Research Article

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Impact of Tool Pin Profiles and Nanopowder Addition to Nugget Zone on Friction Stir Welding of Aluminum Alloys

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ABSTRACT

In this work, Friction stir welding (FSW) process is carried out on AA 2024 and AA 7075 aluminum alloys with Al_2O_3 filled in the nugget zone. The micro hole is performed before welding on the nugget zone to fill nanoparticle addition. Process parameters considered are tool pin profile, tool rotational speed, and welding speed. Three different types of tool pin profiles are considered namely square, hexagon and circular in cross-section. Taguchi L_9 experimental steps are followed to perform the experiments. Performance parameters considered are tensile strength, bending strength and micro hardness of the welded sample. The performance of FSW samples is influenced by material mixing, which is significantly influenced with tool pin profile. Tool pin profile is directly influenced by contact area, material mixing, fine refined structure and appropriate heat. The result of experimentation is understood as better pulsating action, stir action and material mixing with hexagon pin profile and nano Al_2O_3 filled in the nugget zone. Characterization study is carried out on welded area on FSW sample to evaluate microstructure changes to realize the weld quality. It is observed that the refined microstructure formed after FSW leads to improved mechanical properties.

Keywords: Friction stir welding; Al_2O_3 nanopowder; Tool pin profiles; Mechanical strength.

1. INTRODUCTION

Aluminum alloy has significant properties such as corrosion resistance and high strength to weight ratio. It is widely preferred in aerospace, automobile and marine industries. Application of fusion welding on aluminum leads to poor welding strength, porosity and cracks due to solidification. To avoid this limitation, solid state welding is used to join aluminum alloy by various researchers. In solid state welding, heat is generated due to stirring action of tool to join the work piece. It has advantages in terms of zero melting, no secondary phase formation and unnecessary chemical reaction. In this process, non-consumable electrode is used. Tool pin profile is the main parameter to generate appropriate heat and metal mixing. Generally, the work piece is clamped in the butt joint position and tool rotation is performed along the line of the joint to induce plastic deformation. Strength and quality of the Frictional Stir Welding (FSW) joints are important for further application. Another research work was attempted by researchers to enhance the strength of the FSW samples by introducing the nanoparticles reinforcement to the nugget zone. Some of the familiar reinforcements are SiC, TiO_2 and Al_2O_3. This will lead to surface nanocomposite (Bhardwaj *et al.* 2019; Devaraj *et al.* 2021; Khan *et al.* 2022; Gaikwad *et al.* 2022).

Zhou *et al.* (2023) investigated the effect of serrated joint width in dissimilar metals of AA 2024 and AA 7075 welding process using FSW. In their research, strength and microstructure behavior after FSW were investigated. The width of joint was changed and investigated their performance. The results revealed that an improved mechanical interlock was observed with the increase in serrated joint width in the FSW process. Gebreamlak *et al.* (2024) performed dissimilar metal (AA 2024 and AA 7075) welding embedded with nano powder in the welding zone. In their study, RSM was used to perform and analyze the experiments. Mechanical strength and microstructure analysis were carried out. The results revealed that microstructure refinement after nano powder reinforcement. Mouria *et al.* (2024) conducted an FSW process by incorporating nanoparticles in the nugget zone. The nanoparticles considered were SiC as well as TiO_2. The results of the experiment showed that mechanical strength and hardness were enhanced with the addition of nanoparticles than without reinforced nanoparticles.

Thimmaraju *et al.* (2016) conducted the FSW process on Al 6082 alloy using various types of tool pin profiles. In their work, mechanical strength and microstructure analysis were carried out. Triangle, square and hexagonal type pin profiles were used. The results of the experiment indicated that the hexagonal type pin

profile performed better. Gopi *et al.* (2021) investigated about tool pin profile effects on mechanical strength of FSW processed Al 6082 alloy. The results showed that tool pin profile influenced the mechanical strength significantly.

Rahmatian *et al.* (2020) performed FSW process on AA5083 by incorporating nano SiC into the nugget zone. Also, the effect of process parameters on response was studied. Mechanical performance in terms of tensile property and hardness of the welded zone were investigated. The results indicate that the addition of SiC to the welding joint region leads to a reduction in grain size and an increase in hardness in the welded area. Singh *et al.* (2019) fabricated aluminum-based nanocomposite using FSW with the addition of nano alumina during welding. The results showed restricted growth of granules in the heat affected zone and microstructure refinement with the addition of nanoparticles in the nugget zone. Singh *et al.* (2022) studied the effect of nanoparticles such as Al_2O_3 and TiO_2 FSW process on Al 606-T6. The results showed that the addition of Al_2O_3 nanoparticles produced a smooth welded surface, increased hardness, and an improved grain structure. Bodaghi *et al.* (2017) performed the FSW process with SiC particle addition in the nugget zone. The effects of process parameters on the response and their optimization were investigated. The results showed a refined microstructure along with improper distribution of nanoparticles.

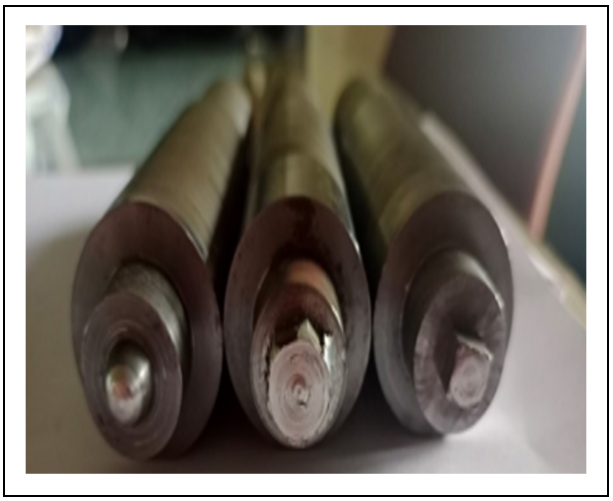


Fig. 1: FSW tool

From the previous studies, it is understood that joining of aluminum alloys using the conventional welding methods called fusion welding may lead to defects, gases, porosity and cracking while solidification. Aluminum materials are generally joined using fusion welding process. Friction stir welding of dissimilar metal poses greater challenges due to chemical composition, melting, and thermal expansion. Tool pin profile is important during the FSW process. Tool pin profile influences the contact area, material mixing, heat generation, flow of material and pulsating action. Another observation from the previous studies is mechanical properties of the FSW joint can be enhanced by adding reinforced particle to the joint. These dissimilar joints are most required in different fields such as light combat aircraft, submarine vehicles and bridge layer tanks. Process parameters also significantly influence the strength of the welded joints. Hence, proper selection of process parameters is important. Addition of nanoparticles to the nugget zone enhances the weld strength. Optimization of process parameters is used to enhance the efficiency of welded joints. Hence, in this work, the effects of tool pin profile and nanopowder addition in the FSW process are investigated.

2. METHODOLOGY

In this research, AA 2024 and AA 7075 aluminum alloys were used as work piece material which are widely preferred in aircraft, defence, military and automotive fields (Zhou *et al.* 2023; Mouria *et al.* 2024; Gebreamlak *et al.* 2024). Dissimilar materials are combined to obtain the synergistic advantages of both base materials. H13 tool steel was used as the tool material. H13 steel belongs to the H-grade tool steels and is a chromium-rich hot work tool steel. It exhibits high toughness and good fatigue resistance. Due to the requirement of high durability under elevated temperature conditions, H13 steel was used. Tool pin profiles significantly influence the performance of the FSW process. Plastic deformation behavior is affected by the tool pin profile, and material flow during FSW depends on the selection of the tool pin profile. (Elangovan *et al.* 2008). The various profiles like square, hexagon and circular were considered in this research.

Fig. 1 shows the various tool pin profiles developed. Frictional Stir Welding process was performed on Vertical Machining Centre (VMC).

Fig. 2 shows the VMC setup for FSW process. Drilling process was carried out on the samples before welding on the line of joints was performed. Microhole diameter (2 mm), depth of the hole (2 mm) and distance between the holes (6 mm) were considered based on previous studies and preliminary work.

Fig. 3 shows the samples after drilling. Al_2O_3 nanoparticles were added before welding. Al_2O_3 nanoparticles possess better hardness, mechanical strength and wear resistance. Based on literature and trial experiments 2 wt% of Al_2O_3 was added in the micro hole.

Fig. 4 shows the SEM image of nano Al_2O_3. Process parameters used in this investigation were profile of tool pin, tool rotational speed and welding speed. Table 1 shows the level of process parameters considered in this investigation. Experiments were executed with the

help of Taguchi L_9 orthogonal experimental design (Divya *et al.* 2021a; Divya *et al.* 2021b; Divya *et al.* 2022).



Fig. 2: Vertical machining centre

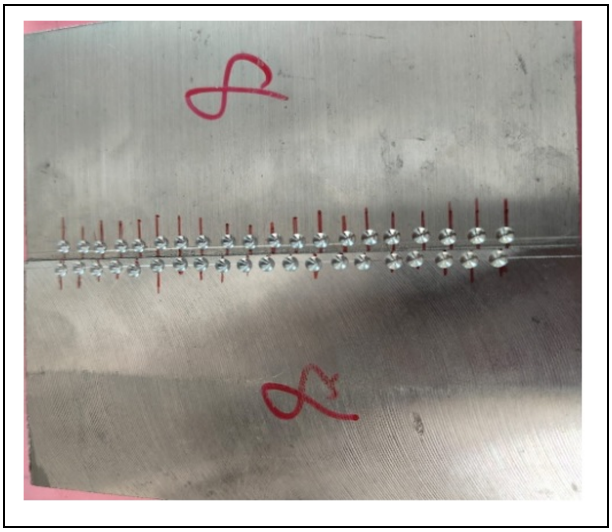


Fig. 3: Samples after drilling process

Fig. 5 shows the welded samples. Responses considered were tensile strength, bending strength and micro hardness. After FSW, a Wire cut Electric Discharge Machine (WEDM) was used for the preparation of sample for tensile test and hardness test. American Society for Testing of Materials ASTM E8-04 was followed for sample preparation.

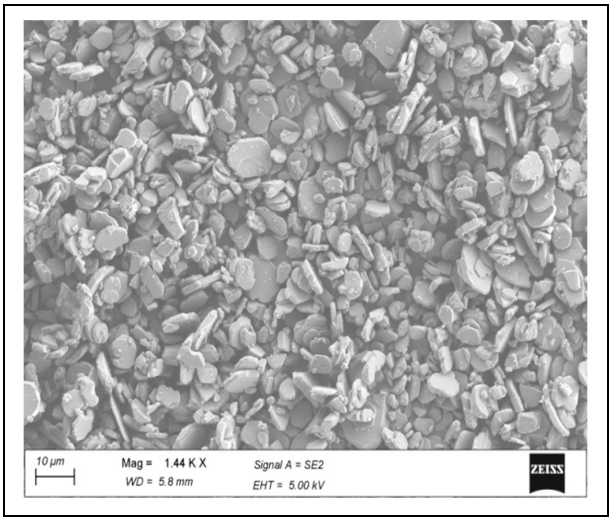


Fig. 4: SEM image of Al_2O_3

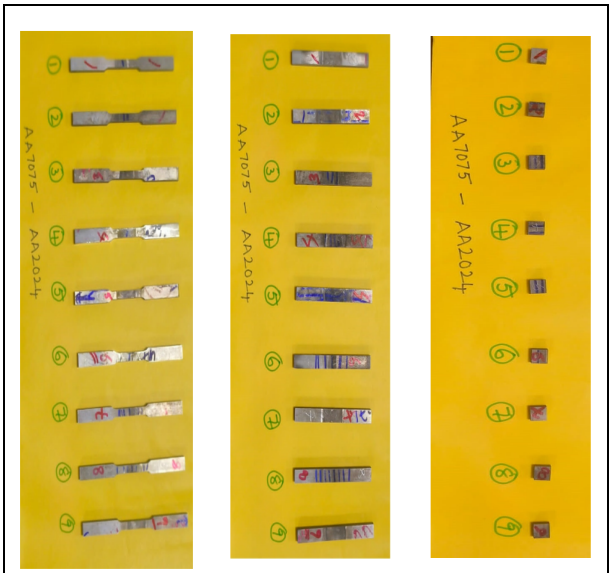


Fig. 5: Welded samples

Fig. 6 represents the WEDM setup. Fig. 7 shows the samples prepared for testing. Ultimate Tensile testing Machine (UTM) was used to carry out tensile strength of FSW samples. A special attachment was used to perform the bending test (ASTM E399) of FSW samples. Vickers micro hardness test was carried out on welded region. Fig. 8 shows the UTM (a) and Vickers micro hardness (b) setup. Table 2 shows the results obtained from the experiments. Fig. 9 shows the tested samples.



Fig. 6: WEDM setup

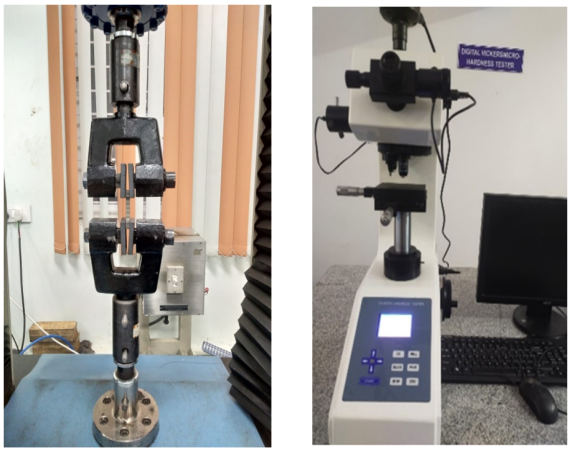


a. Tensile test b. Bending test c. Hardness test

Fig. 7(a-c): Samples for testing

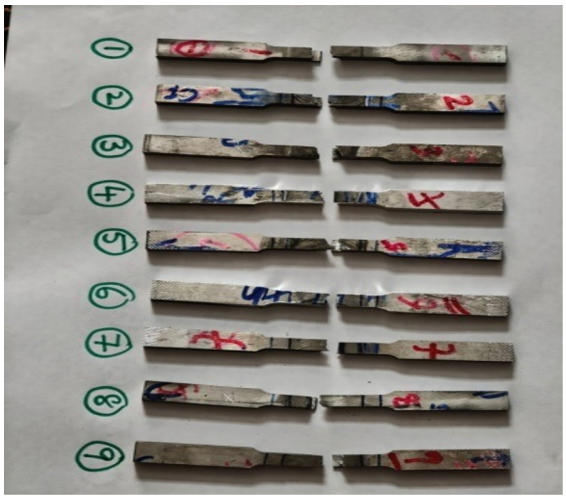
Table 1. Process parameters

Parameters	Level 1	Level 2	Level 3
Tool pin profile	Circular	Hexagon	Square
Tool rotational speed in rpm	600	800	1000
Welding speed mm/min	30	40	50

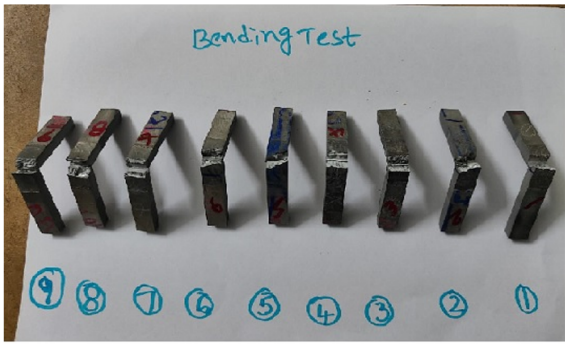


a. Universal Testing Machine b. Micro hardness measurement

Fig. 8(a-b): Testing facilities



a Tensile test



b Bending Test

Fig. 9(a-b): Tested samples

Table 2. Experimental results

Tool pin profile	Tool rotational speed in rpm	Welding speed mm/min	Tensile strength	Bending strength	Micro hardness
Circular	600	30	230	302	209
Circular	800	40	210	299	172
Circular	1000	50	185	274	163
Hexagon	600	40	287	323	294
Hexagon	800	50	268	311	261
Hexagon	1000	30	242	297	234
Square	600	50	272	319	196
Square	800	30	258	304	162
Square	1000	40	235	294	136

3. RESULTS AND DISCUSSIONS

In this work, FSW process was performed on AA 2024 and AA 7075 aluminum alloys incorporated with nano Al_2O_3 in the nugget zone. Also, the effect of different tool profiles and process parameters was investigated in the nanopowder filled environment. Fig. 10-12 show the main effect plot of input parameters on output parameters. The results of the experiments indicated that a high tensile strength was observed with a hexagonal tool pin profile, low rotational speed, and low welding speed.

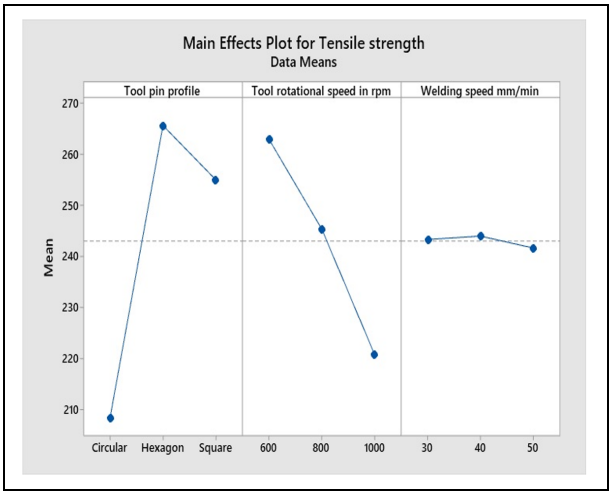


Fig. 10: Main effect plot on tensile strength

Weld quality is an important characteristic of FSW process. The tool material H13 tool steel has higher hot hardness and resists crack due to fatigue. It will be better whenever heat and cooling are involved in a cyclic manner. Tool pin profile significantly affects the welding performance. The tool pin provides adequate mixing and promotes appropriate material flow, which leads to the formation of tunnel defects. The main reason behind the tunnel effect is called as thermo mechanical effect. It also provides higher rubbing action and adequate material flow. The hexagonal profile leads to a higher contact area during FSW, which results in higher tensile strength. This may be due to sufficient heat generation and improved material flow. It is also called pulsating action, which is better with hexagonal profile. Stirring action plays a significant role in FSW process (Elangovan *et al.* 2008).

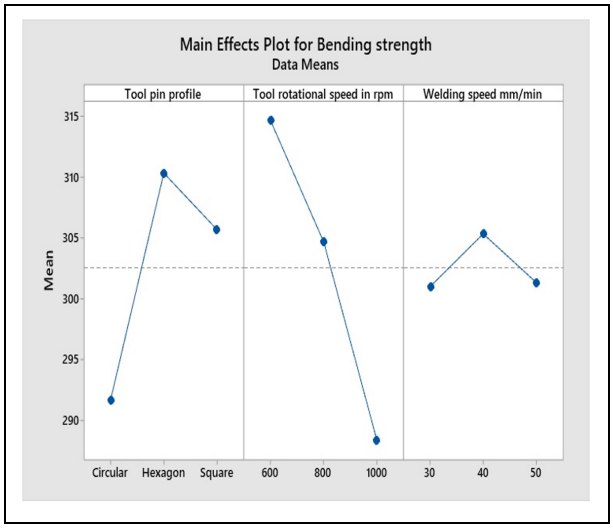


Fig. 11: Main effect plot on bending strength

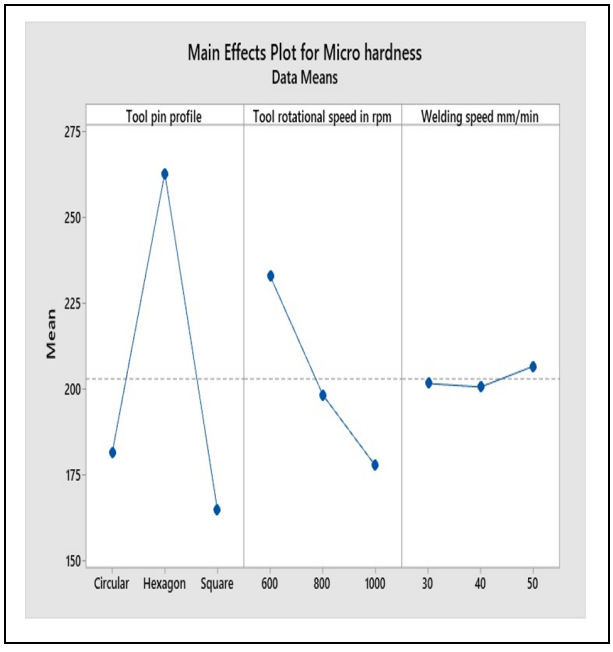
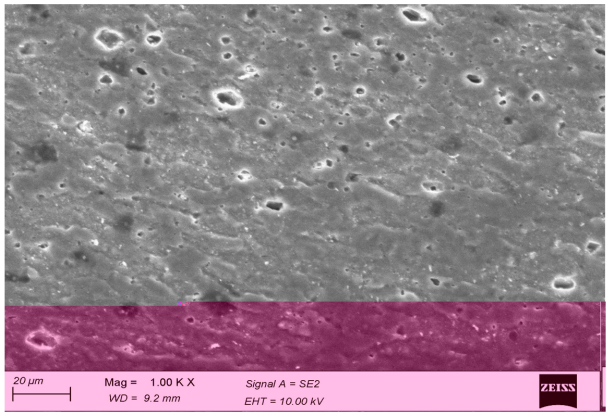
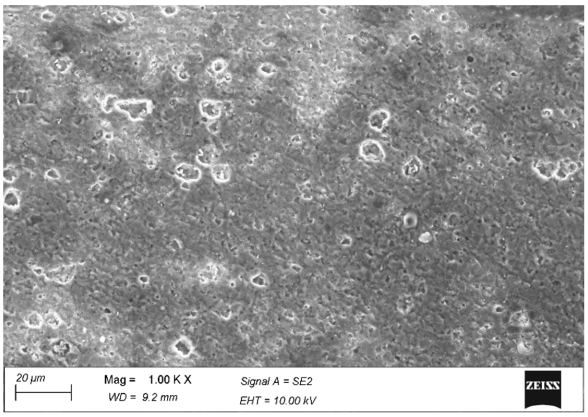


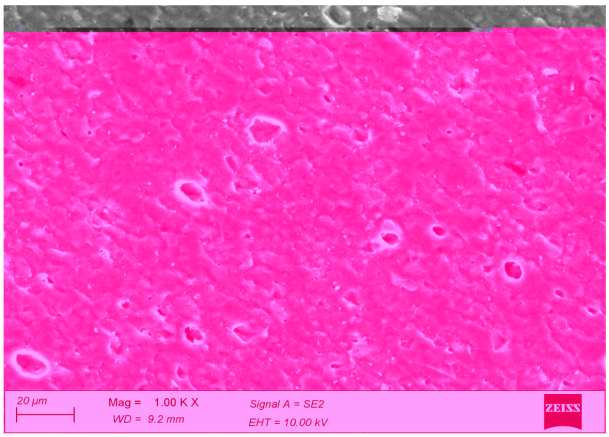
Fig. 12: Main effect plot on micro hardness



a. Circular Profile



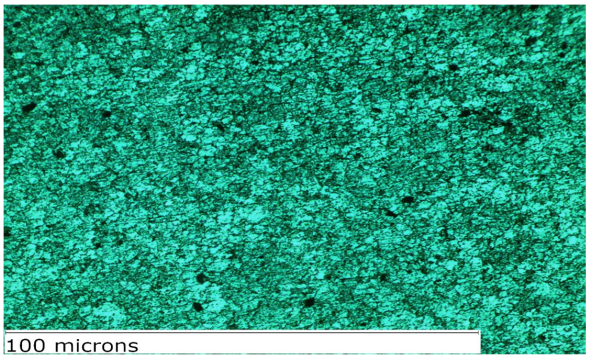
b. Hexagonal Profile



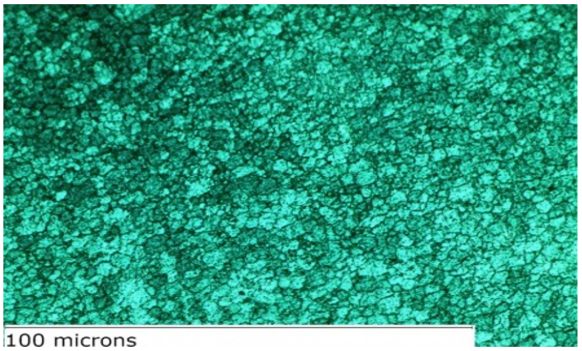
c. Square Profile

Fig. 13(a-c): SEM images after FSW

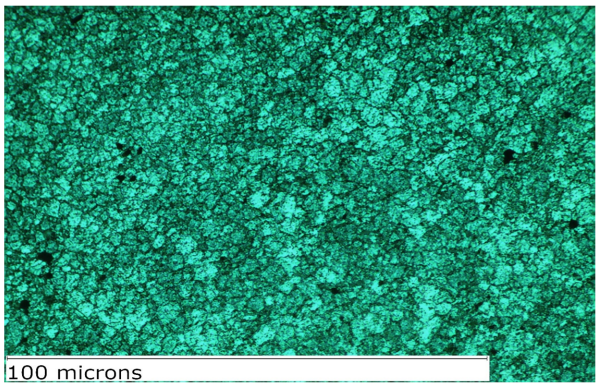
Heat input generation mainly depends on the stirring action. Low rotational speed promotes greater heat generation and longer contact duration with the base material. The microstructure changed to a fine-grained structure, and equiaxed grain formation occurred during this stage. Dynamic recrystallization refers to grain size refinement, which influences the tensile strength of the FSW sample. Dislocation movement and homogenous formation of material are also based on grain size refinement after FSW. Better pulsating action, homogenous material flow and mixing are the indications of quality and defect-free welding. The results revealed that appropriate heat generation and proper material flow, along with quality welding, were achieved with nano Al_2O_3 addition in the weld zone (Padmanaban *et al.* 2009; Vimalraj *et al.* 2021). Nanoparticle addition is used for microstructure refinement. It is generally termed as planning effect. Planning effect is due to the grain boundary migration and refinement of grain after welding. Alumina nanoparticles have high hardness values, which will be useful for obtaining high strength welded samples. The nanoparticle-added weld sample behaves as a nanocomposite due to its higher strength and hardness. The reinforced nanoparticles are termed secondary phase particles, which hinder dislocation motion and influence grain growth. This leads to improved material strength. Also, micro-hardness values are high with the addition of nanoparticles. This may be due to the uniform hardness distribution resulting from the homogeneous dispersion of nanoparticles during FSW. The tensile strength and hardness values were compared with previous literature without nanoparticle addition. It is understood that nanoparticles are uniformly distributed using an appropriate tool pin profile and process parameters. This study also provides guidance for future work on nanoparticle agglomeration in the weld zone. Microstructure and SEM analysis revealed fine and equiaxed grains due to appropriate heat generation and material flow during FSW. (Shehabeldeen *et al.* 2021). Fig. 13 (a-c) and 14 (a-c) show the SEM and microstructure images after FSW. From the SEM analysis, it is understood that voids and material flow after the FSW process influence tensile and bending strength. In addition, proper nanoparticle distribution significantly affects the strength of the FSW joint.



a. Circular Profile



b. Hexagonal Profile



c. Square Profile

Fig. 14(a-c): Microstructure after FSW

4. CONCLUSION

The FSW process was performed by introducing micro holes along the joint line, which were filled with nano Al_2O_3, followed by welding. The addition of nanopowder enhanced tensile strength, bending strength, and microhardness. The optimized parameters were a tool rotational speed of 800 rpm, a welding speed of 40 mm/min, and a hexagonal tool pin profile. Medium levels of rotational and welding speeds resulted in improved strength and hardness. The results showed better properties compared to non-reinforced samples due to nanopowder addition. The tool pin profile significantly influenced the process by promoting sufficient heat generation and material flow during FSW. The hexagonal tool pin profile produced higher strength compared to other profiles. It played a key role in heat generation, grain refinement, material flow, pulsating action, and intermetallic bond formation. Microstructural and SEM analyses confirmed improved mechanical performance of the FSW samples. Reduced voids contributed to higher strength, while uniform nanoparticle distribution enhanced surface integrity and microhardness through fine grain refinement.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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