

## Hardness and Microstructure analysis of Friction Stir Welded AA2024 by various tool pin profiles

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### Abstract

The mechanical properties of friction stir welds (FSW) in 2024-T351 alloys have been investigated. During this process, the influence of tool rotation speed and traverse speed on the microstructural characteristics of friction stir welded AA2024 T351 aluminum alloy was examined. The paper presents that the outcomes of micrographs and hardness of AA2024 was successfully processed by the FSW. Utilizing the three different optimized tools like fluted, hexagonal and pentagonal cylinder tool pin are composes the FSW on 6 mm thick plates of AA2024. Rotational speed and traverse speed of the tool are the two welding parameters were used in this experimental investigation. The welded micrographs produced defect free joints with fine grain structure. Out of three tool pin profiles, hexagonal tool pin achieved enhanced hardness when compared to other two profiles.

**Keywords:** AA2024, FSW, Hardness, Tool pin profiles.

### Introduction

In automotive and aviation enterprises, generally utilizes aluminium alloy for structural demanding applications [1]. The two firms are pushing the boundaries of new inventive items, a necessity for higher capacity and, simultaneously, a lower weight with a robust design. Aluminum alloys are described by a high load capacity [2] comparative with the mass level at a moderately less cost. There are no better anti-corrosive properties and as a rule, they are poorly welded by traditional welding procedures. Welding is a fabrication method used to blend materials, generally thermoplastics or metals together by causing coalescence. During the welding process, the work pieces are melted at the joining interface and also filler material is added to form a pool of molten material which cools to form a stable joint [3].

For the joining aluminum parts, it can be utilized that the welding processes of GTAW (TIG) and GMAW (MIG) and Friction Stir Welding (FSW) as a solid-state joining method [4-6]. Thus, FSW is a very suitable, and increasingly used, for joining high strength aluminum alloys [7] (2xxx, 6xxx, 7xxx and 8xxx series), that currently applied to the aerospace, automotive, marine and military industries. The best application for friction stir welding was the welding for long length of the materials in the application like aviation, shipbuilding, and railroad enterprises. The detailed usages by FSW in some applications like cryogenic fuel tank for space launch vehicles, Production of hollow aluminium boards for profound freezing of fish on fishing boat in shipbuilding industry, and decks, shells and bulkheads for railway carriages. Over the most recent years, the automotive [8] enterprises have been forcefully contemplating the use of FSW in its current circumstance. The drive to build more fuel-efficient vehicles has led to the increased use of aluminium in an effort to save on weight, which also improves recyclability when the vehicles are scrapped. FSW was invented at The Welding Institute (TWI) of UK in 1991 [9] as a solid-state joining technique, and it was initially applied to aluminum alloys [10]. There have been various reports featuring the importance of the microstructural changes because of frictional heat and plastic deformation associated with FSW. Mechanical failure of the welds can occur in the SZ (Stirred Zone), HAZ (Heat Affected Zone), or TMAZ (Thermo Mechanically Affected Zone) area relying upon the measure of energy input which is constrained by the welding process parameters such as rotational and travel speed. Since the behavior of material flow is widely influenced by the material properties like yield strength, ductility and hardness of the parent metal, design of tool, and FSW process parameters, the dependence of weld microstructure on process parameters varies in various aluminum alloys for a given tool design. By knowing the process parameters of welding and their change, the amount of energy input and the heating level of the welded pieces are also changed. By this way, utilizing the appropriately chosen welding process parameters, the optimum state and flow of the materials of the welding pieces are accomplished, necessary for the proper unwinding of the coupling process and obtaining the joint of the necessary quality. Many authors have published a report on quantitative investigation of the influence of parametric friction stir welding on the structural, mechanical and corrosion properties of the aluminum alloys.

Various kinds of literature were deliberated for improving the mechanical properties of Aluminum alloy. Moghaddam et al. 2011 [11] investigated the influence of different feed speeds on mechanical behavior and microstructural properties of friction stir welded Cu-30Zn brass alloy. Liu et al. 2013 [12] found that defect-free joints were obtained in friction stir welded AA 6061-T6 at lower welding speeds. Chanakyan et al. 2021 [13] conducted an experimental study in friction stir welding of AA5052 Aluminium alloy to enhance the mechanical properties of base metal with various tool pin profiles. It is understood that enhanced mechanical property was attained at a welding speed of 30mm/min and rotational speed of 1200 rpm. Jangra et al. 2016 [14] experimentally investigated and optimized the cryogenic treated and without treated AA 6082 alloy by using the friction stir welding technique. Habibnia et al. 2015 [15] performed friction stir welded of 5050 Al alloy and 304 stainless steel plates. It is understood that the offset of the tool is increased up to 1.5mm and elongation in 9%. Dragatogiannis et al. 2015 [16] increased the mechanical properties of friction stir welded dissimilar alloy AA 5083 and AA 6082 with reinforcement of TiC

nanoparticles. Kumar et al. 2008 [17] analyzed the effect of the tool on the flow of material and the formation of the weld during the friction stir welding process. Khan et al. 2016 [18] experimentally analyzed the Mechanical behavior and microstructural characteristics of friction stir welded dissimilar and similar sheets of AA2219 and AA7475 aluminium alloys. It is revealed that the better hardness values in all the joints at the nugget zone because of considerable grain refinement.

In this present investigation, the effect of both rotational speed and traverse speed on the microstructure and mechanical properties of the welded joint in AA 2024-T351 were systematically analyzed in the Friction stir welding technique.

## Experimentation

The experiment was aimed to determine the influence of input welding parameters such as traverse speed, rotational speed of the tool and the axial load is to be kept constant on mechanical behavior and metallurgical characteristics of welded joints. The parent material was aluminum alloy AA 2024-T351 is used in this experimental analysis. The chemical composition of AA2024 plates is listed in Table 1. Table 2 shows the mechanical properties of AA 2024-T351.

Table 1: **Chemical composition of AA2024**

%	4.46	1.5	0.5	0.16	0.15	0.05	0.05	0.01	Bal
Elements	Cu	Mg	Mn	Fe	Zn	Ti	Si	Cr	Al

Table 2: **AA2024 Mechanical Properties**

Properties of AA2024	Tensile strength (MPa)	Hardness (Hv)
	480	132

The dimensions of the friction stir welded AA2024 plates were 100 mm×50 mm×6 mm. The two sides of the base plates are machined on the grinder at a thickness of 6 mm. An austenitic plate is used as a support plate for the welding process. It is kept under the welding plates from the beginning of the FSW process.

For the purpose of welding, a milling machine was utilized in this investigation. The length of the weld was around 90 mm. Welded joints were made as per the arrangements of FSW process parameters which is mentioned in Table 3 with various combinations of traverse speed and rotational speed of the tool. Another parameter axial load was kept constant in this FSW process. High carbon high chromium (HCHCr) steel was used as a tool material for this investigation [19]. Out of different tool materials, high carbon high chromium steel especially applicable for aluminum alloys. When contrasted with other tool materials, the strength of HCHCr is high, great hardness, acquirement of the tool material was ease and expense like less. A tool design has been planned via AutoCAD and it was made by utilizing traditional

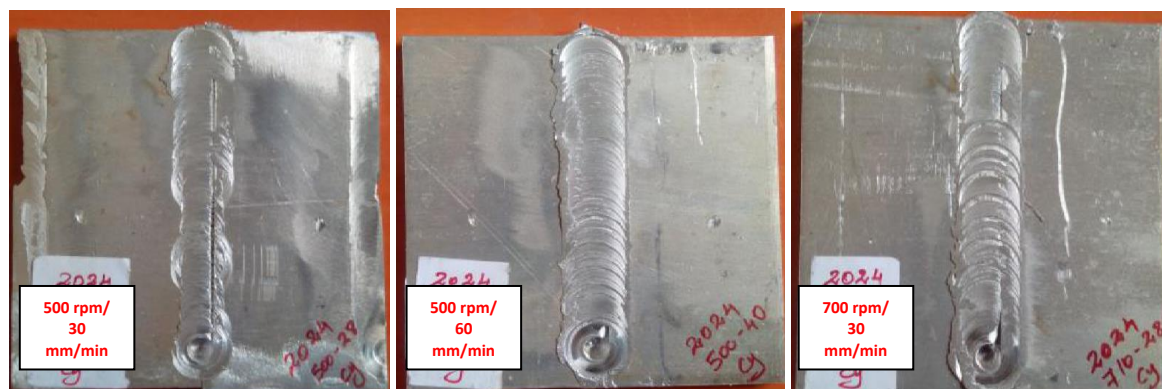
lathe machining. Then the tool was prepared by the combinations of shoulder diameter with 18 mm, pin diameter with 6 mm and pin length with 5.7 mm. Three tool pin profiles were used in this investigation like Fluted Pin Cylinder (FPC), Hexagonal Pin Cylinder (HPC) and Pentagonal Pin Cylinder (PPC). The friction stir welded process parameters are provided in Table 3. Each tool pin profile influence the both the weld parameters. Totally, 18 welded samples are conducted during the friction stir welding process according to process parameter table. The various tool pin profiles are displayed in Fig 1. The fabricated welded specimens with various tool pin profiles are displayed in Fig (2a-2c), respectively.

Table 3: **Process parameters of FSW**

Different Tool Probe Profiles	Rotational Speed - rpm	Weld Speed – mm/min
Fluted Pin Cylinder (FPC) Hexagon Pin Cylinder (HPC) Pentagon Pin Cylinder (PPC)	500	30
		60
	700	30
		60
	1000	30
		60



Fig 1: **Three various tool Pin Profiles (FPC, HPC, PPC)**



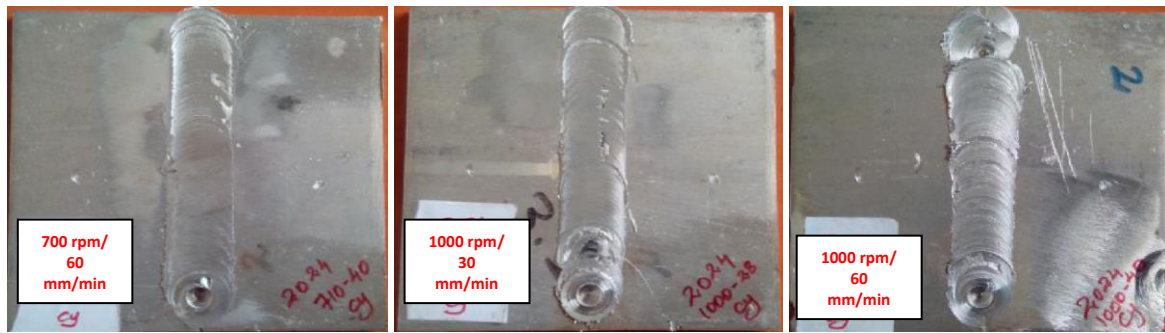


Fig 2a: Fabricated welded specimen by fluted tool pin profile



Fig 2b: Fabricated welded specimen by hexagonal tool pin profile





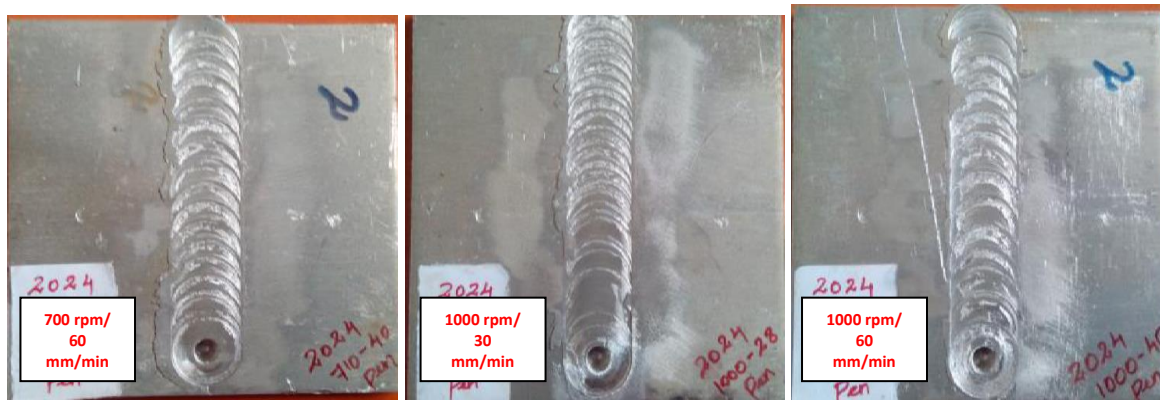


Fig 2c: Fabricated welded specimen by pentagonal tool pin profile

## Results and Discussion

### Hardness Analysis on FSWed AA2024

The hardness profiles were attained along three horizontal directions at a distance of 0.5 mm [20]. Location of measurement area of Vickers hardness on AA2024 FSWed joints as show in Fig 3. The hardness was survived on the various regions like BZ (Base metal Zone), HAZ, TMAZ, and SZ [3]. The different zones of welded zone with different pin profile hardness results are provided in table 4. From the Fig 4 shows that the fluted cylinder profile gives the hardness of advancing and retreating side of the welded specimen. Combination of the parameter 1000 rpm and 60 mm/min weld speed achieves higher hardness values compared to other welded parameters. Similarly, fig 5 and 6 displays the hexagon and pentagon cylinder pin profile composed better hardness in the welded parameter of 1000 rpm rotation speed and 60 mm/min weld speed. Due to the higher traverse speed and rotational speed produced higher friction with maximum temperature. Particularly, out of the three various pin profile Hexagon profile achieved higher hardness when contrasted with other two pin profiles. The Mg<sub>2</sub>Si particles were distributed more in the stirred zone promotes the fine grain is a major reason to enhance higher hardness [21]. In all the zones, advancing and retreating sides produced equal higher hardness because of optimal parametric condition.

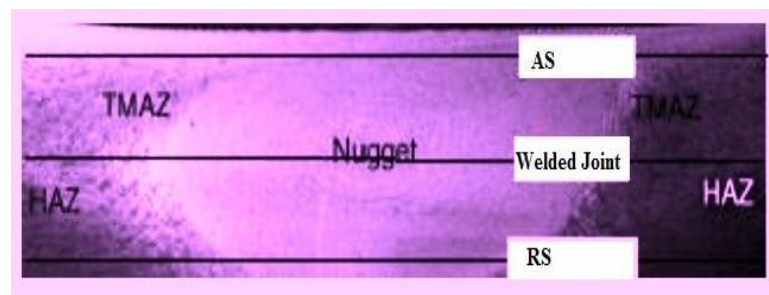


Fig 3: Location of hardness measurement area

Table 4: Various pin profiles with welded specimen hardness

Probe Profile	Rotationa l Speed - rpm	Weld Speed - mm/min	Parent metal BZ	SZ	TMAZ	HAZ
Fluted Cylinder	500	30	75	79	78	77
	500	60	75	82	80	80

	700	30	75	84	82	81
	700	60	75	85	84	83
	1000	30	75	87	85	85
	1000	60	75	89	87	87
Hexagon Cylinder	500	30	75	80	78	77
	500	60	75	82	80	79
	700	30	75	86	86	84
	700	60	75	90	87	87
	1000	30	75	93	90	90
	1000	60	75	95	93	92
Pentagon Cylinder	500	30	75	78	76	76
	500	60	75	80	79	78
	700	30	75	84	82	81
	700	60	75	86	85	85
	1000	30	75	90	89	88
	1000	60	75	92	92	90

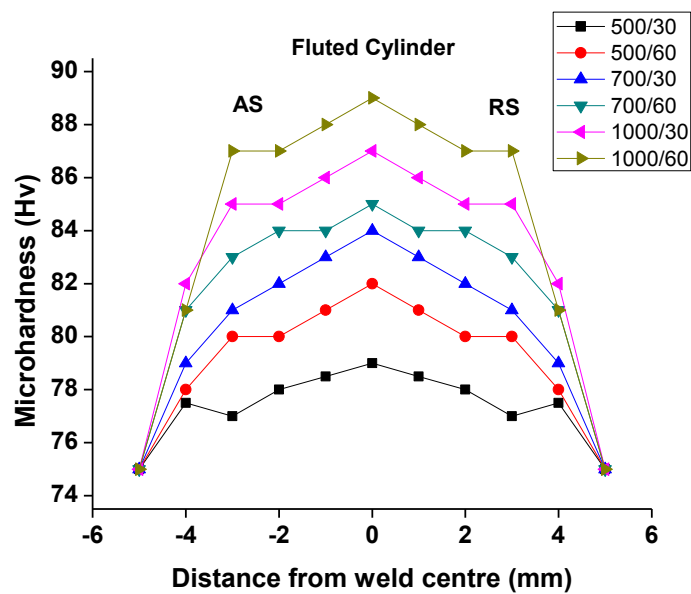


Fig 4: Fluted pin profile hardness

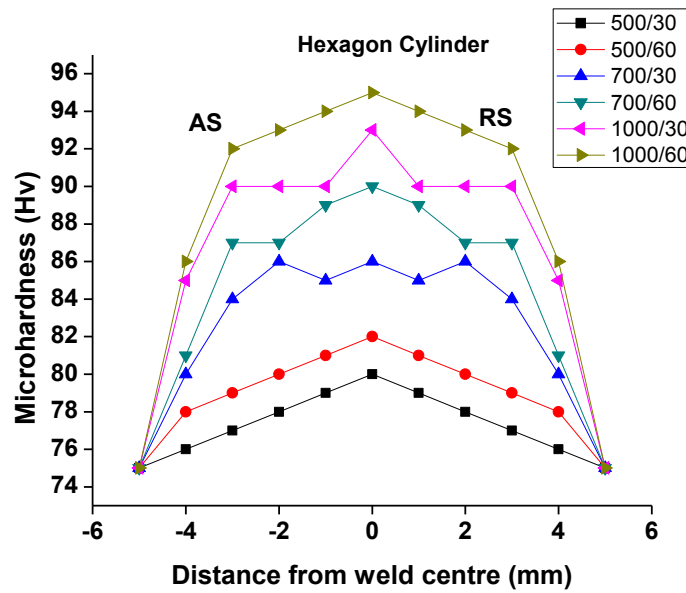


Fig 5: Hexagon pin profile Hardness

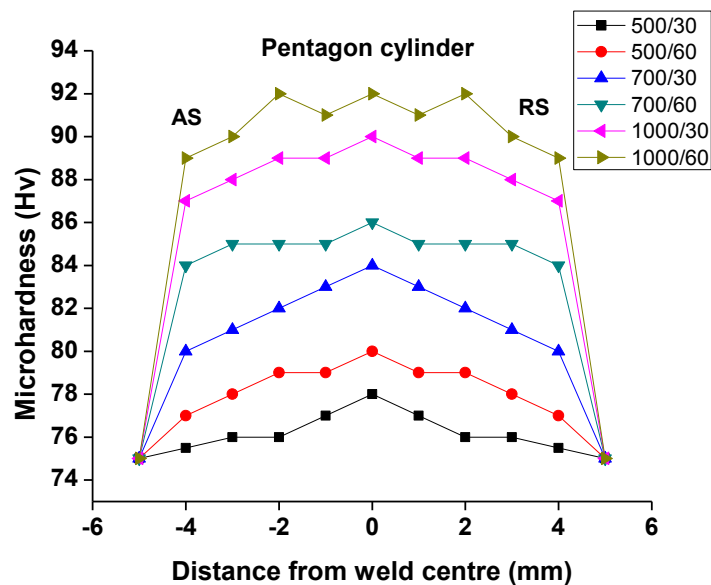


Fig 6: Pentagon pin profile Hardness

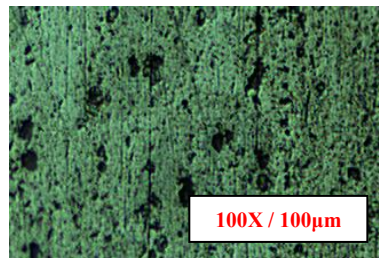
### Microstructure

The characterization of welded AA2024 was utilized by optical microscope with 100X magnification [22]. The entire welded region exhibit fine grains structure. Fig 7 shows the parent metal AA2024 microstructure with received condition. Fig 8 exhibits the microstructure of fluted pin profile of welded metal with 500 rpm & 30 mm/min and 500 rpm & 60 mm/min produce fine grains. Particularly, the minimum rotational speed 500 rpm & weld speed 30 mm/min gets coarse grains due to lack of friction with low temperatures attained during the process. Fig 9 displays the microstructure of fluted pin profile of welded metal with 700 rpm & 30 mm/min and 700 rpm & 60 mm/min composed better grains structure. Fig 10 presents

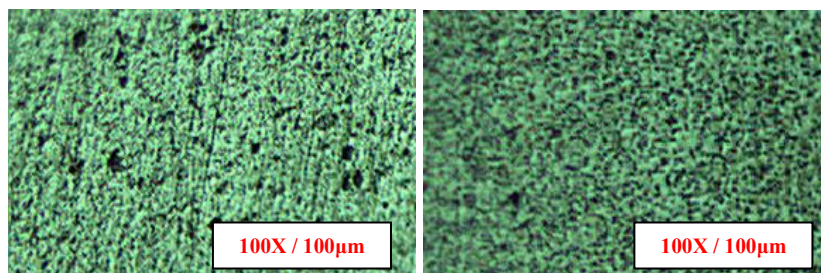


the microstructure of fluted pin profile of welded metal with 1000 rpm & 30 mm/min and 1000 rpm & 60 mm/min attained poor grain structures. Fig 11, 12 and 13 shows the microstructure of hexagon pin profile of welded metal with various parameters 500 rpm, 700 rpm and 1000 rpm of rotational speed & 30 mm/min and 60 mm/min of weld speed attains fine grain with dynamic recrystallisation. Especially, most of the higher hardness obtained in the hexagon pin profile welded specimen. Maximum hardness is one of the evidence for improving the grain structure. The higher strength was achieved by dislocation of density and uniform distribution of grains refinement during the process according to Orowan strengthening mechanism. Fig 14, 15 and 16 exhibits the microstructure of pentagon pin profile welded specimen. Parameters 500 rpm & 30 mm/min and 500 rpm & 60 mm/min produce fine grains with no cracks were formed. Parameters like 700 rpm and 1000 rpm of rotational speed 30 mm/min and 60 mm/min of weld speed obtained poor structure with pores were formed in the stir zone.

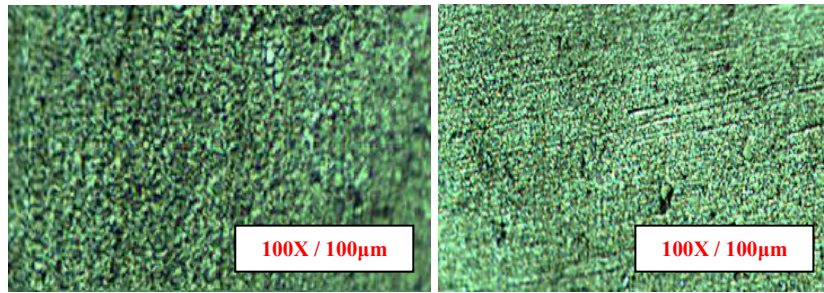
Based on the microstructure results, it is perceived that there is a great contrast in the normal grain size on the grounds that coarse grains of parent metal are changed into fine grains in the stir zone area [23]. This might be because of adequate heat generation and broad plastic deformation of metal. Then furthermore it is noticed that there is a considerable variety in size of the grain in the TMAZ area and stir zone area. Due to the rotational motion from the hardened tool, the grains size in TMAZ is coarser than the stir zone region [24]. The HAZ region is unaffected due to there is no mechanical effects from the hardened tool. The grain structure in HAZ region takes after the parent material grain structure because of no mechanical action from the hardened tool.



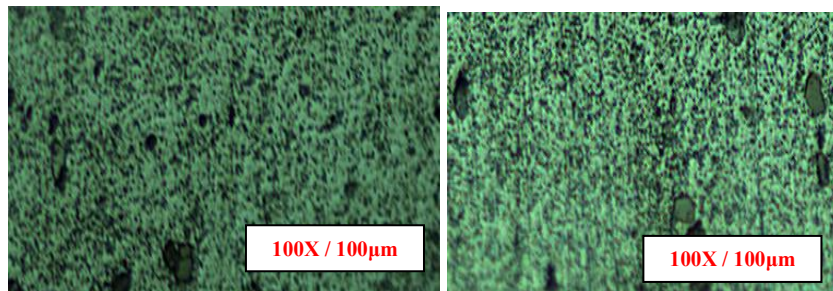
**Fig 7: AA2024 Parent Metal**



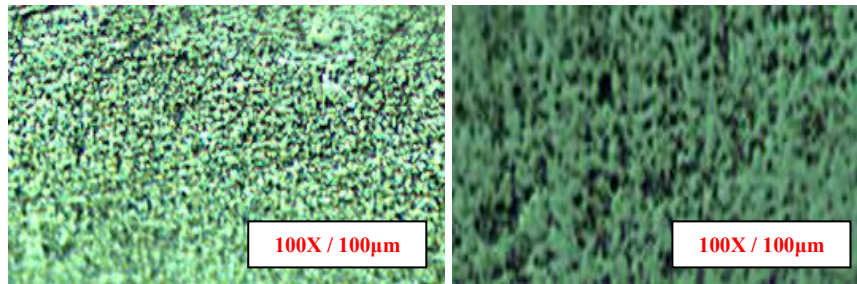
**Fig 8: Fluted pin profile with 500 rpm & 30 mm/min and 500 rpm & 60 mm/min**



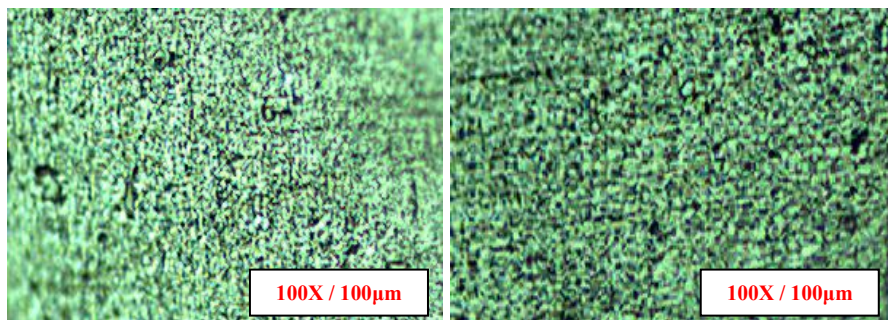
**Fig 9: Fluted pin profile with 700 rpm & 30 mm/min and 700 rpm & 60 mm/min**



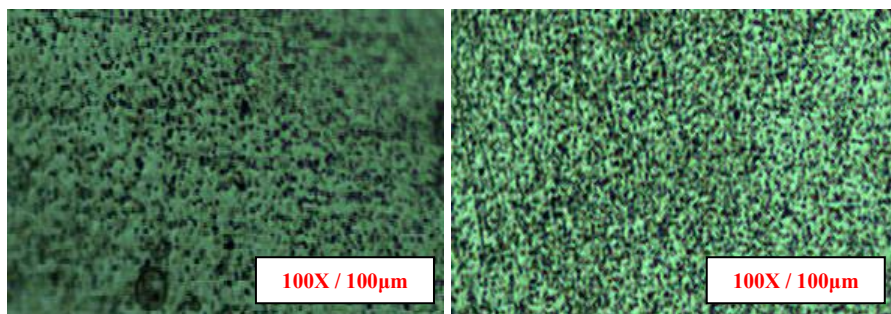
**Fig 10: Fluted pin profile with 1000 rpm & 30 mm/min and 1000 rpm & 60 mm/min**



**Fig 11: Hexagon pin profile with 500 rpm & 30 mm/min and 500 rpm & 60 mm/min**



**Fig 12: Hexagon pin profile with 700 rpm & 30 mm/min and 700 rpm & 60 mm/min**



**Fig 13: Hexagon pin profile with 1000 rpm & 30 mm/min and 1000 rpm & 60 mm/min**



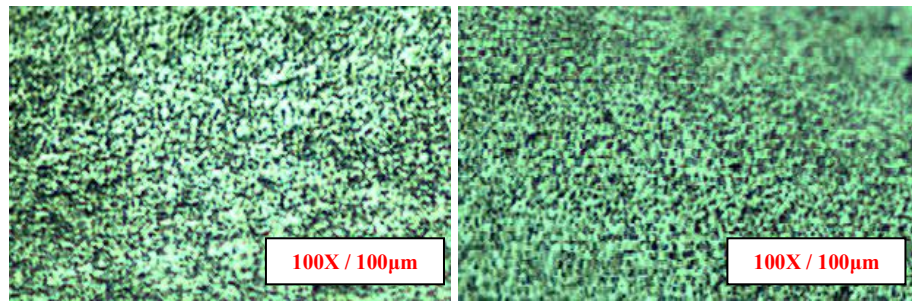


Fig 14: Pentagon pin profile with 500 rpm & 30 mm/min and 500 rpm & 60 mm/min

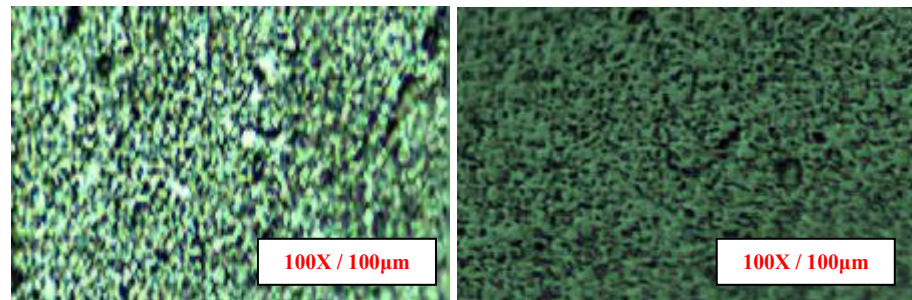


Fig 15: Pentagon pin profile with 700 rpm & 30 mm/min and 700 rpm & 60 mm/min

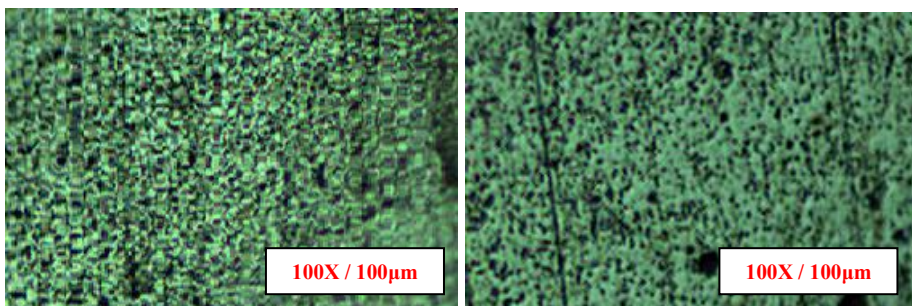


Fig 16: Pentagon pin profile with 1000 rpm & 30 mm/min and 1000 rpm & 60 mm/min

## Conclusion

From the experimental work and their correlation, the accompanying outcomes can be given below:

- In this research, friction stir welded AA2024-T351 was composed effectively by FSW machine with various optimized process parameters tool rotation speed 500, 700 and 1000 rpm and distinct traverse speeds 30 and 60 mm/min to assess their impact on the hardness survey and characterization studies.
- Better microhardness was obtained with higher rotational speed 1000 rpm by three tool pin profiles. Due to greater rotation speed composes the higher friction to accomplish the fine strength.
- The greater hardness was achieved at process parameters 1000 rpm, 60 mm/min and hexagonal tool pin profile combinations due to the reason of increasing tool rotation produces the higher friction and the grain size in SZ was fine. The lesser hardness was attained at the process parameters 500 rpm, 30 mm/min and pentagonal tool pin profile combinations by the reason of decreasing rotation speed gives lesser friction and the grain size in SZ was coarser.

- Tool pin profiles play a vital role in deciding the metallurgical and mechanical behavior of the friction stir welded AA2024.
- Probably all the pin profiles achieve better hardness due to the optimal temperature level and extensive plastic deformation which was best under the tool shoulder and around the pin.
- The results show that the FSW welded joint accomplished with the parameters 1000 rpm, 60 mm/min and hexagonal tool pin profile was higher hardness strength and better grain structure contrasted to the other set of process parameters.

### Data Availability

The data used to support the findings of this study are included within the article.

### Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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