Research Article

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Impact of Tool Pin Profiles and Nanopowder Addition to Nugget Zone on FSW of Aluminum Alloys

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ABSTRACT

Friction stir welding (FSW) process is a type of solid-state welding process. FSW is preferred due to no chemical reaction, melting, secondary phase formation and microstructure-controlled process. The absence of smoke and spark can be categorized as an eco-friendly welding process. In this work, the 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 wedded area on FSW sample to evaluate microstructure changes to realize the weld quality. It is noticed that fine refinement structure after FSW and provides good mechanical properties.

Keywords: FSW; 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 solidifications. To avoid this limitation, solid date 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 FSW joints are important for further application. Another research work 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).

Nikhil and Govindan et al. used the FSW process to perform dissimilar materials of the aluminum alloy welding process. The mechanical strength was predicted by varying the process parameters. Response Surface Method (RSM) concept was used to predict the best combination of process parameters. The result revealed that RSM concept was used to predict the best combination of process parameters. Predicted optimized results enhanced the machining performance. (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 result 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 result 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 result of the experiment was observed 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 result 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 result pointed about tool pin profile was influenced significantly. Mohammed & Birru conducted FSW process on Al6082. Nanoparticle Al_2O_3 was included in the welding zone. Experiments were performed with different tool rotational speeds, traverse feed and hexagonal tool profiles. Two and three weld passes were performed. The result revealed that three weld passes performed better than two passes.

Rahmatian *et al.* (2020) performed FSW process on AA5083 by incorporating nano SiC into the nugget zone. Also, the process parameters effect on response was studied. Mechanical performance in terms of tensile property and hardness of the welded zone was investigated. The result revealed that reduction in grain size and an increase in hardness of the welded area after addition of SiC to the welding joint region. Singh *et al.* (2019) fabricated aluminum-based nanocomposite using FSW and addition of nano alumina during welding process. The result showed restricted growth of granular in the heat affected zone and microstructure refinement with the addition of nanoparticles in the nugget zone. Singh *et al.* (2022) conducted the effect of nanoparticles such as Al_2O_3 and TiO_2 FSW process on Al 606-T6. The result shows that the welded surface is smooth, high hardness and better grain structure with Al_2O_3 nanoparticles. Bodaghi *et al.* (2017) performed FSW process using SiC particle addition to the nugget zone. Process parameters effect on response and its optimization were carried out. The result observed that refined microstructure as well as improper distribution of nanoparticles. Bahrami et al. investigated and developed a metal matrix composite using the addition of SiC nanoparticles to the welding zone during the FSW process. The result revealed the increased tensile strength of FSW samples from 31% to 76% with the help of nanoparticle addition.

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 is greater challenge due to chemical composition, melting, and thermal expansion. FSW is one of the suitable solutions to avoid such an issue. 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 notice from the previous studies is mechanical properties of the FSW joint can be enhance 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 is used to enhance the weld strength. Optimization of process parameters is used to enhance the efficiency of welded joints. Hence, in this work, tool pin profile and nanopowder addition effect of the FSW process are investigated.

2. METHODOLOGY

In this research, AA 2024 and AA 7075 aluminum alloys are used as work piece material which is widely preferred in aircraft, defence, military and automotive fields (Zhou *et al.* 2023; Mouria *et al.* 2024; Gebreamlak *et al.* 2024). Combine dissimilar materials is used to obtain combined advantages of both base materials. H13 tool steel is used as tool material. H13 steel is categorized under H steel and is also called chromium rich based hot tool steel. It has better toughness and fatigue resist materials. The requirement of high durability under a temperature environment, H13 steel is used. Tool pin profiles significantly influence the FSW performance. Plastic information is influenced by the tool pin profile. Material flow during FSW depends on selection of tool pin profile (Elangovan *et al.* 2008). The various profiles like square, hexagon and circular are considered in this research.

Figure 1 shows the developed different tool pin profiles. FSW process is performed on Vertical Machining Centre (VMC).

Fig. 1: FSW tool

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

Fig. 2: Vertical Machining Centre

Figure 3 shows the samples after drilling. Nanoparticle Al_2O_3 is added before in the region of welding to be carried out. Nanoparticle Al_2O_3 possesses better hardness, mechanical strength and wear resistance. Based on literature and trial experiments 2 wt% of Al_2O_3 is added in the micro hole.

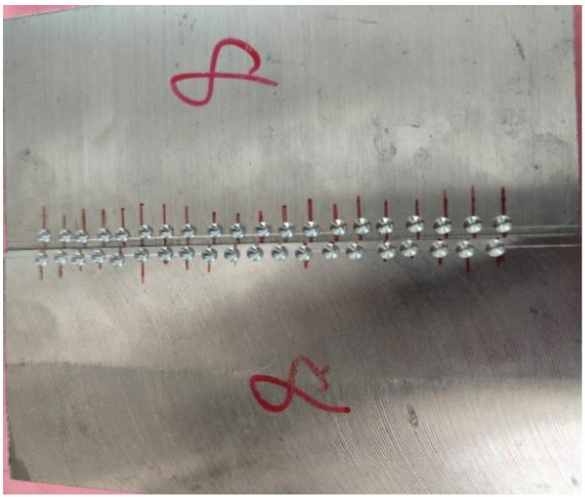


Fig. 3: Samples after drilling process

Figure 4 shows the SEM image of nano Al_2O_3. Process parameters used in this investigation are profile of tool pin, tool rotational speed and welding speed. Table 1 shows the level of process parameters considered in this investigation. Experiments are executed with the help of Taguchi L_9 orthogonal experimental design (Divya *et al.* 2021a; Divya *et al.* 2021b; Divya *et al.* 2022).

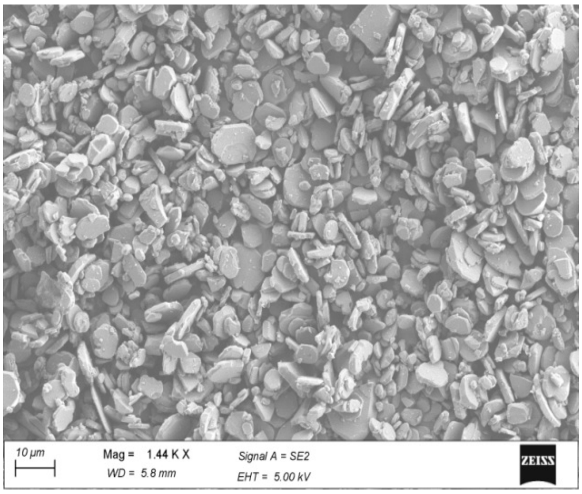


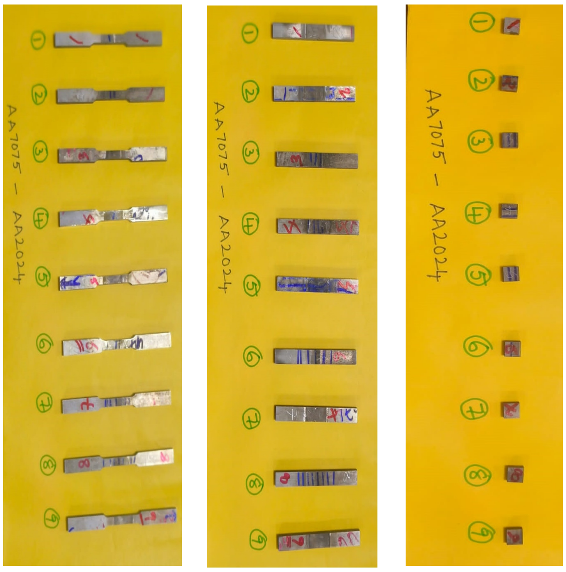
Fig. 4: SEM image of Al_2O_3

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

Fig. 5: Welded samples

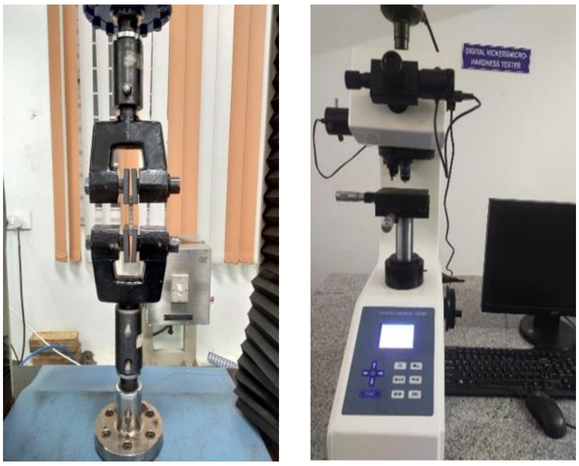
Figure 6 represents WEDM setup. Figure 7 shows the samples prepared for testing. Ultimate Tensile testing Machine (UTM) is used to carry out tensile strength of FSW samples. A special attachment is used to perform the bending test (ASTM E399) of FSW samples. Vickers micro hardness test is carried out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

Fig. 6: WEDM setup



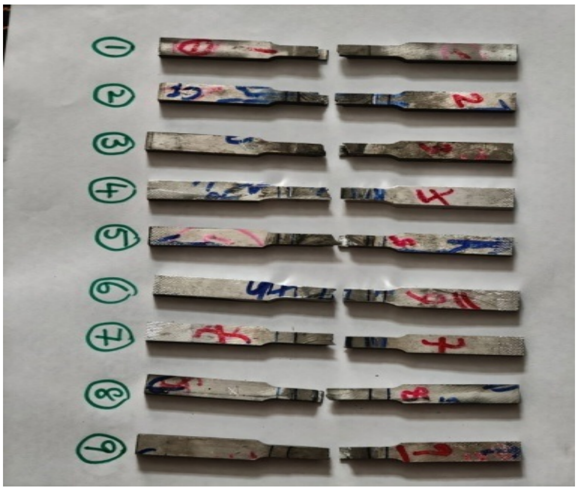
a. Tensile test b. Bending test c. Hardness test

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

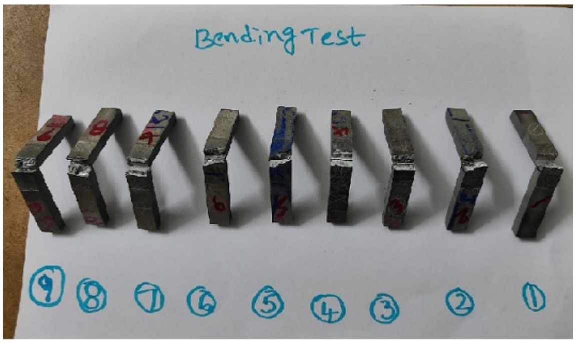


a. Universal Testing Machine b. Micro hardness measurement

Fig. 8(a-b): Testing facilities



a Tensile test



b Bending Test

Fig. 9(a-b): Tested samples

Table 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

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 is 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 is investigated in the nanopowder filled environment. Figure 10-12 shows the main effect plot of input parameters on output parameters. The result of experiments indicated that high value of tensile strength is noticed with hexagonal profile of tool pin, low value of rotational speed and low value of welding speed.

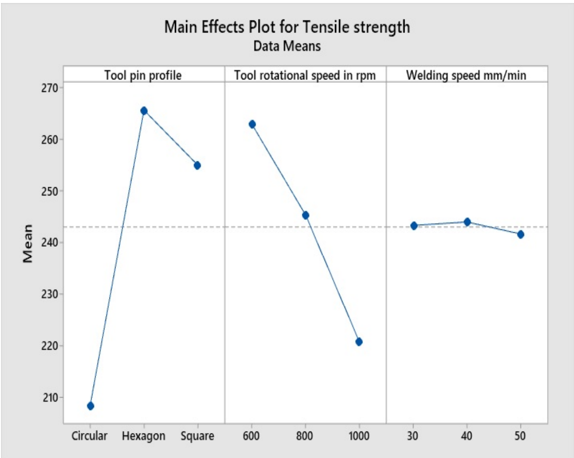


Fig. 10: Main effect plot on tensile strength

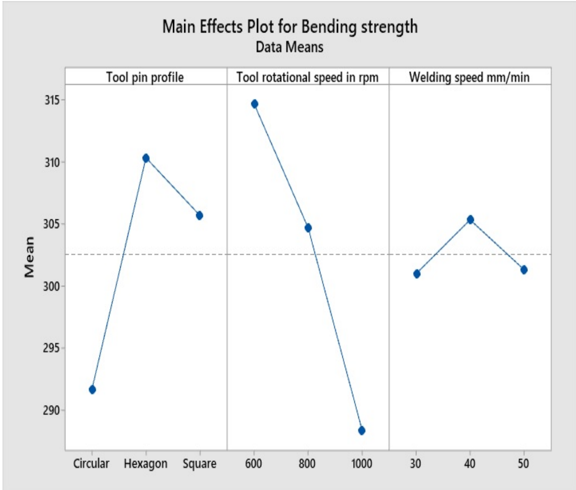


Fig. 11: Main effect plot on bending strength

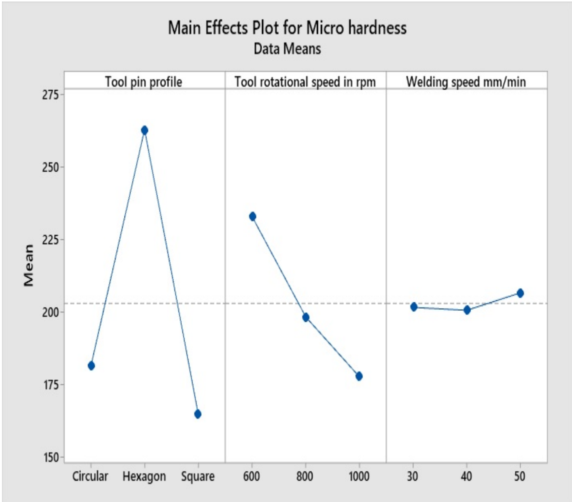
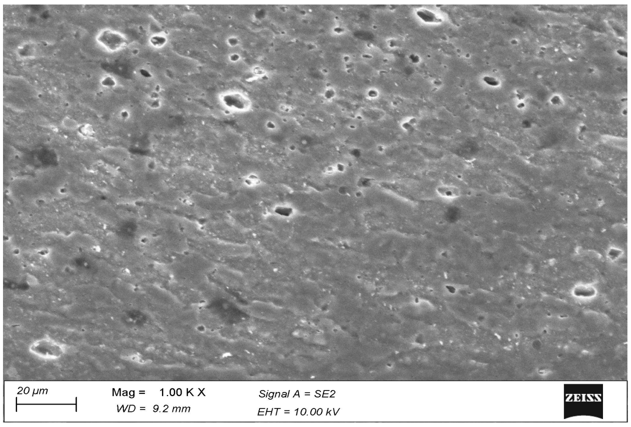
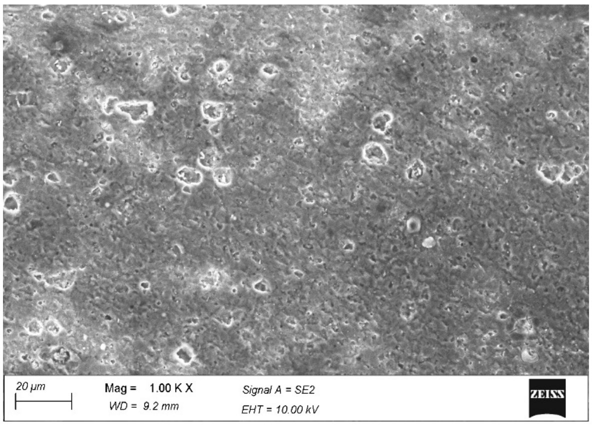


Fig. 12: Main effect plot on micro hardness

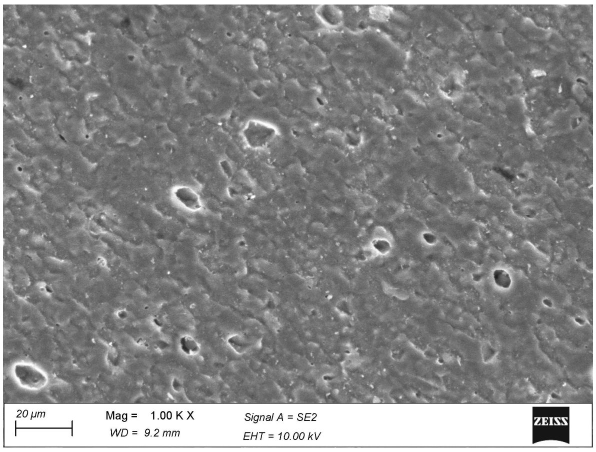
Weld quality is an important characteristic o FSW process. Tool material is used as H13 tool steel, which has higher hot hardness and resists crack due to fatigue. It will be better whenever heat and cooling are involved in cyclic type. Tool pin profile is significantly affecting the welding performance. Tool pin provides adequate mixing and followed by appropriate material flow which will lead to tunnel effect. The main reason behind the tunnel effect is called as thermo mechanical effect. It also provides higher rubbing action and adequate material flow. Hexagonal profile is leads to a high contact area during FSW, which is used to obtain high value of tensile strength. This might be sufficient heat generation and material flow. It is also called pulsating action, which is better with hexagonal profile. Stirring action is playing a significant role in FSW process (Elangovan *et al.* 2008).



a. Circular profile



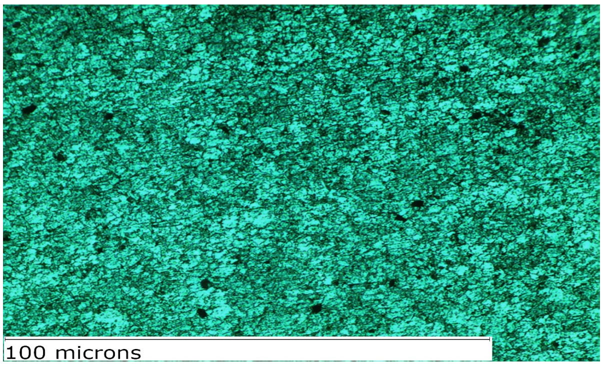
b. Hexagonal profile



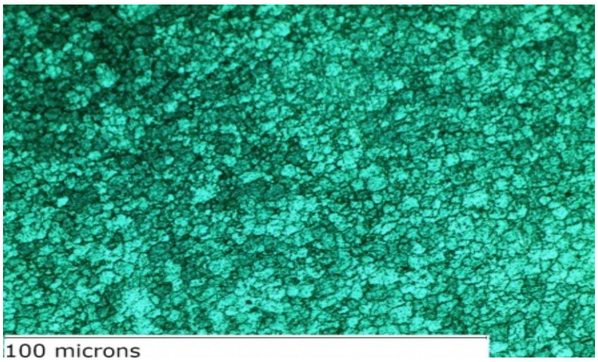
c. Square profile

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

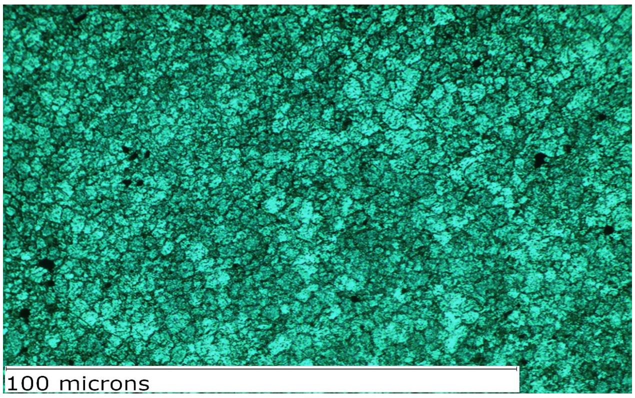
Heat input generation is mainly depended on the stirring action. Low value of rotational speed is proving more heat generation and longer duration in contact with base material. The microstructure changes with fine grained microstructure, as well as equiaxed material flow occurred in this stage. Dynamic recrystallization is called grain size refinement, which will influence 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 result revealed that appropriate heat, proper mixing of flow and followed by quality welding using 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. This nanoparticle added weld sample behaves as a nanocomposite due to its higher strength and hardness. Reinforcement of nanoparticles are termed as secondary phase particles which oppose dislocation migration and result in grain growth increment. This is used to lead higher material strength. Also, micro-hardness values are high with the addition of nanoparticles. This might be consistence hardness distribution of nanoparticle distribution during FSW. Previous literature without nanoparticle addition and their results are compared with tensile strength and hardness value. It is understood that nanoparticles are distributed uniformly using appropriate tool pin profile and process parameters. The study is also used to direct future work about nanoparticle agglomeration in the weld zone. Microstructure and SEM analysis studies revealed that fine and equiaxed grain due to appropriate heat generation and material flow during FSW (Shehabeldeen *et al.* 2021). Figures 13 a-c and 14 a-c shows the SEM and microstructure images after FSW. SEM analysis is carried out for higher tensile and lower tensile strength values to realize the mechanism. From the SEM analysis, it is understood that voids and material flow after FSW process leads to strength interns of tensile as well as bending strength. Also, proper nanoparticle distribution significantly affected the strength value FSW process.



a. Circular profile



b. Hexagonal profile



c. Square profile

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

4. CONCLUSION

- FSW process is performed by introducing micro holes on the line of joints. Nano Al_2O_3 is filled in the micro holes and FSW process is performed. The result of better tensile strength, bending strength and micro hardness are enhanced with nanopowder addition. The corresponding input parameters are tool rotational speed (800 rpm) and medium welding speed (40 mm/min) with a hexagonal tool pin profile. Medium range of tool rotational speed and welding speed are given better strength and hardness of welded sample. The result of the experiment is compared with non-reinforced samples and the results are enhanced through nanopowder addition.

- Tool pin profile is influenced significantly, which induces sufficient heat generation and material flow during FSW process. Hexagonal based tool pin profile is given better strength value than other tool pin profiles. It is realized that profile of tool pin plays a significant role in heat generation in sufficient quantity, microstructure of fine grain refinement, flow of material, pulsating action and intermetallic bond thickness.

- Microstructure and SEM images of FSW sample study are used to realize the strength after FSW samples. Minimum void presented after FSW sample provides higher strength and nanoparticle distribution even also used to enhance the composite surface integrity in nature and fine refinement for micro hardness.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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