635 rpm and different welding speeds of 8mm/min, 12 mm/min, 19 mm/min and 30 mm/min. Subsequently welds were subjected to visual and destructive inspection to identify weld defects (if any) such as voids or tunnel defects. It was found that welds produced at 8mm/min and 12 mm/min welding speed are sound and free from defects.Vickers micro hardness test and tensile test of welds was performed at room temperature in as welded and post weld heat treated (PWHT) conditions for evaluating mechanical properties. Tensile properties of each of these FSW joints were evaluated immediately after fabrication, without post-weld heat treatment, to obtain mechanical properties of as welded (AW) joints. The weldments were solution treated at 550ºC temperature for 4 hours, followed by water quenching and artificial aging at 190ºC for 6 hours. After PWHT, the welded joints were sliced using a power hacksaw and then tensile specimens were prepared as per the ASTM E8M-04 specification. Tensile tests were carried out using a 25 KN; electro-mechanically controlled Universal Testing Machine (H25K-S, Hounsfield). The 0.2% offset yield strength; ultimate tensile strength, strain and percentage elongation were recorded. A Vickers micro hardness tester (LeitzWetzlar) was employed for measuring the hardness across the joint with a load of 100 grams and 10 seconds dwell time.A scanning electron microscope was used to characterize the modes of fracture of the tensile tested specimens. Microstructural analysis was carried out to study microstructure and various unique features associated with different zones of friction stir welds using a light optical microscope (Zeiss).

## 3. RESULTS AND DISSCUSION

## 3.1. Microstructure

3.1.1. Microstructure of Base Material

Microstructures of base material are given in Figure (1). It can be observed that there are fine precipitates ($Zn_2Mg$) in matrix of Al solution in 7039 Al-alloy while there is no such type of precipitates in commercial structural aluminium. Further, it can be noticed that grainsof aluminium solid solution in commercial aluminium are finer than 7039 alloy.

3.1.2. Microstructure of Weld

The microstructure of the joints was examined at various locations in the transverse direction of friction stir welded joint of commercial structural aluminium and Al-Zn-Mg (7039 Al alloy) alloy. Optical microscope was used to obtain microstructureof weld in transverse direction. Micrographs of FSW region are shown in Figure (2) and from the figure it is clear that nugget have a different microstructure than that of base. The most prominent feature of the friction stir welded joint is nugget zone, which is symmetric about the weld centre line and of size approximate equal to tool pin diameter. As the temperature generated by FSW process is not high enough and deformation was not severe, no effect was shown in the base metal on 7039 alloy side while it is visible on commercial structural aluminiumside. Material mixing in weld nugget is highly depends upon "onion ring" pattern.

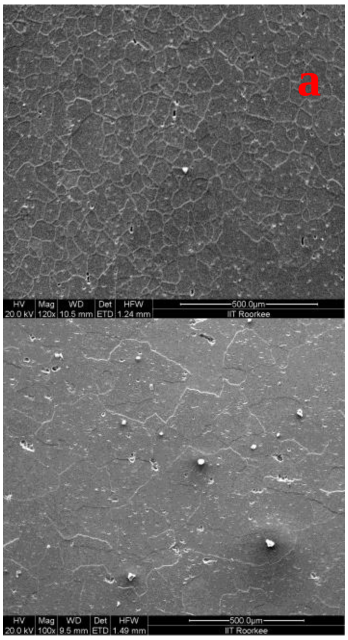


**Fig. 1: Microstructure of as received materials, (a) Commercial Structural Aluminium, (b) 7039 Al-alloy**

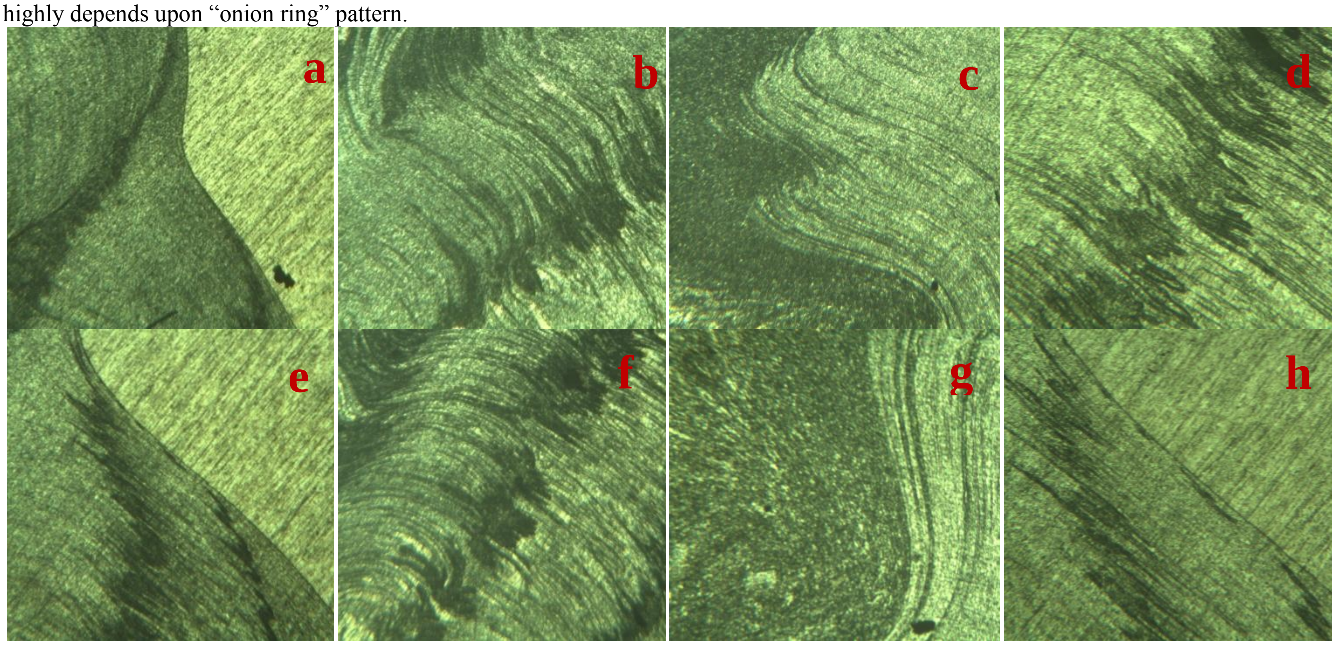


**Figure 2: Microstructure of friction stir welds at 50X. (a) interface at 7039 Al-alloy side, (b) nugget, (c) interface at Comm. Str.aluminium side & (d) material mixing pattern at 8mm/min welding speed.(e) interface at 7039 Al-alloy side, (f) nugget, (g) interface at comm. Str.aluminium side & (h) material mixing pattern at 12 mm/min welding speed**

Figures 2 (d & h) shows visible change in "onion ring" pattern at different welding speed. It shows that material mixing in weld nugget depends on the welding speed and it also affects mechanical properties of weld. There is no visible change occurs in microstrcture at both the welding speed after post weld heat treatment.

## 3.2. Mechanical properties

### *3.2.1.MechanicalProperties of Base Material*

The mechanical properties of base material were found out by micro hardness and tensile tests. The average micro hardness value of commercial aluminium was found 66.6 HV while 7039 Al-alloy have micro hardness of 115 HV which is much high as compare to commercial structuralaluminium. The yield strength and ultimate tensile strength is very high in 7039 Al-alloy as compare to commercialstructural aluminium. Mechanical properties of base material are given in Table (3).

*3.2.2. Mechanical Properties of Weld*

Mechanical properties of friction stir welded joint were characterized in terms of microhardness and tensile properties in as welded and heat treated condition. Characterizations of mechanical properties of friction stir welded joint were carried out to compare the mechanical properties of weld to base material.

### 3.2.1. Hardness

*3.2.1.1. Hardness Distribution at 8 mm/min Welding Speed*

The hardness across the weld cross section in transverse direction of the FSW joints was measured by Vickers micro hardness tester with 0.5 mm spacing. The measured microhardness values are presented in Figure (3) for weld joint in as welded and heat treated condition produced using 8 mm/min welding speed. The hardness curve is highly asymmetrical with respect to the weld center line because of non-uniform field of plastic flow and both the base material is highly different in there mechanical properties.

**Table 1: Chemical Composition (wt.%) of Comm. Str. Aluminium**

| | |
|---|---|
| Mg | 0.11 |
| Si | 0.13 |
| Zn | 0.17 |
| Fe | 0.62 |
| Cu | 0.05 |
| C | 0.32 |
| Mn | 0.01 |
| Al | Balance |

**Table 2: Chemical Composition (wt.%) of 7039 Al-alloy**

| | |
|---|---|
| Mg | 2.37 |
| Si | 0.31 |
| Mn | 0.68 |
| Fe | 0.69 |
| Cu | 0.55 |
| Zn | 4.69 |
| Al | Balance |

The minimum hardness of 56.6 HV is obtained in base material of commercial aluminiumand maximum hardness of 153.5 HV is obtained in HAZ in the advancing side of weld after post weld heat treatment. The hardness varies in the weld nugget from 82 HV to 130 HV. Large variation of hardness in weld nugget was found because of the both of the material which was welded, having very different in mechanical property.

**Table 3: Mechanical Properties of Unwelded Base Materials**

| Material | 7039 Al-alloy | Comm. Str. Al. |
|---|---|---|
| Yield strength (YS) (MPa) | 268 | 128.6 |
| Ultimate tensile strength (UTS) ( MPa) | 342 | 161.6 |
| Vickers Microhardness at 100 gms load (HV) | 135 | 56.6 |
| Elongation (%) | 12.54 | 12.98 |

After heat treatment the hardness in structural aluminium decreases while in 7039 Al-alloy increases. The hardness of commercial aluminium varied from 72 HV to 80 HV after heat treatment which is much more as compare to that in as welded condition. The hardness in 7039 Al-alloy decreased after heat treatment and it varies in between 110 HV to 116 HV.

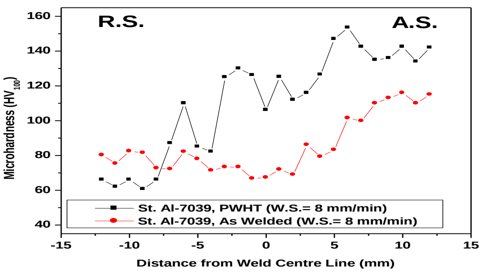


**Figure 3.Hardness distributions in joints welded using 8 mm/min Welding speed in as welded and Heat treated conditions**

The hardness of weld nugget varied from 66.7 HV to 86 HV which is quite less as compare to post weld heat treated condition. The hardness variation is zigzag in weld nugget from retreating side to advancing side after heat treatment as compare to in as welded condition because of grain refinement and precipitation hardening.

*3.2.1.2. Hardness Distribution at 12 mm/min Welding Speed*

The hardness varies in the weld nugget from 71 HV to115 HV in as welded condition while it varies from 59 HV to 130 HV after post weld heat treatment as shown in figure (4). The maximum hardness occurs in the advancing side of weld where 7039 Al-alloy was place and it is of 152.7 HV after post weld heat treatment. The variation of hardness is high in weld nugget produced using 12 mm/min welding speed as compare to weld nugget produced using 8 mm/welding speed. After increasing the welding speed variation in hardness distribution occurs because of different heat input at different welding speed. After heat treatment the hardness in structural aluminium increases but in 7039 Al-alloy, it is decreases.

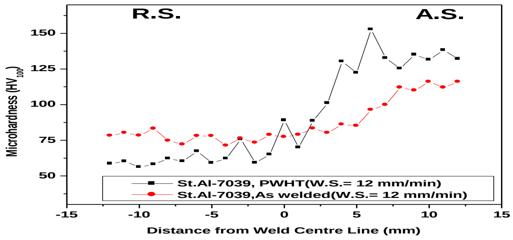


**Figure 4.Hardness distributions in joints welded using 8 mm/min Welding speed in as welded and Heat treated conditions**

### 3.2.2. Tensile Strength

Tensile test were carried out in transverse direction of weld. Tensile strength of weld and base are given in table 4.

**Table 4: Tensile Properties of Welds**

| Material Condition | YS (MPa) | UTS (MPa) | Elonga-tion (%) | Efficie-ncy (%) |
|---|---|---|---|---|
| 7039 Al-alloy | 268 | 342 | 12.54 | - |
| Comm.Pure Al | 128.6 | 161.6 | 12.98 | **100** |
| A.W.(8 mm/min) | 80.9 | 109.6 | 10.55 | 67.82 |
| PWHT (8 mm/min) | 38.92 | 98.3 | 16.12 | 60.83 |
| A.W.(12 mm/min) | 76.2 | 118.3 | 12.75 | 73.20 |
| PWHT (12 mm/min) | 37.92 | 70.7 | 14.55 | 43.75 |

*3.2.2.1. Tensile Strength at 8 mm/min Welding Speed*

Engineering stress and strain diagrams for base metal, as welded and heat treated friction stir welds produced using 8 mm/min welding speed are presented in Figure (5). From stress-strain curve it is evident that strength of 7039 al-alloy is very high as compare to commercial structural aluminium. Strength of weld joint is less than both of base material in as welded and heat treated condition. The yield strength and tensile strength of as welded and heat treated FSW joints are inferior to unwelded base material. The yield strength and ultimate tensile strength of weld is less than low strength base material (commercial aluminium). Sharp loss was observed in yield strength and tensile strength after heat treatment. Because of heat treatment grains refined, which reduces the strength and increases the elongation.In as welded condition yield strength decreases by 37.1% and ultimate tensile strength decreases by 32.2% as compare to commercial structural aluminium. After heat treatment the yield strength decreases 69.7% while yield strength decreases by 39.2% as compare to commercial structural aluminium.

*3.2.2.2. Tensile Strength at 12 mm/min Welding Speed*

The yield strength at 12 mm/min welding speed is low as compare to 8 mm/min welding speed while ultimate tensile strength increases but after heat treatment both yield strength and ultimate tensile strength decreases because of grain coarsening. Variation in tensile properties is shown in figure (6). In as welded condition yield strength decreases by 40.7% and ultimate tensile strength decreases by 26.8% as compare to commercial structural aluminium while after heat treatment the yield strength decreases 70.5% and ultimate tensile strength decreases by 56.3%.

## 3.3. Fracture Surfaces of Tensile Test Samples

Scanning Electron Microscope was used to characterize the micro fracture surfaces of the tensile tested specimens to understand the failure patterns. SEM photographs of as welded and heat treated FSW joints were taken for whole joint surface of the fractured specimen, as shown in Figure (7&8). Tensile properties are highly depending upon the hardness distribution. Materials were failed at lowest hardness region. In both the welding condition all welds were failed in commercial structural alloy or interface of HAZ and base of commercial structural alloy. This is due to because the strength is in weld nugget is increases after welding by the mixing of high strength material. All of the fractured surfaces consist of dimples of varying size and shape. These show that all failures are ductile in nature. The characteristic of fracture surfaces are given in table 5.

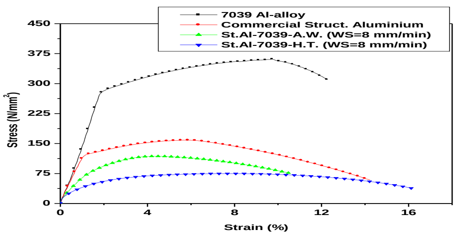


**Figure 5. Engineering stress and strain diagrams for base metal, as welded and post weld heat treated friction stir weld produced at 8 mm/min welding speed.**

## 4. CONCLUSION

In this work the effect of friction stir welding of commercial structural aluminium in as welded and post weld heat treatment was examined on microstructure and mechanical properties. Following conclusions are derived from the results of this work:

1. The hardness curve is highly asymmetrical with respect to the weld center line. There is very high variation found in hardness of FSW joints in as welded condition. The hardness in weld nugget is increases from lower hardness material (commercial structuralaluminium) to higher hardness material (7039 Al- alloy).
2. After post weld heat treatment the hardness in weld nugget and 7039 Al-alloy increases but it decreases in commercial structural aluminum.
3. The yield strength and ultimate tensile strength decreases after heat treatment but the percentage elongation increases as compare to in as welded condition at both welding speed.
4. At high welding speed ultimate tensile strength increases as compare to low welding speed in as welded condition but it is reverse after post weld heat treatment.
5. The yield strength of weld produced at higher welding speed decreases approximately by 5.8% while ultimate tensile strength increases by 8.26% as compare to low welding speed.
6. After PWHT yield strength decreases by 2.8 % and ultimate tensile strength decreases by 28 %.
7. The welding process softens the material significantly which decrease the hardness, tensile strength and increases the ductility of the material. A sharp increase of 19.47% in percentage elongation was observed for the heat treated joint produced at low welding speed.

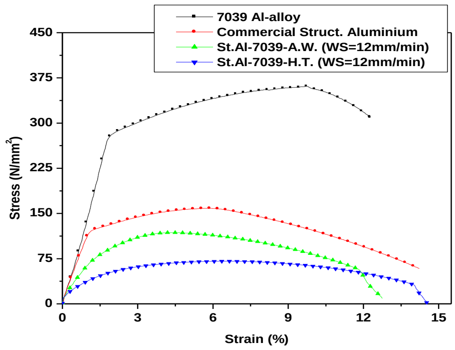


**Figure 6. Engineering stress and strain diagrams for base metal, as welded and past weld heat treated friction stir weld at 12 mm/min welding speed**

**Table 5: Fracture properties of Tensile tested samples**

| Welding Condition | Fracture Location | Fracture Characteristic | Fracture Mechanism | Tested Samples |
|---|---|---|---|---|
| As welded (8 mm/min) | Interface of Comm.Al base /HAZ | River like pattern | Cleavage |  |
| Heat treated (8 mm/min) | Interface of Comm.Al base /HAZ | Dimples | Microvoid coalescence |  |
| As weld (12 mm/min) | Interface of Comm.Al base/HAZ | River like pattern | Cleavage |  |
| Heat treated (12 mm/min) | Interface of Comm.Al base/HAZ | Dimples | Microvoid coalescence |  |

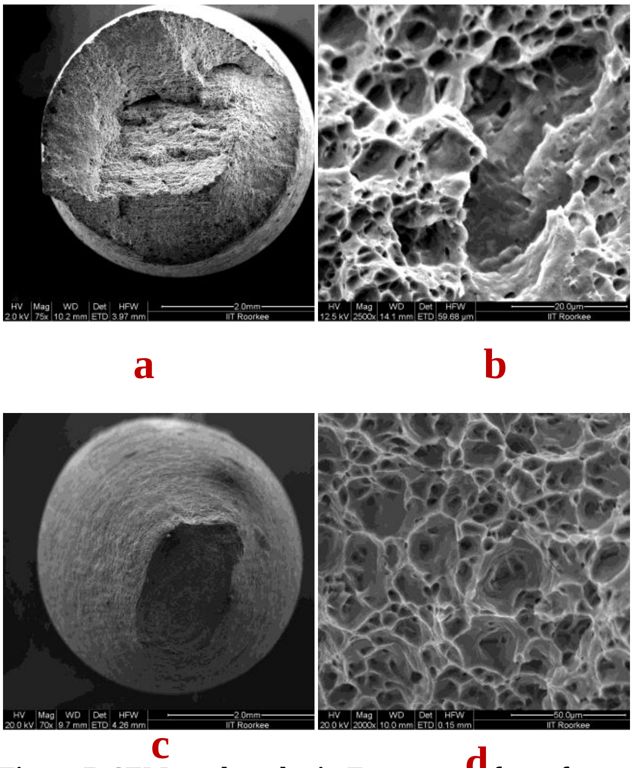


**Figure 7. SEM used to obtain Fracture surface of as welded and heat treated tensile specimen of FSW joints (a & b) as welded, (c & d) Heat Treated at 8 mm/min welding speed**

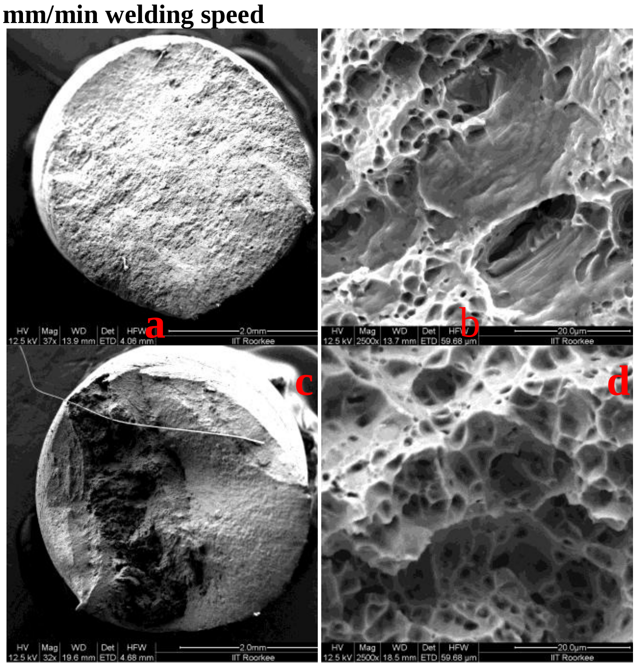


**Figure 8. SEM used to obtain Fracture surface of as welded and heat treated tensile specimen of FSW joints, (a & b) as welded (c & d) Heat Treated at 12 mm/min welding speed**

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