The Effect of Tool Rotation Speed on Local and Global Mechanical Behavior of Friction Stir Spot Welded (FSSW) AA7075-T6 Aluminum Alloy Sheets

Hadji I, Boutaghou Z and Badji R

Abstract— This investigation focused on the impact of tool rotation speed on the mechanical and metallurgical characteristics of friction stir spot welded (FSSW) AA7075-T6 aluminum alloy sheets. To achieve this, aluminum alloy plates were joined using FSSW with four distinct welding parameters consisting of rotation speeds of 725, 1000, 1500 and 1800 rpm and a constant insertion depth of 3.2 mm. To evaluate the mechanical properties and strain field evolution of the welded joint AA7075, a lap shear and digital image correlation (DIC) tests were conducted. In the spot-welded specimens, the highest tensile strength value (2200 N) was found in plates welded at a tool rotation speed of 1500 rpm. The results from a hardness distribution indicate that the thermomechanical affected zone (TMAZ) is the softest area in the weldment, and the fracture typically occurs in this region. The results from DIC clearly show that the strain was heterogeneously distributed across the specimen, mainly due to the microstructural changes in the welded zone.

Keywords— AA 7075-T6, Digital image correlation, Friction stir spot welding, Mechanical properties.

I. INTRODUCTION

Friction Stir Welding (FSW) has made a significant impact in various industries because of its advantages. The automotive industry specifically has adapted a variation of the process, known as Friction Stir Spot Welding (FSSW). Mazda Motor Company introduced this spot welding method based on FSW in 2003[1], [2]. Unlike other fusion welding methods, FSSW eliminates fusion defects such as pores and hot cracks. Additionally, FSSW exhibits high mechanical properties, low distortion, and low residual stress due to the minimal temperature difference during welding. Unlike other spot joining techniques like riveting and resistance spot welding, FSSW does not require pre-drilling, and there is no increase in weight after welding.

The impact of tool rotational speed, a crucial welding parameter, has been investigated in previous studies [3]–[6]. The results of these studies indicate that rotational speed has a varying effect on welding performance. According to Cao et al. [7], tensile strength initially increases with an increase in tool rotational speed but decreases with further increase. Meanwhile, Zhang et al. [8] found that joint performance decreases with increasing rotational speed according to the results of tensile tests. Gerlich et al. [9] stated that insufficient material transport occurs when the tool rotation speed is set at 750 rpm.

This study aimed to determine the effect of tool rotation speed, a critical factor in the welding performance of AA 7075-T6 Aluminum alloy sheets using FSSW, on the mechanical properties of the welding. Tensile tests and microhardness tests were conducted, and a metallographic examination of the welding zone was conducted using an optical microscope.

Digital Image Correlation (DIC) is a non-contact, full-field measurement technique that has become increasingly popular in recent years for studying the mechanical behavior of materials and structures. One of the key benefits of using DIC for FSSW is its ability to accurately measure small displacements and strains [10], [11]. This is particularly important for studying the welding process, as the high local strains and plastic deformation that occur during FSSW can be difficult to measure using other techniques.

II. MATERIAL AND METHOD

In this study, AA7075-T6 aluminum alloy plates measuring 100x30x2 mm in size were used. AA7075-T6 sheets were spot welded by using the FSSW method (Fig. 1.a). The chemical composition of the AA7075-T6 used is shown in Table 1. The FSSW process utilized H13 hot work tool steel, a material known for its high wear resistance, toughness, and machinability, as the welding tool. The tool consisted of a pin, shoulder, and was designed with a 14 mm shoulder diameter, 6 mm pin diameter, and 3 mm pin length. It was manufactured through machining and the end zone (pin and shoulder) were hardened through heat treatment. The tool used for the experimental study is presented in Fig. 1b.

Manuscript received Mars 1, 2023.

H. I, B. Z. and B. R. Authors are with Research Centre in Industrial Technologies - CRTI P.O.Box 64, Cheraga 16014 Algiers, Algeria

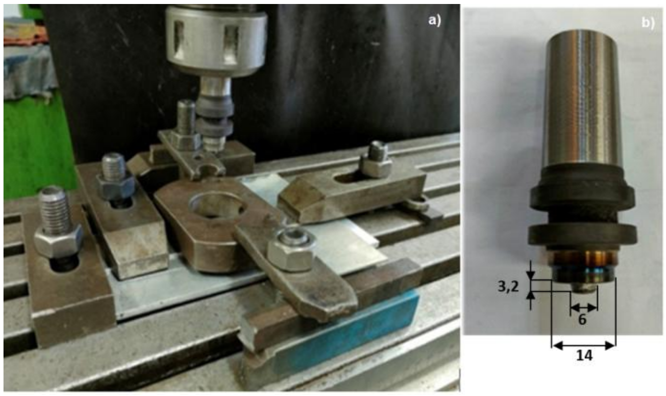

Fig. 1. a) Friction Stir Spot welding system, b) Tool used in the FSSW

TABLE 1. THE CHEMICAL COMPOSITION OF AA7075-T6

Alloy	Cu	Zn	Mg	Mn	Si	Cr
7075 – T6	1.83	6.52	2.45	0.22	0.35	0.21

FSSW welding was carried out on AA7075-T6 by using a 4.2 kW universal milling machine with a vertical head. The welding was performed at four different rotational speeds (725, 1000, 1500 and 1800rpm) with a 20 second dwelling time at a 30mm x 30mm overlap area. The milling machine was set to rotate the tool clockwise and the FSSW process, which includes plunging, stirring, and retraction stages, was initiated as shown in Fig. 2.

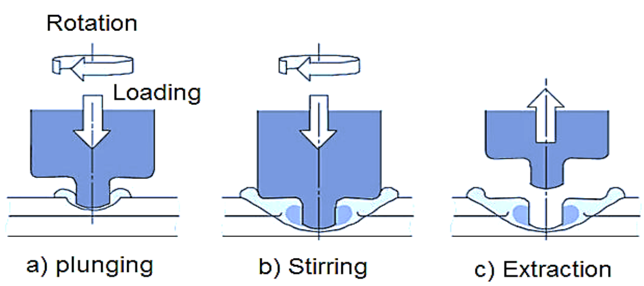

Fig. 2. Schematic representation of the FSSW process

During the initial phase, the tool tip rotated at a set speed and penetrated the part at a rate of 0.3 mm/s in a perpendicular direction along the milling table. The table was then lifted until the shoulder of the rotating tool, with its pin inserted into the work piece, made contact with the base metal. The penetration amount was adjusted, and a 20-second dwell time was observed. To evaluate the mechanical properties, we conducted tensile testing using a universal tensile testing device with a capacity of 10 kN. The specimens were loaded at a rate of 1 mm/min under standard room conditions. To analyze the microstructure, we used a ZEISS optical microscope. After sanding and polishing, the specimens were etched and analyzed. The Vickers hardness values were determined by applying a 200g load for 15 seconds in a hardness test.

III. Results and Discussion

A. Metallographic Characterization of the Weld

The results of the FSSW process performed with different tool rotation speeds are displayed in Fig. 3. Through the examination of the welded joints produced with varying parameters, it was found that the joints were seamless with good penetration. However, in the welding zone of aluminum plates welded at low tool rotation speeds, the joint interface was visible and an amount of porosity was present (as shown in Fig. 3a). In contrast, the welding zone of aluminum plates welded at high tool rotation speed (1500 rpm) did not exhibit any visible interface or porosity (as depicted in Fig. 3b). It was also noted that the stir zone increased with an increase in tool rotation speed, which is in agreement with the findings of Bozzi et al. [12], who attributed the increase in stir zone to a higher generation of heat.

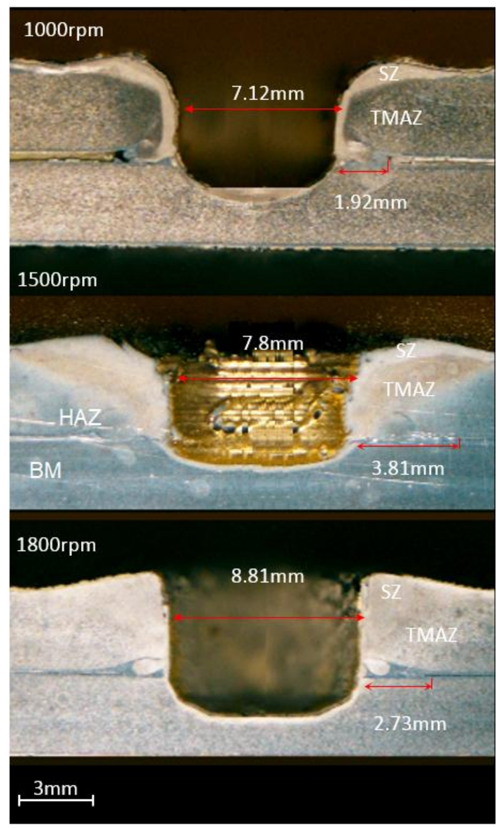

Fig.3. The optical macrographs of welded joints obtained using different rotation speeds, a) 1000 rpm, b) 1500 rpm, and c) 1800 rpm

B. Examination of Lap-Shear and Fracture behavior

At various rotational speeds, Fig. 4 shows macrographs of a fractured joint that failed in shear fractures. The upper sheets are shown on the left figures, viewed from the bottom, while the lower sheets are shown on the right figures, viewed from the top. The fractures occurred between the upper sheet and the loading side of the lower sheet, indicating shear fractures in all joints. Increasing the rotational speed did not have an impact on the fracture mode. Welds experienced shear

https://doi.org/10.17758/EARES13.EAP0523101

fractures, while the thinner area of the upper sheet was where the tensile fracture first occurred, propagating circumferentially before culminating in a shear fracture. Additionally, an increase in rotational speed led to a larger diameter of the button remaining in the upper sheet. Zahou et al. [13] et Yoon et al. [14] observed similar failure modes.

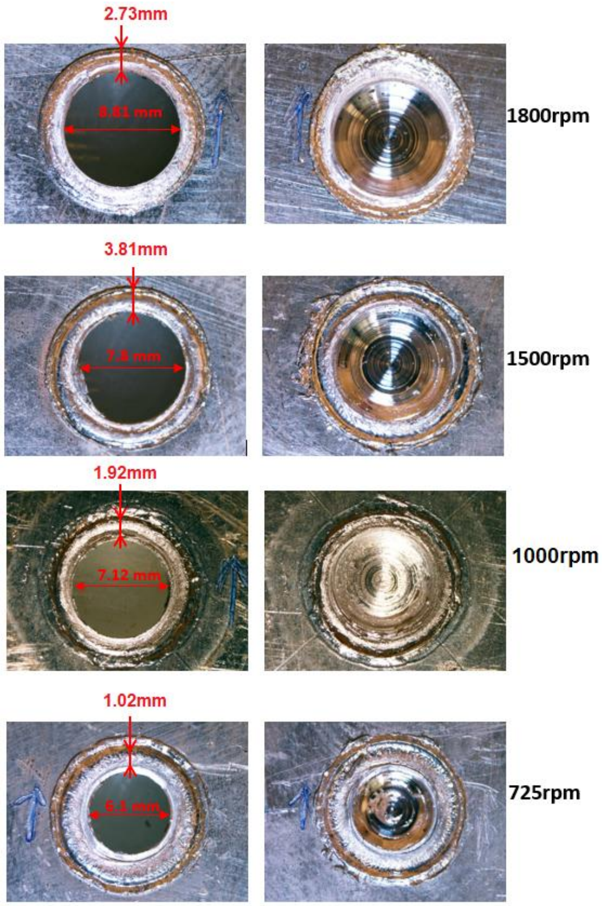

Fig.4. Macrographs of welding zones on the top and bottom plates after the tensile test

Fig. 5 presents the tensile-shear forces and elongation relationship of the welded parts obtained using different rotation speeds, showing an increase in the tensile force with increasing tool rotation speed. The highest tensile-shear load value of 2200N is obtained at a tool rotation speed of 1500 rpm. Paidar et al. [15] and Patel et al. [16] both determined that the tensile strength increased with increasing tool rotation speed and obtained the highest strength value at 1500 rpm. Bozzi et al. [12] explained the increase in tensile strength with increasing tool rotation speed as being due to the larger size of the stir zone. Additionally, Babu et al. [17] reported in their work on FSSW-AA2014 that the bond width increased up to 1500 rpm but decreased at higher RPMs due to excessive heating. Venukumar et al. [18] reported that the weld strength was affected by high heat generation during the high tool rotational speed. In other way, the higher strength can be achieved at lower tool rotational speed.

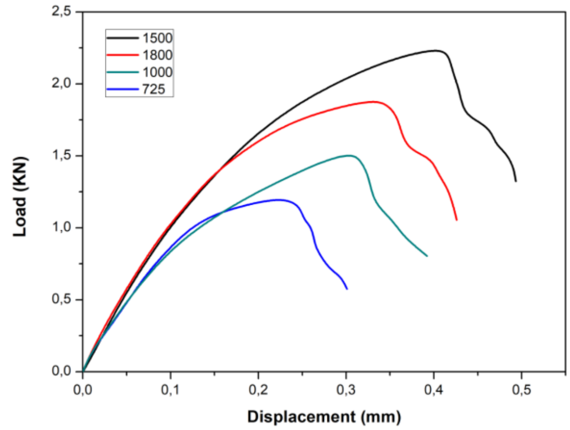

Fig.5. Force-elongation curves obtained from the tensile for different rotation speeds (725, 1000, 1500 and 1800 rpm)

C. Investigation of Hardness Values

Fig. 6 presents the relationship between the Vickers hardness values of the welded parts obtained using different rotational speeds. The microhardness tests were conducted 0.3mm above the joint interface, and it was observed that the hardness values were higher in the base material (BM), Thermomechanical affected zone (TMAZ) and stir zone (SZ), and lower in the Heat affected zone (HAZ). Similar results were found for hardness values at different tool rotation speeds. However, for the sample joined with 725 rpm, it was found that the hardness values decreased in the region closer to the welding center, indicating a smaller stir zone. According to Chen et al. [19], the decrease in hardness value is caused by the formation of coarse grains due to over-aging, while the increase in hardness in the stir zone is attributed to high temperature and plastic deformation, causing dynamic recrystallization and a fine grain structure. Similar results were obtained by Zhang et al. [20], who also attributed the decrease in hardness value to thermal cycling.

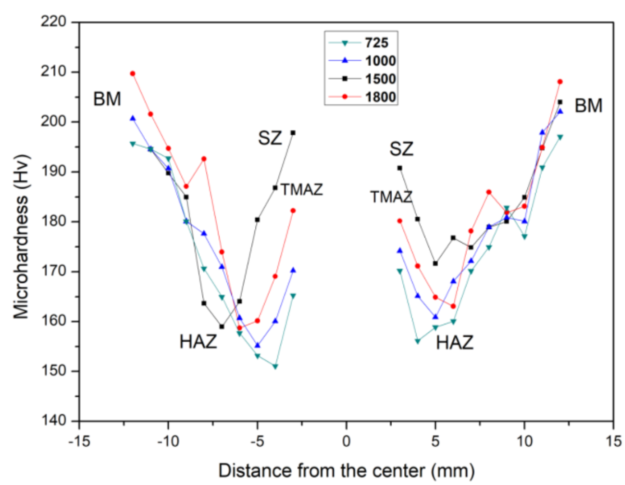

Fig. 6. Vickers hardness of plates joined by FSSW using different rotational speeds (1000, 1500 and 1800 rpm)

D. Deformation behavior by using Digital Image Correlation

The strain field determined for the upper and bottom surface of the sheet at different stages is shown in Fig 7. This effectively represents the assumed behavior of crack initiation and propagation. Regions with elevated levels of strain indicate the existence and spread of underlying cracks. On the loaded side of the top sheet of AA7075 alloy, the strain concentration is present beyond the SZ and is distributed circumferentially. On the loaded side of the bottom sheet, there is also a strain concentration, but the value of the strain is relatively low, indicating the limited development of cracks. Furthermore, the strain variation on the lower surface of the AA7075 Alloy sheet suggests that there is some minor circumferential propagation of cracks, which is primarily associated with the secondary bending that occurs during Tensile-Shear testing.

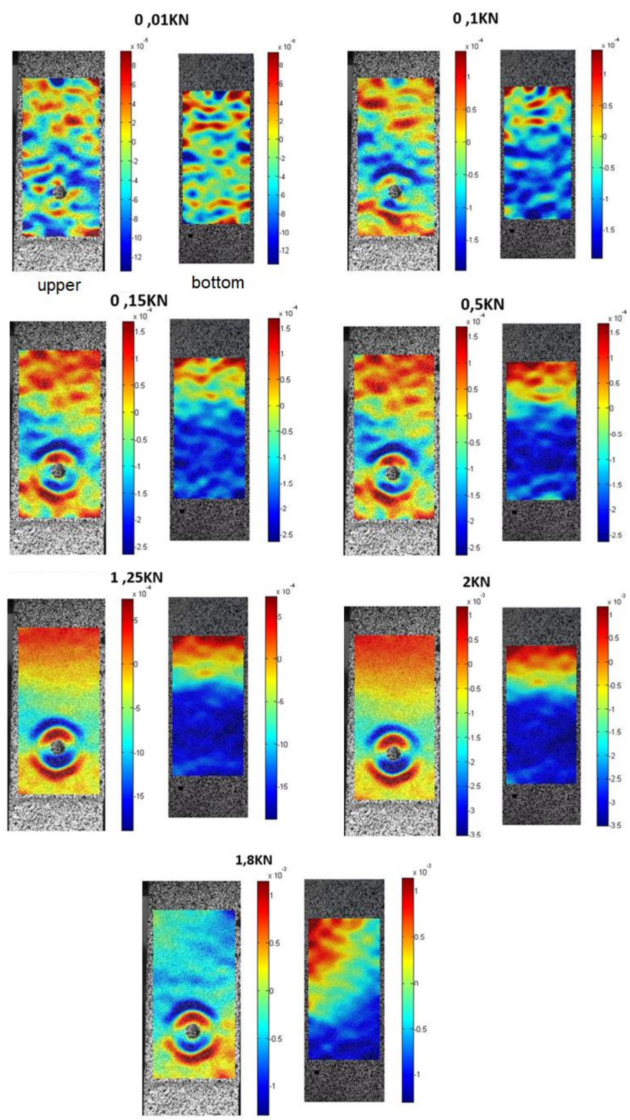

Fig.7. strain field determined for sheet upper and bottom surface at different stages for 1500rpm tool rotation speed

In the lap shear test, the upper sheet undergoes tensile stresses along the interface on the loaded side, while compressive stresses affect the free side [11], [21]. As a result, cracks form initially on the loaded side, leading to higher overall strains than on the free side. The strain asymmetry is evident in the strain distribution along the z-axis in Fig. 8. On the loaded side, the strain in all interfacial regions increases locally with force, and as such, the entire interface contributes to the strength.

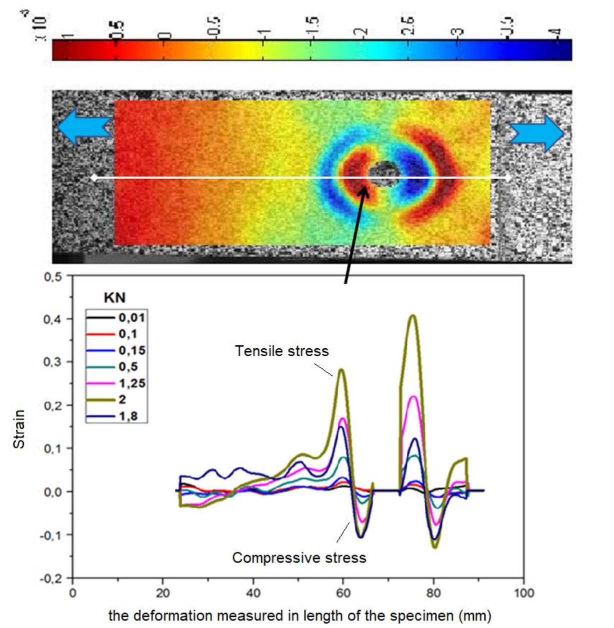

Fig.8. strain profile along z-axis at different stages for 1500rpm tool rotation speed.

IV. CONCLUSION

Successful Friction Stir Spot Welding of AA7075-T6 joints was conducted with tool rotation speeds ranging from 725 rpm to 1800 rpm.

The mechanical properties were observed to be predominantly affected by the tool rotation speed. The welds' tensile/shear and cross-tension loads increased as the rotation speed increased from 725 rpm to 1500 rpm and then decreased at 1800 rpm. The maximum tensile/shear occurred at a rotational speed of 1500 rpm, with a value of 2200N.

At a lower tool rotation speed (725 rpm), the hardness values in the welding center region decreased, indicating a smaller stir zone. Vickers hardness varied across the cross-section of the weld, with compressed material areas showing higher values.

On the loaded side of the top sheet of AA7075 alloy, there was a strain concentration beyond the stir zone that was distributed circumferentially.

Microscopic examination of the weld zone's cross-section revealed planar cracks at the two plates' intersection that were not detected by radiography testing.

REFERENCES

[1] M. M. C. T. Iwashita, "Method and apparatus for joining," *Pat. Publ.*, no. US6601751 B2, 2003.

[2] I. T. Kano Y, Inuzuka M, Yamashita S, Nakashima Y, Nagao Y, "application FSSW," *Japanese patents*, no. P2000-355770;, p. 355-770, 2000.

[3] S. Suresh, K. Venkatesan, E. Natarajan, and S. Rajesh, "Influence of tool rotational speed on the properties of friction stir spot welded AA7075-T6/Al2O3 composite joint," *Mater. Today Proc.*, vol. 27, pp. 62–67, 2020. https://doi.org/10.1016/j.matpr.2019.08.220

[4] S. Memon, M. Paidar, S. Mehrez, K. Cooke, O. O. Ojo, and H. M. Lankarani, "Effects of materials positioning and tool rotational speed on metallurgical and mechanical properties of dissimilar modified friction stir clinching of AA5754-O and AA2024-T3 sheets," *Results Phys.*, vol. 22, no. November 2020, p. 103-962, 2021. https://doi.org/10.1016/j.rinp.2021.103962

[5] W. Li, J. Li, Z. Zhang, D. Gao, W. Wang, and C. Dong, "Improving mechanical properties of pinless friction stir spot welded joints by eliminating hook defect," *Mater. Des.*, vol. 62, pp. 247–254, 2014.

[6] C. A. G. Aita, I. C. Goss, T. S. Rosendo, M. D. Tier, A. Wiedenhöft, and A. Reguly, "Shear strength optimization for FSSW AA6060-T5 joints by Taguchi and full factorial design," *J. Mater. Res. Technol.*, vol. 9, no. 6, pp. 16072–16079, 2020. https://doi.org/10.1016/j.jmrt.2020.11.062

[7] M. Cao, X., Jahazi, "Effect of tool rotational speed and probe length on lap joint quality of a friction stir welded magnesium alloy," vol. 45, no. July, pp. 1–7, 2011. https://doi.org/10.1016/j.matdes.2010.06.048

[8] Z. Zhang, X. Yang, J. Zhang, G. Zhou, X. Xu, and B. Zou, "Effect of welding parameters on microstructure and mechanical properties of friction stir spot welded 5052 aluminum alloy," *Mater. Des.*, vol. 32, no. 8–9, pp. 4461–4470, 2011. https://doi.org/10.1016/j.matdes.2011.03.058

[9] A. Gerlich, P. Su, M. Yamamoto, and T. H. North, "Effect of welding parameters on the strain rate and microstructure of friction stir spot welded 2024 aluminum alloy," *J. Mater. Sci.*, vol. 42, no. 14, pp. 5589–5601, 2007. https://doi.org/10.1007/s10853-006-1103-7

[10] B. Zhang, X. Chen, K. X. Pan, M. Li, and J. N. Wang, "Thermo-mechanical simulation using microstructure-based modeling of friction stir spot welded AA 6061-T6," *J. Manuf. Process.*, vol. 37, no. November 2018, pp. 71–81, 2019. https://doi.org/10.1016/j.jmapro.2018.11.010

[11] B. Fu *et al.*, "Revealing joining mechanism in refill friction stir spot welding of AZ31 magnesium alloy to galvanized DP600 steel," *Mater. Des.*, vol. 209, p. 109997, 2021. https://doi.org/10.1016/j.matdes.2021.109997

[12] S. Bozzi, A. L. Helbert-Etter, T. Baudin, V. Klosek, J. G. Kerbiguet, and B. Criqui, "Influence of FSSW parameters on fracture mechanisms of 5182 aluminium welds," *J. Mater. Process. Technol.*, vol. 210, no. 11, pp. 1429–1435, 2010. https://doi.org/10.1016/j.jmatprotec.2010.03.022

[13] J. C. F. L. Zhou, L.Y. Luo, T.P. Zhang, W.X. He, Y.X. Huang, "Effect of rotation speed on microstructure and mechanical properties of refill friction stir spot welded 6061–T6 aluminum alloy," *Int. J. Adv. Manuf. Technol.*, vol. 5, no. 1, pp. 1–8, 2017.

[14] H. O. N. . Sung-Ook, Y.O.O.N., Myoung-Soo, K.A.N.G., Yong-Jai, K.W.O.N., Sung-Tae, "Influences of tool plunge speed and tool plunge depth on friction spot joining of AA5454-O aluminum alloy plates with different thicknesses," *Trans. Nonferrous Met. Soc. China*, vol. 22, pp. 629–633, 2013. https://doi.org/10.1016/S1003-6326(12)61776-2

[15] A. S. Paidar, M., Khodabandeh, A., Najafi, H., Rouh-aghdam, "Effects of the tool rotational speed and shoulder penetration dep- th on mechanical properties and failure modes of friction stir spot welds of aluminum 2024-T3 sheets," *J. Mech. Sci. Technol.*, vol. 28, no. 12, pp. 2–3, 2014. https://doi.org/10.1007/s12206-014-1108-0

[16] V. V. Patel *et al.*, "Effect of Tool Rotation Speed on Friction Stir Spot Welded AA5052-H32 and AA6082-T6 Dissimilar Aluminum Alloys," *Metallogr. Microstruct. Anal.*, vol. 5, no. 2, pp. 142–148, 2016. https://doi.org/10.1007/s13632-016-0264-2

[17] G. J. Babu, S., Sankar, V., Ram, "Microstructures and mechanical properties of friction stir spot welded aluminum alloy AA2014," *J. Mater. Eng. Perform.*, vol. 22, pp. 71–84, 2013. https://doi.org/10.1007/s11665-012-0218-z

[18] S. Venukumar, S. Muthukumaran, S. G. Yalagi, and S. V. Kailas, "Failure modes and fatigue behavior of conventional and refilled friction stir spot welds in AA 6061-T6 sheets," *Int. J. Fatigue*, vol. 61, pp. 93–100, 2014. https://doi.org/10.1016/j.ijfatigue.2013.12.009

[19] B. Zhang, X. Chen, K. Pan, and C. Yang, "J-integral based correlation evaluation between microstructure and mechanical strength for FSSW joints made of automotive aluminum alloys," *J. Manuf. Process.*, vol. 44, no. May, pp. 62–71, 2019. https://doi.org/10.1016/j.jmapro.2019.05.039

[20] Z. Jamili-Shirvan, M. Haddad-Sabzevar, J. Vahdati-Khaki, and K. F. Yao, "Mechanical and thermal properties of identified zones at a Ti-based bulk metallic glass weld spot jointed by friction stir spot welding (FSSW)," *J. Non. Cryst. Solids*, vol. 544, no. April, p. 120-188, 2020. https://doi.org/10.1016/j.jnoncrysol.2020.120188

[21] C. Herbelot, T. D. Hoang, A. Imad, and N. Benseddiq, Damage mechanisms under tension shear loading in friction stir spot welding," *Sci. Technol. Weld. Join.*, vol. 15, no. 8, pp. 688–693, 2010. https://doi.org/10.1179/136217110X12813393169417