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A N I N T E R N A T I O N A L J O U R N A L

Effect of Preheating on Microstructure and Tensile Properties of Friction Stir Welded AA7075 Aluminium Alloy Joints

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ABSTRACT

The high strength AA7075 aluminum alloy is commonly used in the aerospace components due to its exclusive mechanical properties like lightweight and high strength. This alloy cannot be welded by fusion welding techniques due to solidification cracking which severely degrade the mechanical properties of the joint. In contrast, through friction stir welding (FSW) process solidification relate defects can be eliminated. Anyhow, the strength of friction stir welded joint is influenced by process parameters and tool parameters. These parameters govern the heat input, metal flow, microstructure evolution and mechanical properties of the weld. In normal welding condition, (without preheating) heat is generated by friction force which is produced between tool and workpiece. In this paper an added heat input through preheating the metal before weld. This preheating temperature effects on microstructure, microhardness and tensile properties of the joints were investigated. From this study the following conclusions are derived. Sufficient heat input should be given to obtain defect free and quality joint. The results showed that, preheating the base metal to 100 °C prior to welding improved the tensile strength and joint efficiency compared to the joints made without preheating.

Key words: Aluminum alloy, Preheating, Friction stir welding, Tensile strength, Microstructure

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INTRODUCTION

Friction Stir Welding (FSW) is a solid state welding process which was developed by TWI in the United Kingdom two and half decades before. In this technique, a nonconsumable rotating tool is plunged at the interface of base metals. This thermo-mechanical action between the tool and base metal produce frictional heat, as the result a base metal around the tool is locally plasticized. This plasticized metal at the front of the tool is extruded and forged at the back end of the tool when tool moved forward, thus the weld joint is produced [1-3].

In commercial point of view, productivity of friction stir welded component is a challenging task. It means that increasing welding speed beyond optimal value is not possible. As the welding speed increases the heat input reduces as well as the corresponding heating area around the tool also reduces which leads to poor quality weld joint [4]. In addition higher welding speed also leads to tool failure, for this reason many researcher have been replaced costly tools [9]. Few authors have improved welding speed of friction stir welding by preheating the base metal with external heat source [5-9].

In normal friction stir weld preheating of base metal is achieved by increasing the dwell time period in the plunging stage. Increasing dwell time period does not offer significant temperature improvement in weld [5]. For preheating external heating can be used, it is recognized through analytical model that external heat can enhance quality of the weld and also increase the welding speed [6]. Preheating of base metal of the weld improved the strength and Vickers hardness of the weld joint [7]. External heating provide at the bottom of the weld plate also improved the strength of the weld [8]. Different methods of preheating are employed, Yaduwanshi, et al. used plasma for preheating in friction stir welding to weld aluminum alloy[12], Lotfi et al. designed a preheating setup and optimized its process parameters [13], and Sun et al. applied gas welding torch for preheating in friction stir spot welding of carbon steel weld [9]. Form these literatures it can be suggested that preheating with gas weld torch is the simple and effective approach among these preheating techniques. This simple gas weld torch heating was implemented in this research.

Preheating can improve the welding speed but it reduces the frictional stress of base metal which results in less friction heat generation [5]. It also reduces shear stress and stirring action, reducing of these values beyond certain limit will lead to defected joint [1]. The preheating can support the loss of heat generation. So it is required to study the effect of preheating temperature on mechanical strength of weld. Never the less, the characteristic changes in FSW with preheating temperature not yet studied. Maximum possible preheating temperature for better strength of weld has not been reported elsewhere. Hence, an attempt has been made to investigate the relations between preheating temperature and mechanical characteristics of friction stir welded AA7075-T651 aluminum alloy joint. The study focuses on improvement of tensile strength, finding of optimal preheating temperature and analysis the changes in microstructure under preheated condition.

EXPERIMENTAL WORK

The rolled aluminum alloy AA7075-T651 plate of thickness 6.35mm was used as parent metal for this investigation. Chemical composition and mechanical properties of this base metal are listed in Table 1 and Table 2 respectively. The plate was reduced into rectangles of dimension 100 mm length and 75 mm width. These machined plates were welded in normal to the rolling direction using computer numerical controlled FSW machine (22 kW, 4000 rpm, 6 ton). A taper pin threaded profiled tool made of super high speed steel was used to fabricate all the weld joints. The tool geometry of the tool is given in the Fig. 1.

Table 1 Chemical composition of AA7075-T651 aluminum alloy

Mg	Cu	Cr	Fe	Ti	Si	Mn	Al
2.5	1.4	0.19	0.14	0.07	0.04	0.02	Remainin g

Table 2 Mechanical properties of AA7075-T651 aluminum alloy

Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness ($HV_{0.05}$)
599	479	7.5	210.00

Tool Dimensions:

Length of the pin (L) - 5.7mm
Major diameter of the pin (dM) - 6mm
Minor diameter of the pin (dm) - 5mm
Shoulder diameter (D) - 18 mm Pitch of thread - 1mm

Fig. 1 Taper pin threaded profiled tool.

The selected process parameters for this research yielded defect free joint. The used parameters to fabricate the normal weld are tool rotational speed of 900 rpm, welding speed of 25 mm/min and tool title angle of 1.5°. To study the effect of preheating temperature the above process parameters were kept constant and preheating temperature alone was varied as 100 °C, 150 °C, 200 °C, and 250 °C. With these temperatures five preheated weld joints were fabricated. These fabricated weld joints are shown in Fig. 2. Here, preheating of base metal was achieved by gas torch. Tool followed preheating torch to allow the base metal to heat. During the welding, peak temperature of each joint was measured near to the stir zone. These temperatures are given in table 3. The joint fabricated without preheating is referred as PRERT joint. Other joints are referred as follows: PRE10 (preheated to 100 °C), PRE15 (preheated to 150 °C), PRE20 (preheated to 200 °C), PRE25 (preheated to 250 °C). These welded joints were cut and machined to obtain unnothched and notched tensile specimens with dimension as specified in ASTM E8 M-04 guidelines [14]. The dimensions of the tensile specimen are shown in Fig. 3. The tensile test was carried out in 100 kN, servo controlled universal testing machine (Model: UNITEK 94100, Make: FIE – BLUESTAR, INDIA). The metallographic samples were prepared and etched with Keller’s reagent to expose the microstructure in different zones of weld nugget. The microstructure of the weld samples were examined using optical microscope. Scanning electron microscope (SEM) was used to view the features at fractured surfaces of broken tensile specimens. The hardness values were measured along the weld centerline by using a Vickers microhardness testing machine with a load of 0.05 kg and a dwell time of 15s at 1mm step.

Table 3 Measured peak temperature of each joint

Type of Joints	PRERT	PRE 10	PRE 15	PRE 20	PRE 25
Temperature (°C)	319	331	367	398	411

Fig. 2 Photograph of fabricated joints.

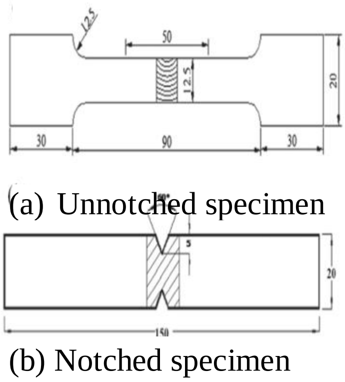

Fig. 3 Dimensions of tensile specimen

RESULTS

Macrostructure Analysis

Asymmetric weld regions were observed in all weld joints. Friction stir weld is commonly divided into four different regions they are Stir Zone (SZ), Thermo-mechanical Affected Zone (TMAZ), Heat Affected Zone (HAZ) and Base Material (BM) [2]. Fig. 4 shows top surface appearance and corresponding cross-sectional macrograph of all joints. Semicircular traces were observed on top of welds these traces became smoother with increasing preheating temperature [15]. Here increase in heat input makes the surface smoother. It is found that SZ width of preheated weld joints is larger than that of PRERT joint. The stir zone width increased up to 150 °C (PRE15) preheating temperature and it decreased drastically thereafter. The maximum stir zone width is measured as 8.1 mm in PRE15 joint. The width of retreating side thermo-mechanical affected zone (RS-TMAZ) is greater than the width at advancing side thermo-mechanical affected zone (AS-TMAZ) in all the joints [10]. From this macro level assessment, all joints were defect free except PRE25 joint, in this joint lack of fill defect was found on top it is also visible in cross-sectional macrographs [4].

Joint type	Top surface of the joint	Cross section of the joint	Defect and zone width
PRERT			No defects SZ : 6.8 mm AS-TMAZ: 1.7mm RS-TMAZ: 2.2 mm
PRE10			No defects SZ width: 7.5 mm AS-TMAZ: 2.3 mm RS-TMAZ: 3.0 mm
PRE15			No defects SZ width: 8.1 mm AS-TMAZ: 2.5 mm RS-TMAZ: 3.5 mm
PRE20			No defects SZ width: 6.9 mm AS-TMAZ: 2.5 mm RS-TMAZ: 3.7 mm
PRE25			Tunnel defects SZ width: 6.8 mm AS-TMAZ: 2.4 mm RS-TMAZ: 4.0 mm

Fig. 4 Surface appearance and corresponding cross-sectional macrograph of all joints

MICROSTRUCTURE ANALYSIS

The base metal microstructure is shown in Fig. 5, it consists of course and elongated grains with $MgZn_2$ precipitates present in grain boundaries [13, 16]. The microstructures of Stir zone (SZ), thermo-mechanical affected zone (TMAZ) and heat affected zone (HAZ) of all welds were analyzed under optical microscope. These optical microscope images are presented in Fig. 6. Grain structures were also studied in top (shoulder affected stir zone), middle and bottom (pin affected stir zone) of the SZ region, which is shown in Fig. 7. Examining these three stir zone regions in PRERT joint, low aspect ratio coarse grains is observed in the shoulder affected region, these grains are coarser than that of in the middle SZ region [11]. The finer grains are observed in the pin affect region than that in middle stir zone region it is due to sufficient stirring action caused by tool [25]. Similar type of grain pattern at SZ is observed in all preheated weld joints. Stir zone is dynamically recrystallized into equiaxied grains through plastic deformation due to high temperature and high pressure in all joints [11].

The average grain size values of SZ in PRERT, PRE10, PRE15, PRE20 and PRE25 are 6 µm, 8 µm, 8 µm, 10 µm and 10 µm respectively. TMAZ is not dynamically recrystallized but deformed due to minimum strain. These zone grain sizes are linearly proportion to preheat temperature. HAZ is not affected by strain but it experienced the thermal cycle during welding due to this reason the grains present in HAZ region became coarsened [13]. Two different pin-hole defects are shown in

Figure.5 Base metal microstructure

Fig. 8. The defect showed Figure 8a was found at (800 rpm) low spindle speed. This defect is presented for comparison study purpose alone it is taken from this preliminary work. Figure 8b shows the pin-hole defect found in PRE20 weld joint. Comparing these two images, the pinhole defect in PRE20 has partially melted metal, where as in the other defect partially melted metal has not found.

TENSILE PROPERTIES

The average tensile test results of different weld conditions are given in table 4. The tensile strength of the friction stir welded joints is inferior to that of the base metal [17]. PRE10 and PRE15 weld joints are observed higher ultimate tensile strength (UTS) than PRERT weld. However PRE10 weld joint produced maximum ultimate tensile strength of 385 MPa and its joint efficiency was 64 %. The improved joint efficiency of this joint is 11 % due to preheating of base metal. The PRE20 weld joint produced

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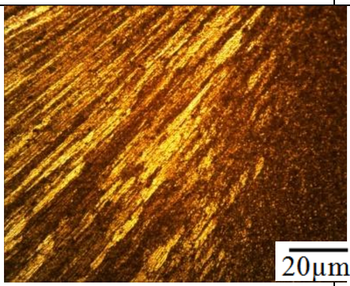
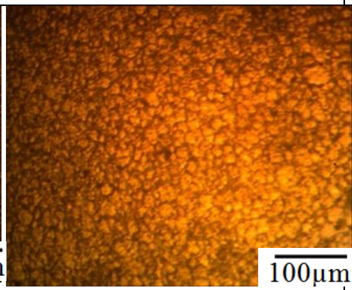
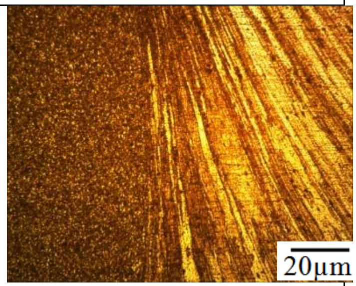
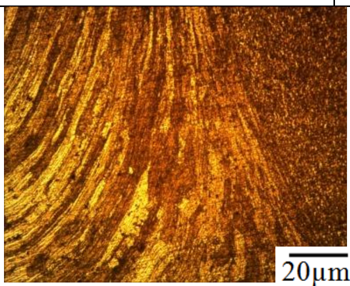
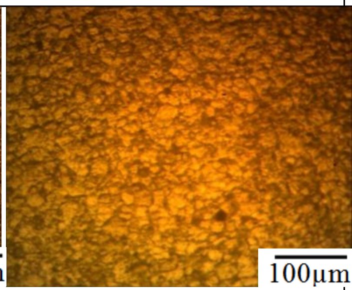
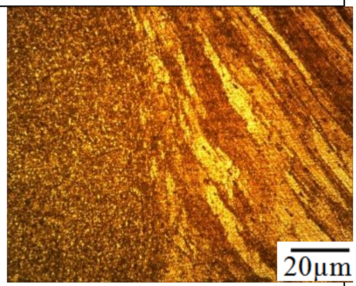
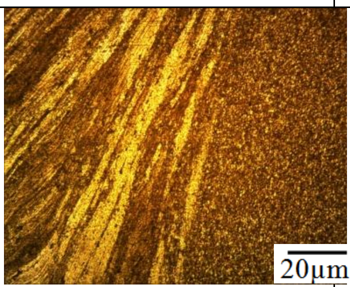
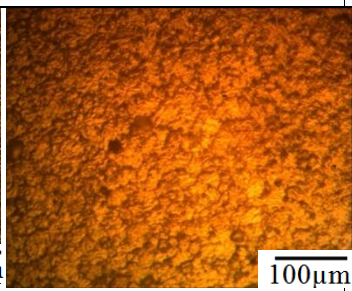
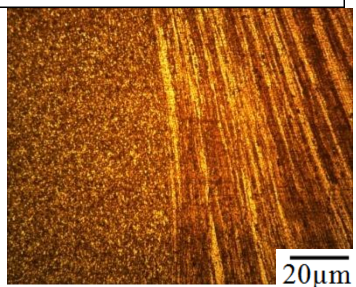
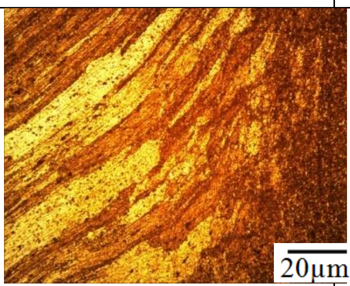
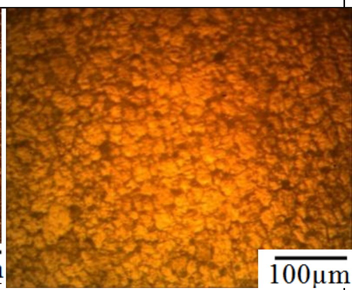
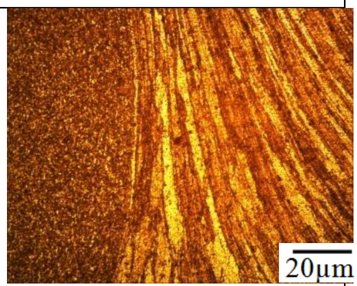
Joint type	RS-TMAZ	Stir Zone	AS-TMAZ
PRERT			
PRE10			
PRE15			
PRE20			

Fig. 6 Microstructure image of thermo-mechanical affected zone and stir zones

TENSILE PROPERTIES

The average tensile test results of different weld conditions are given in table 4. The tensile strength of the friction stir welded joints is inferior to that of the base metal [17]. PRE10 and PRE15 weld joints are observed higher ultimate tensile strength (UTS) than PRERT weld. However PRE10 weld joint produced maximum ultimate tensile strength of 385 MPa and its joint efficiency was 64 %. The improved joint efficiency of this joint is 11 % due to preheating of base metal. The PRE20 weld joint produced lower ultimate tensile strength compared to all other joints because of presence of defect in it. PRE25 weld joint is not tested because of presence of defect. The percentage of elongation increased initially up to 150 °C (PRE15) than it decreased. The maximum percentage of elongation of 5.31 % is measured in PRE15 weld, but its UTS value is lower than the PRE10 weld joint. This higher percentage of elongation of PRE15 weld joint is also evidenced in the load-displacement curve (Fig. 9) preheating temperature improved the ductility of this joint. The fracture location and corresponding fracture surface microstructure of all the tensile specimens are shown in Fig. 10. PRE10 and PRE15 joints were fractured at AS-HAZ [17, 21]. PRERT and PRE20 weld joints fractured AS TMAZ [18]. Even they failed in different locations, ductile mode of failure is observed in facture location microstructures. Notched tensile specimens fracture location and corresponding fracture surface microstructure of all joints is shown in Fig. 11. The value of notch strength ratio (NSR) is found to be around one in all specimens it means that the joints are notch ductile [18].

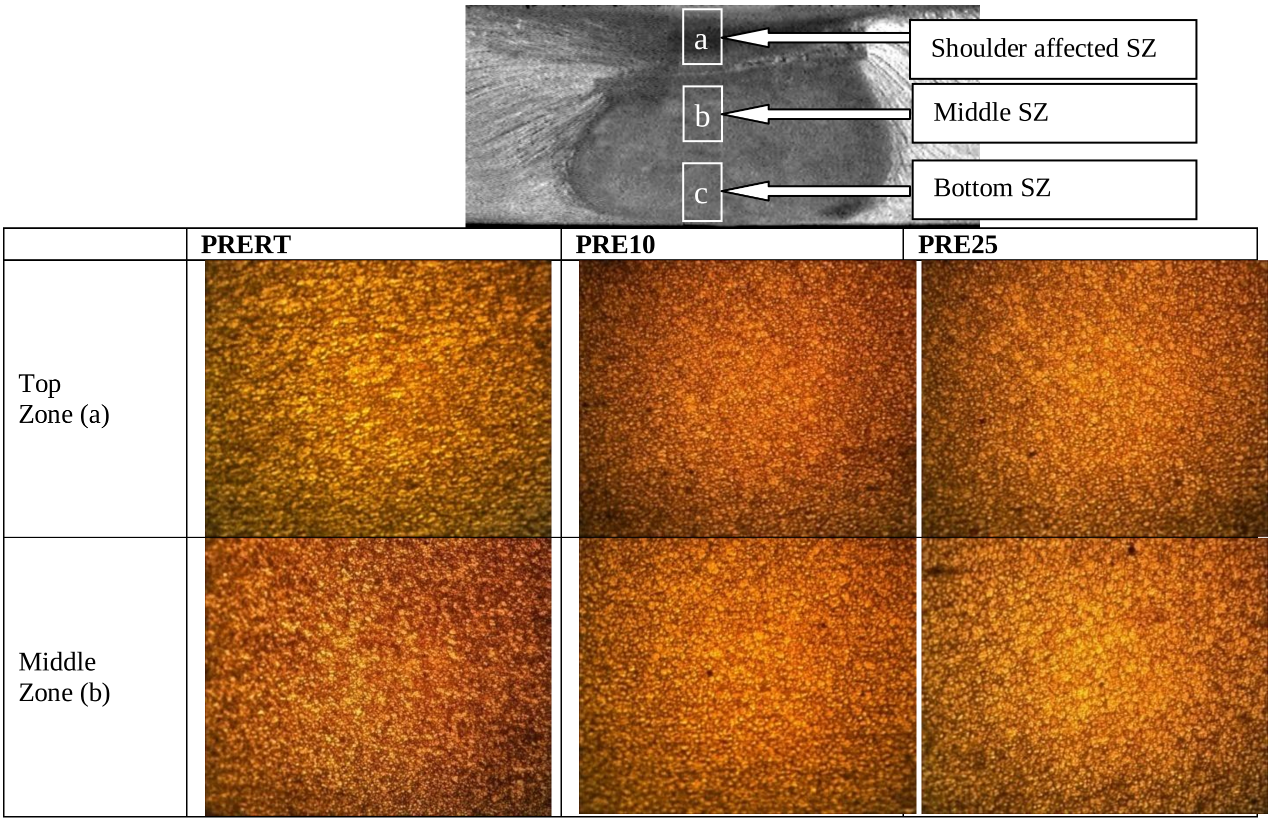


Fig. 7 Grain structures in top stir zone and middle stir zone

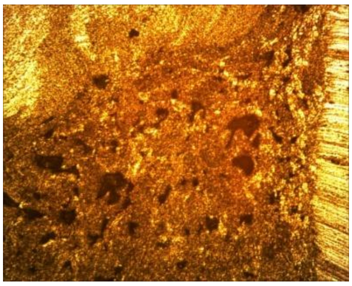


Fig. 8 (a) Pin hole defect formed in low spindle speed

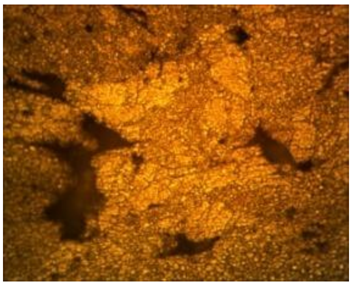


Fig. 8 (b) Pin hole defect in PRE20 weld joint

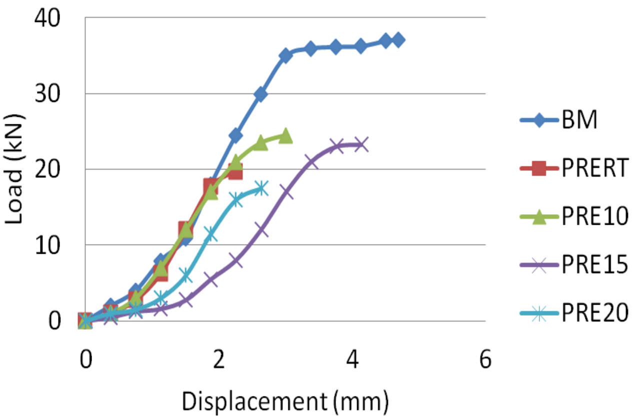
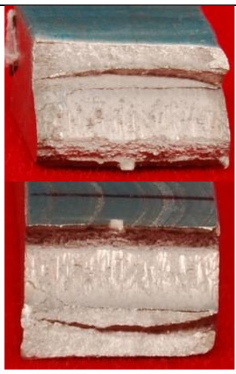
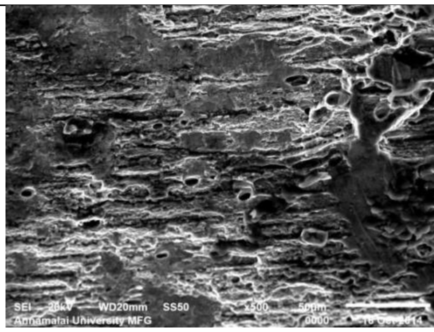
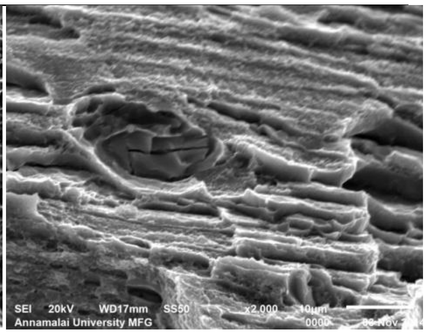
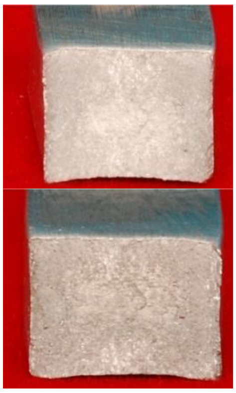
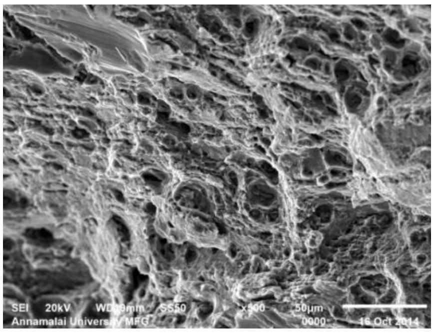
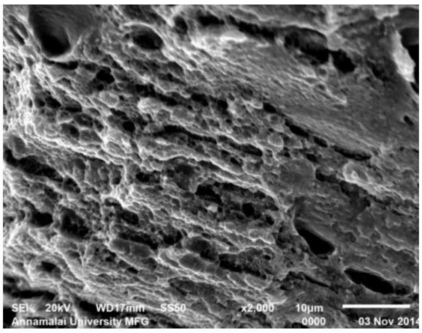


Fig.9 Load Vs displacement curves in tensile test

Joints	Sample	Fracture surface	SEM of Fracture surface	SEM of Fracture surface
PRERT				
PRE10				

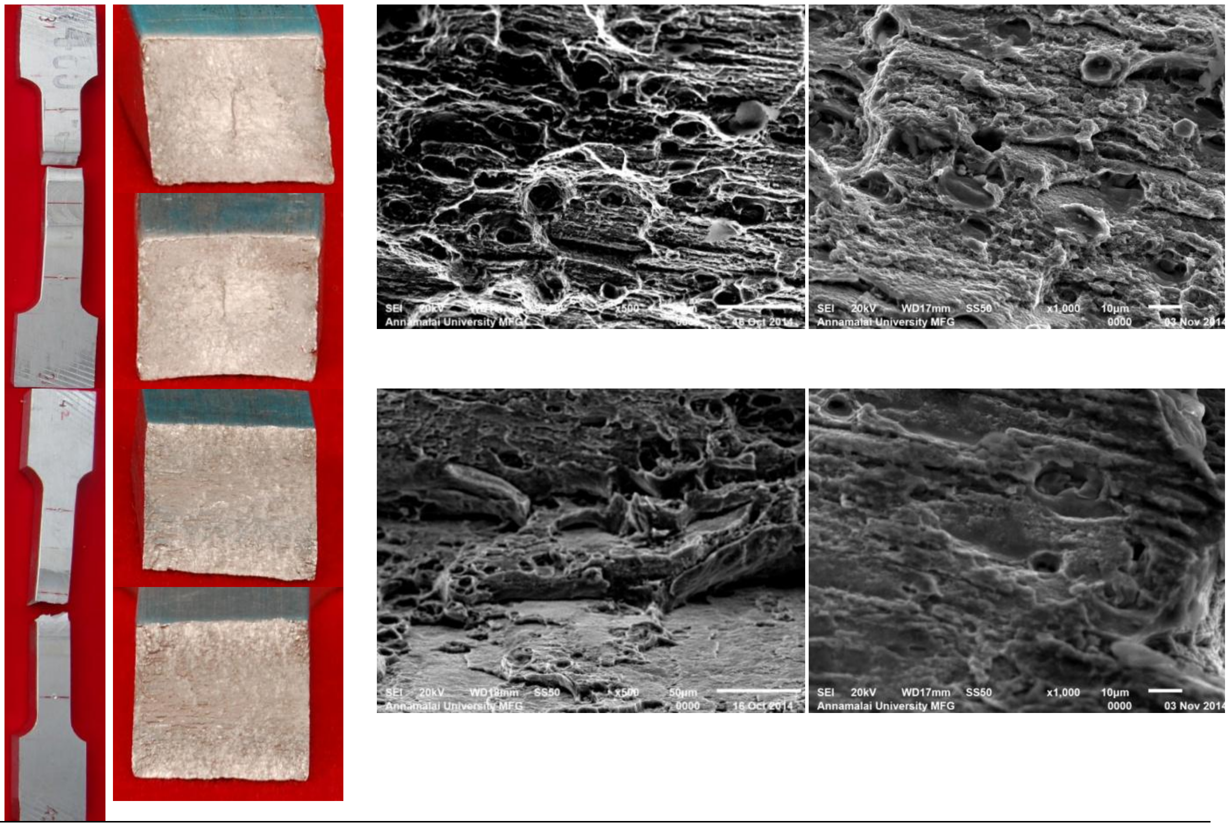
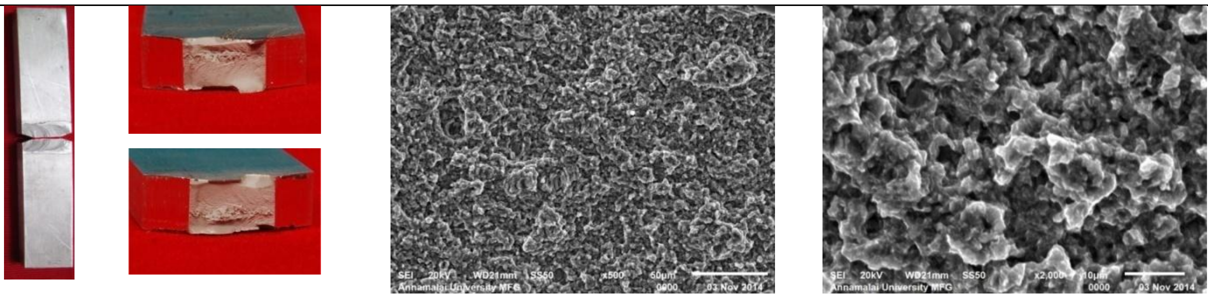
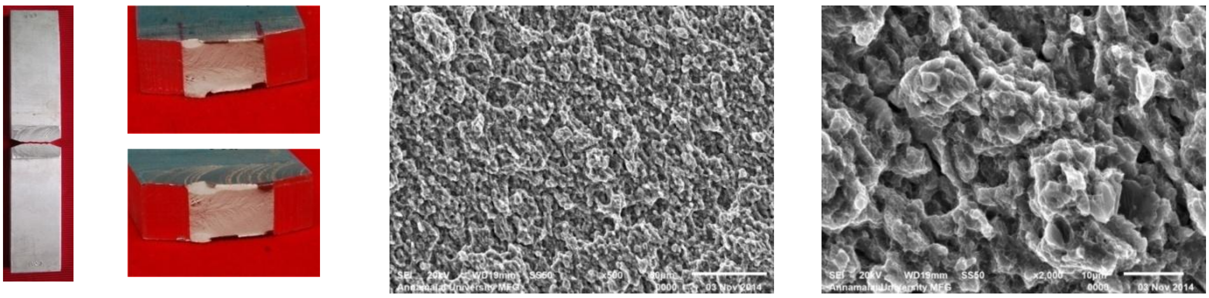
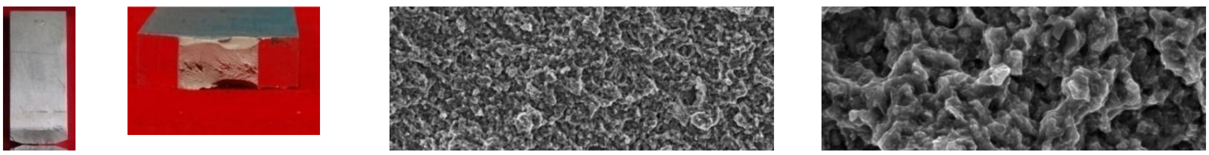
PRE15	
PRE20	

Fig. 10 Fracture location and corresponding Fracture location microstructures of unnotched tensile specimens

Joints	Sample	Fracture surface	SEM of Fracture surface	SEM of Fracture surface
PRERT				
PRE10				
PRE15				

PRE20

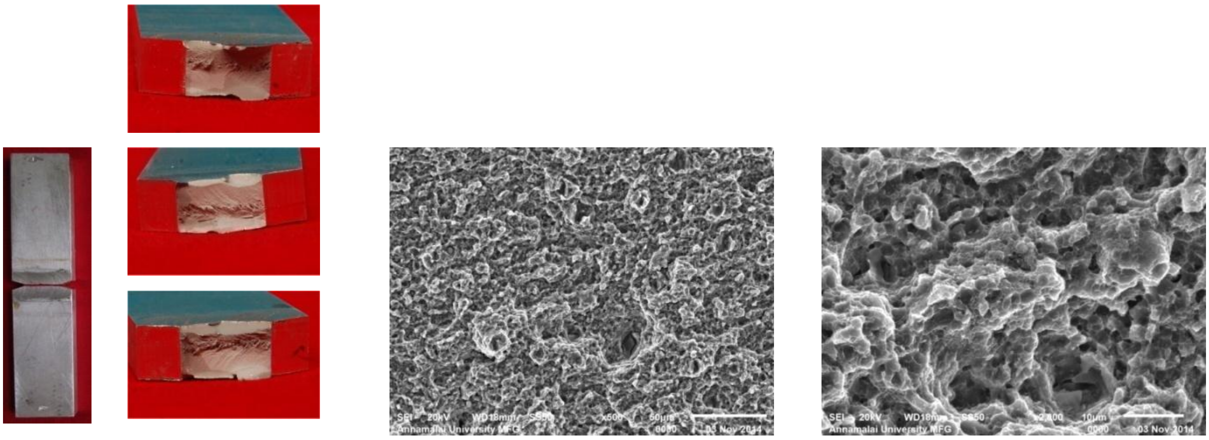


Fig. 11 Fracture location and corresponding Fracture location microstructures of notched tensile specimens

MICROHARDNESS

The microhardness profiles of all joints are measured at the center line of the cross section of the weld, this profile plot is represented in Fig. 12. Hardness profile is observed as 'W' in shape [17]. Intermediate hardness value is measured at stir zone. TMAZ is revealed lower hardness value while higher hardness is observed in base metal [17]. In HAZ, the hardness is gradually increasing from TMAZ value to the base metal value. From hardness profile diagram, it is revealed that the width of RS-TMAZ is greater than the width of AS-TMAZ for all weld joints, but AS-TMAZ hardness value is considerably higher than RS-TMAZ [19, 20]. The average hardness valve at the stir zone of PRERT, PRE10, PRE15, and PRE20 are 138.4, 136.18, 131.47, and 129.46 HV respectively. In PRE15, and PRE20 weld joints, preheating of the base metal decreases the hardness value in all weld zones as well as increases the weld zone width of these joints. In PRE10 weld joint, stir zone width only increases and the hardness of this zone is slightly lower than the normal weld joint (PRERT) but hardness in heat affected zone is slightly higher than normal weld joint.

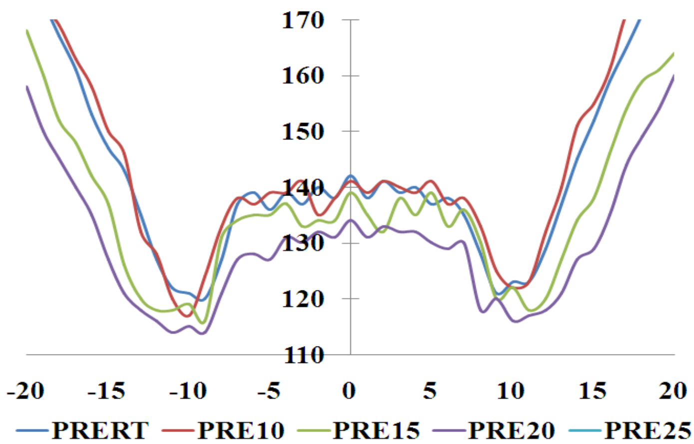


Fig. 12 Hardness profile plot

DISCUSSION

The presence of pinhole defect and lack of fill defect in PRE20 and PRE25 welds respectively reduce the process temperature which reduces the stir zone width in these joints [4]. The reduction in heat is because of the following; one decrease the coefficient of friction due to local melting of metal around the pin and the other is absorbed by the latent heat of melting of the metal [23]. But in the widths of thermomechanical zone and heat affected zone of these joints are increased as well as hardness reduced due to over ageing temperature and slow cool [26]. In the joint PRE20 (Fig 8b) had the pinhole defect and surrounded by partially melted metal, this is due to excess heat input to this joint. Here, the increasing in heat input did not continue in development of stir zone size due to slipping of tool. Since excess heat reduces flow stress and reduced coefficient of friction cases tool to Slip at thermomechanical zone [24]. Due to this no recrystallization take place near to pinhole defect. This microstructure image is the evidence results

In normal friction stir welding, the increase heat input to the weld joint leads to reduce the stir zone region [22]. But, in contrast to the above, the stir zone size is increased even in addition of heat input it is one of the significant effect by preheating. Rising in preheating temperature reduces the shear strength and widens the heated area, this combined effect facilitated in enlarging the stir zone width of PRE10 and PRE15 welds.

Slightly low aspect ratio fine grains are found in PRERT weld joint microstructure (Fig.7) at the shoulder affected region. It is result of low heat input observed and tool wake over in the region [11]. This low heat input is the reason for rough semicircular traces on the top of weld in this joint. In PRE10 and PRE15 weld joints low aspect ratio fine grains are disappeared and also weld top surfaces became smoother. Stir zone grain size is increased with preheating temperature it was due to rise in temperature of the plate, which led to slow cooling. Because of slow cooling welding grain undergo nucleation resulting static grain growth in stir zone of the weld [9].

PRERT was fractured at TMAZ in advancing side. In normal weld joint (PRERT) the weak area is present at TMAZ interface in advancing side [17] the same result was obtained in this research also. But PRE10 and PRE15 joints fractured at the at HAZ region, it shows that preheating of base metal makes alter the week area from TMAZ to HAZ in these joints it is also a evidence for better integration between stir zone and TMAZ. This is another finding which support for improved strength in PRE10 and PRE15 weld joints.

Microhardness of the joint depends on thermal cycle in which the weld joint undergoes. In friction stir welding different zone will have different peak temperature and consecutive cooling time this leads to different grain size at different weld regions, which decide the hardness value of the joint. According to the Hall–Petch equation, hardness and grain size are inversely proportional. Due to this phenomenon, hardness has decreased with the increase in preheat temperature in preheated weld joints [27]. Peak ageing temperature of precipitation hardened AA7075 aluminum alloy is 140 °C [13]. Addition to this for AA7075 aluminum alloy maximum hardness is achieved at 150°C in short duration, above is over ageing [26]. Whereas in PRE15, joint was heated above peak aging temperature, which is over aged so formation of soft zone is higher than PRE10. It is evident from hardness test results of PRE15 weld had lower hardness than PRE10 joint also higher weld zone width than PRE10 joint. These make PRE15 weld joint in lower tensile strength.

The temperature was measured in the HAZ during welding of PRE10 is 133 °C is near to peak aging temperature, during this temperature coarsening process of the second phase particles will take place in the HAZ [28]. It evidenced in microhardness plot, hardness value at HAZ of PRE10 weld joint is higher than that of PRERT weld joint. Improved hardness, better integration between stir zone and TMAZ and stir zone development are supporting PRE10 weld joint for maximum ultimate tensile strength.

CONCLUSION

In this investigation an attempt was made to analyze the effect of preheating temperature on the tensile properties and microstructure characteristic of AA7075 aluminum alloy. Form this investigation the following conclusions are derived
i)Preheating of base metal above peak ageing temperature will not provide better joint efficiency.
ii) Preheating of weld improves the stir zone size and TMAZ size which is not possible in the normal FSW procedure
iii) Preheating provides another source of heat input apart from the spindle speed, so strength of stir zone is improved. Stirring effect is also improved through preheating.
iv) Of the four levels of preheating temperature applied, the joint made with a preheating temperature of 100 °C showed higher tensile properties than the other preheated joints and improvement in joint efficiency is 11 %.

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