Vol. 03, Iss. 3 (2025) 361-369, DOI: 10.61552/JME.2025.03.012

Journal of Materials and Engineering

www.jme.aspur.rs

Research article

Applications of Nanoparticle to the Nugget Zone in Frication Stir Welding Process for Preparation of Surface Nanocomposite

Ragunam Chandana[a,*], K. Saraswathamma[a]

[a]*Department of Mechanical Engineering, Osmania University, Hyderabad, Telangana, India.*

Keywords:

Surface nanocomposite
Friction stir welding
Nanoparticle
Strength
Turning process

* Corresponding author:

Ragunam Chandana
Email:
chandanasatishbabu@gmail.com

Received: 20 November 2024
Revised: 20 December 2024
Accepted: 16 January 2025

A B S T R A C T

Nano particles are used to enhance the strength of the surface when mixed with appropriate ratio. In this work, metal matrix based surface nanocomposite is attempted through Friction stir welding (FSW) process. FSW is a type of solid-state welding process does not involve any chemical reaction, melting, secondary phase formation and also microstructure-controlled welding process. FSW process is performed on AA 2024 and AA 7075 aluminum alloys when filled with nano Al2O3 in the nugget zone. In this regard, micro hole is introduced before welding on the nugget zone for filling of nanoparticle addition. Process parameters considered are weight % of nanoparticle, tool rotation speed, and welding speed. Response parameters considered are tensile strength and bending strength. Taguchi L9 experimental steps are followed to perform the experiments. The result of the experiment is realized that surface nanocomposite is developed by varying the weight percentage of nanoparticle to the welding zone. The result of the experiment is understood that nanopowder addition is used to enhance the strength. The better strength is noticed with 2% nano particle due to proper stir action and material mixing. Process parameters are significantly influence the strength of the welded sample. FSW process is easiest method to produce surface nanocomposite with better strength.

1. INTRODUCTION

Metal matrix composite is category of light weight material in which matrix are light weight metal such as aluminum and magnesium are used. Reinforcement particles are namely alumina; silicon carbide and boron nitride are dispersed uniformly. MMC can be manufactured using stir casting method [1-5]. In this research, the focus of MMC manufacturing through friction stir welding process by introducing reinforcement with different weight ratio in the welding zone. Solid-state welding methods involve the fusion of surfaces in a thermoplastic state, which is created from the frictional heat either between the surfaces or by an external tool. FSW employs a rotating tool that traverses the joint, heating and forging the metals. As the tool start to rotate and moves in the length of the joint, it induces heat and get material soften, effectively blending them and removing the interface. FSW is one of the solid-state welding processes in which sufficient heat is generated due to string action of tool and followed by induced local heat intensity. It uses non consumable based tool and contains shoulder and pin. The shoulder and pin of the tool are main parameter for generation of sufficient heat and appropriate metal flow [6-11].

Joining of aluminum alloy is widely used in aerospace, automobile and marine industries due to its significant properties like corrosion resistance, and high strength to weight ratio. Conventional welding on aluminum alloy has different issues like poor weldability, solidification-based crack and porosity. It has significant advantages like no melting, unwanted secondary phase formation and no chemical reaction. To eliminate this issue solid state welding is attempted by various researchers [12, 13].

The tools used in FSW play a crucial function in the efficiency of weld joint. They are specifically designed to withstand the high temperatures and mechanical stresses. The choice of FSW tool type is directly influencing the welding process's outcome, including weld quality, mechanical properties, and suitability of different material combinations. Each tool type offers unique advantages, making them essential elements in achieving high-quality and reliable friction stir welds [14, 15].

The incorporation of nanoparticles in the nugget zone of FSW holds significant importance due to several advantageous effects it can impart to the welded joint. Nanoparticles, often added as reinforcement materials, it enhance the strength of the weld. They act as strengthening agents, effectively reinforcing the microstructure of the weld and reducing defects such as voids and porosity. Moreover, nanoparticles are used to refine the grain structure of the weld, and increased resistance to fatigue and crack propagation. This refinement is particularly beneficial to improve high strength and durability of joint [16-19].

2. LITERATURE REVIEW

Nikhil and Govindan [20] et al. utilized FSW process to execute dissimilar aluminum alloy welding. The mechanical strength was estimated by varying the process parameters. Response Surface Method (RSM) idea was used to estimate the best combination of process parameters. The result indicated that RSM idea was significant for prediction the optimum combination of process parameters. Predicted optimized results were improved the performance of welded joint. Zhou et al. [21] investigated that serrated joint width effect in FSW process for joining of dissimilar metals of AA 2024 and AA 7075. In their work, strength and microstructure performance after FSW were investigated. The widths of joint were changed and investigated their performance. The result indicated that enhanced mechanical strength was noticed with increase of serrated joint width in FSW process. Gebreamlak et al. [22] executed that dissimilar metal (AA 2024 and AA 7075) welding embedded with nano powder in the welding zone. In their research, RSM was used to analysis the experimentation. Mechanical strength and microstructure analysis were investigated. The result pointed out that enhanced strength and microstructure refinement after nano powder reinforcement in the welded samples. Mouria et al. [23] investigated about FSW process by included nano particle in the nugget zone. The nano particles considered were SiC and TiO_2. The result of the experiment was noticed that mechanical strength and hardness were improved with the incorporating of nano particle.

Thimmaraju et al. [24] conducted FSW process on Al 6082 alloy using different tool pin profiles. In their study, mechanical strength and microstructure analysis were investigated. Triangle, square and hexagonal type pin profiles were considered. The result of experiment was indicated that hexagonal type pin profile performed better than other profile considered. Gopi and Mohan [25] investigated the effect of about tool pin profiles on mechanical strength in FSW processed Al 6082 alloy. The result revealed that tool pin profile was influenced appreciably. Mohammed and Birru [26] performed FSW process on Al6082. Nano particle Al_2O_3 was incorporated in the welding zone. Experiments were designed with different tool rotational speed, traverse feed and hexagonal tool profile.

Two and three weld passes were executed. The result discovered that three weld pass was performed better than two pass.

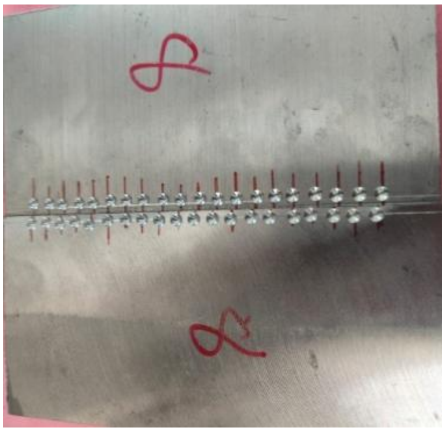
Singh et al. [27] developed aluminum-based nanocomposite using FSW by adding nano alumina while welding process. The result revealed that heat affected zone with restricted growth of granular and refinement of microstructure due to addition of nano particle in the nugget zone. Singh et al. [28] used two different types of nanoparticles such as Al2O3 and TiO2 in FSW process. The result showed that welded surface was smooth, higher hardness and better grain structure with the addition of Al2O3 nano particle. Bodaghi and Dehghani [29] used FSW process and added SiC nano particle to the nugget zone. Process parameters effect on response and its optimization were investigated. The result was pointed out that refined microstructure as well as improper distribution of nano particle in the welded samples. Bahrami et al. [30] developed a metal matrix composite with the help of SiC nanoparticle addition to the welding zone during FSW process. The result showed that increased tensile strength of FSW samples 31% to 76% due to nano particle addition.

From the literature, it is realized that joining of aluminum using conventional welding method called fusion welding may leads to defects, gases, porosity and cracking while solidification. Also, joining of aluminum with matrix elements through fusion welding method leads to segregation of particles. FSW is one of the suitable solutions to avoid such a issue. Mechanical properties of the FSW joint can be enhanced through by adding reinforced particle to the joint. Friction stir welding of dissimilar metal is greater challenge due to chemical composition, melting, and thermal expansion. These dissimilar joints are most requirement in different filed such as light combat aircraft, submarine vehicle and bridge layer tank. Tool pin profile is influencing the contact area, material mixing, heat generation, flow of material and pulsating action. Process parameters are also significantly influencing the strength of the welded joints. Hence, the effort towards to estimate the better strength through applying optimum process parameters in the addition of nanoparticles environment.

3. EXPERIMENTAL SETUP

Dissimilar material joining is used to achieve combined advantages of both base materials. It is currently used in aircraft, defense, military and automotive field. The dissimilar grade of AA 2024 and AA 7075 aluminum alloys are considered in this project [20-23]. The dimension of 150 mm length, breadth 50 mm and thickness of 4 mm used as dimension of raw materials. Power hacksaw is used to cut the required dimension from raw materials. Before FSW process, raw material is cleaned to eliminate rust and dirt. Geometry of tool pin is significantly played a role in material mixing and flow during FSW. Tool material is used as H13 tool steel. Chromium rich based hot tool steel is classified into H steel category. H13 steel is categorized into high chromium-based steel which has good toughness properties as well as fatigue resistance. It is widely preferred where the requirement of higher durability of more temperature environment. The major process parameters of the FSW considered are % weight of nano particle, tool rotational speed and welding speed. Tool pin shape considered is hexagonal shape. Taguchi method is a unique method to plan, analyze and investigate the process parameters effect. Taguchi L9 is a standard experimental design to perform with minimum number of experiments with more interaction [31-33]. Computer based vertical CNC machine is utilized to execute the FSW process Figure 1 a-d shows the experimental facilities used.

(a) Tool pin profile with hexagonal shape



(b) Work piece for FSW process with micro drilling

(c) Vertical Machining Centre

(d) FSW samples

Fig. 1 a-d Testing facilities.

Nano particle Al2O3 is added before in the region of welding to be carried out. Nano particle Al2O3 possesses better hardness, mechanical strength and wears resistance. Based on literature and trial experiments 2 wt%, 3wt % and 4wt% of Al2O3 is added in the micro hole. In this regard micro holes (200 μm) are performed using drilling process. Figure 2 shows SEM image of nano Al2O3.

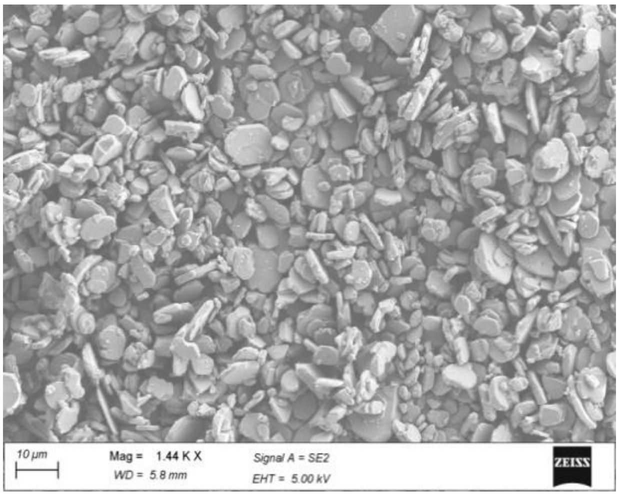


Fig. 2. SEM image of Al2O3.

Response parameters are outcome of the experiments performed. It is also called quality of weld obtained. In this work two responses are considered. Responses considered are tensile strength and bending strength. After FSW, Wire cut Electric Discharge Machine (WEDM) is used to preparation of sample for tensile strength and bending strength. ASTM E8-04 is adopted to prepare the sample and followed by testing. Figure 3 represents WEDM setup. Ultimate Tensile testing Machine (UTM) is used to carry out tensile strength of FSW samples. Figure 4 a-b shows the UTM setup. Table 1 and 2 shows the process parameters and experimental results. Figure 5 and 6 show the sample prepared for testing and tested samples.

Table 1. Process parameters.

Parameters	Level 1	Level 2	Level 2
% weight of nano particle	2%	3%	4%
Tool rotational speed in rpm	550	750	950
Welding speed mm/min	30	40	50

Table 2. Experimental results.

Sl.No.	% weight of nano particle	Tool rotational speed in rpm	Welding speed mm/min	Tensile strength	Bending strength
1	2	650	30	253	305
2	2	750	40	261	311
3	2	850	50	268	318
4	3	650	40	274	314
5	3	750	50	281	320
6	3	850	30	289	331
7	4	650	50	228	285
8	4	750	30	233	293
9	4	850	40	241	301

Fig. 3. WEDM setup.

Fig. 4 Testing Facilities (Universal Testing Machine and Bending strength).

Tensile test Bending test

Fig. 5. Samples for testing.

Tensile test Bending test

Fig. 6. Tested samples.

4. RESULTS AND DISCUSSION

In this work, metal matrix-based surface nano composite is developed using FSW process Figure 5 and 6 show the main effect plot of input parameters on output parameters. The result of experiments is indicated that tensile strength with higher value from hexagonal profile of tool pin, low value of rotational speed and low value of welding speed. Weld quality is an important characteristic after FSW process. Tool material is used as H13 tool steel which has higher hot hardness and resist crack due to fatigue. It will be better whenever heat and cooling are involved in cyclic type. Profile of the tool pin is appreciably 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 in the tunnel effect is called as thermomechanical effect. It also provides higher rubbing action and adequate material flow. Hexagonal profile is lead to high contact area during FSW which is used to obtain better tensile strength. This is because of sufficient heat generation and material flow using hexagonal tool pin. It is also called pulsating action which is better with hexagonal profile.

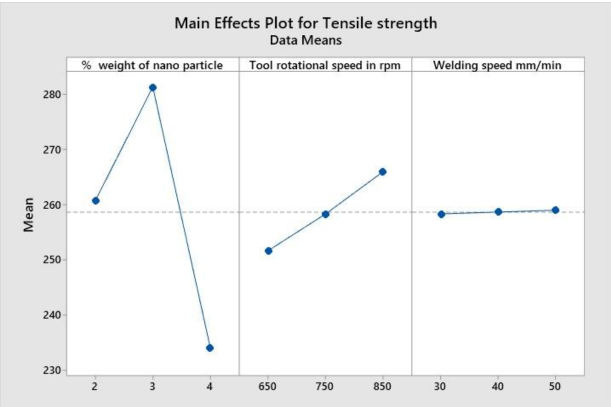


Fig. 5. Main effect plot for tensile strength.

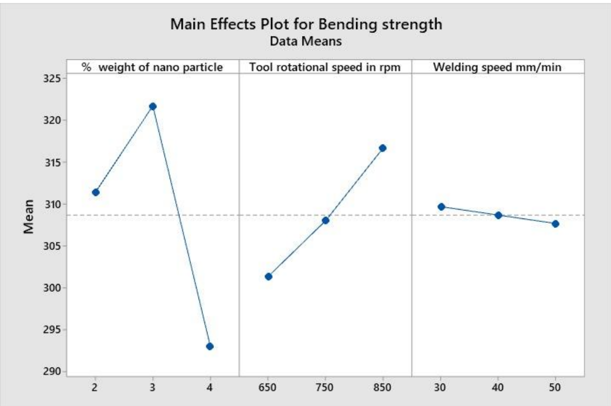
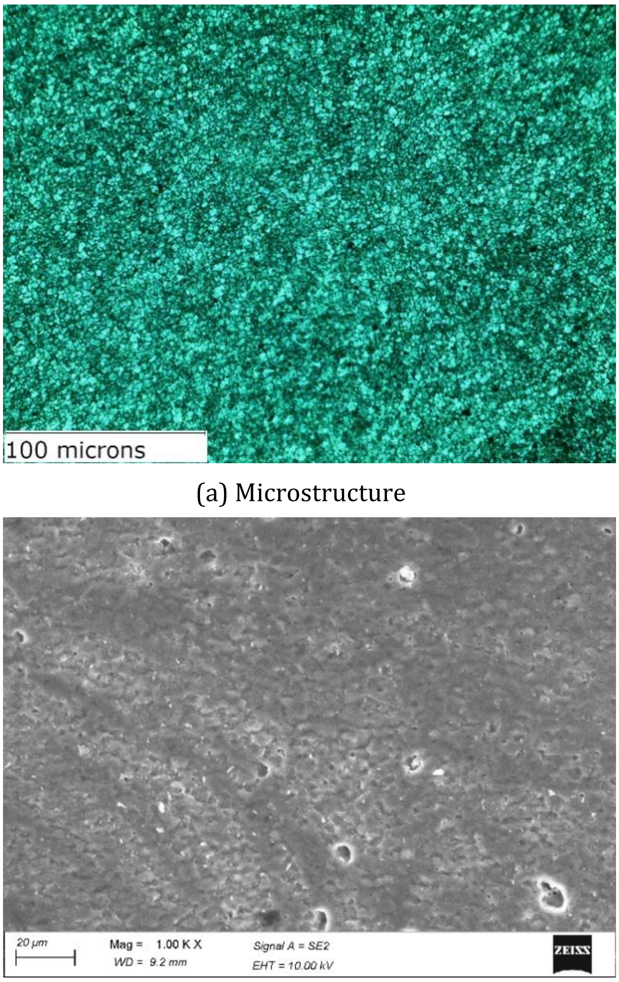


Fig. 6. Main effect plot for bending strength.

Stirring action is playing a significant role in FSW process. 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. Figure 7 a-b shows the microstructure image with fine grained microstructure as well as equiaxed material flow at better strength condition. Dynamic re-crystallization is called as 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 indication of quality and defect free weld. The result revealed that appropriate heat, proper mixing of flow and followed by quality weld using nano Al2O3 addition in the weld zone.



(a) Microstructure

(b) SEM image

Fig. 7. a-b Microstructure and SEM image.

Surface nano composite is developed using FSW process by introducing nano Al2O3 to the welding zone. The percentage of nano Al2O3 is significantly influenced the strength of the FSW samples. It is understood the result FSW welded joint in terms of strength. The result of the welded joint in terms of strength and hardness are better due to the process parameters as well as addition of reinforcement. Addition of reinforcement with higher percentage (4%weight) leads to brittleness and reduction of hardness. The low value (2%weight) and medium value (3%weight) of nano powder addition is used to increase the strength and hardness. Higher value of nano powder addition is noticed with lesser strength reduction and hardness.

5. CONCLUSIONS

- Surface nano composite is developed using friction stir welding on dissimilar material. VMC is used for performing the experiments. Results are analyzed with the help of main effect plot.
- Tool pin profile is influenced the mechanical performance of welding strength. The result revealed that mechanical performance is influenced by area of contact, effective material mixing flow and strength. It is understood that tool pin profile is influenced significantly which is induced sufficient heat generation and material flow during FSW process. It is realized that profile of tool pin is played a significant role in heat generation in sufficient quantity, microstructure of fine grain refinement, flow of material, pulsating action and inter metallic bond thickness.
- Micro holes are introduced using drilling process in the welding zone and filled with nano powder before welding. FSW process is conducted using addition of Al2O3 nano particle. The result revealed that nano particle addition is enhanced the mechanical strength.
- The result of the 2 % weight variation of nano powder to the welding zone is significantly improved the strength and hardness.
- The result of tensile strength (234 N/mm2) and micro hardness (261VHN) are enhanced with nano powder addition. The corresponding input parameters are of tool rotational speed (600 rpm) and medium welding speed (40 mm/min) with hexagonal tool pin profile. Low range of tool rotational speed and welding speed are given better strength and hardness of welded sample.
- Microstructure and SEM images of FSW sample with nano particle incorporated are shown fine grained.
- FSW with the different tool pin profile, nano powder effect, nano powder size effect, raw material and other optimization tools are the future work directed from this work.

Acknowledgement

The authors would like to thank Department of Mechanical Engineering, Vignan Institute of Technology and Science, Hyderabad, Telangana for provided the Vertical Machining Centre (AICTE-MODROB-Ref No: F.No: 9-226/IDC/MODROB/Policy-1/2019-20) to perform experiments.

REFERENCES

[1] S. Devaraj, R. Malkapuram, and B. Singaravel, “Performance analysis of micro textured cutting insert design parameters on machining of Al-MMC in turning process,” *Int. J. Lightweight Mater. Manuf.*, vol. 4, no. 2, pp. 210–217, 2021, doi: 10.1016/j.ijlmm.2020.11.003.

[2] D. Sandiri, R. Malkapuram, and S. Balasubramaniyan, “Experimental investigation of textured inserts on machining performance of Al-MMC using Taguchi method,” *Tribol. Ind.*, vol. 44, no. 1, p. 54, 2022, doi: 10.24874/ti.1019.12.20.04.

[3] C. H. Saikrupa, G. C. Reddy, and S. Venkatesh, “Experimental investigation of cutting conditions in turning of Al-MMC,” *Mater. Today Proc.*, vol. 76, pp. 488–494, 2023, doi: 10.1016/j.matpr.2022.11.154.

[4] S. A. Khan, S. Poria, and P. Sahoo, “Machining characteristics of stir-cast Al-TiB2 composites in dry turning,” *Int. J. Metalcast.*, vol. 18, no. 1, pp. 835–855, 2024, doi: 10.1007/s13369-024-08885-y.

[5] S. Devaraj, R. Malkapuram, and B. Singaravel, “Application of TOPSIS method for prediction of optimum design parameters of micro hole textured cutting inserts in turning of Al-MMC,” *Int. J. Veh. Struct. Syst.*, vol. 13, no. 4, pp. 471–476, 2021, doi: 10.4273/ijvss.13.4.15.

[6] B. Singaravel, T. Niranjan, K. Deepa, C. Anusha, and M. M. Reddy, “Application of Taguchi Coupled With Overall Evolution Criteria In Friction Stir Welding Process for Process Parameters Optimization,” in *Optimization of Advanced Manufacturing Processes*, Apple Academic Press, 2024, pp. 153–165, doi: 10.1201/9781003487128-9.

[7] T. Niranjan, B. Singaravel, B. Chakradhar, and S. S. Raju, “Process parameter optimization in friction stir welding process using Taguchi method,” *Mater. Today Proc.*, 2024, doi: 10.1016/j.matpr.2023.04.426.

[8] B. Singaravel, B. Chakradhar, D. S. Rajan, and A. K. Kumar, “Optimization of friction stir welding process parameters using MCDM method,” *Mater. Today Proc.*, vol. 76, pp. 597–601, 2023, doi: 10.1016/j.matpr.2022.12.095.

[9] M. M. Patel and V. J. Badheka, “A review on friction stir welding (FSW) process for dissimilar aluminium to steel metal systems,” *Weld. Int.*, vol. 38, no. 2, pp. 91–115, 2024, doi: 10.5772/intechopen.1004831.

[10] R. Kesharwani, K. K. Jha, M. Imam, C. Sarkar, and I. Barsoum, “Comparison of microstructural, texture and mechanical properties of SiC and Zn particle reinforced FSW 6061-T6 aluminium alloy,” *J. Mater. Res. Technol.*, vol. 26, pp. 3301–3321, 2023, doi: 10.1016/j.jmrt.2023.08.161.

[11] K. Harachai and S. Prasomthong, “Investigation of the optimal parameters for butt joints in a friction stir welding (FSW) process with dissimilar aluminium alloys,” *Mater. Res. Express*, vol. 10, no. 2, 026514, Feb. 2023, doi: 10.1088/2053-1591/acbb54.

[12] R. P. Verma, K. N. Pandey, K. András, R. Khargotra, and T. Singh, “Difficulties and redressal in joining of aluminium alloys by GMA and GTA welding: A review,” *J. Mater. Res. Technol.*, vol. 23, pp. 2576–2586, 2023, doi: 10.1016/j.jmrt.2023.01.183.

[13] K. N. Uday and G. Rajamurugan, “Influence of process parameters and its effects on friction stir welding of dissimilar aluminium alloy and its composites–a review,” *J. Adhes. Sci. Technol.*, vol. 37, no. 5, pp. 767–800, 2023, doi: 10.1080/01694243.2022.2053348.

[14] S. R. Nathan, V. Balasubramanian, A. Gourav Rao, T. Sonar, M. Ivanov, and C. Rajendran, “Influence of tool plunging rate on mechanical properties and microstructure of friction stir welded DMR249A high strength low alloy (HSLA) steel butt joints,” *Mater. Test.*, vol. 65, no. 10, pp. 1528–1538, 2023, doi: 10.1515/mt-2023-0043.

[15] K. Elangovan, V. Balasubramanian, and M. Valliappan, “Effect of tool pin profile and tool rotational speed on mechanical properties of friction stir welded AA6061 aluminium alloy,” *Mater. Manuf. Processes*, vol. 23, no. 3, pp. 251–260, 2008, doi: 10.1080/10426910701860723.

[16] B. Rahmatian, K. Dehghani, and S. E. Mirsalehi, “Effect of adding SiC nanoparticles to nugget zone of thick AA5083 aluminium alloy joined by using double-sided friction stir welding,” *J. Manuf. Processes*, vol. 52, pp. 152–164, 2020, doi: 10.1016/j.jmapro.2020.01.046.

[17] T. A. Shehabeldeen, N. M. El-Shafai, I. M. El-Mehasseb, Y. Yin, X. Ji, X. Shen, and J. Zhou, “Improvement of microstructure and mechanical properties of dissimilar friction stir welded aluminum/titanium joints via aluminum oxide nanopowder,” *Vacuum*, vol. 188, p. 110216, 2021, doi: 10.1016/j.vacuum.2021.110216.

[18] M. Bodaghi and K. Dehghani, “Friction stir welding of AA5052: the effects of SiC nano-particles addition,” *Int. J. Adv. Manuf. Technol.*, vol. 88, pp. 2651–2660, 2017, doi: 10.1007/s00170-016-8959-8.

[19] C. Vimalraj and P. Kah, “Experimental review on friction stir welding of aluminium alloys with nanoparticles,” *Metals*, vol. 11, no. 3, p. 390, 2021, doi: 10.3390/met11030390.

[20] B. Nikhil and P. Govindan, “Effect of tool probe geometry on the material flow and mechanical behaviour of dissimilar AA2024/AA7075 friction stir welded joints,” *Int. J. Interact. Des. Manuf. (IJIDeM)*, pp. 1–20, 2024, doi: 10.1007/s12008-023-01717-7.

[21] Y. Zhou, Y. Deng, J. Zeng, Y. Ou, L. Hu, Z. Li, and B. Liu, “Effect mechanism of serrated joint design on microstructure and mechanical properties of AA2024 and AA7075 alloy friction stir welding,” *Int. J. Adv. Manuf. Technol.*, vol. 130, no. 1, pp. 459–473, 2024, doi: 10.21203/rs.3.rs-2772408/v1.

[22] G. Gebreamlak, S. Palani, B. Sirahbizu, and R. Čep, “Experimental investigation and optimization of nano Al_2O_3 mixed FSWed joint between AA2024-T351 and AA7075-T651 by response surface approach,” *Front. Mech. Eng.*, vol. 10, p. 1393088, 2024, doi: 10.3389/fmech.2024.1393088.

[23] P. K. Mouria, R. M. Singari, and R. Wattal, “Microstructural and mechanical response of SiC and TiO_2 particles reinforced friction stir welded AA7075 and AA2024,” *Int. J. Interact. Des. Manuf. (IJIDeM)*, pp. 1–13, 2023, doi: 10.1007/s12008-023-01667-0.

[24] P. Thimmaraju, K. Arkanti, G. C. Reddy, and K. B. G. Tilak, "Comparison of microstructure and mechanical properties of friction stir welding of Al 6082 aluminum alloy with different tool profiles," *Mater. Today: Proc.*, vol. 3, pp. 4173–4181, 2016, doi: 10.1016/j.matpr.2016.11.092.

[25] S. Gopi and D. G. Mohan, "Evaluating the welding pulses of various tool profiles in single-pass friction stir welding of 6082-T6 aluminium alloy," *J. Weld Join*, vol. 39, pp. 284–294, 2021, doi: 10.5781/JWJ.2021.39.3.7.

[26] S. Mohammed and A. K. Birru, "Friction stir welding of AA6082 thin aluminium alloy reinforced with Al_2O_3 nanoparticles," *Trans. Indian Ceram. Soc.*, vol. 78, pp. 137–145, 2019, doi: 10.1080/0371750X.2019.1635046.

[27] T. Singh, S. K. Tiwari, and D. K. Shukla, "Friction-stir welding of AA6061-T6: The effects of Al_2O_3 nano-particles addition," *Results Mater.*, vol. 1, p. 100005, 2019, doi: 10.1016/j.rinma.2019.100005.

[28] T. Singh, S. K. Tiwari, and D. K. Shukla, "Novel method of nanoparticle addition for friction stir welding of aluminium alloy," *Adv. Mater. Process. Technol.*, vol. 8, pp. 1160–1172, 2022, doi: 10.1080/2374068X.2020.1855397.

[29] M. Bodaghi and K. Dehghani, "Friction stir welding of AA5052: The effects of SiC nano-particles addition," *J. Adv. Manuf. Technol.*, vol. 88, pp. 2651–2660, 2017, doi: 10.1007/s00170-016-8959-8.

[30] M. Bahrami, M. F. Nikoo, and M. K. B. Givi, "Microstructural and mechanical behaviors of nano-SiC-reinforced AA7075-O FSW joints prepared through two passes," *Mater. Sci. Eng. A*, vol. 626, pp. 220–228, 2014, doi: 10.1016/j.msea.2014.12.009.

[31] C. Divya, L. Suvarna Raju, and B. Singaravel, "Experimental investigation on solid lubricant supply methodology in turning process," *Mater. Manuf. Processes*, vol. 36, no. 15, pp. 1781–1788, 2021, doi: 10.1080/10426914.2021.1945097.

[32] C. Divya, L. S. Raju, B. Singaravel, and T. Niranjan, "Performance investigation of micro hole textured cutting inserts on power consumption and its measuring methodology in turning process," *Alexandria Eng. J.*, vol. 61, no. 4, pp. 3125–3130, 2022, doi: 10.1016/j.aej.2021.08.043.

[33] C. Divya, L. S. Raju, and B. Singaravel, "Application of image processing for tool flank wear measurement and optimization using the Taguchi method," *Arab. J. Sci. Eng.*, pp. 1–9, 2024, doi: 10.3390/lubricants12030069.