Relationship between mechanical behavior and process factors in friction stir welding aluminum alloys

Nabila DELLAL[1], Mohammed MERZOUG*,[1], Abdelatif MIMMI[1], Nabil BENAMARA[1]

*Corresponding author
[1]Laboratory of Materials and Reactive Systems (LMSR), Mechanical Engineering Department, Djillali Liabes University, City Larbi Ben Mhidi, P.O. Box 89, 22000 Sidi Bel Abbes, Algeria, m_merzoug01@yahoo.fr*

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Abstract: *The friction stir welding (FSW) procedure is the main topic of this research study among the various welding techniques. The study focuses on the interaction between the mechanical properties of 3003 aluminum alloy and the process parameters (rotation speed, welding speed, and dwell time) in the form of rolled plates of 2 mm thickness, end-to-end and welded at 90° and 45°. The welds were made by varying the speed of rotation (1000, 2000 rpm) and setting the tool feed at 500 mm/min. This experimental approach is also based on varying the tilt of the welding tool from 0° to 2°. It has been shown that the studied parameters play an important role in the characterization and optimization of the above mentioned weld joints. Therefore, and based on the results obtained, the use of the 90° joint remains the best in terms of strength.*

Key Words: *FSW process, 3003 aluminum Alloy, tool inclination, welding parameters, mechanical strength*

1. INTRODUCTION

In many industrial programs steels are conveniently replaced by non-ferrous alloys, in most cases using aluminum alloys, the joining of those materials can occasionally cause serious problems. Loss of structural variations in solid kingdom and super thermal and electric conductivity cause issues in fusion and resistance welding of aluminum alloys. That led to the improvement of Friction Stir Welding a strong country joining approach in which the joined cloth is plasticized through heat generated via friction among the surface of the plates and the touch surface of a special device, composed of important elements: shoulder and pin [1]. Aluminum alloy AA3003 plays a crucial role in the choice of lightweight structural materials and is widely used in the automotive industries, heat exchangers, boxes, garage tanks, fan blades, and walkways [2-4]. In a study conducted on aluminum alloy 3003-H12, welding strength accelerated with growing welding speed or reducing rotational velocity [5-6].
In other studies, the tensile strength of the welded joint of AA3003 aluminum is equal to 75% of that of the base metal, giving a defect-free joint [7-8]. For welding of AA6061 aluminum alloy, tapered cylindrical, and square pin profiles have been used to fabricate the joints at three different rotational speeds (1500, 2000 and 2500 rpm) with two traverse speeds of 20 and 40

mm/min. Mechanical characteristics of the joints, such as their hardness and tensile strength, have been assessed and examined. Tensile characteristics have been found to be significantly impacted by the design of the tool pin profile [9].

On the other hand, lap joints in the AA5052-H32 improved the hardness of the SZ and TMAZ. Moreover, in the SZ demonstrated greater hardness values than the TMAZ and HAZ [10]. However, the tensile strength would drop to a minimum value 165 MPa under the operating conditions of 800 rpm for the rotational speed, 60 mm / min for feed speed, and 2° for tool tilt angle.

For dissimilar joining of aluminum alloys by controlled temperature weld of tensile strength is improved on different clamping materials and backing of specially used for conjunction of speed 100 mm/min, rotational speed 900 rpm, tilt angle 3° and tensile strength 426 MPa, elongation 7.1 % and efficiency of joint strength 94.8 %. Hongyu Wei et al [11] observed defects (voids and cracks) in the stir zone (SZ) due to low rotational speed (ω) and low tool traverse speeds (v) and also at high ω and high v, and they proved that for the sample welded at ω = 1500 rpm and v = 47.5 mm/min the best performance under mechanical loading was with elongation and tensile strength of 24.72%.

An experimental study was carried out by Mimmi et al [12] at different speeds: 1000 rpm and 2000 rpm to see the effect of the variation in the speed of the tool on the transient temperature distribution inside the weld area. They observed that the temperature gradually decreases with increasing welding speed, due to the metallurgical transformation caused by the high rotational speed.

As stated, the best joining method for aluminum alloy in solid state is by using FSW. However, there are some constraints in using the FSW method due to its still new technology and there are still some flaws and drawbacks for which more study need to be conducted. Although there are only few parameters for the FSW process to be controlled, those different parameters highly affected the result on the joint material in term of solidification and strength of the materials. Consequently, any defect in the joint will cause problems when it comes to the application. In an industrial project, a high degree of safety and reliability is a very important factor.

In this method, we primarily use the FSW process to characterize several butt-welded samples utilizing the 3003 aluminum alloy. The relationship between the welding process parameters and the mechanical characteristics of the weld joint is the basis of the research.

The main objectives of this research are as follows:

- To investigate how tilt angle tool and welding parameters (rotating speed, welding speed, dwell time) affect the quality of the weld.
- Thermocouples positioned 10 mm from the stir zone (SZ) center are used to anticipate the temperature during the welding process.
- To investigate the effect of parameters on the mechanical properties (tensile, hardness).

2. EXPERIMENTAL METHODE

The studies were carried out using 3003 aluminum alloy with a thickness of 2mm. Table 1 shows the chemical composition of base materials, whereas Table 2 shows the mechanical properties of aluminum alloys. The plates were finished and welded to a dimension of (220mm x 140mm)for 90° welds, and (165mm x 60mm) for 45° welds, using a tool in X210Cr12a threaded cylindrical pin (5.2 mm diameter and 1.9 mm in length) and shoulder (19.5 mm diameter), with a tensile strength TS = 870 MPa (Fig. 1).

Table 1. Chemical composition of 3003 aluminum alloy

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
96,7	0,9	0,9	0,13	1,3	0	0	0,3	0,1

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 – FSW tool used

The detailed experimental plan with all possible combinations of process parameters is mentioned in Table 3. We varied the tool welding speed to be from 125 to 500 mm/ min and the tool speed from 1000 to 2000 rpm.

An illustration print of the joints produced with the different welding is presented in Fig. 2. The cutting operation of samples on the welded plates is shown in the diagram presented in Fig. 3, where the geometric dimensions are expressed in mm [13].

The tensile tests were carried out on an INSTRON tensile machine, controlled by the MTS software, as shown in Fig. 4.

Table 3. Process parameters

Runs	Rotation speed (rpm)	Welding speed (mm/min)	Tilt of the welding tool (i°)	Dwell time (s)
01	500	2000	2	20
02	250	2000	2	20
03	125	2000	2	20
04	125	2000	2	10
05	500	1000	0	10
06	500	1000	2	20
07	250	1000	2	20
08	250	1000	0	10
09	125	1000	2	10

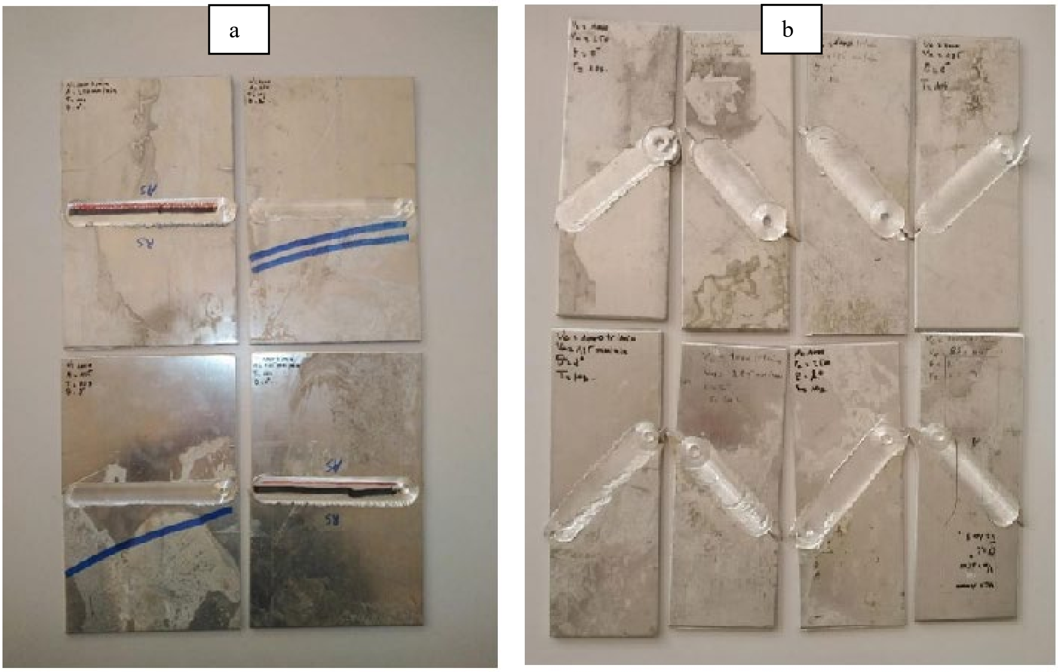
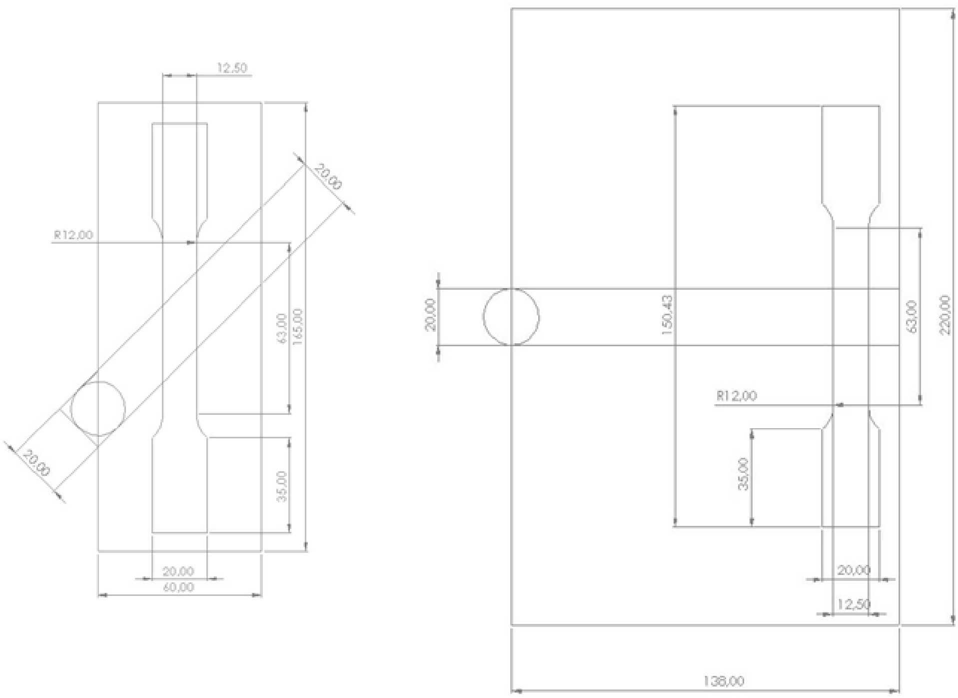


Fig. 2 – Example of welded joints obtained with different welding velocity:
a) Weld joints at 90°; b) Weld joints at 45°



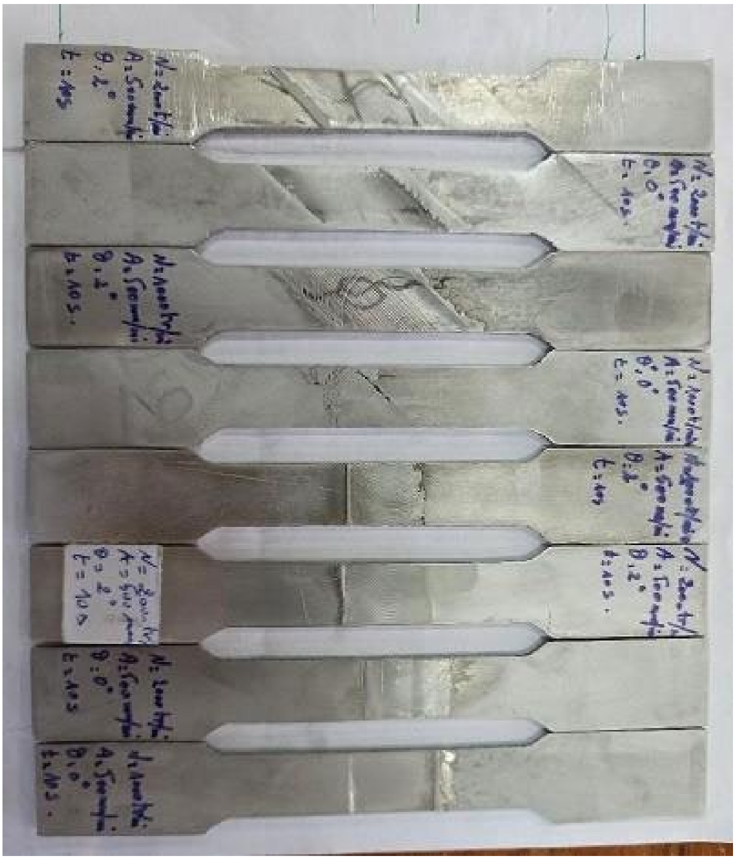


Fig. 3 – Cutting of samples on welded plates according to *ASTM E8 M 04* (Dimensions in mm)

Before During After

(a) Weld joint at 90°

Before During After

(b) Weld joint at 45°

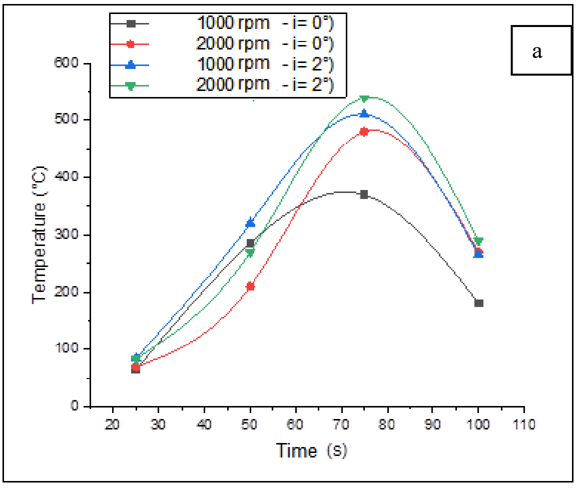
Fig. 4 – Dumbbell-shaped specimen's tensile tests measured by the extensometer

3. RESULTS AND DISCUSSIONS

3.1 Temperature profiles

Fig. 5 shows temperature profiles with varying tool speeds. Fig 5.a represents the evolution of the temperature during the linear welding of the plates as a function of time and with two positions of the tool (at 0° and 2°). It is observed that the curves have the same appearance for all the parameters chosen.

The temperature value is maximum 550°C for a rotation of 2000 rpm for an angle of inclination of 2°, the lowest 350°C is estimated for a rotation of 1000 rpm with tool not inclined (0°). By comparing the values obtained, it can be seen that at the end of the cycle, the temperatures become practically equivalent. This means that at the beginning of the cycle, the high temperatures are localized at the surface of the pin. Then, at the end of the cycle, the strong heat spreads to a zone on the periphery of the pin [14].



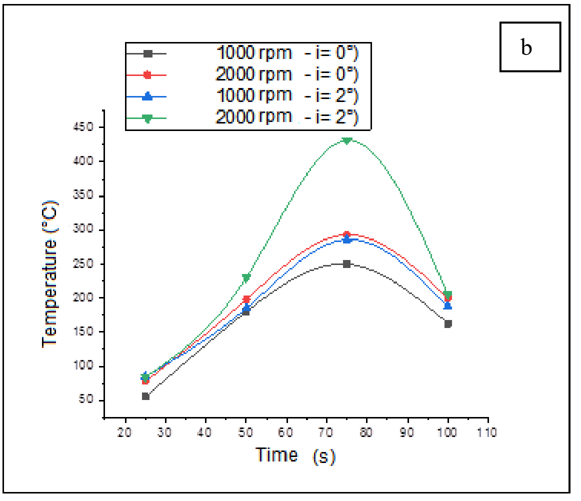


Fig. 5 – Temperature profiles: a) Weld joints at 90°; b) Weld joints at 45°

Fig. 5.b shows the temperature profile obtained for two rotational speeds equal to 1000 and 2000 rpm. We note that the evolution is identical to that seen previously. The measurements show that the temperature value is maximum 420°C for a rotation of 2000 rpm and that the lowest are obtained by the rotation speed of 1000 rpm.

3.2 Micro hardness measurements

Fig. 6 depicts the experimentally recorded variations in micro hardness across the weld centerline.

The cylindrical pin achieved a symmetrical hardness distribution with regard to the center line of the FSW keyhole for all the applied tool rotation speeds of 1000, and 2000 rpm, as given in Fig. 6a and Fig. 6b, respectively.

Micro hardness tests were prepared in order to characterize the hardness profile in the vicinity of the weld affected area i.e. NZ, TMAZ, and HAZ in the FSW specimens. Tables 4 and 5 summarize all the results obtained by micro hardness for the two configurations.

Table 4. Micro hardness results weld joints at 45°

Rotation speed/ Welding speed Tilt /Time	Weld joints at 45°					
		HAZ (RS)	ZATM (RS)	NZ	HAZ (AS)	TMAZ (AS)
2000 rpm 500 mm/min 0° - 10s	Test 1	40.9	41.3	41.3	41.8	34
	Test 2	37.4	41.1	40.6	38.2	36
	Test 3	60.9	38.9	47.4	37.1	32
2000 rpm 500 mm/min 2° - 10s	Test 1	47.5	40.3	56.3	43.5	29.7
	Test 2	41.8	38.4	37.9	36.2	30.5
	Test 3	46.2	35.7	37.3	38.7	29.9
1000 rpm 500 mm/min 2° - 10s	Test 1	47.4	45	43.6	41.3	38
	Test 2	65.6	41.6	46.8	45.8	33.6
	Test 3	48.3	41.6	42.2	55.8	39.5

Table 5. Micro hardness results weld joints at 90°

Rotation speed/ Welding speed Titl /Time	Weld joints at 90°					
		HAZ (RS)	ZATM (RS)	NZ	HAZ (AS)	TMAZ (AS)
2000 rpm 500 mm/min 0° - 10s	Test 1	49.2	44.9	38.9	54.4	56,1
	Test 2	50.1	46.8	43.1	43.4	41
	Test 3	47.2	43.1	35.1	41.5	55.6
2000 rpm 500 mm/min 2° - 10s	Test 1	46.7	52.8	50.9	42	38.5
	Test 2	46.7	44.2	42.1	42.3	38.2
	Test i 3	79	75.7	33.4	62.1	50.7
1000 rpm 500 mm/min 2° - 10s	Test 1	58.7	43.4	40.4	43.3	42.2
	Test 2	36.9	38.3	39.7	36.7	57.1
	Test 3	40.2	43.2	42.5	43.3	48.3
1000 rpm 500 mm/min 0° - 10s	Test 1	52.6	34.6	53	41	52.4
	Test	62.7	40.4	45.6	44.3	47.3
	Test 3	49.1	54.5	47.7	37.6	48.4

The results of the experiment demonstrated that the reduction in hardness in the HAZ and ZATM zones can be minimized by taking these factors into account.

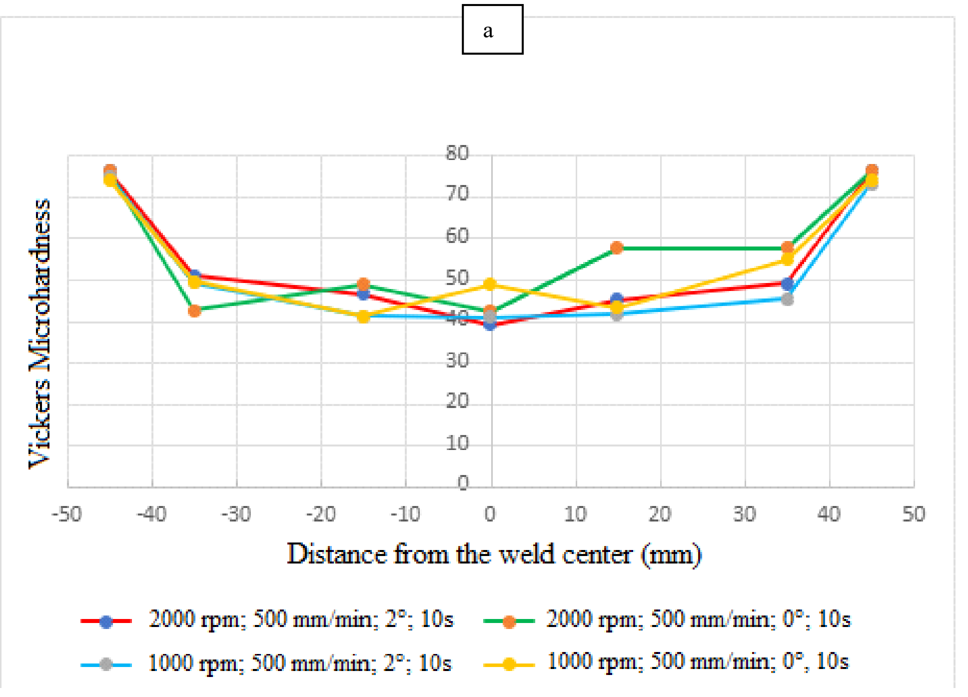
However, the increased hardness of the SZ was mostly due to the development of dynamically recrystallized equiaxed fine grains and the potential intermetallic fragmentation process that occurred during the stirring action [15-17].

The HAZ zone experiences high temperatures during the welding process, which can cause changes in the microstructure of the base alloy and reduce its hardness. The significant residual stresses generated during the FSW welding process can also affect the microstructure and hardness of these areas.

It can be concluded that the high dislocation density generated by extreme plastic deformation during the welding process promotes the increased hardness of the TMAZ above the HAZ [18-19].

Finally, the presence of impurities in the material can also negatively affect the hardness of the HAZ and ZATM zones.

It is worth noting that reducing the hardness in the HAZ and ZATM zones may be a necessary compromise to achieve a strong, high quality weld. However, by choosing appropriate welding parameters, and applying appropriate heat treatments, it is possible to minimize the reduction in hardness in these areas. Such measures will help ensure the quality and strength of the weld.



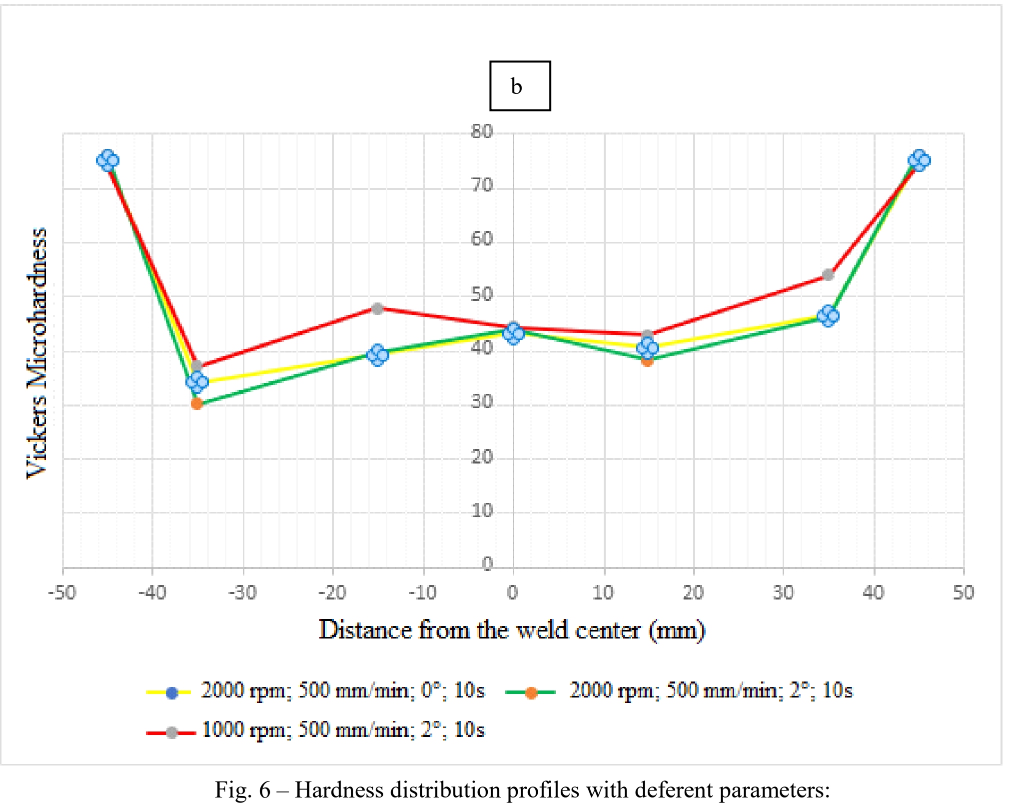
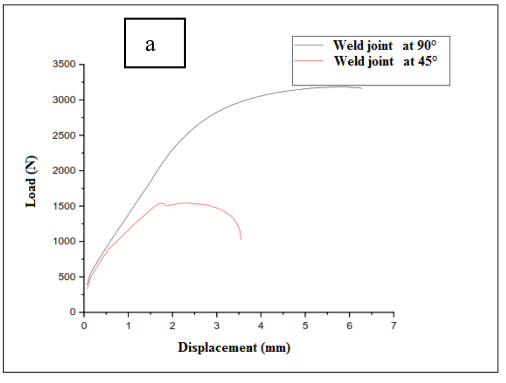
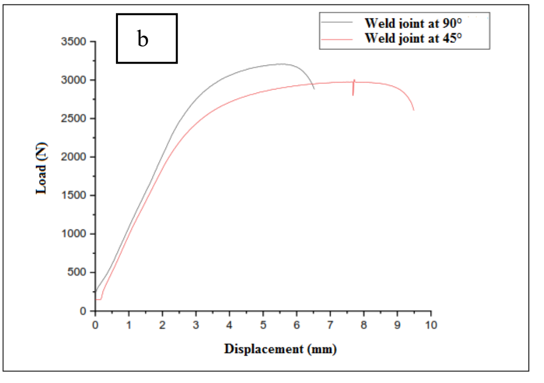


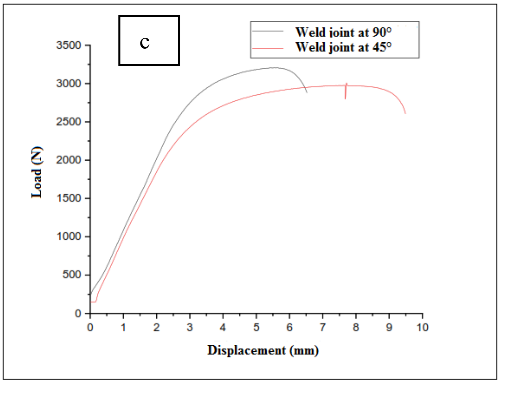
Fig. 6 – Hardness distribution profiles with deferent parameters:
a) Joints at 90°; b) Joints at 45°

3.3 Tensile characteristics

Fig. 7 shows the engineering load-displacement curve of all fabricated weld joints. In Fig.7a, joint at 90° with rotation speed 1000 rpm shows linearity up to an elongation of 2.3mm, then it loses its linearity after reaching the approximate value of 2500N which corresponds to the start of shrinkage at the level of the HAZ (heat affected zone) in the Retreating side (RS), whereas for welding at 45°, the specimen exhibits lower tensile strength compared to that welded at 90°. From the results, the defects found are mainly lack of penetrations, wormhole or voids [20]. This tensile properties among are obviously linked to the refined and recrystallization grain structures [21].







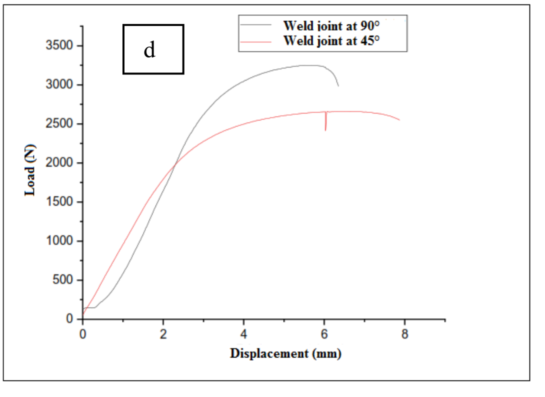
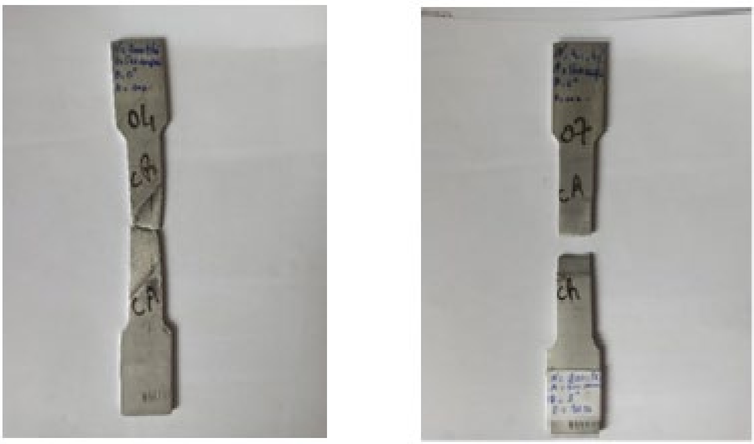


Fig. 7 – Load curve – displacement
(Titl i = 0°, 2°, Welding speed = 500 mm/min, Rotation speed=1000 and 2000 rpm)

The crack appears almost instantly after the tensile test begins. The comparison does not have too much scientific value due to the presence of a wormhole or voids on test specimen n 2. Practically Fig. 7.b for a weld at 2000 rpm, gives the same observations and remarks as Fig. 7.a. With increasing toolthe tensile strength increases due to the phenomenon of grain refinishing. Due to higher rotational speed of tool, massive aggregate of heat outcome in sever plastic deformation and due to course of evolution of ultrafine grains of high density [22]. Moreover, on contrast with sample specimen 1 and 2 (Fig 7.b), analogous drift is observed in Fig. 7.c, sample 4 welded at 45° reveals tensile–shear load of 2808 N else Sample 3 have tensile–shear load of higher value 3204 N.
Fig 7.d shows an elastic behavior of the structure which is subjected to tensile with a slight secondary bending. Figure distinctly shows light on that the joints welded at 90° exhibits tensile strength of higher value juxtaposed that the weld at 45°. Overall, it can be remarked

that the tensile results confirmed the hardness results for all the produced joints.
Fig. 8 shows the fractured specimens post tensile tests. In Fig. 8 .b (Joints at 90°), it is observed that the fracture occurs on the retreating side in the HAZ of the specimen. This behaviour indicates that the mechanical strength of the welded joint is higher than the base metal due to very high residual stresses [23]. For samples welded at an angle of 45° (Fig. 8.a), cracks almost always initiate on the lowest side of the weld on the withdrawal side of the heat-affected zone, which is a characterization of ductile failure mode. This finding is in agreement with that distinguished by Niu et al [24].The consistency in surface fracture implies that the ductility of the materials involved in the joint formation was sustained post welding, despite some percentage elongation variances.That resulted in finer recrystallized grains within the stirred zone and thermo-mechanically affected zone [25].



(a) (b)

Fig. 8 – Fractured specimens: (a) Joints at 45°; (b) Joints at 90°

3.4 Bending Test

The bending quality of the base materials was successfully tested by the three-point strategy. The bending tests were performed on the face and the root of the joint (Fig. 9).Fig. 9.a illustrates the bending samples. Fig. 9.b indicates weld samples used for the bend test. A bending test was successfully conducted to assess the weld samples' joint strength (bond strength). Bend tests were used as an important tool to understand the ductility and toughness of friction stir welds.
Figs .10a, 10b show a graphical representation of the bending strength values for defect-free and defective weld samples. Bending tests were conducted on all the weld joints by the three-point bend method to evaluate the flexural strength of the weldments. For all the FSW experimental work, rotational speed and welding speed significantly the bowing quality the bending strength by influencing the heat generated in the weld zones. These tests are very sensitive to defects near the surface of the welded, such as root flaws [26].
The coated metal under the shoulder cannot stream adequately during the welding process due to insufficient heat generation. This problem can be alleviated by optimizing the process parameters, particularly by decreasing the welding speed and increasing the rotational speed and the depth of the pin penetration in the Base Metal. At the welding speed of 500mm/min, rotational speed 2000rpm, the temperature did increase enough, so the Base Metal adequately soften to go higher bending strength.The results of bending test are conducted in

accordancewith the tensile test results, which means, that the best bending force values were achieved with the same parameters.

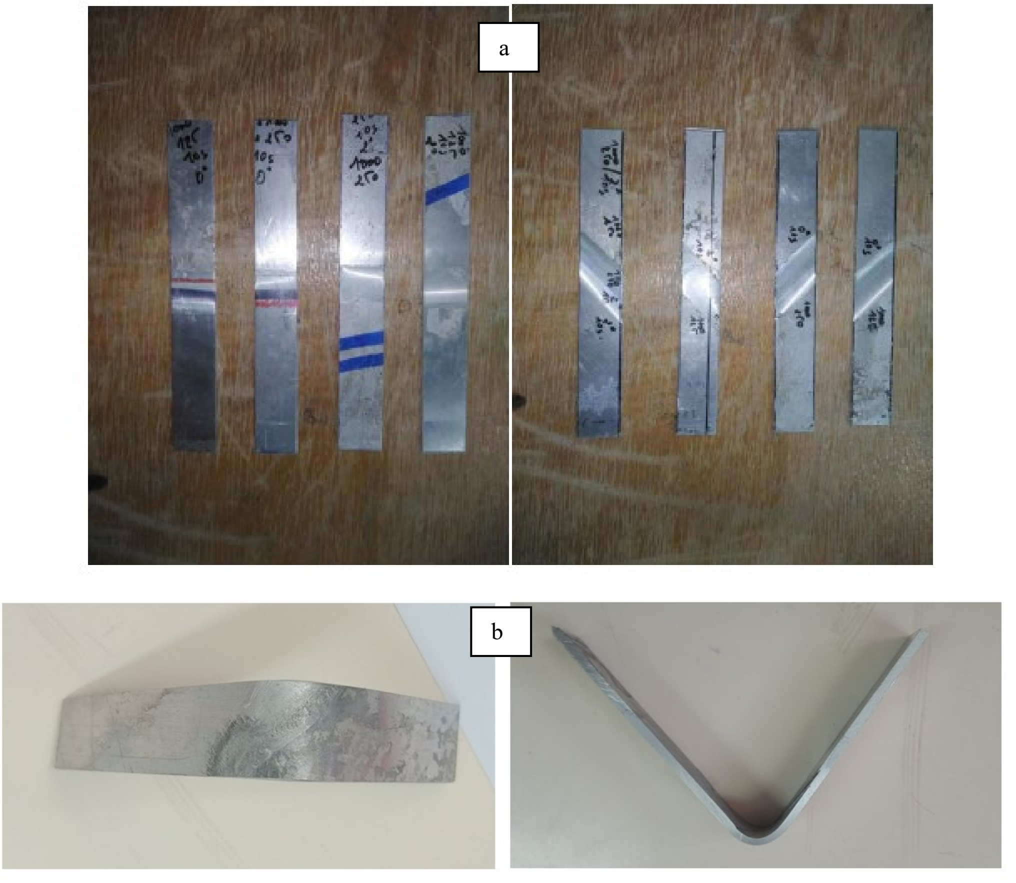
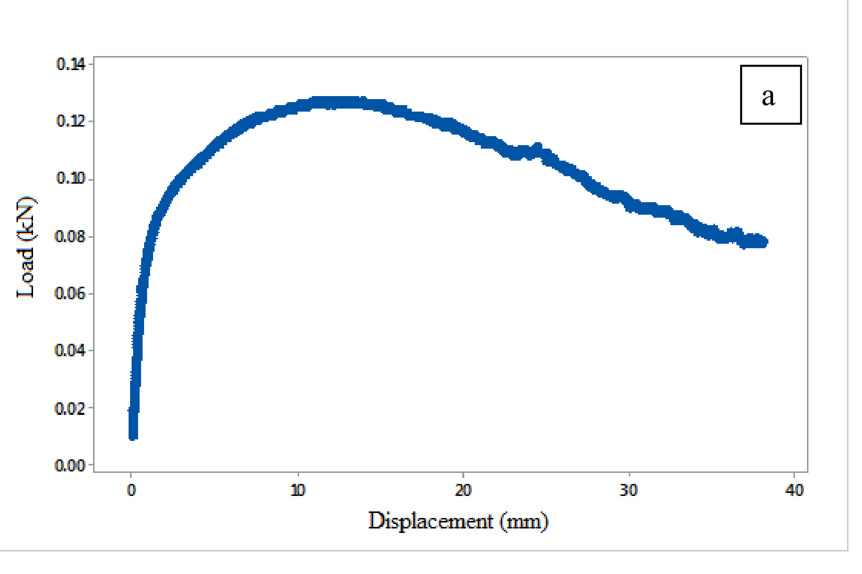


Fig. 9 – a): Bending specimens; b): Photographic view of bend samples after the experiment



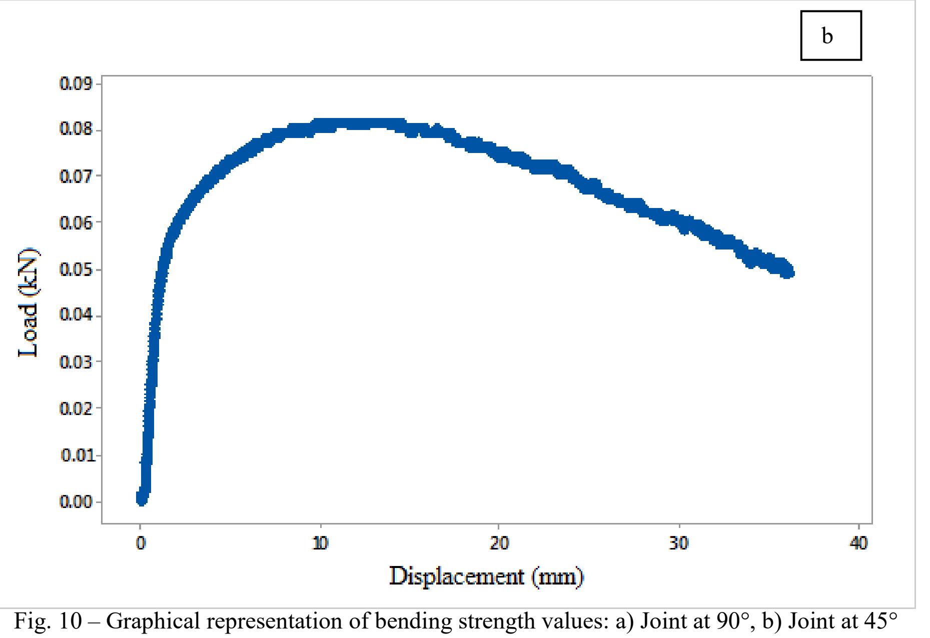


Fig. 10 – Graphical representation of bending strength values: a) Joint at 90°, b) Joint at 45°

4. CONCLUSIONS

The main objective of this study is to understand the friction stir welding process of butt welded joints with different characteristics (at 45° and 90°). Based on the results, this study clearly showed that there is a good agreement between the welding parameters chosen and the material to be used.

The main conclusions are as follows:

- For the two configurations used, those which have the best resistance to the tensile-shear force remain the specimens welded at 90° with a maximum recorded force of 3250N compared to that recorded with the specimens welded at 45° which is 2946N.
- Better appearance of the weld joint with the tilt of the welding tool (i= 2°).
- The fracture almost always took place in the heat affected zone (HAZ) for the two configurations used and in particular on the retreating side (RS).

Overall and on the basis of these observations, we can say that the use of these two butt welding methods remains relative in terms of use, so that he 90° one is more interesting for its greater resistance to the tensile force, while that at 45° has a better percentage elongation before fracture.

REFERENCES

[1] G. Raghu Babu, K. G. K. Murti, G. Ranga Janardhana, An experimental study on the effect of welding parameters on mechanical and microstructural properties of AA 6082-T6 Friction Stir Welding butt joints, *ARPN Journal of Engineering and Applied Sciences,* vol. **3**, no. 5, 2008.

[2] G. Di Bella, F. Favaloro, C. Borsellino, Effect of Process Parameters on Friction Stir Welded Joints between Dissimilar Aluminum Alloys: A Review, *Metals,* vol.**13**, no. 7, 1176, 2023.

[3] K. Liu, X. G. Chen, Development of Al–Mn–Mg 3004 alloy for applications at elevated temperature via dispersoid strengthening, *Materials and Design,* vol. **84**, pp.340-350, 2015.

[4] M. M. R. Jaradeh, T. Carlberg, Solidification Studies of 3003 Aluminium Alloys with Cu and Zr Additions, *Journal of Materials Science and Technology*, vol. **27**, no 7, pp. 615-627, 2011.

[5] C. Chanakyan, S. Sivasankar, M. Meignanamoorthy, S. V. Alagarsamy, Parametric Optimization of Mechanical Properties via FSW on AA5052 Using Taguchi Based Grey Relational Analysis, *Incas Bulletin*, vol. **13**, no 2, pp. 21-30, https://doi.org/10.13111/2066-8201.2021.13.2.3, 2021.

[6] O. Ekinci, Effect of tool rotational speed on friction stir spot welds of AZ31B Mg alloy to AISI 304 stainless Steel, *Materials Testing,*vol.**66**, no 4, pp. 534-543, 2024.

[7] G. Amit, K. R. Punit, K. K. Atul, Optimization of Friction Stir Welding Parameters for AA3003 Aluminum Alloy Joints Using Response Surface Methodology, *International Journal of Mechanics and Solids*, vol. **12**, no 1, pp. 15-26, 2017.

[8] I. Chekalil, A. Miloudi, M. P. Planche, A. Ghazi, Prediction of mechanical behavior of friction stir welded Joints of AA3003 aluminum alloy, *Frattura ed Integrità Strutturale*, vol. **54**, pp. 153-168, 2020.

[9] P. R. Srinivasa, A. F. O. Bawazir, M. Awang, A. M. A. Rani, S. Jebaraj, Effect of Tool Geometrical Parameters on Friction Stir Welding Joint Properties of Aluminium Alloy AA6061, *Journal of Engineering and Applied Sciences*, vol. **11**, no 22, 2016.

[10] M. Z. A. Mohamed, M. M. El-Sayed Seleman, I. Albaijan, A. Abd El-Aty, Microstructure, Texture, and Mechanical Properties of Friction Stir Spot-Welded AA5052-H32: Influence of Tool Rotation Rate, *Materials,* vol. **16**, no 1, 3423, 2023.

[11] H. Wei, M. Tariq, G. Hussain, I. Khan, M. I. Khan, W. A. Khan, Butt Joining of Bi-Layered Aluminum Sheets through Friction Stir Welding: Tensile Stresses, Bending Stresses, Residual Stresses, and Fractrography, *Metals*, vol. **9,** 384, 2019.

[12] A. Mimmi, M. Merzoug, A. Ghazi, Prediction of the temperature recorded in lap joint at during the friction stir welding, *Engineering Review,* 2023.

[13] M. Merzoug, A. Ghazi, A. Lousdad, N. Benamara, A. Miloudi, A. Boulenouar, Effect of the parameters affecting the properties during friction stir welding of AA 5083 H111 alloy, *Materials Physics and Mechanics*, vol. **51**, no 5, pp. 115-125, 2023.

[14] A. Mimmi, M. Merzoug, A. Ghazi, N. Dellal, Mechanical behavior of structures welded with friction stir lap Welding process, *Materials Physics and Mechanics*, vol. **51**, no 2, pp. 150-162, 2023.

[15] P. K. Rana, R. G. Narayanan, S. V. Kailas, Friction Stir Spot Welding of AA5052-H32/HDPE/AA5052-H32 Sandwich Sheets at Varying Plunge Speeds, *Thin-walled structures*, vol. **138,** pp. 415-429, 2019.

[16] Tiwan, M. N. Ilman, Kusmono, Microstructure and Mechanical Properties of Friction Stir Spot WeldedAA5052-H112 Aluminum Alloy, *Heliyon*, vol. **7**, no 2, 2021.

[17] M. Merzoug, M. Mazari, L Berrahal, A Imad, Parametric Studies of the Process of Friction Spot StirWelding of Aluminium 6060-T5 Alloys,*Material and Desig,*vol. **31**, pp. 3023-3028, 2010.

[18] M. Z. A. Mohamed, M. E. S. S. Mohamed, A. Ibrahim, E. A. Ali, Microstructure, Texture, and Mechanical Properties of Friction Stir Spot-Welded AA5052-H32: Influence of Tool Rotation Rate, *Materials*, vol. **16**, 2023.

[19] I. T. Abdullah, Influence of the Tunnel Defect in Al 6061-T651 welded by FS on the Bending, Tensile, and Stress Concentration Factor, *International Journal of Current Engineering and Technology*, vol.**7**, no 4, 2017.

[20] I. Mumvenge, A. Akinlabi Stephen, P. M. Mashinini, S. Fatoba, J. Okeniyi, T. Esther, E. T. Akinlabi, Evaluation of Friction Stir Welds by X-ray Digital Radiographic Non-Destructive Approach, *Science and Engineering*, vol. **413**, no 1, 2018.

[21] Y. Birol, S. Kasman, Effect of welding parameters on microstructure and mechanical properties of friction stir welded EN AW 5083 H111 plates, *Materials Science and Technology,* Vol. **29**, no 11, pp. 1354-1362, 2013.

[22] M. Sajed, J. W. G. Guerrero H. A. Derazkola, A Literature Survey on Electrical-Current-Assisted Friction Stir Welding, *Applied Science*. Vol. **13**, no 2, 1563, 2023.

[23] B. Abna, S. Gashtiazar, M. Javidani, Friction Stir Welding of Non-Heat Treatable Al Alloys: Challenges and Improvements Opportunities, *Cristals,* vol. **13**, 576, 2023.

[24] P. L. Niu, W.Y. Li, D. L. Chen, Strain hardening behaviour and mechanisms of friction stir welded dissimilar joints of aluminium alloys*, Materials Letters*, vol. **231**, pp. 68-71, 2018.

[25] A. N. Abed, G. S. Sadi, Investigation the Mechanical Properties of 2024AA of Friction Stir Processing, *Journal of Physics: Conference Series*, **1973**, 012045, 2023.

[26] S. K. Naimuddin, M. T. Ahamad, V. Kampurath, Y. Ali, Mechanical properties of friction stirwelding joints of similar and disimilar aluminium alloys AA6061 and 6082, *International Journal of Mechanical Engineering and Technology (IJMET),* Vol. **7**, no 4, pp. 256-266, 2016.