Microstructural Evaluation of Friction Stir Welded Aluminium Alloy 6063

R. Muthu Vaidyanathan, Mahaboob Patel, N. Sivaraman, Mebratu Markos, Tsegaye Alemayehu

Abstract: Friction Stir Welding (FSW) is a vital solid-state process that can produce a joint with high quality and strength. The microstructure of the friction stir welded parts needs to be studied to use this method for multiple applications. FSW eliminates fusion fastening issues such as crack, porosity, and shrinking solidification. In the present work, AA6063 material was welded with prominent parameters, rotational speed, transverse speed, and axial load. The microstructure of distinct weld regions including the nugget area, heat affected zone, thermo-mechanically affected zone, and parent metal has been examined by optical microscopy. In this investigation the fine equiaxed grains were observed in the thermo-mechanically affected zone and nugget zone of various samples.

Index Terms: FSW, Friction stir welding, Microstructure, AA6063, Mg_2Si

I. INTRODUCTION

Friction stir welded Aluminium alloys 2xxx, 5xxx, 6xxx, 7xxx series are the widely used in various applications including automobile industries, aerospace industries, defense, railway fabrication, high-speed ships, construction of heavy structures and so on, due to its high strength and low cost. In general, aluminium alloys have excellent ductility, corrosion resistance, and thermal characteristics [1],[2]. The traditional fusion welding process produces the weld joints with some defects like crack, voids, solidification shrinkage, and solid inclusions. These weld defects, affect the strength and quality of the joints [3].

Friction stir welding technique is one among the solid-state welding procedure in recent years. This is the most important welding processes for joining materials like ferrous, non-ferrous, polymers, etc., below the melting point [4], [5]. For the joining of aluminum and alloy, the Welding Institute has developed and patented friction stir welding in 1991. In subsequent years, it has been developed for ferrous, nonferrous and plastic products [6]. The rotating tool pin turned to the butt faces of the materials and crosses over the joint line. The frictional heat was triggered by relative movement between instrument and material, helping the plunger portion collapse the material to generate the joint under plastic deformation. The shoulder also anticipates the expulsion of materials from the joint [7].

In the FSW process, welding parameters such as transverse speed, rotational speed, shoulder diameter, tool tilting angle, pin geometry, and axial force are the key aspects for the frictional heat generation on the joint. The different welding parameters are having a significant role in increasing the strength and microstructure refinement on the workpiece [8]. The proper welding parameters are causing the orderly defect-free joint than the fusion welding. The perfect weldments were produced with elevated rotational speed and lower transverse speed. Also, they observed a less material flow on greater shoulder diameter than the less shoulder diameter. Researchers have investigated the microstructure of different areas of weld such as base metal, heat affected zone, thermo-mechanically affected zone, and nugget zone. In the interfacial region higher hardness was quantified as a result of recrystallization [9]. The parameters of FSW were optimized by Taguchi technique, to obtain greater mechanical characteristics and welding microstructures. As a result of 1100rpm rotational speed and 100 mm/min transverse speed, the maximum temperature was noticed as 347^{o}C. It achieved the maximum tensile strength of the weld joint as 76.80% of base metal. They found a defect-free, stirred zone, and in the heat-affected area of all the specimens the fracture has occurred. They reported that higher turbulence on the weld line due to its high rotational speed produces tunnel defects in the joint [10]. In an examination of effects on the ratio of shoulder diameter to pin diameter (D/d), it composes the dynamically recrystallized grains on the stirred zone of AA6063 material by a felicitous D/d ratio. Additionally, this leads to achieving higher strength and hardness on the welded joint. It has been reported that the rise in the ratio of D/d leads to poor material mixing on the interfacial and this impacts on the quality of welded joints [11], [14].

K. Huang et al. [12] has characterized the different mechanism of dynamic recrystallization (DRX) microstructure due to the hot deformed process, such as continuous dynamic recrystallization (CDRX), discontinuous dynamic recrystallization (DDRX) and geometric dynamic recrystallization (GDRX). The CDRX was developed due to the homogenous mixture on the materials at a higher temperature in hot deformation.

Revised Manuscript Received on 30 July 2019.
* Correspondence Author
R. Muthu Vaidyanathan*, Department of Mechanical Engineering, Wolaita Sodo University, Wolaita Sodo, Ethiopia.
Mahaboob Patel, Department of Mechanical Engineering, Wolaita Sodo University, Wolaita Sodo, Ethiopia.
N. Sivaraman, Department of Mechanical Engineering, Wolaita Sodo University, Wolaita Sodo, Ethiopia.
Mebratu Markos, Department of Mechanical Engineering, Wolaita Sodo University, Wolaita Sodo, Ethiopia.
Tsegaye Alemayehu, Department of Mechanical Engineering, Wolaita Sodo University, Wolaita Sodo, Ethiopia.

Due to a low stack of fault energy on hot deformation, especially on aluminium and magnesium alloys and stainless-steel material, composes the DDRX, and GDRX is formed on metallic materials to its higher temperature and lower strain rate on hot deformation, it produces equiaxed grains on the materials. Wen-Ying GAN et al. [13] says that the hardness of the stir zone is minimal compared with other areas, because the material is softened in the stir zone by the heat due to friction stirring, and 'U' formed curve was discovered when assessing the hardness of the material. The microhardness of the retracting side is more as compared to the advancing side [14]. The mechanical strengths such as yield and ultimate tensile strength are maximum at as-welded condition than the post weld heat treated. But the post weld heat treated specimens have a prominent percentage of elongation than the as-welded condition [15]. Vahid M. Khojastehnezhad et al. [16] have investigated the incorporation of copper insert plate on FSW. They were reported that intermetallic components result in a higher hardness on the nugget zone. It produces a good metallurgical bonding between Al-Cu-Al material and this shows a higher mechanical strength. The remarkable joint efficiency was noticed in Al-Cu-Al plates about 89.1% of the Al base metal than the Al-Al joint. Yilin sun et al. [18] were studied the effect of Mg_2Si intermetallic component. In general, Mg_2Si is a hard intermetallic component. This helps to elevate the harness and tensile strength of the material. Silicon and magnesium contents in the aluminium alloy materials produce the intermetallic phases on the interfacial joints by the solid-state welding process [19].

In this work aluminium alloy 6063 is used for friction stir welding and microstructure analysis on the different region of the weldment by the optical microscope.

II. Experimental Procedure

A. Tool Process

The tool is made up H13 steel with the size of 15mm of shoulder diameter, 7mm length of shoulder, straight cylindrical probe with 5mm diameter and length of 4mm were used to make the weld on the joint line. The weld tool was heat treated at 105°C for 60 minutes and then quenched. Further, this quenched tool was tempered at 600°C for 90 minutes followed by the cooling at room temperature.

B. Development of Design of Experiments

The design of experimental strategy was used to create a correlation of process parameters with a small number of welding tests. FSW recognized its important process parameter and its ranges using the Taguchi model. Table 1 shows the information of process parameters. The impact of the method parameters was associated with the weld nugget hardness and microstructure.

Table-1 Weld parameters [17]

Sample	Rotational Speed (rpm)	Transverse Speed (mm/s)	Axial Load (N)
A	1000	0.5	4000
B	1000	1	6000
C	1500	1	4000
D	1500	0.5	6000

C. Material

In this work, aluminium alloy 6063 were used for the friction stir welded microstructure analysis. The material was cut to a length of 150 mm, a width of 100 mm and 5 mm thickness and it is illustrated in fig.1. Table 2 shows the chemical composition of AA6063.

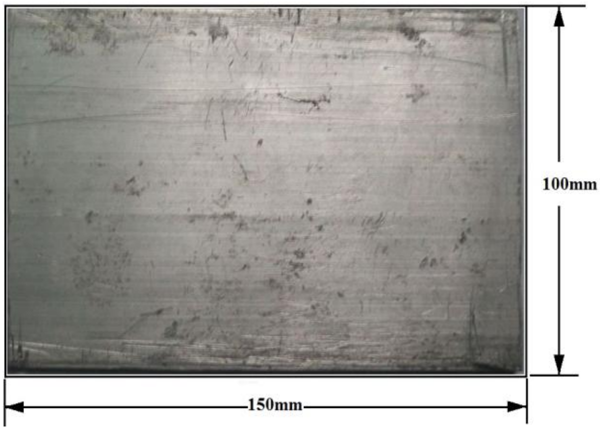

Fig.1. Cut material for the welding process

D. Process

The work involves three parameters such as tool rotational speed, transverse speed and axial load [17].

Fig.2. Material clamped on FSW machine

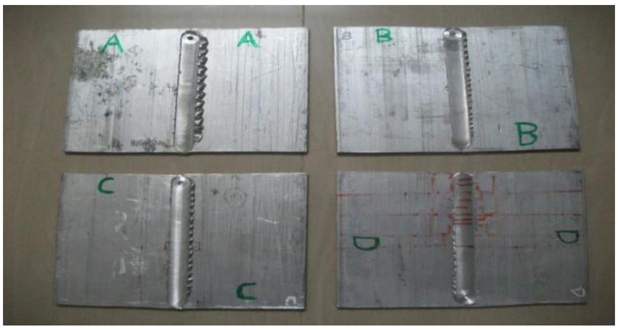

Fig.3. Friction Stir Welded specimen's

First, the cut specimens were clamped on the friction stir welding machine (fig.2.) and this has been welded in four samples, A, B, C, and D, with different parameters and the welded specimens were shown in fig.3. The parameters are measured as two level and four DOE concentrations.

Table-2 Chemical Composition of Aluminium Alloy 6063

Elements	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
AA6063	0.2-0.6	0.35	0.1	0.1	0.45-0.9	0.1	0.1	0.1	Bal

E. Microstructure Characteristics

The molded specimens were illustrated on fig.4. The specimens are sliced perpendicular to the weld interface, using a water-cooling low-speed saw to determine the microstructural characteristics of welded joints. The metallographic samples were polished with the polishing paper of grain 320, 600 and 1200 with water and alumina paste for smooth finishing, and the final polishing step is carried out with soft velvet cloth and distilled water to ensure a smooth finish. After polishing, the samples are graded to show clearly the microstructure and the acids in the etchant attack the grains and give a clear picture of the grains. Keller's etchant, used in aluminum alloys, is made by 1% quantity of hydrofluoric acid, 1.5% volume HF, 2.5% volume nitric acid and 95% of distilled water. The etched samples are washed thoroughly to remove the carbon deposits and make dried study the microstructure under the optical microscope.

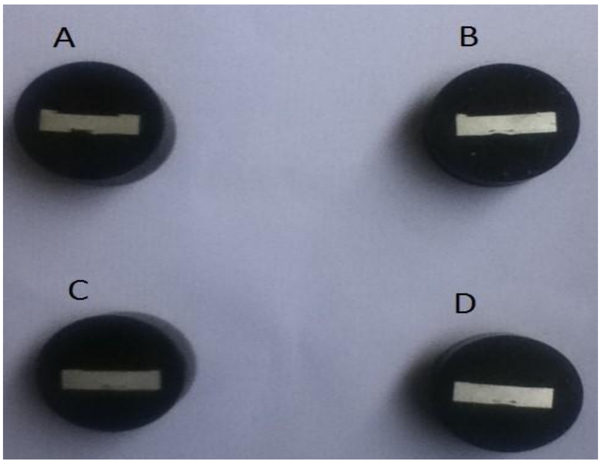

Fig.4. Molded specimens for Microstructure examination

III. RESULT AND DISCUSSION

It is very important to examine the microstructure to understand the mechanical characteristics of the materials. The mechanical properties are widely associated with the microstructure of the joint. Many researchers have found the dynamically recrystallized equiaxed grains in the nugget zone [13] - [15].

A. Microhardness

The various zones of welded cross-section like nugget zone, heat affected zone, and thermo-mechanically affected zone exhibit the higher hardness and the hardness of the base metal are comparatively lesser than the other regions. The elevated hardness recorded due to the recrystallization of grain on the weld portion [15], [17]. The microhardness of various samples is presented in table 3. It is observed that elevated rotational speed, lesser transverse speed, and higher axial force produced the higher hardness on the nugget zone. Among all the samples, the sample 'D' with 1500rpm, 0.5mm/sec, and 6000N are exhibits the maximum hardness of 47.3HV. The sample 'C' and "D" has more hardness than the other samples on the weld nugget zone [17].

Table 3 Microhardness Values [17]

Hardness Location	Sample			
	"A"	**"B"**	**"C"**	**"D"**
Parent metal	45.1	46.0	42.2	37.9
HAZ Zone	46.5	46.4	46.2	46.5
Nugget Zone	44.4	46.1	47.2	47.3

The lower transverse speed of 0.5mm/sec was causing the higher hardness on heat affected zone of samples 'A' and 'D'. These variations in the hardness could be understood from microstructure examination. The hardness of various zones of welded samples was plotted in the graph illustrated in fig.5.

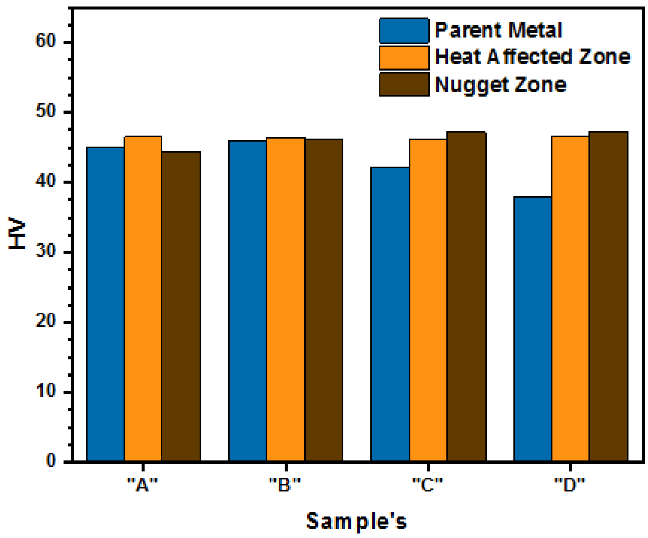

Fig.5. Microhardness of various regions on the welded samples

Retrieval Number: B1933078219/19©BEIESP
DOI: 10.35940/ijrte.B1933.078219
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

B. Microstructure

A microstructural investigation was held on the cross-section normal to the weld line by optical microscope. The fig 6 - 9 shows the micrographs of various zones of friction stir welded samples. The microstructure in figure 6. (a) shows that the eutectic grains are present on the parent metal of sample 'A' in a bigger size. In fig.6. (b), finer grains were observed on thermo-mechanically affected zone and nugget zone due to the stirring action on the weldments. In the heat impacted area, however, the coarser grains seemed to be encountered. The intermetallic component Mg_2Si was developed due to the coalescence in the weldment. The microstructure of a parent metal at the left and of a nugget area at the right side of the sample 'A' is evident in fig.6. (c).

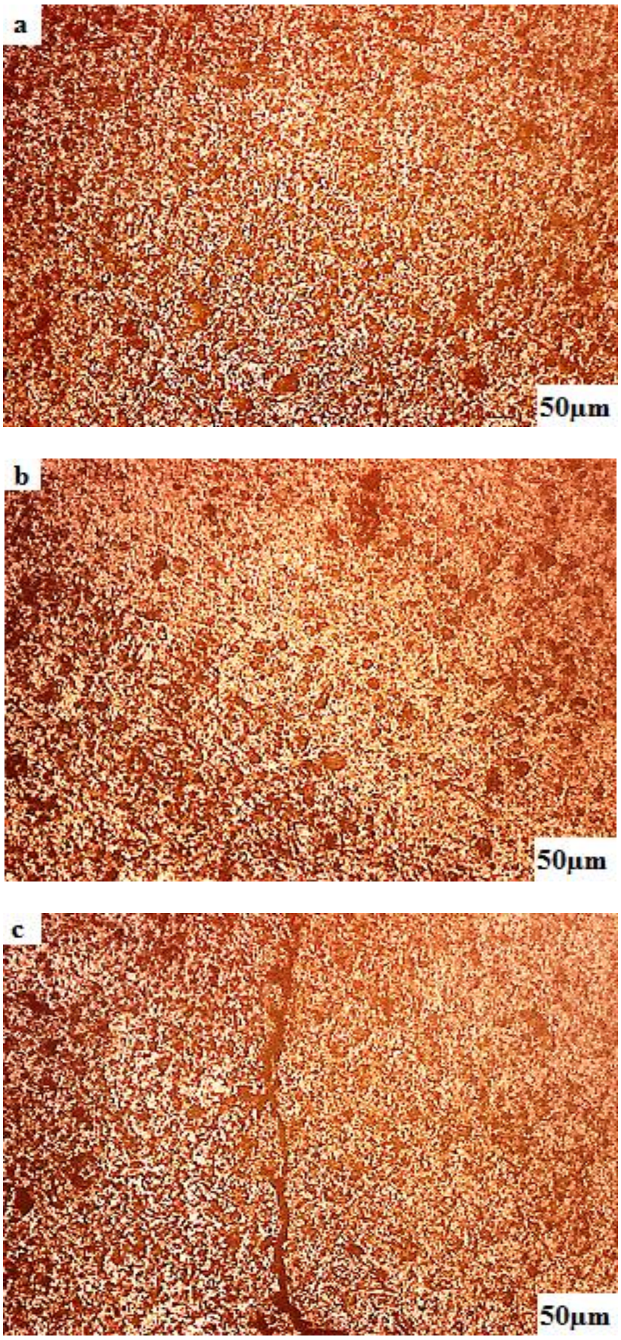

Fig.6. Sample A, Parent metal (a), Parent and Nugget zone (b), and Nugget zone (c) micrographs.

Because of the coalescence, the nugget area had a fine equiaxed grain, and also, the nugget area had a crack because of the lack of frictional heat produced during the joining phase owing to lower rotational and transverse velocity. On the nugget area and heat impacted area some dimples are found, due to partial dissolution of eutectic grains.

Figures 7(a), 8(a), and 9(a) demonstrate the parent metals of the 'B' and 'C' samples, during the examination, the undissolved particles in the material were found to differ in grain size. Fig.7. (b) shows the parent metal and nugget zone microstructures. In TMAZ the grain orientation was seen in a different direction and also, it is normal to the parallel grains of parent metal.

In the sample 'B', intermetallic of Mg_2Si particles was found. It helps to raise the hardness of HAZ, TMAZ, and nugget zone. Moreover, stress and heats were leading the grains to be re-crystallized.

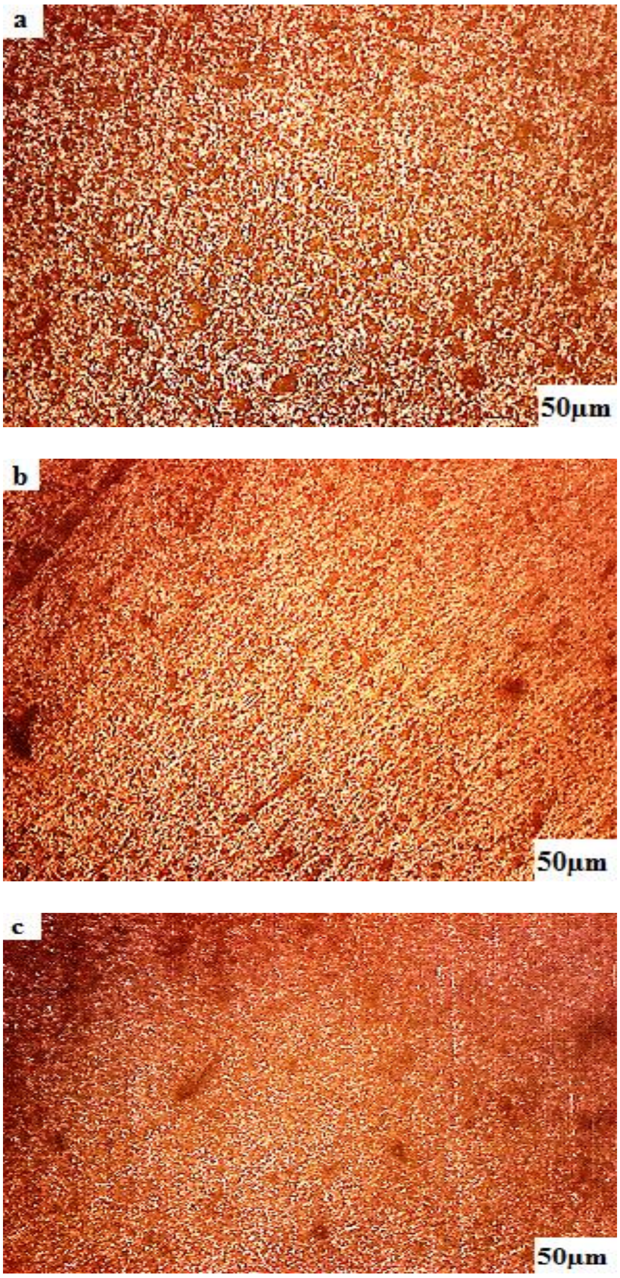

Fig.7. Sample B, Parent metal (a), Parent and Nugget zone (b), and Nugget zone (c) micrographs.

Retrieval Number: B1933078219/19©BEIESP
DOI: 10.35940/ijrte.B1933.078219
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

The fragmentation and re-crystallization cause the fine equiaxed microstructure on the nugget zone of fig.7. (c). Also, the defect-free weld joint is found on this sample 'B'.

The microstructure of parent, HAZ is on right side and TMAZ, nugget zone is on left side of sample 'C' is shown in fig8. (b). In this some dimple was observed on HAZ, while eutectic grains are fragmented and flow in the direction of rotation.

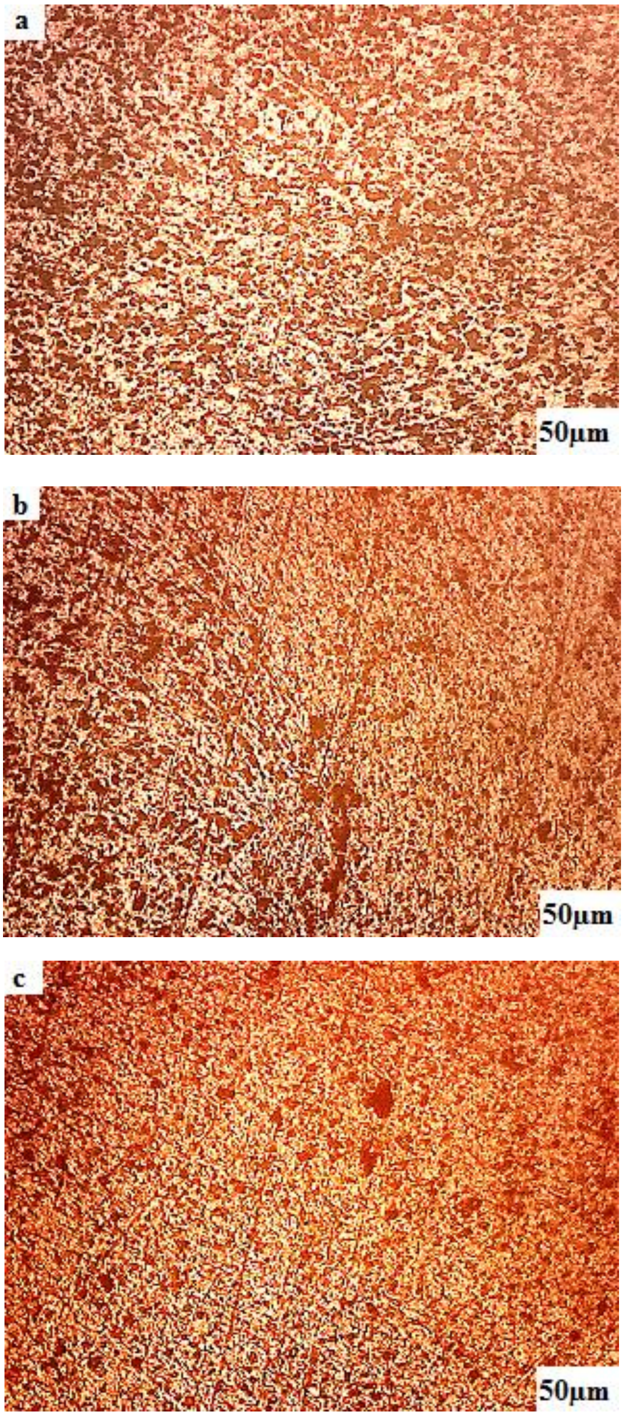

Fig.8. Sample C, Parent metal (a), Parent and Nugget zone (b), and Nugget zone (c) micrographs.

The weld nugget zone is Shown in fig.8. (c). Lack of fusion observed probably due to insufficient heat and stress of the process. Dynamic re-crystallized equiaxed grains are the main reason for the rise in hardness. R Muthu V et al. [17] were reported that material flow helps to increase mechanical strength.

The Fig. 9. (b) on the right the metal parent and a nugget zone to the left. The nugget zone shows fine partially dissolved eutectic grains, and it is partially precipitated due to lack of heat generation on FSW. It exhibits the rotational speed, transverse speed, and axial force are not enough to owe frictional heat.

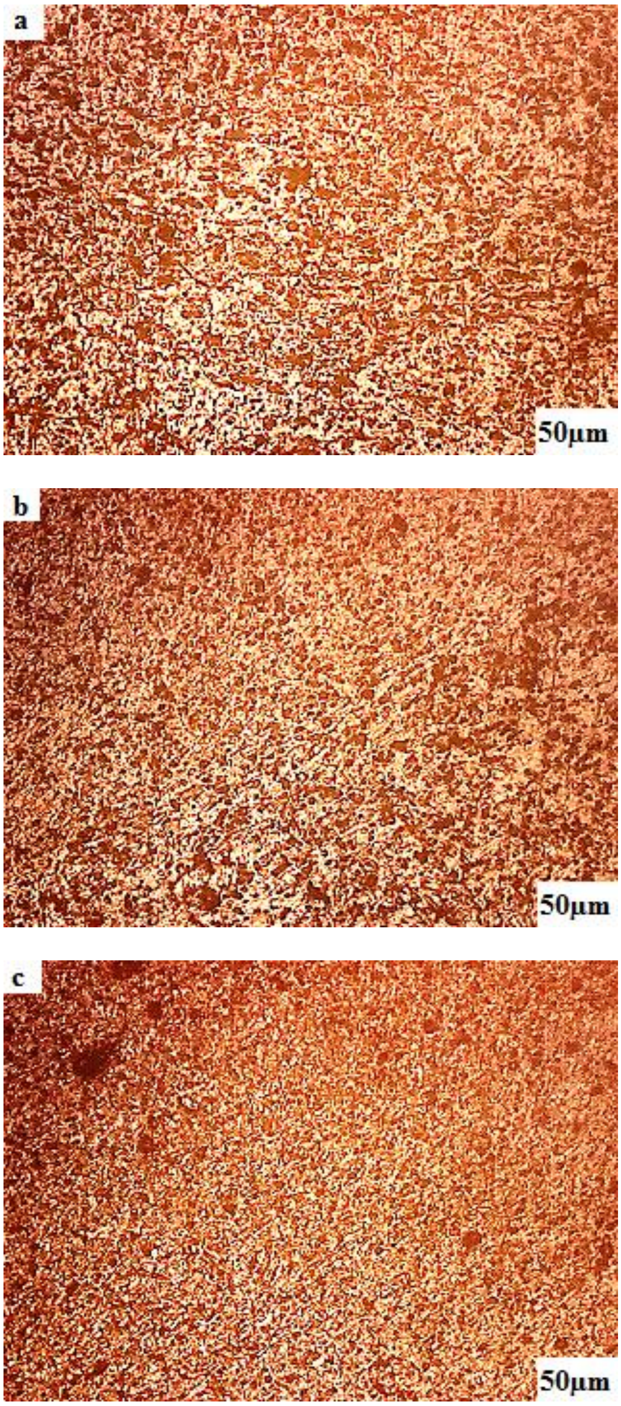

Fig.9. Sample D, Parent metal (a), Parent and Nugget zone (b), and Nugget zone (c) micrographs.

The fig.9. (c), shows the parent metal and FSW zone with complete fusion and could not be resolved into distinct layers. The only difference is in the grain sizes. The grains at the nugget is finer and coarser at the parent metal.

IV. CONCLUSION

The material AA 6063 was joined effectively by friction stir welding with different parameters and optical microscopic analysis of the welding samples was conducted.

- An intermetallic particle Mg_2Si was discovered in all samples of the TMAZ and the weld nugget area, it helps to increase the microhardness of the weld over the parent metal.
- The fine equiaxed grains were noticed on the nugget zone, due to the dynamic recrystallization.
- The sample ‘B’ and ‘C’ obtained the defect-free weldment.
- In this evaluation, some dimples were found on the nugget zone of sample ‘A’ and ‘C’
- The sample ' A ' had a crack in the nugget zone due to welding parameters 1000rpm, 0,5mm / sec, and 4000N.

REFERENCES

1. Xueqi Lv, ChuanSong Wu, Chunliang Yang, G.K. Padhy, ”Weld microstructure and mechanical properties in ultrasonic enhanced friction stir welding of Al alloy to Mg alloy”, Journal of Materials Processing Tech, Volume 254 (2018), pp. 145–157.
2. M. Iangovan, S. Rajendra Boopathy, V. Balasubramanian, “Effect of tool pin profile on microstructure and tensile properties of friction stir welded dissimilar AA 6061-AA 5086 aluminium alloy joints”, Defence Technology, Volume11 (2015), pp. 174-184.
3. Mohammad Mahdi Moradia, Hamed Jamshidi Avala, Roohollah Jamaatia, Sajjad Amirkhanloub, Shouxun Jiba, “Microstructure and texture evolution of friction stir welded dissimilar aluminum alloys: AA2024 and AA6061”, Journal of Manufacturing Processes, Volume 32, April 2018, pp. 1-10.
4. Shayan Eslami, Paulo J. Tavares, P. M. G. P. Moreira, “Friction stir welding tooling for polymers: review and prospects”, International journal of advanced manufacturing technology, March 2017, Volume 89, Issue 5–8, pp. 1677–1690.
5. Rajasekar. A, T. Prabhu, “Finite Element Analysis of Friction Stir Welding of Al2024 and 6063aluminium Alloy”, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 4, Special Issue 13, December 2015.
6. Yumei Yue & Guoqiang Wang, Kang Yang, Baosheng Wu & Dejun Yan, “Friction stir butt welding thin aluminum alloy sheets”, The International Journal of Advanced Manufacturing Technology, June 2018, Volume 96, Issue 9–12, pp. 3139 – 3147.
7. Bharat Raj Singh, Singh Bharat Raj, ” A Handbook on Friction Stir Welding”, LAP Lambert Academic Publishing, 01 Jun 2012, Saarbrucken, Germany.
8. Omar S. Salih, Hengan Ou, W. Sun, D.G. McCartney, “A review of friction stir welding of aluminium matrix composites”, Materials and Design, Volume 86 (2015), pp. 61–71.
9. E.T. Akinlabi, (2012b), “Effect of Shoulder Size on Weld Properties of Dissimilar Metal Friction Stir Welds”, Journal of Materials Engineering and Performance, July 2012, Volume 21, Issue 7, pp. 1514–1519.
10. Manigandan Krishnan, Senthil Kumar Subramaniam, “Investigation of Mechanical and Metallurgical Properties of Friction Stir Corner Welded Dissimilar Thickness AA5086-AA6061 Aluminium Alloys”, Materials Research. 2018; Vol. 21, no.4.
11. Noor Zaman Khan*, Zahid A. Khan, Arshad Noor Siddiquee, “Effect of shoulder diameter to pin diameter (D/d) ratio on tensile strength of friction stir welded 6063 aluminium alloy”, 4th International Conference on Materials Processing and Characterization, Materials Today: Proceedings 2 (2015), pp. 1450 – 1457.
12. K. Huang, R. E. Logé, “A review on dynamic recrystallization phenomena in metallic materials”, Materials & design, Volume 111, December 2016, pp. 548-574.
13. Wen-ying GAN, Zheng ZHOU, Hang ZHANG, Tao PENG, “Evolution of microstructure and hardness of aluminum after friction stir processing”, Transactions of Nonferrous Metals Society of China, Volume 24, Issue 4, April 2014, pp. 975-981.
14. M.J. Jones, P. Heurtier, C. Desrayaud, F. Montheillet, D. Allehaux, J.H. Driver, “Correlation between microstructure and microhardness in a friction stir welded 2024 aluminium alloy”, International Journal of Minerals, Metallurgy, and Materials June 2015, Volume 22, Issue 6, pp. 627–638
15. R.K.R. Singh, Chaitanya Sharma, D.K. Dwivedi, N.K. Mehta, P. Kumar, ”The microstructure and mechanical properties of friction stir welded Al–Zn–Mg alloy in as welded and heat treated conditions”, Materials and Design, Volume 32(2), February 2011, pp. 682-687.
16. Vahid M. Khojastehnezhad, Hamed H. Pouras, “Microstructural characterization and mechanical properties of aluminum 6061-T6 plates welded with copper insert plate (Al/Cu/Al) using friction stir welding”, Transactions of Nonferrous Metals Society of China, Volume 28, Issue 3, March 2018, pp. 415-426.
17. R. Muthu Vaidyanathan, Mahaboob Patel, N. Sivaraman, D. Tedwors, “Effects of process parameters on friction stir welding of 6063 aluminum alloy”, International journal of design and manufacturing technology (IJDMT), volume 6, issue 1, January - April (2015), pp. 01-09.
18. Yilin Sun, Chong Li, Yongchang Liu, Liming Yu, Huijun Li, “Intermetallic phase evolution and strengthening effect in Al–Mg2Si alloys with different Cu/Ni ratios”, Materials letters, volume 215,15 March 2018, pp 254-258.
19. Yiqing chen, Hui Zhang, Ziang Zhu, Guangchen Xu, Lan a. Luo, and Lihua Liu, “Inhibiting Brittle Intermetallic Layer in Magnesium/Aluminum Bimetallic Castings via In Situ Formation of Mg2Si Phase”, Metallurgical and Materials Transactions B, April 2019, pp. 1-6.