DOR: 20.1001.1.2322388.2021.9.1.6.2

Research Paper

Effect of Tool Pin Shape on Defect-Free FSP and Particles Distribution in SiC/Al6061 Composites

Mortza Ezzati[1], Parviz Asadi[*2], Mostafa Akbari[3]

1. Student, Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran.

2. Assistant professor, Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran.

3. Assistant professor, Department of Mechanical Engineering, Technical and Vocational University (TVU), Tehran, Iran

ARTICLE INFO

Article history:

Received 23 July 2020
Accepted 11 August 2020
Available online 1 January 2021

Keywords:
FSP
Pin Shape
Material flow
Defect formation
Reinforcing particles distribution

ABSTRACT

In this research, Al-SiC composites were produced using FSP tools with different pin shapes to investigate the distribution of reinforcing particles in the base metal. First, to obtain the optimal rotational and traverse speed and tilt angle, several tests were performed on different parameters. The results showed that the rotational speed of 1250 rpm and the traverse speed of 100 mm/min in all tools produced flawless samples. Then, tools with different tool pin profiles of triflate, cylindrical, threaded, triangular, square, and hexagonal were utilized in this study. The distribution of reinforcing particles in the base metal was studied using a light microscope. The results showed that the cylindrical tool was not able to distribute particles in the base metal even after four passes of the process and was not a suitable tool for composite production. Tools with flat surfaces, such as square and triangular tools, have performed better in distributing reinforcing particles in the base metal. The results showed that the presence of a kind of eccentricity and pulse production in these tools had improved the distribution of particles. Threaded and hexagonal tools have the best performance in the distribution of reinforcing particles in the base metal and can be introduced as a suitable tool for composite products in the FSP process. The results of this study also showed that the change in the direction of tool rotation improved the distribution of reinforcing particles in all tools.

[*] **Corresponding Author**:
Emails Address: asadipar@gmail.com; parvizasadi@ut.ac.ir

1. Introduction

Aluminum and its alloys are widely used in the construction of aircraft, ships, and means of transport due to their special appeal in the production of lightweight products. 6061 aluminum alloy is used for structural applications due to its exceptional resistance to corrosion, machinability, and strength. When it comes to structural applications, 6061 aluminum alloy angle is one of the most commonly used shapes. However, these alloys are not strong enough for all engineering purposes, especially in applications where surface contact is present. For this reason, their use has been limited. To this end, several methods have been used by researchers to improve the performance of these alloys. Maurya et al. [1] fabricated composites with different weight percent of SiC content via the stir casting method, and their result showed that hardness and tensile strength were significantly improved up to 5 wt% of SiC particles. Chandla et al. [2] fabricate low-cost, lightweight metal matrix composite using Al 6061 as matrix material and alumina (Al_2O_3) and bagasse ash as reinforcing material through the stir casting process. They did not achieve a good distribution of reinforcing particles in the metal phase using this method, although the hardness of the composites relative to the base metal increased.

Friction stir processing was developed based on the principles of friction stir welding [3, 4]. Basically, the parameters and microstructural changes of these two processes are similar. However, the purpose of friction stir processing is not to join or weld two metal sheets but to modify the structure, change the grain size, increase the strength, make the structure uniform in terms of grain size, sediment distribution, and the creation of surface composites are the achievements of this process [5]. In friction stir processing, the rotating tool sinks into the integrated sheet to make local microstructural modification after processing to enhance the desired properties. Later, this process was used to produce surface layer composites, homogenize parts produced by powder metallurgy, modify the microstructure of metal-based composites, and improve the properties of cast alloys. Obtaining uniform distribution of reinforcing particles in the metal matrix is quite a challenging task. One of the significant problems in composite production is reinforcement particle agglomeration that worsens the composites' mechanical properties [6]. In FSP, the material flow pattern mainly depends on the tool pin profile so, the tool pin profile is the most influencing parameter on the distribution of reinforcing particles in the metal matrix. Various tool pin profiles like conical, triangular, threaded, square, cylindrical, etc., have been used in different investigations. Elangovan et al. [7] investigated the effect of tool pin shape and tool shoulder diameter on the quality of aluminum stir zone. In their research, they used five tools (simple cylinder, threaded cylinders, conical, triangular, and square) and three different shoulder diameters (18, 15, and 21 mm). They reported that two pins with square and triangular geometry produce defect-free areas and have the highest hardness compared to other geometries among the five pins used. In this study, only the effect of tool pin shape on the microstructure enhancement, such as grain size in the SZ, has been investigated, and no reinforcing particles have been used. Khodaverdizadeh et al. [8] investigated the microstructural and mechanical properties of the joints produced between the copper sheets using different pins of the FSW tool. They concluded that using a square pin produced a joint with finer grains and thus improved mechanical properties. However, Faraji et al. [9] stated that the triangular tool creates more refined grains in the SZ than the square tool. Azizieh et al. [10] found that threaded tools are the most suitable tool for composite production. Zhao et al. [11] concluded that a threaded taper pin had the best material flow in comparing four pins of different shapes. Also, the sample produced with this pin had better strength and appearance than other pins such as threadless cylindrical, threaded cylindrical, and threadless taper. Another essential point in this study is the undeniable superiority of threaded tools over non-threaded tools. Also, the flow of materials in threadless pins (both conical and cylindrical) is not suitable, and the lack of materials in the processed area causes tunnel defects in the advancing side. Khojastehnezhad et al. [12] investigated of mechanical properties of friction stir processed Al 6061/Al2O3-Tib2 hybrid metal matrix composite. In this study, they examined the main welding parameters such as rotational speed and linear velocity and did not study the geometry of the tool.

Material flow during FSP is the reason for distributing reinforcing particles in the metal matrix. As a result, the study of material flow patterns is crucial to understand the effect of tool pin profiles on particle distribution. However, it is challenging to use experimental methods to study the flow of matter during the process due to severe deformation as well as high temperatures. Therefore, numerical methods based on the FEM have been developed to model material flow. Akbari et al. [13] investigated the flow of material generated by the circular and threaded tool pin profiles during the fabrication of composite using FSP. Their material flow results clearly identified the reason for the proper distribution of ceramic particles when using the threaded tool.

Akbari et al. [5, 14] simulated material flow in dissimilar friction stir lap welding of brass and aluminum using coupled Eulerian and Lagrangian method. The material flow simulation results clearly showed how brass and aluminum are mixed in the stir zone. Akbari et al. [13] investigated the material flow of different locations in the stir zone (SZ), including the advancing side, the retreating side, the shoulder-affected area, and the pin-affected area 3D finite element method.

In this study, the different pin shapes used in several previous studies were collected, and the effect of these pins on the distribution of reinforcing particles in the base metal was systematically investigated. In previous research, as mentioned, one or more limited pins were generally used to produce the composite, which did not allow for a comprehensive comparison between the performance of the different pins. For this purpose, by using different pins of the tool, the performance of each of them will be examined, and the appropriate pin shape will be introduced.

2. Experimental method

In order to produce the composite, 6061-O aluminum sheets with a thickness of 5 mm were used. The chemical composition of this alloy is given in Table 1. The dimensions of 6061 plates for the FSP experiments are illustrated in Figure 1a.

Table 1. Chemical composition of 6061 aluminum plates (wt%).

Al	Mg	Si	Cu	Fe	Mn	Cr	Zn	Ti
97.265	0.89	0.61	0.265	0.56	0.106	0.271	0.001	0.015

Fig. 1. FSW tools dimensions used in this study

SiC reinforcing particles with an average size of 5 microns were used in this study. To produce the composite by the FSP method, first, grooves were made with dimensions of 0.8mm width and 1.4mm depth in aluminum samples, and particles were embedded inside these grooves. The surface of the aluminum specimens was then sealed with a pinless tool to prevent reinforcing particles from escaping during the process. The FSP process was then performed using different input parameters to produce the composite.
To investigate the effect of tool pin shape on the distribution of reinforcing particles in the base metal, FSP tools with different pin shapes of triflate, cylindrical, threaded, triangular, square, and hexagonal were employed (Figure 1). Moreover, the pitch distance of the threaded pin profile tool was 1mm. 2344 steel was used to make the tools. After making the tools, the heat treatment process was performed.
The composite samples were polished and etched according to metallurgical methods to investigate their microstructural properties. Olympus optical microscope with 50, 100, 200, and 500x magnifications was used to examine the macrostructure and microstructure.

3. Simulation of friction stir processing

The FSP is simulated by the finite element method using Deform 3D software and based on the Lagrangian method to predict the material flow in the stir zone [15, 16]. In order to simulate the material flow, it is necessary to introduce the properties of 6061 aluminum alloy in Deform software, which was selected from the Deform materials library. These properties include plastic, elastic, and thermal data, depending on the type of application. The plastic behavior of the samples is determined by the flow stress function or flow stress data. The current stress in this software is expressed for aluminum alloys under Eq. (1).

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \qquad (1)$$

In this relation, σ is the stress flow, ε is the effective plastic strain, ε¯ is the effective strain rate, and T is the temperature.
The constant shear friction model was used for modeling friction between the FSP tool and the workpiece. The tool was meshed with about 7500 tetrahedral elements with an average size of 0.85 mm. The workpiece was also meshed with about 35,000 tetrahedral elements (Figure 2). The size of the elements in the workpiece is divided into three parts. The average size of the elements in part under the pin was considered 0.85 mm for contact accuracy. By moving away from the tool, the size of the elements was considered larger to reduce the process analysis time.

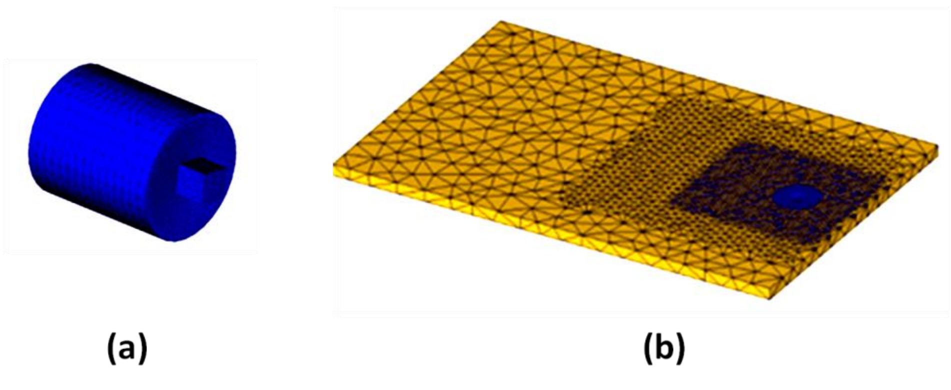


Fig 2. Meshed tool and workpiece.

4. Result and discussion

4-1- The effect of rotational and traverse speed

Table 2 shows the number of processed samples with different parameters. The results show that at rotational speeds higher than 1250 rpm, more heat is generated in the SZ, which leads to irregular material flow. At speeds below 1250 rpm, the heat generated is not sufficient to soften the stir zone material and causes surface defects and tunnel cavities. Defects also occur at traverse speeds above 100 mm/min due to insufficient time to distribute the reinforcing particles. At traverse speeds below 100 mm/min, the heat generated increases, causing the material to overflow and causing cavities and tunnels in the processed zone. In this research, composite samples will be produced with a rotational speed of 1250 rpm and a traverse speed of 100 mm/min.

Table 2. Processed samples with different parameters

Pin shape	speed		Sample cross-section image	Defect	quality
	Rotational	Traverse			
Cylindrical	800	31.5		Hole	Defective
Cylindrical	1000	63.5		Hole	Defective
Cylindrical	1000	63.5		Hole	Defective
Cylindrical	1600	160		Hole	Defective
Cylindrical	1250	100		-	Sound
Triangular	1250	100		-	Sound
Triangular	1250	100		-	Sound
Hexagonal	1250	100		-	Sound
Triflate	1250	100		-	Sound
Threaded taper	1250	100		-	Sound
Threaded cylinderical	1250	100		-	Sound

4-2- Effect of tilt angle on defect formation

Tilt angel is one the most influencing parameters on FSPed quality, such as mechanical and microstructural properties. Moreover, tool tilt angle has a significant effect on the heat generation and material flow and, as a result, the formation of defects such as tunnels and wormholes during the composite fabrication.

This parameter usually was selected in previous investigations without any investigation, and the optimum value of this parameter may not be used. In this study, to choose the proper value of tilt angle, three different values of 0, 2, and 3 degrees were numerically and experimentally investigated to produce composites (Figure 3).

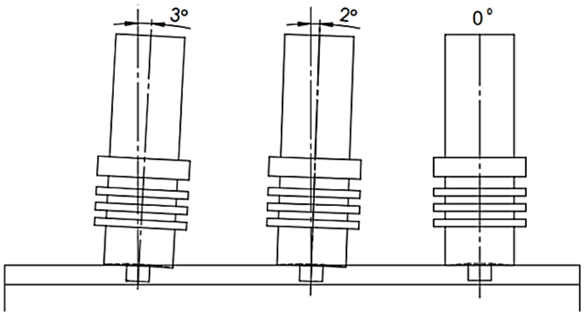


Fig 3. Different tilt angles used in this study

The simulation result of FSP using different tilt angles is shown in Figure 4. Using a tilt angle of 0° results in forming a large tunnel on the advancing side, as shown in this figure. The tunnel size is decreased by increasing the tilt angle to 2°. As shown from this figure, no defect can be found by using a tilt angle of 3°.

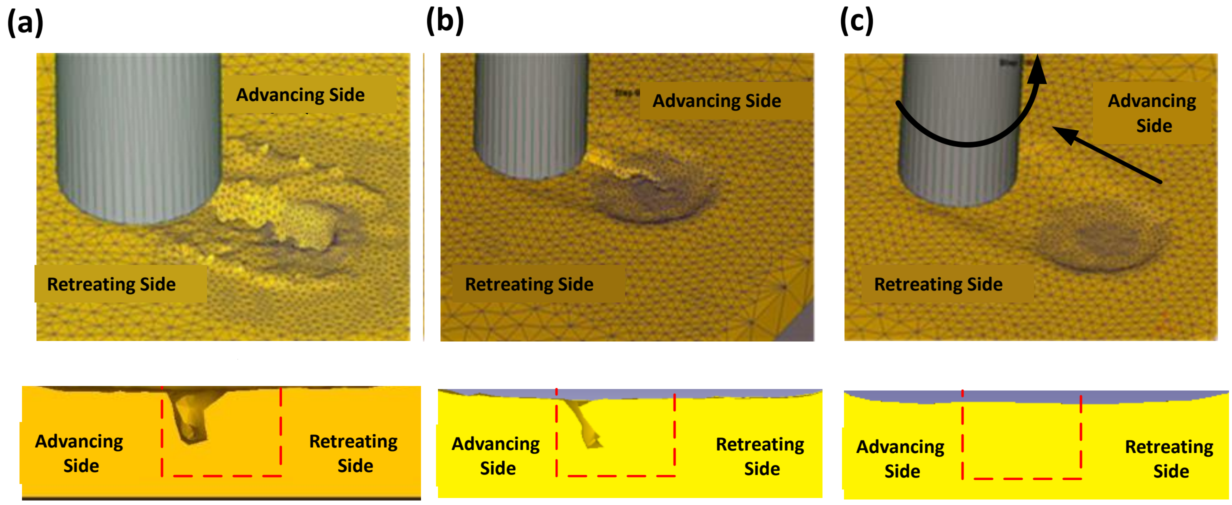


Fig 4. Simulation results of FSP by using different tilt angles at the surface of a workpiece

The experimental results of different samples proceed by different tilt angles are shown in Figure 5. As shown from this figure, numerical results are in good agreement with the experimental results. Moreover, the tilt angle of 3 results in the sound sample. When the tilt angle is zero, the material in contact with the tool shoulder flows in a direction parallel to the shoulder surface. However, a tilt given to the tool results in pushing the material downward from retreating to advancing side along the trailing edge due to the combined action of rotational and translational movement of the tool. This downward movement of material at the shoulder's trailing end can be considered a forging action due to the tool tilt angle [17, 18].

An increase of tool tilt angle results in an increase of forging action on the trailing edge of the weld, thereby filling the cavities which otherwise remain at a lower tool tilt angle. Moreover, the increase in tool tilt results in reduced material to be transported from, leading to a trailing edge on the top material surface. There is a slight increase in temperature due to an increase in the plastic deformation heat associated with the forging action of the FSP tool. An increase in the temperature decreases the material's viscosity, leading to increased material flow moving with high velocity filling the surface defects.

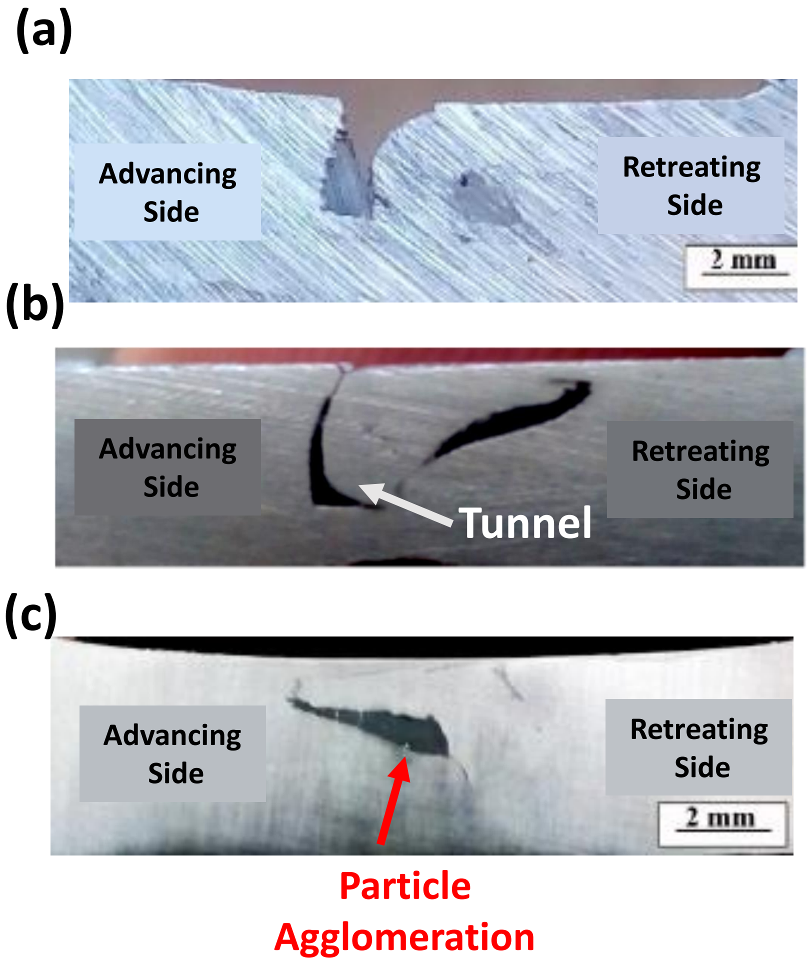


Fig 5. Experimental results of FSP by using different tilt angles of a) 0º, b) 2º and c) 3º

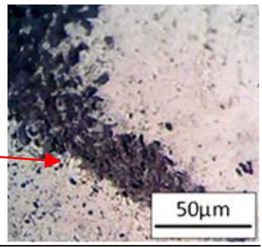
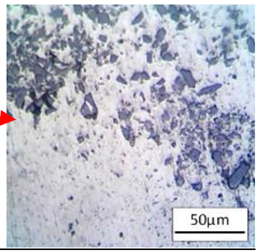
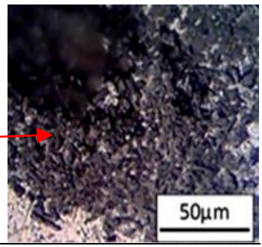
4-3- Effect of pin shape on particles distribution

Non-uniform distribution of reinforcing particles in metal-based composites has significant effects on the failure characteristics and plastic deformation of composites. Uniform distribution of reinforcement in the metal matrix phase is one of the challenges encountered in metal matrix composite during processing which highly influences its strength. There are many parameters that constitute this issue; however, FSP pin shape is the most influencing factor in distributing particles. As a result, investigating the effect of pin profile on particle distribution seems crucial. To study the effect of pin shape and pass number on particle dispersion in the base alloy, a microstructural investigation was carried out.

Macroscopic and microscopic images of the FSPed sample fabricated by cylindrical pin profile are shown in Table 3. Samples were produced in one, two, and four pass processes. As shown in the table, the cylindrical tool could not disperse the reinforcing particles homogeneously in the base metal even after four passes. Reinforcing particles were agglomerated mainly at the pin root in all samples, so a circular pin profile cannot distribute particles in the metal matrix. It can be concluded that cylindrical tools are not suitable tools for composite production using the FSP method.

In order to investigate the cause of the accumulation of reinforcing particles when using a cylindrical tool, the material flow during the process is modeled. Figure 6 shows the material flow during FSP. Several points are located along the centerline to study the dispersion of the reinforcing particles during the process. The results show that the material flow patterns at the upper and lower levels of the composite layer thickness were different. In this way, the material in part close to the shoulder due to more heat production became softer and had more material flow than the lower part of the stir zone. Therefore, the main driver of the material flow is the cylindrical tool. It is clear that due to the lack of oscillating mixing and the ability to move the material by the pin, the distribution of particles in the processing area is entirely irregular and accumulated.

Table 3. Macro and micro images of FSPed sample fabricated with circular pin profile

Pass number	Macroscopic image	Microscopic image
1		
2		
4		

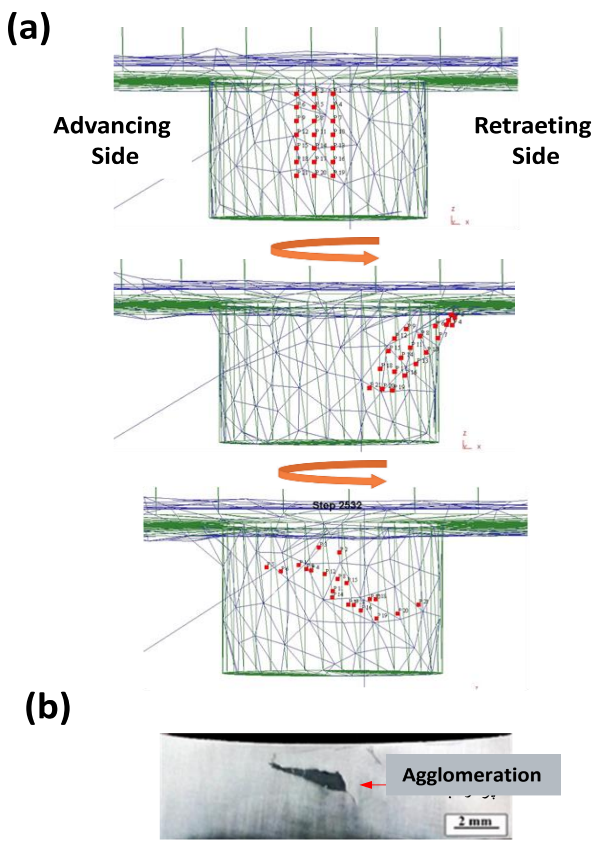


Fig. 6. a) The material flow during FSP using circular pin profile, b) Experimental particle distribution

Macroscopic and microscopic images of the FSPed samples fabricated by triangular pin profile are shown in Figure 7. The sample fabricated with one pass of the process shows the inhomogeneous distribution of particles in the metal matrix. By increasing the pass number, the distribution of particles in the metal matrix is enhanced. Moreover, FSPed samples were fabricated with and without changing the rotational direction between passes. As shown in Figure 7, the microstructural inhomogeneity is more evident in the FSPed samples fabricated without changing the tool rotational direction. The reinforcing particles are mainly accumulated on the advancing side (AS), and the asymmetric distribution of particles around the SZ center can be seen. Change in the tool rotational direction between passes results in alteration of the location of the AS and RS together and consequently the material flow pattern, which improves the distribution of the particles. Moreover, the particles are not distributed near the plate top surface, and a bond with a very low percentage of particles can be found in this area that may be related to the absence of vertical material motion.

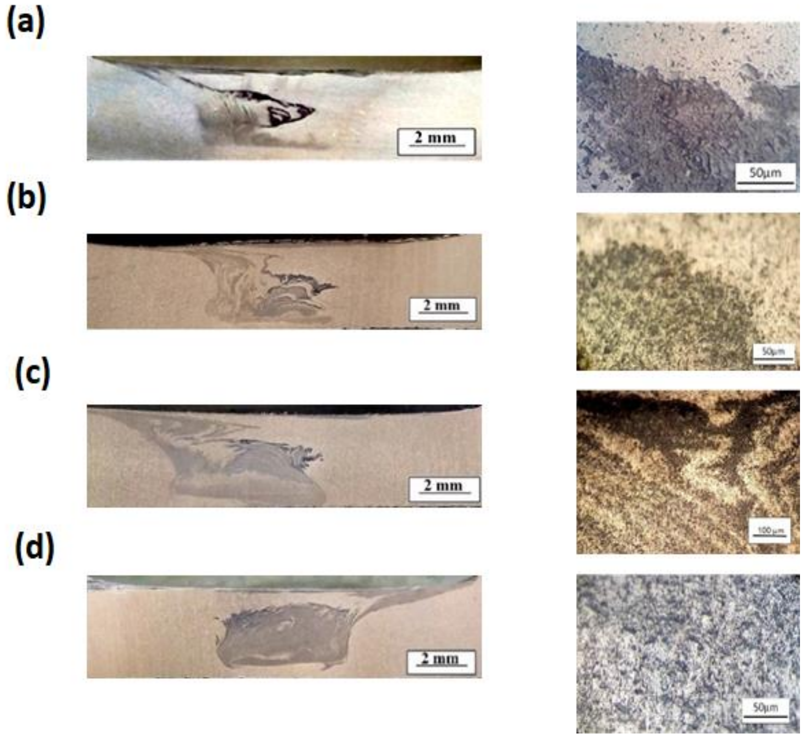


Fig. 7. Macro and micro images of FSPed sample fabricated with triangular pin profile at a) one pass, b) two passes, c) four passes, d) four passes with direction change

Macroscopic and microscopic images of samples fabricated by square pin profile are shown in Figure 8. Like the triangular pin profile, reinforcing particle distribution in the FSPed sample fabricated with four passes and with change in the rotational direction is the best. However, different bands involving different percentages of reinforcing particles were found in the SZ. Particle distribution is improved compared to cylindrical tools, which is due to the higher eccentricity and pulsation effect of the pin shape with a flat surface which increases the material flow.

Macroscopic and microscopic images of samples fabricated by hexagonal pin profile are illustrated in Figure 9. Reinforcing particles are distributed uniformly in the metal matrix in the FSPed sample fabricated with four passes with a change in the rotational direction. However, particles are not distributed uniformly in FSPed samples fabricated by one, two, and four passes without change in tool rotational speed.

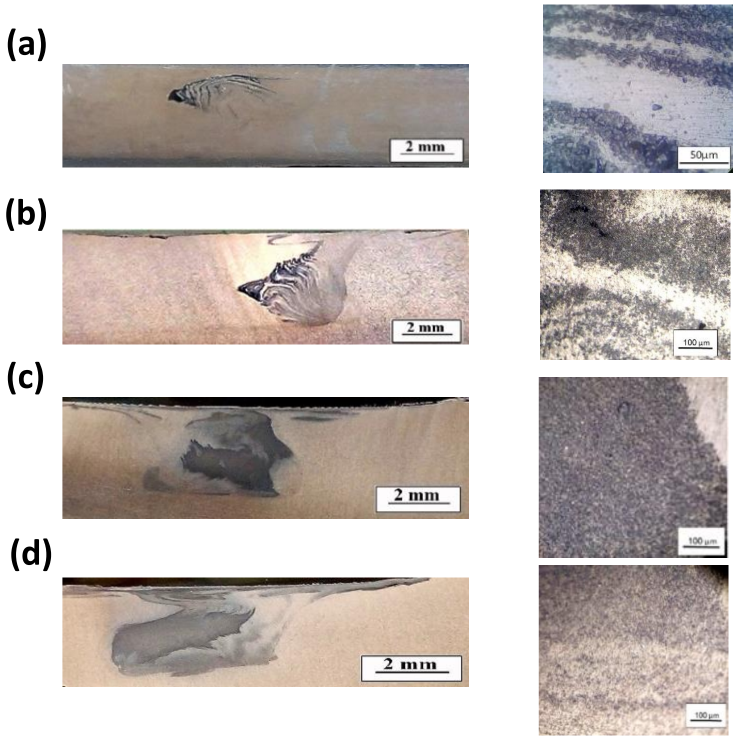


Fig. 8. Macro and micro images of FSPed sample fabricated with square pin profile at a) one pass, b) two passes, c) four passes, d) four passes with direction change

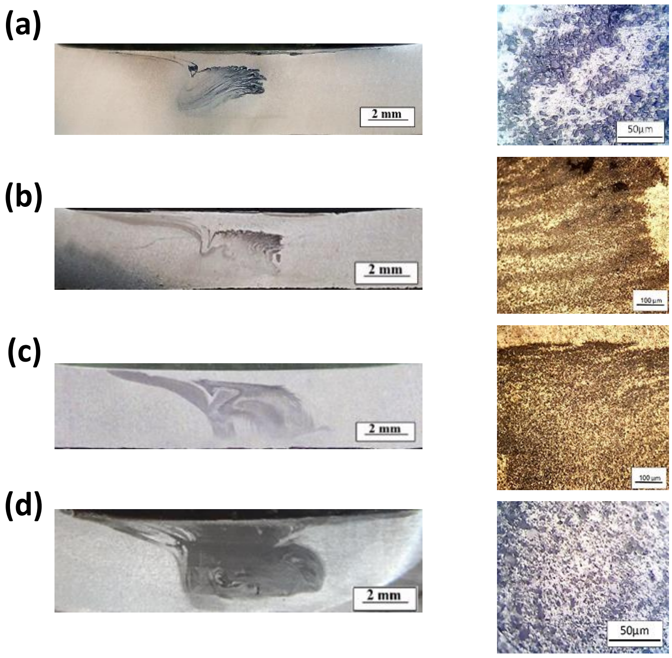


Fig. 9. Macro and micro images of FSPed sample fabricated with hexagonal pin profile at a) one pass, b) two passes, c) four passes, d) four passes with direction change

Macroscopic and microscopic images of workpieces fabricated by triflate pin profile are shown in Figure 10. The particle distribution of the FSPed sample fabricated with one pass is much better than circular, triangular, square pin profiles. The distribution of particles in the SZ in the FSPed sample fabricated by two passes is almost uniform. Moreover, increasing pass number or changing rotational direction has less impact on particle distribution than other pin profiles. By changing tool rotational direction between passes or increasing passes from two to four, the particle distribution does not improve significantly. As a result, compared to hexagonal pin profile, using triflate pin leads to achieving uniform particle distribution at lower passes, leading to savings in time and cost.

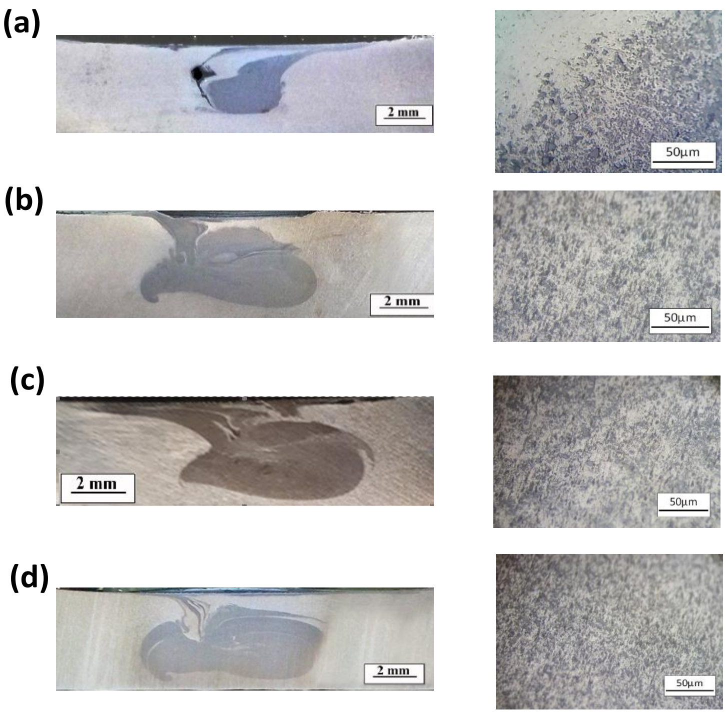


Fig .10. Macro and micro images of FSPed sample fabricated with triflate pin profile at a) one pass, b) two passes, c) four passes, d) four passes with direction change

Macroscopic and microscopic images of the workpieces produced by the threaded pin profile are shown in Figure 11. As shown from the table, excellent particle distribution is achieved by using a threaded pin profile. The patterns of material flow caused by threaded pin profiles are simulated numerically to consider the particle distribution pattern in the aluminum matrix (Figure 12). As can be seen from this figure, the particles, in addition to rotating around the pin, also experience vertical motion due to the presence of a thread in the pin. This vertical motion eliminates the difference in the number of particles distributed in the different layers of the composite .Moreover, the threads of the tool also crush the reinforcing particles, making them more refined and preventing them from accumulating [13, 19, 20].

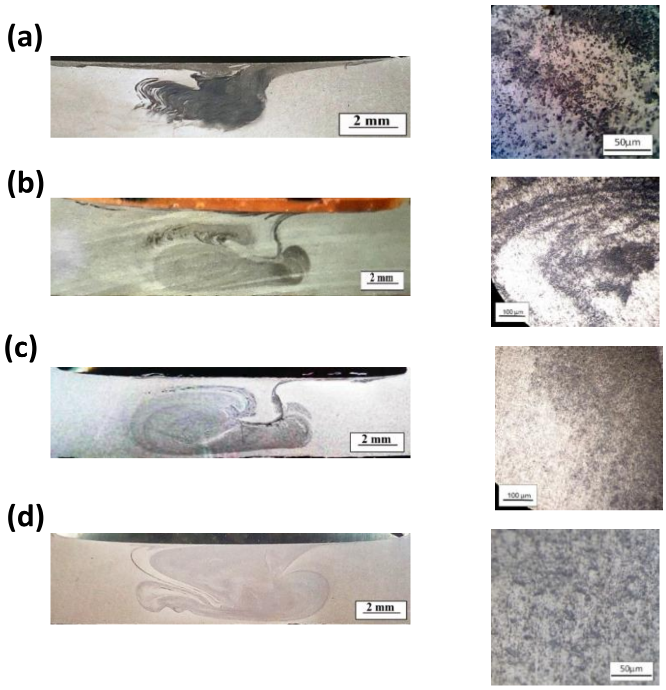


Fig. 11. Macro and micro images of FSPed sample fabricated with hexagonal pin profile at a) one pass, b) two passes, c) four passes, d) four passes with direction change

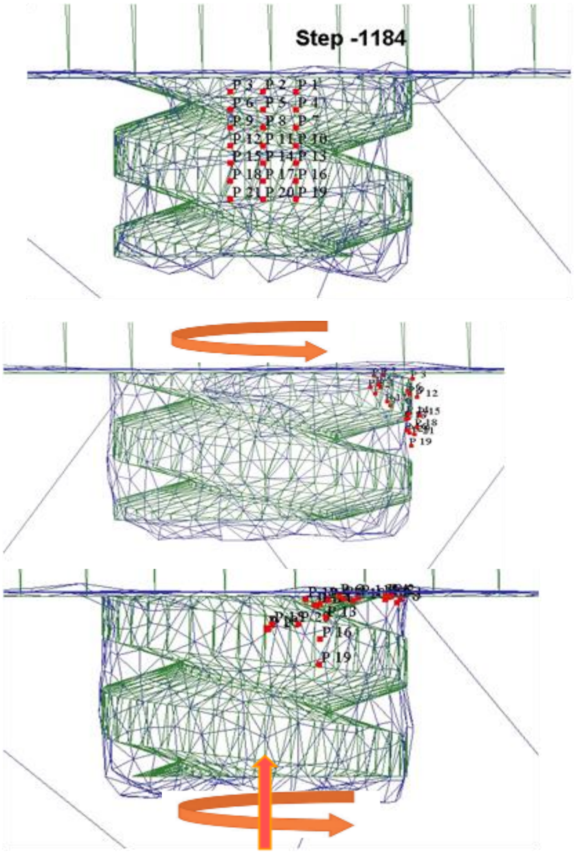


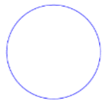
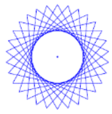
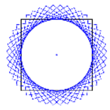
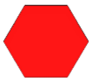
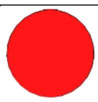
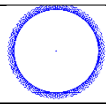
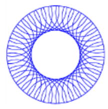
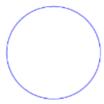
Fig. 12. the material flow during FSP using threaded pin profile

Tool pin profiles with flat faces, including triangular, hexagonal, square, and triflate pin profiles, are associated with eccentricity, which is defined as the ratio of the dynamic volume swept by the tool to its static volume. This ratio equal to 1, 2.41, 1.2, and 1.5 for triangular, hexagonal, square, and triflate, respectively (see Table 4), determines the direction of plasticized material flow from the advancing to the retreating side of the tool. In addition, the eccentricity of the pin shape is associated with dynamic orbit. The dynamic orbits of all pin profiles utilized in this study are demonstrated in Table 4. The pin profiles with flat faces produce a pulsating stirring action in the flowing material because of flat faces. As shown from the table, triangular, hexagonal, square, and triflate pin profiles produce 62.5, 125, 83.3, and 125 pulses/s when the tool rotates at a speed of 1250 rpm (Table 4). There is no such pulsating action in the case of cylindrical profiles. It illustrates that the pulsation effect of the hexagonal pin is severe than the square and the number of pulses generated by the hexagonal pin is 50% more than the square pin; however, the rotating arm is bigger for the square pin. As illustrated before, particle distribution in the FSPed sample fabricated with hexagonal pin profile is more uniform than square pin profile. This may show that the pulsation effect of the pin is dominated factor in distributing particles.

Moreover, the triflate pin profile has a higher dynamic to static ratio than the hexagonal pin profile, and the number of pulses made by both pin profiles is the same. Therefore, as stated before, FSPed fabricated with triflate pin profile could distribute particles uniformly at lower passes that may be due to higher dynamic to static ratio amount of triflate pin profile. As a result, in a pin with flat surfaces, two critical parameters influence the distribution of particles in the matrix (a) first, the pulsation effect of the tool is the most influential parameter, and (b) dynamic to static ratio.

As illustrated from the previous section, hexagonal, triflate, and threaded pin profiles are appropriate for distributing particles in the metal matrix by two different mechanisms. Comparing the threaded and hexagonal pin shapes, the revolving arm in the hexagonal pin is much bigger and is planer rather than threaded. However, it should be noticed that fine threads on a small scale cause higher material flow in the threaded pin. As a result, well particle distribution in metal matrix fabricated by the hexagonal and triflate pin is due to the pulsing effect of the flat surface, where the distribution of particles in metal matrix fabricated bay threaded pin profile is due to vertical motion generated by this pin profile.

Table 4. Impact of tool pin profile on perturbation area

Pin profile	Static Area (mm^2)	Area Occupied by the Pin in Dynamic Condition	Dynamic Area (mm^2)	Dynamic/ Static	The portion of Dynamic Orbit	No. of pulses per second
	28.27		28.27	1		-
	11.7		28.27	2.41		62.5
	17.98		28.27	1.57		83.5
	23.38		28.27	1.2		125
	18.8		28.27	1.5		125
	25.5		28.27	1.1		-

5. Conclusion

In this research, the effect of pin shape on the distribution of reinforcing particles within the base metal during the production of composites by the FSP method is investigated. First, some experiments were performed to find the optimal parameters of rotational speed, traverse speed, and tilt angle. The results showed that 3-degree tilt angle, 1250 rpm rotational speed, and 100 mm/min linear speed could produce perfect samples. The results showed that the cylindrical tool was not able to distribute the particles evenly even after the fourth pass of the process. The square and triangular tools showed better powder distribution than the circular tools due to the edge surfaces of the pins. The triflate tool distributes the particle process evenly in the first and second passes, and this distribution does not improve much as the number of passes increases. Hexagonal and threaded tools in the fourth pass of the process evenly distribute the particles in the base metal. The distribution of particles using threaded and hexagonal tools in the fourth pass was better than the triflate tool, although the edge tool in the second pass compared to other tools after two passes had the best distribution process.

References

[1] N. Kumar Maurya, M. Maurya, A.K. Srivastava, S.P. Dwivedi, A. kumar, S. Chauhan, "Investigation of mechanical properties of al 6061/sic composite prepared through stir casting technique", Materials Today: Proceedings, Vol. 25, No. 2020, pp. 755-758.

[2] N.K. Chandla, Yashpal, S. Kant, M.M. Goud, C.S. Jawalkar, "Experimental analysis and mechanical characterization of al 6061/alumina/bagasse ash hybrid reinforced metal matrix composite using vacuum-assisted stir casting method", Journal of Composite Materials, Vol. 54, No. 27, 2020, pp. 4283-4297.

[3] Z.Y.M. R.S. Mishra , I. Charit, "Friction stir processing: A novel technique for fabrication of surface composite", Materials Science and Engineering, Vol. A341, No. 2003, pp. 307-310.

[4] R.S. Mishra, Z.Y. Ma, "Friction stir welding and processing", Materials Science and Engineering: R: Reports, Vol. 50, No. 1–2, 2005, pp. 1-78.

[5] M. Akbari, P. Asadi, R.A. Behnagh, "Modeling of material flow in dissimilar friction stir lap welding of aluminum and brass using coupled eulerian and lagrangian method", The International Journal of Advanced Manufacturing Technology, Vol. 113, No. 3, 2021, pp. 721-734.

[6] M.H. Shojaeefard, M. Akbari, P. Asadi, A.

Khalkhali, "The effect of reinforcement type on the microstructure, mechanical properties, and wear resistance of a356 matrix composites produced by fsp", The International Journal of Advanced Manufacturing Technology, Vol. No. 2016, pp. 1-17.
[7] K. Elangovan, V. Balasubramanian, "Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in aa6061 aluminium alloy", Materials & Design, Vol. 29, No. 2, 2008, pp. 362-373.
[8] H. Khodaverdizadeh, A. Heidarzadeh, T. Saeid, "Effect of tool pin profile on microstructure and mechanical properties of friction stir welded pure copper joints", Materials & Design, Vol. 45, No. 0, 2013, pp. 265-270.
[9] G. Faraji, O. Dastani, S.A. Mousavi, "Effect of process parameters on microstructure and micro-hardness of az91/al2o3 surface composite produced by fsp", J. of Materi Eng and Perform, Vol. 20, No. 9, 2011, pp. 1583-1590.
[10] M. Azizieh, A.H. Kokabi, P. Abachi, "Effect of rotational speed and probe profile on microstructure and hardness of az31/al2o3 nanocomposites fabricated by friction stir processing", Materials & Design, Vol. 32, No. 4, 2011, pp. 2034-2041.
[11] Y.-h. Zhao, S.-b. Lin, L. Wu, F.-x. Qu, "The influence of pin geometry on bonding and mechanical properties in friction stir weld 2014 al alloy", Materials Letters, Vol. 59, No. 23, 2005, pp. 2948-2952.
[12] V.M. Khojastehnezhad, H.H. Pourasl, A. Bahrami, "Estimation of mechanical properties of friction stir processed al 6061/al2o3-tib2 hybrid metal matrix composite layer via artificial neural network and response surface methodology", Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, Vol. No. 2021, pp. 14644207211034527.
[13] M. Akbari, M.H. Shojaeefard, P. Asadi, A. Khalkhali, "Wear performance of a356 matrix composites reinforced with different types of reinforcing particles", J. of Materi Eng and Perform, Vol. 26, No. 9, 2017, pp. 4297-4310.
[14] M. Akbari, P. Asadi, "Dissimilar friction stir lap welding of aluminum to brass: Modeling of material mixing using coupled eulerian–lagrangian method with experimental verifications", Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, Vol. 234, No. 8, 2020, pp. 1117-1128.
[15] G. Buffa, J. Hua, R. Shivpuri, L. Fratini, "A continuum based fem model for friction stir welding—model development", Materials Science and Engineering: A, Vol. 419, No. 1–2, 2006, pp. 389-396.
[16] G. Buffa, J. Hua, R. Shivpuri, L. Fratini, "Design of the friction stir welding tool using the continuum based fem model", Materials Science and Engineering: A, Vol. 419, No. 1–2, 2006, pp. 381-388.
[17] P. Chauhan, R. Jain, S.K. Pal, S.B. Singh, "Modeling of defects in friction stir welding using coupled eulerian and lagrangian method", Journal of Manufacturing Processes, Vol. 34, No. 2018, pp. 158-166.
[18] N. Dialami, M. Cervera, M. Chiumenti, Effect of the tool tilt angle on the heat generation and the material flow in friction stir welding, ed., 2019,
[19] M. Akbari, M.H. Shojaeefard, P. Asadi, A. Khalkhali, "Hybrid multi-objective optimization of microstructural and mechanical properties of b4c/a356 composites fabricated by fsp using topsis and modified nsga-ii", Transactions of Nonferrous Metals Society of China, Vol. 27, No. 11, 2017, pp. 2317-2333.
[20] M. Akbari, M.H. Shojaeefard, P. Asadi, A. Khalkhali, "Wear and mechanical properties of surface hybrid metal matrix composites on al–si aluminum alloys fabricated by friction stir processing", Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, Vol. 233, No. 5, 2017, pp. 790-799.