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Mechanical behavior of structures welded with friction stir lap welding process

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Abstract. The friction stir welding (FSW) process has been developed to obtain good joint mechanical and process properties. The development of FSW for lap joint manufacturing will expand the number of applications that can benefit from this technology. In this paper, experimental methods were performed on FSW lap joints, including interface morphology and mechanical properties. Microhardness measurements, lap shear testing, resulting material flow, and the effect of flow variation on the next mechanical properties of FSW butt lap joints in aluminum alloy 3003. The study also presents the effect of different parameters welding on the quality of lap joints. The hardness in the welded region gives importance to the influence of the studied parameters on the different zones of the weld. The fracture shows the characteristics of ductile-brittle mixed fracture.

Keywords: Friction stir welding, lap joint, aluminium 3003, parameters, tensile shear test, properties

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Introduction

Friction stir welding (FSW) is a relatively new welding process that may have significant advantages compared to the fusion processes as follows: joining of conventionally non-fusion weldable alloys, reduced distortion and improved mechanical properties of weldable alloys joints due to the pure solid-state joining of metals [1-3]. The utilization of lap joints in airplane structures expands the mechanical properties of the joints and influences weight decrease [4]. Lap joints are used to assemble parts in the transportation industry. These process specialties have made FSW very practical for joining dissimilar alloys. In this process, the heat is originally derived from the friction between the welding tool (including the shoulder and the probe) and the welded material, which causes the welded material to soften at a temperature less than its melting point [5-9]. Lately, some researches have been performed on friction stir welding of dissimilar aluminum lap joints. FSW can also assemble different joint configurations, such as lap, butt, and T-joints, of which the lap joints are widely applied in vehicle and aircraft design and manufacturing [10-12]. Of importance for friction stir lap welding (FSLW), how-ever, is the greater diligence necessary in developing and optimizing tool designs and process parameters to break the surface oxide layer on two planar surfaces and mitigate the three main defects, i.e., kissing bonds, hooking, and top workpiece thinning [13].Examples include aircraft wing-box, structural panel plate, rail carriers and ship decks [14-15]. When these methods are applied to aluminum work pieces, the melting and re-

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solidification is highly detrimental to the material and is known to result in hot cracking, hydrogen cracking, and liquation cracking; not to mention the loss of strength due to dissolution of strengthening precipitates formed during the heat treatment process. The best results were obtained for overlap FSW joints between thin sheets of AA7075-T6 and AA6022-T4 when the welding parameters of tool geometry and welding speed are varied successfully at speeds of up to 500 mm/min [16].

For the friction stir welding of AA 3003 aluminum alloy with different initial microstructures, the results showed that the size of recrystallized grains and the amount of second-phase particles in the weld nugget zone (WNZ) decreased with decreasing welding ambient temperature [17]. Buffa et al. [18] studied an on the lap joining of AA2198-T4 aluminum alloy blanks by FSW is by varying the joint configuration and the tool geometry and rotational speed. They found that the use of cylindrical–conical pin tools and the correct choice of the relative sheet positioning increase the welded nugget extension and integrity, improving the mechanical performances of the obtained joints.

Hakan Aydin et al. [19], studied the effect of welding parameters (rotation speed and welding speed) on the mechanical properties of 3003-H12 aluminum alloy joints produced by friction stir welding where the weld strength increased with increasing the welding speed or decreasing the rotation speed. To produce the best weld quality, these parameters have to be determined for each component and alloy.

In another study [20], FSW lap joint that the thickness of IMC layer increases from 7.7 to 58.1 μm with decreasing welding speed, which significantly affects the strength of the joint. Fatigue properties of the welded joints of AA 3003-H14 aluminum alloy were evaluated based on the superior tensile properties for FSW at 1500 rpm rotational speed and 80 mm/min welding speed with 89 % welding efficiency [21]. Barlas [22] studied the effect of tool tilt angle on tensile-shear failure load and weld zone properties for 1050 aluminum plates under tool rotation speed of 1200 rpm and tool travel speed of 30 mm/min. The results indicated that best joint performance of about 4.8 kN was achieved at 2.5°. The temperature field around the pin tool is asymmetric, with slightly higher temperatures reported on the retreating side (RS) of the FSW in aluminum alloys [1].

The effectiveness of these parameters on the properties of friction stir welds as well as the realization of their influence on the properties of the weld are the subject of studies carried out by several researchers [23-26].

A great number of studies have been focused on to determine the microstructural and mechanical properties of the joints of heat treatable 3XXX aluminum alloys [27-29]. This last is the alloy which has been widely used in purpose alloys for moderate-strength applications requiring good workability, such as stamping, spun and drawn parts and products, chemical equipment, storage tanks, fan blades, walk ways, flooring, and truck and trailer components [29].

The object of this paper is to develop and high mechanical properties for AA3003 during friction stirs lap welding, as well as the influence of the factors affecting the quality of the joint. Therefore, a methodology was adopted in order to identify the determining parameters with respect to the evolution of the mechanical properties. The effect of welding control parameters and tool design on process response was investigated.

Experimental method

The materials used were AA 3003 alloys of 2 mm thickness. Samples were cut according to the shape shown in the Fig. 1. The external sheets were welded parallel to the rolling direction while the central sheet was put in the long transverse direction for FSW process in order tolimit potential effect of rolling texture. The chemical composition of the aluminum 3003 sheet is presented in Table1, and the mechanical properties of the sheets are presented in Table 2.

Table 1. Chemical composition of 3003 aluminum alloy

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
96.70	0.90	0.90	0.13	1.30	0.00	0.00	0.30	0.10

Table 2. Mechanical properties of 3003 aluminum alloy

E, MPa	YS, MPa	UTS, MPa	A, %	RS, MPa	Hv
60000	110	160	5.6	127	51

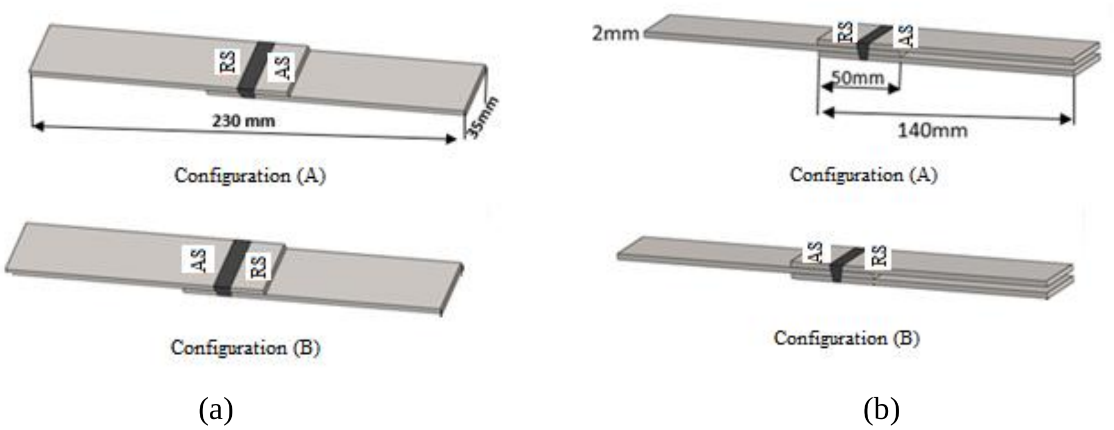


Fig. 1. Lap shear specimens: a) single lap, b) double lap

Two welding tools used for the single and double overlap joint is made of steel type 42CrMo4 (Fig. 2), it has the mechanical properties (Rm = 750/1300 MPa, A= 10-14 %, Re = 500/900 MPa and E = 210000 MPa).

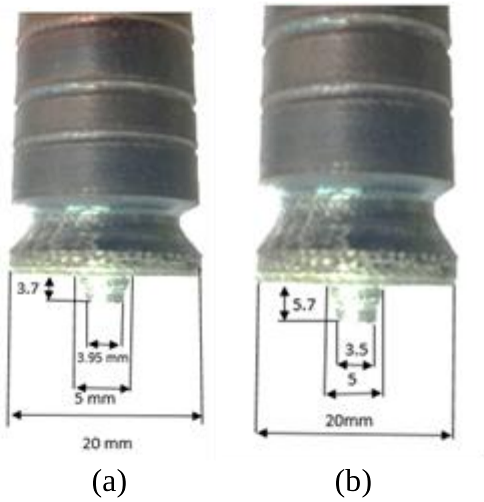


Fig. 2. Types of tools used for FSLW: a) single lap, b) double lap

A configuration of a typical single and double lap joint, used as the basic design in this work, to ensure the overlap configurations additional sheets was placed under the bottom work pieces.

The welding process was carried out along the rolling direction into two different shapes using a FSW machine and a mechanical clamping system. On the advancing side, the motor speed resulting from the rotation of the instrument is in the same direction as the translation speed of the instrument, and for the retreating side, the two speeds (axial and longitudinal) are mutually reinforcing. This causes asymmetry in the flow of materials affecting the microstructure and the mechanical properties, as shown in Fig. 3, for each FSW form (single and double lap) we distinguish two configuration according to the rotation and welding direction as shown in (Fig. 3(a,b)), an asymmetric metal flow is obtained. An advancing side and a retreating one are observed in the joint section: the former is characterized by the "positive" composition of the tool feed rate and of the peripheral tool velocity; on the contrary, in the latter the two velocity vectors are opposite. What is more, in the section a vertical movement of the material is observed due to both the tilt angle and the tool pin geometry, mixing the two sheets of material [30]. FSLW was conducted at selected rotation speeds of 1000, 1400 and 2000 rpm and selected travel speeds of 160, 200 and 250 mm/min. After the FSW welding process, the tensile test was carried out on an INSTRON tensile machine, controlled by the MTS software, as shown in Fig. 4 at a transverse speed of 2 mm/min. The hardness of the weld cross-section was measured point-wise at speeds (1400 rpm and 200 mm/min) in both forms single and double lap with a load of 1000 g and a dwell time of 10 s.

(a) (b)

Fig. 3. Stir welded Lap joint: (a) configuration (A), (b) configuration (B)

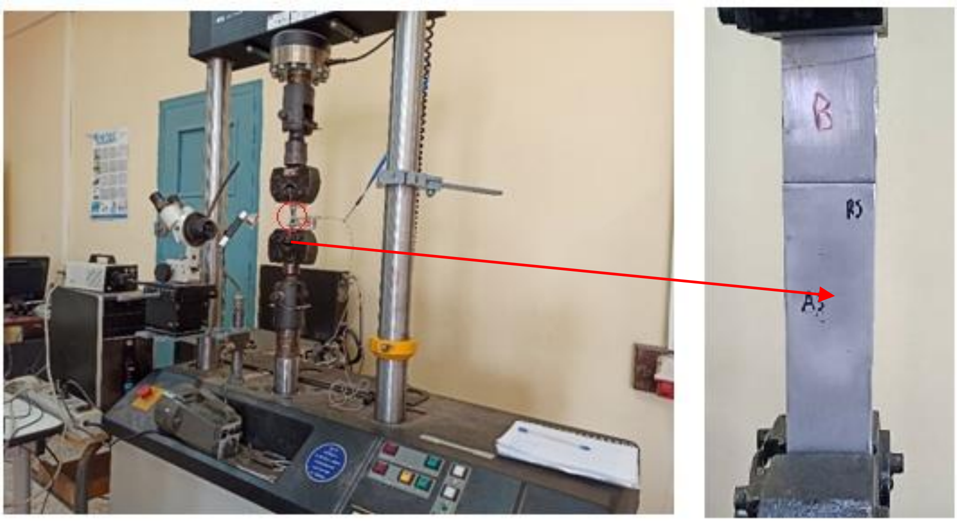
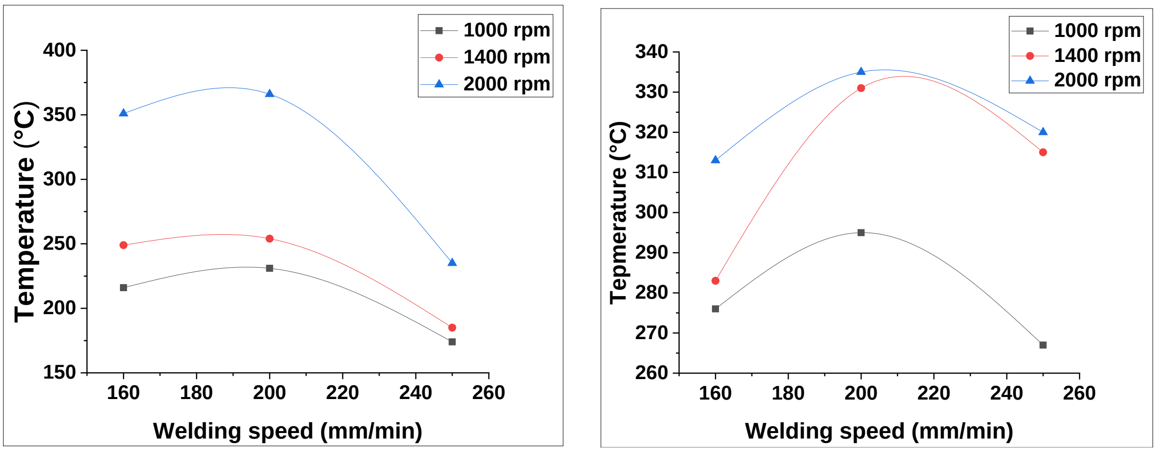


Fig. 4. Testing machine INSTRON and specimen for tensile test

Results and discussions

Effect of welding speed on the heat production. Fig. 5 shows the effect of welding speed on the temperature. A heat input change was performed in FSW using different traverse speed, which ranged from 160 to 250 mm/min. Experimental treatments that were conducted at different tool rotational speeds: 1000 rpm and 2000 rpm, were chosen to study the effect of variation in tool rotational speed on the transient temperature distribution within the welding zone.It is noted that the temperature decreases gradually with the increasing welding speed and this is attributed by the high rotational speed results in the metallurgical transformation.

A slow rotational speed avoids that the weld zone reaches the appropriate temperature with enough plastic deformation, due to the lack of heat input [31]. The temperature profiles have a uniform plot during the welding process which is trending symmetrically toward the peak of thermal cycles, and dropping after passing through the maximum temperature.



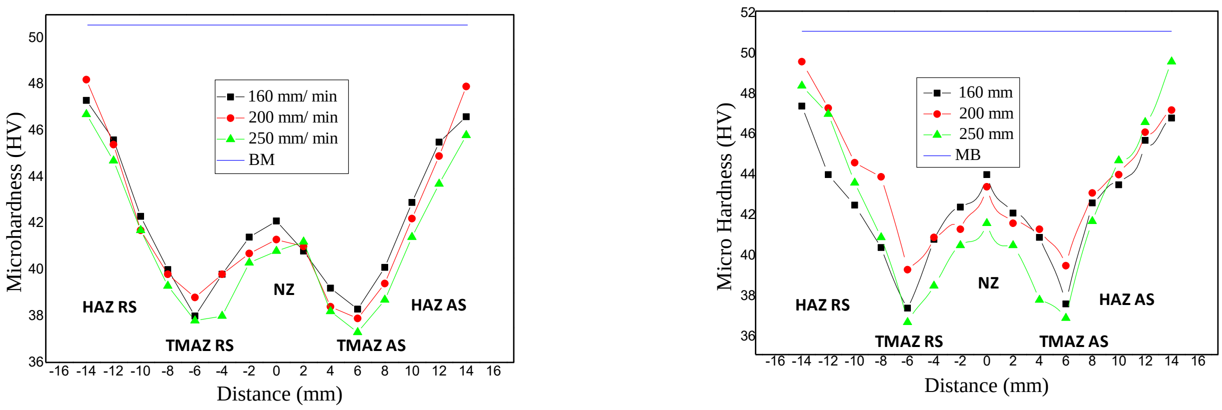
(a) (b)

Fig. 5. Temperature profiles of different welding speed: (a) single lap and (b) double lap

Microhardness measurements. The Fig.6 shows the evolution of the hardness by defeating the speed of advance (160, 200, 250) mm/min and even the speed of rotation (1400 rpm), in both forms (single lap and double lap) on a SHIMADZU HMV-2000. In the hardness measurement, we used a load 1000 g for 10 seconds per point and distance between the two points was 2 mm along 28 mm in hardness Vickers (H_V).

The value of the stiffness in areas HAZ, TMAZ and NZ decreases from the value in BM due to the decrease in the displacement density resulting from FSW. We notice from the Fig.6 that the value of the hardness decreases from the area HAZ in a direction TMAZ in various measurements until it reaches a minimum value and then rises in a direction NZ and this is due to the recrystallization of the grains because of the welding process [32]. We also note a slight decrease in hardness value in the area of NZ with an increase in welding speed [33].

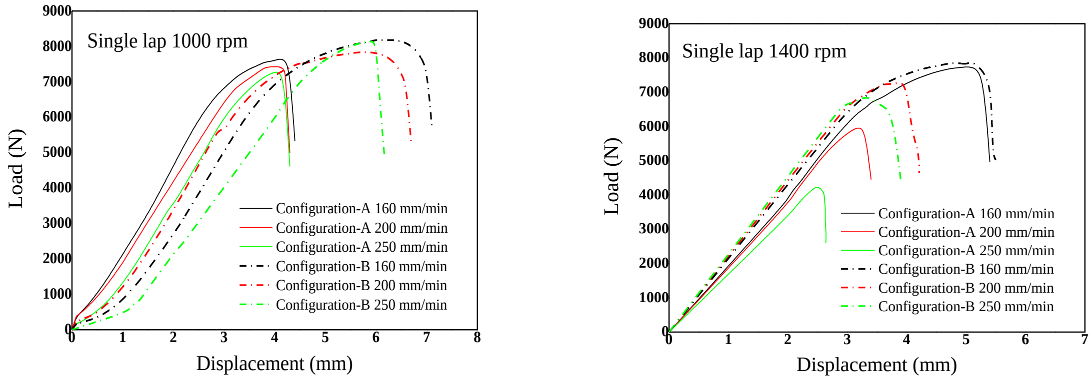
The hardness in the welded region is significantly lower with respect to the base material (50 µHV for single lap, 48 µHV for double lap). The high temperature achieved during the FSW process can be considered as the major cause of this softening effect. Even just a few microhardness values are reported for reasons of synthesis, it is possible to assert that the width of the softened region and the microhardness values recorded in the same region are influenced by the welding process parameters [34].



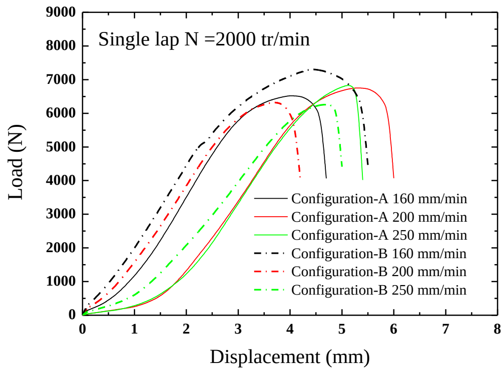
(a) (b)

Fig. 6. Hardness distribution profiles: a): single lap; b) double lap

Tensile strength test. We measured the tensile properties on the single and double lap in both configuration (A and B) are presented in Figs. 7 and 8, using constant tool rotation speeds of 1000 rpm (Fig.7(a)), 1400 rpm (Fig. 7(b)), 2000 rpm (Fig. 7(c)), and tool displacement speeds of 160, 200 and 250 mm/min. To analyze the evolution of the mechanical with the welding parameters, averaged over several trials, is calculated.



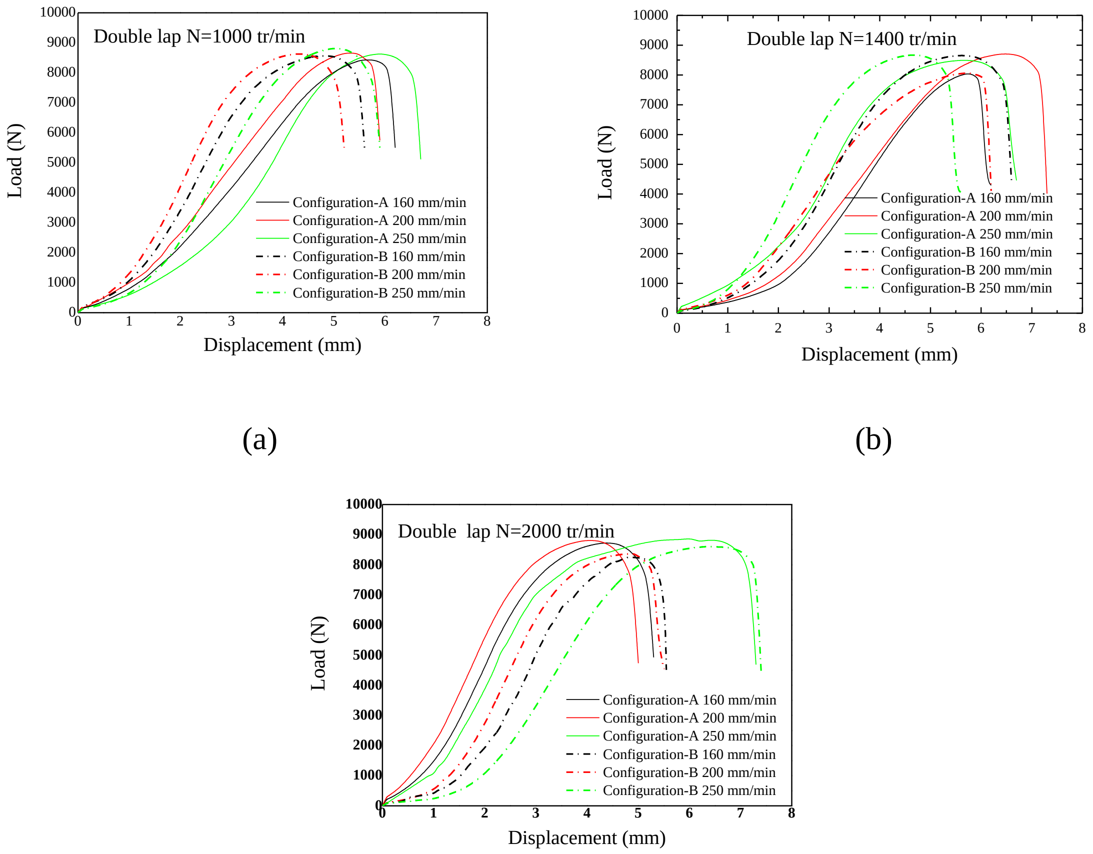
(a) (b)



(c)

Fig. 7. Load curve – displacement (Single lap): constant tool rotation speeds of 1000 rpm (a), 1400 rpm (b), 2000 rpm (c)

The results were presented according to the same parameter's to highlight the differences in mechanical resistance of the two configurations (A and B). Fig. 7 shows some representative curves, this figure shows that the load is maximum when the welding speed is equal to 160 mm/min (configuration B) Where the advancing side (AS) of the joint bore the main load, they reach a low value for a welding speed equal to 250 mm/min and rotation 1400 rpm (Fig.7(b)).



(c)

Fig.8. Load curve – displacement (double lap): constant tool rotation speeds of 1000 rpm (a), 1400 rpm (b), 2000 rpm (c)

The load-displacement curve showed that the joint made at 1000 rpm possessed bigger displacement. Overall, for the configuration (B) the joint tensile shear performance was excellent.

Failure modes. In shear tests, the friction stir welding present two failure modes [35]. The first is shear fracture or interfacial fracture, which starts at the transition point and spreads toward the free edge of the tool pin hole, and the second is mixed-mode fracture. Thinning of the top sheet metal at the tool shoulder edge due to the shoulder cut also favors this failure mode. Mode III failures are associated with moderately higher shear strengths and larger fracture energies compared to Mode II [36]. For the tensile/ shear samples, the crack initiates in the tip of the hook and then propagates along the hook. In addition, as mentioned above, when the joint is subject to the external loading, the upper sheet bends upward and the lower sheet bends downward, which leads to the nugget rotation seen in Fig. 9.

Fig.9. Shear specimen during the tensile test

Figure 10 groups the specimens after the tension test. The fracture was observed to occur predominantly in or near the interface of the SZ/TMAZ on the advancing side (AS) of the top workpiece (Fig. 10(a)), where the severe stress concentration arising from the presence of the hooking defect caused the crack to propagate directly into the top workpiece.

A total separation of the two sheets is observed in the case of the joint with double overlap (Fig. 10(b)). The fracture surfaces broken in this way, two characteristic zones can be seen in the weld area, which occurs on the advancing side (AS) of weld, and the area, which is visible in the retreating side of weld. The presence of such an area on the retreating side (RS) of joint is due to insufficient dispersion of oxides from the surfaces, which are only rubbed into weld area and form strongly adherent layer, thus reduces the mechanical properties of the joint [4].

(a) (b)

Fig.10. Different modes of fracture: a) single lap; b) double lap

Weld microstructures and properties of single and double lap FSW joint. Metallographic experiments using optical microscopy and scanning electron microscope found that the weld cross-section could be divided into nugget zone (SZ), thermomechanically affected zone (TMAZ) and heat affected zone (HAZ) as shown in Fig. 11. Analysis of each zone revealed that the material in SZ region underwent dynamic recrystallization process and redistribution of the strengthening phase [37-38]. The transformation of the microstructure into finer equiaxed grains caused the preexisting cracks to disappear [39]. For the TMAZ on both sides of the friction stir welded joint material, TMAZ (advancing side) has obvious contour boundary, and the TMAZ (retreating side) contour boundary is relatively blurred. It is generally believed that this phenomenon is related to the material flow direction [39].

The Heat Affected Zone (HAZ) is the region which lies closer to the weld-center and has experienced a thermal cycle during welding which has modified the microstructure and/or the mechanical property, there is no plastic deformation in this region. There is a distinct boundary between the recrystallized zone and the TMAZ [39].

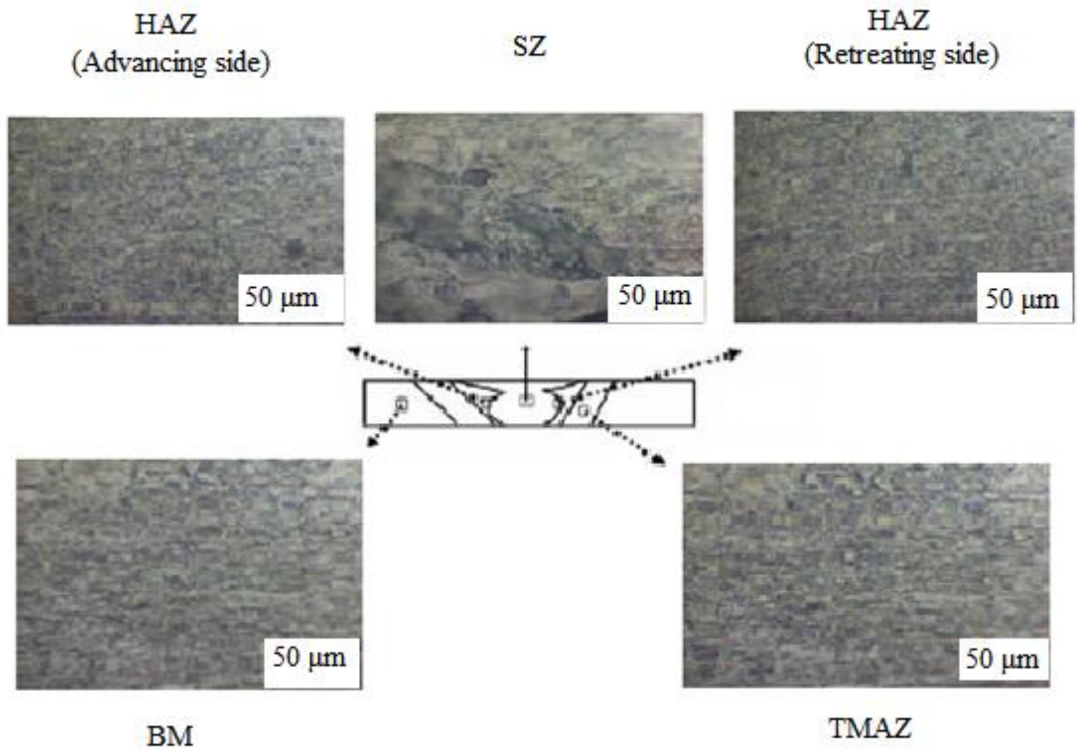


Fig.11. Metallographic cross-section of the FSLW weld (1000/160)

The microstructure of the double lap joint was characterized by Light Microscopy and SEM in the base materials and in the weld nugget zone. The microstructure of the Base Materials (BM) and characteristic zones of the FSW double lap joint are shown in Fig. 12. This figure is a Polarized Optical Micrograph of the BMs showing the equiaxed grains of the 3003 top and bottom sheets with a mean size of 10 µm, while the middle sheet has elongated grains in the longitudinal direction. The equivalent grain diameter measured are between 0.17 and 67.14 µm, calculated by the intercept method.

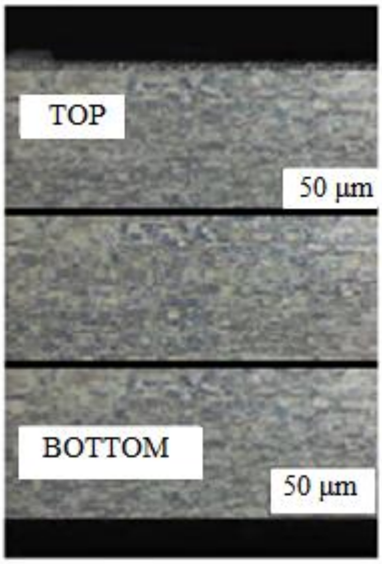


Fig.12. Microscopy of double lap FSW joint (1000/160).

Conclusions

The present work was designed to identify the most influential and optimal friction stir welding process parameters on joint strength during FSLW welding of aluminium alloy AA3003. This study focuses on the influence of three factors (speed, feed rate, welding time). In particular, the changes in microstructure, microhardness, and tensile properties of were investigated. It was found that the welding process treatment induces higher microhardness values and lower longitudinal residual stress in the weld zone surface. The flow of material is facilitated around the tool pin, while the surface hardness is improved at the same time.

The important conclusions are derived from this study are:

- For aluminium 3003 alloy welds, fracture strength was found to be very sensitive to pin positioning during FSLW.
- A maximum failure load of 9000 N was exhibited by the FSLW joints (double lap) fabricated with the optimized parameters of 1000 tr/min rotational speed, 250 mm/min welding speed. Also, this value (fractured at SZ) for the pin penetrated welds is itself higher than the maximum value (fractured at the SZ or interface) reported in literature when pin penetrating condition used.
- Beyond the HAZ, it can be seen that the stresses gradually tend towards zero when passing through the HAZ zone.

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