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1. INTRODUCTION

THE FSW TECHNIQUE

The assembly of metals has been a fundamental topic for many years. In particular, with regard to lightweight alloys several problems have been found using traditional fusion welding technologies; joints defects such as voids and inclusions can seriously compromise the mechanical performances of the welds. Moreover, gas protection shields have to be used with such techniques, making the processes themselves more complex. At the beginning of the 1990s The Welding Institute presented an innovative solid state welding operation, friction stir welding (FSW), capable of producing sound joints even when working with materials typically considered difficult to weld or to be "unweldable" by traditional fusion technologies. Fig.1.Shows the Schematic diagram of Friction Stir Welding process.

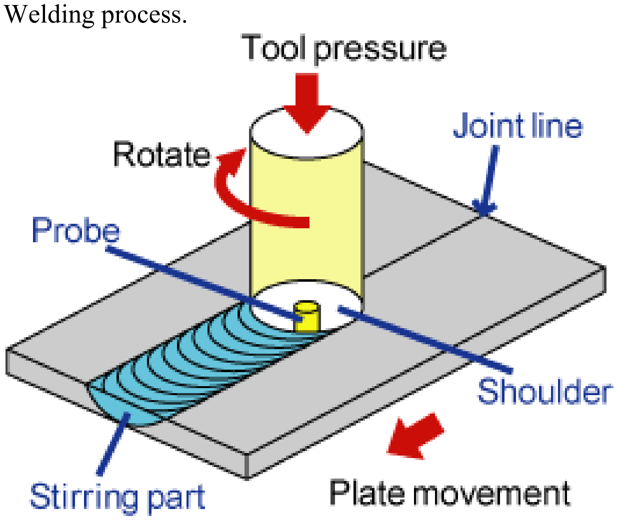


Fig.1.1 Schematic of Friction Stir Welding process

The friction stir (FS) welded material produces three different areas: the weld nugget (WN), the thermo-mechanically affected zone (TMAZ) and the external heat affected zone (HAZ) The microstructure of the weld nugget is usually very fine and equiaxed, ensuring elevated mechanical strength and ductility. In fact, some authors showed the microstructure in the weld nugget zone to undergo a continuous dynamic recrystallization process, leading to elevated temperature mechanical properties. The FSW process is a solid-state process, therefore the solidification microstructure is absent in the welded metal and the presence of brittle inter-dendritic and eutectic phases is avoided.

In the FSW process, two plates are kept in contact along the joint line the work piece consisting of a shoulder and a pin is rotated and the pin is inserted in the material while the shoulder remains on the top of the joint in contact with the plate surface pressed with a constant force. The material softens and flows around the tool as it is progressed along the processing line; forging occurs under the pressure applied by the tool shoulder. The severe plastic deformation is due to the flow of the material around the rotating and advancing tool. The flow depends on the welding parameters and tilt angle.

2. TENSILE TESTING

Tensile testing, also known as tension testing, is a fundamental materials science test in which a sample is subjected to uniaxial tension until failure. The results from the test are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. Properties that are directly measured via a tensile test are ultimate tensile strength, maximum elongation and reduction in area. From these measurements the following properties can also be determined: Young modulus, Poisson's ratio, yield strength, and strain-hardening characteristics.

3. HARDNESS

Hardness is the measure of how resistant solid matter is to various kinds of permanent shape change when a force is applied. Macroscopic hardness, is generally characterized by strong intermolecular bonds, but the behaviour of solid materials under force is complex; therefore, there are different measurements of hardness: scratch hardness, indentation hardness, and rebound hardness.

Hardness is dependent on ductility,elastic stiffness,plasticity,strain,strength,toughness, viscoelasticity,and,viscosityCommon examples of hard matter are ceramics, concrete,certain metals and superhard materials, which can be contrasted with soft matter.

1.3.2 MEASURING HARDNESS

There are three main types of hardness measurements: scratch, indentation, and rebound. Within each of these classes of measurement there are individual measurement scales. For practical reasons conversion tables are used to convert between one scale and another.

- **Scratch hardness**

Scratch hardness is the measure of how resistant a sample is to fracture or permanent plastic deformation due to friction from a sharp object. The principle is that an object made of a harder material will scratch an object made of a softer material. The most common test is Mohs scale, which is used in mineralogy. One tool to make this measurement is the sclerometer.

- **Indentation hardness**

Indentation hardness measures the resistance of a sample to permanent plastic deformation due to a constant compression load from a sharp object; they are primarily used in engineering and metallurgy fields. The tests work on the basic premise of measuring the critical dimensions of an indentation left by a specifically dimensioned and loaded indenter. Common indentation hardness scales are Rockwell,Vickers,Shore,and Brinell.

Rebound hardness

Rebound hardness, also known as dynamic hardness, measures the height of the "bounce" of a diamond-tipped hammer dropped from a fixed height onto a material. This type of hardness is related to elasticity. The device used to take this measurement is known as a scleroscope.

OBJECTIVE AND METHODOLOGY

3.1. SCOPE

Friction stir welding is a novel process mainly used for the joining of aluminium alloys. The various properties of the friction stir welding were characterized by many publishers. Despite, the effect of post weld treatment on tensile and microstructural characteristics of friction stir welded AA 7075-T651 aluminium alloy joints .Thus an attempt is made for the research on the. Effect of post weld treatment on tensile and microstructural characteristics of friction stir welded AA 7075-T651 aluminium alloy joints.

3.2. RESEARCH OBJECTIVES

The objective of this research is to characterize the effect of post weld treatment on tensile and microstructural characteristics of friction stir welded AA 7075-T651 aluminium alloy joints. Mechanical properties that are tensile behavior of friction stir welded joints and study the micro structure of the base metal and the stir zone evolved during the friction stir welding of Aluminum alloy 7075-T651. The tensile strength determines the mechanical efficiency and joint efficiency of the welded joints. The ability to withstand the tensile load can be predicted using the tensile testing machine. The mechanical properties such as ultimate tensile strength and yield strength and an effort are made to find out a relation between the tensile properties of the as welded and post weld treated joints compared with the base material.

4. RESULTS AND DISCUSSION

4.1TENSILE PROPERTIES

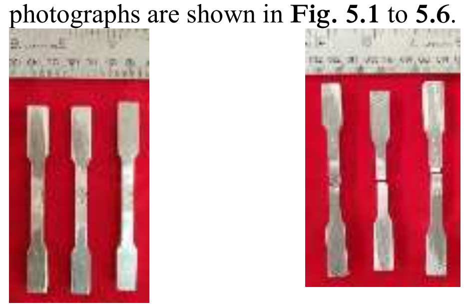
The results of the transverse tensile test carried out for the FSW joints in AW, AA and STA conditions along with the PM are presented in Table 2; for each condition three specimens were tested and the average value is presented. The yield strength and tensile strength of the un-welded PM are 510 MPa and 563 MPa respectively with an elongation of 16%. However, the FSW joint exhibited lower tensile and yield strength of 315 MPa and 394 MPa respectively in comparison with the PM, in the as-welded (AW) condition. This suggests that FSW has caused a huge reduction in tensile strength (30%) in AA7075-T651 Aluminium Alloy, similar results were reported elsewhere [10,11]. The artificial aging treatment performed on the FSW joint has further lowered the yield strength and tensile strength to a value of 251 MPa and 314 MPa respectively resulting in reduction of joint efficiency by 14 % in comparison to AW joint. The AA treatment has also caused an increase in elongation by 2 % in comparison with the AW joint. The STA treatment has increased the yield strength and tensile strength value to 346 MPa and 445 MPa respectively resulting in increase of joint efficiency by 9 % in comparison to AW joint. However, the STA treatment has caused a decrease in elongation by 1% to the AW joint. The Notch Strength Ratio (NSR) i.e. the ratio between tensile strength of notched specimen and tensile strength of unnotched specimen for all the joints are greater than unity which shows that the material is notch ductile in all the conditions. The failure location of smooth tensile specimens was observed at the advancing side of the themo-mechanically affected zone (AS-TMAZ) in all the three joints

Table. 2. Transverse tensile properties of base metal and FSW joint.

Joint type	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50mm gauge length (%)	Notch tensile strength (MPa)	Notch strength Ratio (NSR)	Joint efficiency (%)	Failure location
PM	510	563	16	571	1.01	-	
AW	335	394	12	410	1.04	70	AS-TMAZ
AA	251	314	14	449	1.43	56	AS-TMAZ
STA	346	445	11	512	1.22	79	AS-TMAZ

(PM: Parent metal; AW: As-welded; AA: Artificially aged; STA: Solution treated and aged)

The ratio between the tensile strength of a welded joint and the tensile strength of unwelded parent metal is known as the joint efficiency. The As-welded (AW) joints showed a joint efficiency of 70%, while the STA joints exhibited high joint efficiency (75%).Tensile tested specimen photographs are shown in **Fig. 5.1** to **5.6**.



Before test After test

Fig.5.1 AS Welded joint tensile smooth specimens

Before Test After test

Fig.5.2. AS Welded joint tensile notched specimens

Before Test After test

Fig.5.3.AA Joint unnotched tensile specimens

Before test After test

Fig.5.4 AA joint notched tensile specimens

Before Test After test

Fig.5.5.ST+AA Joint unnotched tensile specimens

Before test After test

Fig.5.6. ST+AA Welded joint notched tensile specimens

4.2 MICROHARDNESS

The hardness survey across the weld cross section was conducted along the mid thickness of the joint using a Vickers micro hardness testing machine and the hardness profile was presented in Fig. 5.7. The stir zone (SZ) of AW joint does not show any considerable hardness difference in comparison with the PM hardness. The hardness value for the AW joint has got a drop in the TMAZ region on both sides of the joint. The lowest hardness for the AW joint was observed at the AS-TMAZ. The AA treatment has resulted in increase of hardness value in the stir zone region and decrease in the TMAZ region. The STA joint has shown the highest hardness for all the regions of the weld in comparison with AW and AA joints. The STA treatment has shown a significant increase in hardness values across the FSW joint.

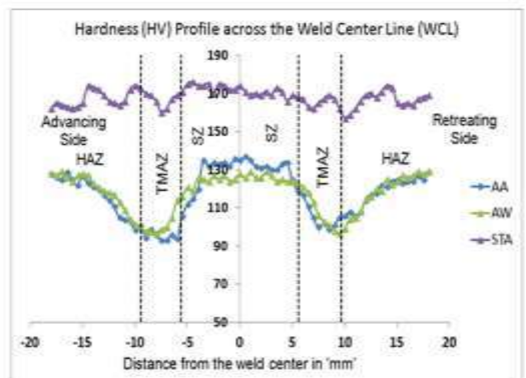


Figure 5.7 Hardness Profile across the weld joint along the mid thickness

5.3. MICROSTRUCTURE

The optical micrograph of parent material is shown in Fig. (5.8.). The Fig. (8b-d) represents the optical micrographs of stir zones in AW, AA and STA conditions respectively. The optical micrograph of the SZ region in AW condition is shown in Fig. (5.8b) reveals fine and equiaxed grain structure, due to the dynamic recrystalization in the region during FSW. The optical micrograph of the stir zone in AA condition is shown in Fig. (5.8c) which reveals no alteration to the size of fine equiaxed grains when subjected to the AA treatment. The optical micrograph of stir zone in STA condition is shown in Fig. (5.8d) which reveals the increase in grain size due to STA treatment.

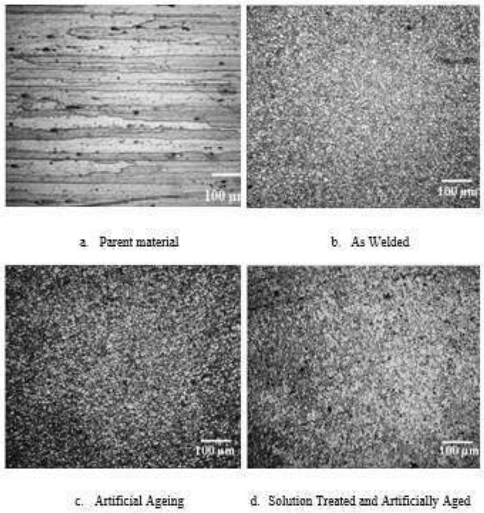


Figure 5.8 Optical microstructure of stir zone

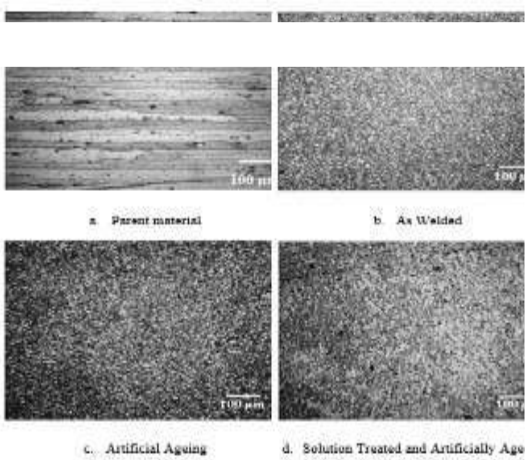


Figure 5.9 Optical micrographs of TMAZ regions at various heat treated conditions

The optical micrographs of AS-TMAZ and RS-TMAZ in AW condition is shown in Fig. (5.9a) and Fig. (5.9b). The AS-TMAZ and RS-TMAZ reveals the reveals the highly distorted structure of the matrix with considerable elongation in the grains due to the strain imparted in this region during FSW. The optical micrographs of the AS-TMAZ and RS-TMAZ in AA condition is shown in Fig. (5.9c) and Fig. (5.9d) respectively. The AS-TMAZ and RS-TMAZ shows no alteration in the grain size due to the AA treatment. The optical micrograph of AS-TMAZ and RS-TMAZ in STA condition joint is shown in Fig. (5.9e) and Fig. (5.9f). The AS-TMAZ and RS-TMAZ shows partially annealed condition of the highly deformed matrix and finer dark spots in the region which might be the finer precipitates which precipitated during the STA treatment.

5.4 FRACTOGRAPHY

In order to study the effect of post weld heat treatment on the fracture mode during tensile testing SEM examination of the fracture surfaces was carried out. The SEM fractographs of the unnotched and notched tensile specimens for PM, AW, AA and STA conditions were shown in Fig. (5.7) and Fig. (5.6) respectively.

The fracture surface of the PM unnoched tensile specimen shown in the Fig. (5.7a) consists of a large number of microscopic voids of varying sizes which are surrounded by fine dimples. The large micro voids are associated with the coarse precipitates which were fractured during the tensile loading and the smaller were associated with the finer precipitates. The PM unnoched tensile specimen fracture surface also reveals featureless flat regions along with the regions of dimple fracture with :condary cracking. The fracture surface indicates ...at the fracture is partly intergranular and partly transgranular with mixed mode of failure.

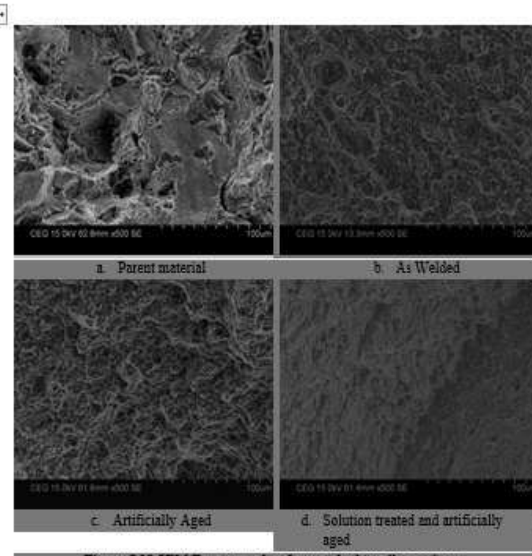


Figure 5.10 SEM Fractographs of unnotched tensile specimen

The SEM fractograph of unnotched tensile specimen in AW condition is shown in Fig. (5.10b) which consists of micro voids and dimples of various sizes indicating ductile mode of failure. The micro voids of various sizes associated with brittle precipitates acts as the crack initiation sites during initial loading. The fracture surface of the AA condition tensile specimen is shown in the Fig. (5.10c) which consists of large number of dimples of various sizes with much deeper voids than the AW condition un notched tensile specimen fracture surface (refer Fig. 5.10b). The coarser precipitates available in the AA joint acts as the failure initiation sites during tensile loading and the large precipitate to precipitate distance resulted in formation of deeper voids. Fig. (5.10d) shows the fracture surface of unnotched tensile specimen in STA condition. The fracture surface consists of much shallower and fine dimples in comparison to other joints without much elongation owing to the STA treatment which resulted in finer precipitates.

Fig. (5.11) shows the SEM fractograph of notched tensile specimens in PM, AW, AA and STA conditions. Fig. (5.11a) shows the fractograph of notched tensile specimen of PM with largely populated dimples conforming the ductile mode of failure involved in the specimen. Fig. (5.11b) shows the the fractograph of notched tensile specimen in AW condition which reveals finer granular appearance due to the finer recrystallized grains evolved during FSW along with voids. Fig. (5.11c) shows the the fractograph of notched tensile specimen in AA condition which reveals fine dimples with much larger voids attributed to the coarse precipitates. Fig. (5.11d) shows the the fractograph of the notched tensile specimen in STA condition which reveals finer dimples along with featureless bands and very few smaller voids attributed to the dissolved and reprecipitated finer precipitates during STA treatment..

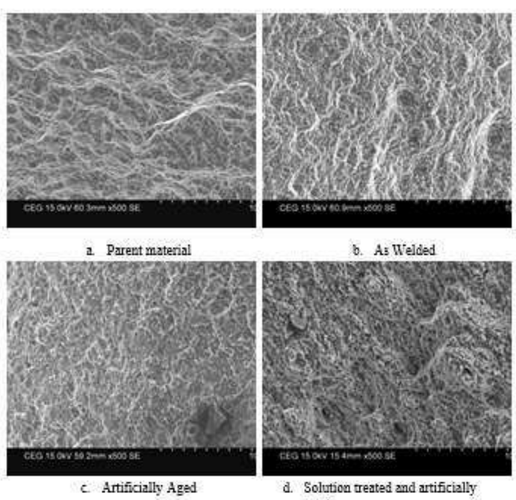


Figure 5. 11 SEM Fractographs of notched tensile specimen

5.5 DISCUSSION

5.5.1 Effect of Friction stir welding

The AW joint has lower tensile strength than PM. The SZ has higher hardness value than TMAZ regions due to the dynamic recrystallization phenomenon occurring in the region during FSW. The fine grains which formed during the recrystallization compensates for the softening due to the precipitate dissolution in the SZ during FSW (refer Figure 5.7) are attributed to the hardness values of this region equivalent to the PM [15]. The failure of AW joint has occurred at the AS-TMAZ region which has the lowest hardness value (96.6 HV). The reduction hardness in the AS-TMAZ region is attributed to the coarsening of precipitates during the FSW process (refer Fig. 5.5c). The fracture surface of the AW joint shows ductile mode of failure which is the evidence for the softening which occurred in the TMAZ region during FSW (refer Fig. 7b).

5.5.2 Effect of Artificial Aging treatment

The AA treatment to the FSW joint has deteriorated the tensile properties of the FSW joint with subsequent reduction in hardness values in the TMAZ region (93 HV). In contrast the hardness in the SZ has increased slightly during the AA treatment. The SZ which has undergone dissolution of fine precipitates during FSW has re-precipitated during the AA treatment and thereby resulting in increased hardness in this region. Since, the fine intermediate ή precipitate, a transition phase and precursor to the equilibrium $MgZn_2$ phase, is the most important strengthening phase in age-hardenable Al-Zn-Mg alloys [16]. The TEM image of the stir zone (refer Fig. 4c) shows that the fine precipitates which has undergone coarsening by agglomeration during AA treatment. The high dislocation density present in the AS-TMAZ acts as shorter diffusion path for the solute atoms to agglomerate and coarsen the precipitates. As the result of coarsening and reduction in dislocation density the hardness in TMAZ region has decreased and width of the soft zone has also increased in comparison with the AW joint. The SEM fractograph of the AA treated joint shows highly ductile mode of failure with deeper elongated voids as the result of coarsening and softening in the AS-TMAZ region (Refer Fig. 5.10c).

5.5.3 Effect of solution treated and artificial aging treatment

The tensile test results have shown that the STA treatment has marginally improved the tensile strength (445 MPa) of the FSW joint with a drastic improvement in hardness values across the FSW joint (refer Fig. 5.7), similar results were observed by Barcellona et al, [17,18]. The solutionizing process during the STA treatment has caused the dissolution of precipitates in to the matrix. The artificial ageing process in the STA treatment caused the re-precipitation of finer θ' ($Mg(Zn,Al,Cu)_2$), in the stir zone (Refer Fig. 5.8d) with coarse Al_7Cu_2Fe precipitates. The distorted AS-TMAZ with high dislocation density has under gone partial annealing during the STA treatment. The annealing effect has reduced the strain induced in TMAZ region during FSW with reduction in dislocation density. Hence, the failure of STA joints was observed in AS-TMAZ region. The hardness profile of the STA joint shows that STA treatment has increased the hardness of the joint drastically. The STA joint almost had a mean hardness value across all the regions of the joint with lowest hardness in AS-TMAZ region. The increase in hardness value has resulted in marginal increase in tensile strength of the STA joint. The fracture surface of the STA joint show much finer, shallow un-elongated dimples due the fine precipitates which formed during the STA treatment (refer Fig. 5.10d).

6.0 CONCLUSIONS

i. Aluminium alloy yielded a joint efficiency of 70%.
ii. The AA treatment has found to deteriorate the tensile properties and hardness of AA 7075 Aluminium alloy FSW joint.
iii. The STA treatment is found to be beneficial in marginally increasing the tensile strength of the FSW joint with significant increase in hardness across the joint

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