Combined Impact of SiC/TiB$_2$ Nanoparticles in Friction Stir Welding of Different Aluminium Alloys

Kalaiselvan SP [1], Sriram Desikan [2], Ramesh babu R [3], Ramanathan K [4], S. Vijayakumar [5,], Sanjeev Kumar Shah[6], Varinder Singh [7]*

[1,2,3,4] Department of Mechanical Engineering, Indra Ganesan College of Engineering, Tamil Nadu.

[5] Department of Mechanical Engineering, Bonam Venkata Chalamayya Engineering College (Autonomous), Odalarevu, Andhra Pradesh 533210, India.

[6] Department of Electronics & Communication Engineering, Uttaranchal Institute of Technology, Uttaranchal University, Dehradun-248007, Uttarakhand, India.

[7] University School of Mechanical Engineering, Research & Incubation Centre, Rayat Bahra University, Chandigarh-Ropar NH 205, Greater Mohali, Punjab, 140103, India

Abstract. In this work, Friction Stir Welding process was done on the dissimilar alloys AA8014 and AA2024, with focus on analysing mechanical properties such as tensile strength (UTS), hardness (BHN), and wear rate (WRT). The influence of SiC/TiB2 nanoparticles, with Wt% ranging from 2 to 8 wt%, was examined on the mechanical properties. The rotational speed (RS) was changed from 1200 rpm to 1400 rpm, while the welding speed was kept at a constant 150 mm/min throughout the process. The results specified that an increase in RS to 1400 rpm, combined with 8 wt% , improved the ultimate UTS to 239.4 MPa. SEM examination of the fractured surface revealed that micro dimples were produced at this higher rotational speed. This phenomenon is attributed to the more intense stirring action at 1400 rpm, which leads to turbulent material flow in the stir zone. The resulting turbulence could cause uneven particle distribution and entrap air or other voids, contributing to the formation of micro dimples in the weld nugget.

Keywords: FSW, AL alloys, SiC/TiB2 nanoparticles, SEM analysis and mechanical properties

1. Introduction

The FSW process is a kind of solid-state joining technique that frequently combines multiple materials into one at temperature lower the melting point of the substrate material. The primary advantage of this solid-state process is that it eliminates the production of molten weld pools and solidification defects, in contrast to traditional welding methods like arc and gas welding, etc [1][2]. Suresh.S et.al studied the mechanical characteristics of FSW 6061-T6 Al ally enriched with SiC nanoparticle. Weld samples are generated both with and without the joint's incorporation. The joints' microhardness and lap shear strength are examined. A stereo zoom microscope is used to examine the fracture surfaces and the cross section of welds. Using SEM test, the microstructure as well as distribution of particles in the nugget zone are investigated. It is found that the weld qualities are greatly impacted by the grain size, which is in turn determined by the reinforcement of SiC nanoparticles. The sample containing 29% SiC exhibited the highest BHN of 93 HV and the supreme shear load 2650.5 N. it is determined that the chosen set of process parameters is sufficient to create sturdy Al/SiC composite joint [3].
Barmouz. M et.al[4] created Cu composites reinforced by 30 nm & 5 µm particles of SiC on the pure copper sheet. in the absence of SiC particles, results in a large increase in % elongation and a drop in copper strength. UTS and % elongation is reduced by the adding nano SiC particles. The UTS and resistance to wear are improved, the percent elongation is decreased, and the volume fraction is increased or the size of the reinforced particles is decreased.

Corresponding author: vijaysundarbe@gmail.com

Paidar.M et.al [5] studied FSW of 2024-T3 aluminium alloy. There was discussion on how the mechanical and metallurgical properties were affected by silicon carbide (SiC) nanoparticles. Investigations were also conducted into how particles affected wear and tensionshear tests. The procedure was carried out at a steady 1000 rpm rotational speed. The mechanical properties were significantly impacted by the accumulation of SiC nanoparticles to the weld during FSSW, according to the results. As barriers, nanoparticles actually stopped grain development in the Stir zone.

Sahoo.A.K et.al [6]examined SiC/Al2O3 friction stir welded joints made of AA1100. The results show that improving the mechanical characteristics of the friction stir welded joints is significantly influenced by the kind and amount of reinforcing. The mechanical characteristics of welded connections with enhanced friction-stir were contrasted with those of the base material & welded joint with reduced friction. The best outcomes were obtained with Al2O3 and SiC reinforced particles at 2% and 3%, respectively.

Experiments were carried out by Kim, S. et al. [7] examine the mechanical characteristics and microstructure of vibration-assisted μ-FSW with SiC nano-reinforcement addition. In order to minimise the welding time, four coin-type vibrators were used for the vibration-assisted μ-FSP on the material for the dispersion of reinforcement particles. Particle aggregation was limited to the presence of SiC nano-reinforcement. with vibration support, the SiC particle dispersion was uniform. Furthermore, the dispersion of SiC nano-reinforcement caused further dislocations in the plasticised material because of the aided vibration.

GRA was used to optimise process factors in the Al 7075/SiC composites, as discussed by V. Gosavi et al. [8].The objective of the experimental investigation was to examine and determine the most significant process variables, ranking them according to the percentage of each variable that affected the weld characteristics using GRA.With a percentage contribution of 50.83%, welding speed was shown to be the most influential factor for the current set of process variables based on optimised process variables acquired using GRA and ANOVA.

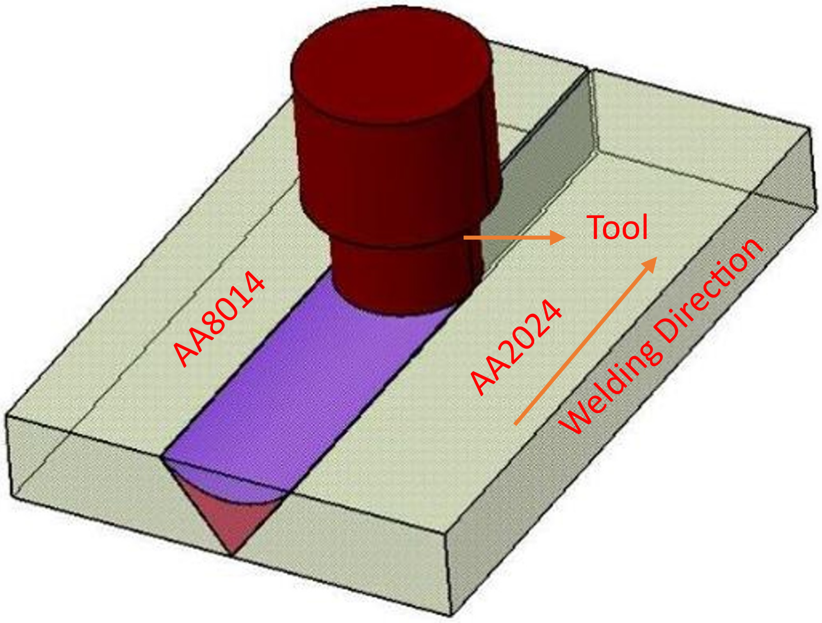
Hassanifard, S. et al. [9] assess the fatigue and tensile responses of aluminium 7075-T6 joints when Alumina particles are introduced into the NZ. The pre-existing small hole on the top of the bottom plates was filled with alumina particles, and the upper and lower plates were stacked on top of each other to create a localised composites in the disconcerted zone of the weld joints. Next, in the nonappearance of alumina particles, the tensile value of the localised composite zone were compared to those of the joints as-welded. The 1% Al2O3 particles in the stirred zone of the joints somewhat increased the UTS, and the composite joints' fatigue lifetimes were increased up to 2.5 times over their as-welded counterparts.
Adel Mahmood et al. [10]investigated the effects of the process parameters on the wear behaviour of an AMC/SiC particles. The results showed that the welding process variables' microstructural changes improve the BHN and wear properties of the welding zone and significantly affect the wear resistance of the joints.
Using a Taguchi L9-OA, experiments were directed with 3 mm AA3003/SiC plates, as reported by Sachin kumar et al.[11]. We chose three levels of process parameters. An analysis was conducted to determine how these process parameters affected the mechanical properties of joints. It also included an ANOVA investigation. According to the results, spindle speed, rather than welding speed or tool load, is the primary process parameter that influences the joint characteristics. A 3kN tool load, 90 mm/min of welding speed, and 1000 rpm spindle speed all resulted in improved joint strength.
Österreicher et al. [12]examined the effects of post heat treatments on the mechanical properties when friction stir welding Ti-6Al-4V and EN AW-7075 in a butt configuration. Tensile strengths were attained, which greatly above strength values reported in previous investigations, of 441 MPa at the welded condition and 505 MPa following heat treatment. Durable fracture was noted, and microscopic analysis revealed no signs of the development of brittle intermetallic phases. The findings indicate that FSW exhibits great potential as a dissimilar connecting material for use in upcoming aerospace applications.

2. Materials and methods

The material consists of aluminum alloy plate of grade AA8014/AA2024, extensively recognized for their high strength-to-weight ratio making them suitable for structural applications [13][14][15]. These plates were used in a butt joint for FSW experiments. Figure 1(a) presents a diagrammatic picture of the FSW setup, including the plates and the welding tool. The chemical composition of both alloys, detailed in Table 1 which contribute to its enhanced mechanical properties.

Table. 1. composition AA8014 and AA2024 alloys (in wt.%).

Material	Mn	Fe	Mg	Si	Zn	Ti	Cr	Al
AA8014	0.12	1.5	0.57	0.6	0.59	0.12	0.15	remaining
AA2024	0.6	0.45	1.1	0.35	0.15	0.43	0.18	remaining



The welding process was performed using FSW machine which provides the necessary force and precision for successful welding. A robust clamping system was essential to ensure the plates were securely fastened to the machine bed. Proper clamping is critical to withstand the axial and lateral forces generated during the FSW process, which could otherwise cause bending, misalignment, or instability in the plates.

To achieve uniform joints, it was critical to maintain alignments and prevent themovement during the welding operation. This ensured that the tool maintained consistent contact & penetration along the joint line, ensuing in a defect-free weld with superior mechanical properties. The clamping mechanism played a vital role in ensuring the weld qulaity, allowing for the accurate and reproducible results throughout the experiments [16].

3. Testing

As per ASTM-E8 standard, tensile test specimens were extracted using WEDM to confirm dimensional surface integrity. Tensile tests were conducted using UTM on FSW specimens, adhering strictly to the recommended strain rate and gauge length for consistent data on tensile strength and elongation [17]. For wear test, a Pin-On-Disc apparatus was employed to assess the wear rate of the samples. The specimens were machined to Ø16 mm × 38 mm dimension and cleaned them with acetone to remove any contaminants or debris before test. Their initial weights were accurately noted using an digital balance after the wear process. During the wear test, the sample was located in a pin holder and taken into contact with a rotating disc, 150 mm in diameter, which served as the counterface material. A constant normal load was applied while varying sliding speed and distance to investigate the wear characteristics. Brinell hardness measurements were performed to assess hardness variation along the cross-sections of the welded joints. BHN testing machine equipped with a 1.5 mm diameter indenter was employed, applying a 150 kgf of load. Multiple indentations were made across the weld nugget and base material to map the hardness distribution, which is crucial for understanding the localized mechanical properties and performance of the welded components under service conditions[18]

4. Result and Discussion

FSW was performed on AA8014 and AA2024 alloys, incorporating varying weight percentages (2 to 8wt%) of reinforcements (SiC/TiB_2) while maintaining a constant welding speed (150 mm/min) throughout the entire process. The rotational speed (RS) was varied (1200 rpm to 1400 rpm) to observe its influence on key mechanical properties.

The analysis of UTS, as illustrated in Figure 2, shows significant variation based on the rotational speed and reinforcement content. For a reinforcement weight percentage of 4 wt%, the UTS values increased with higher rotational speeds:

- At a RS of 1200 rpm and 8 wt% reinforcement, the UTS was recorded at 227.6 MPa, represented by the black line.
- When the RS was increased to 1300 rpm with the same 8 wt% reinforcement, the UTS improved to 234.6 MPa, depicted by the red line.
- Additional increasing the RS to 1400 rpm while maintaining the reinforcement at 8 wt%, the UTS peaked at 239.4 MPa, shown by the blue line.

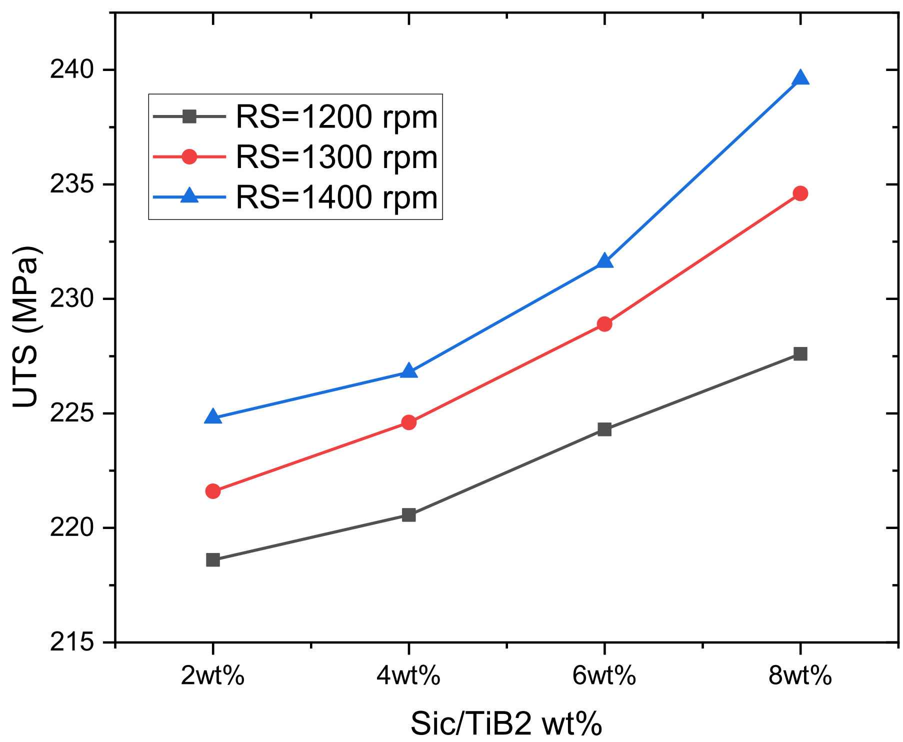


Figure.2. Ultimate tensile strength results for different SiC/TiB2 wt%

 https://doi.org/10.1051/e3sconf/202458803017

both reinforcement content and rotational speed play a perilous role in the enhancing the tensile strength of the welded joints. As the rotational speed increases, the UTS values improve because of better stirring action, which enables improved bonds between the matrix and the reinforcement. The analysis of BHN, as depicted in Figure 3, revealed significant distinctions in hardness based on both rotational speed and reinforcement content during the FSW process. The results indicated that as the RS increases, the BHN of the welded joints improves due to better dispersion and bonding of the reinforcement particles within the Al matrix. At a RS of 1200 rpm with an 8 wt% reinforcement content (SiC/TiB_2), the BHN was verified at 82.9 Hv, which duplicates a moderate development in the hardness attributed to the presence of the reinforcements.

When the RS was increased to 1300 rpm while maintaining the 8 wt% reinforcement, the BHN rose to 85.6 Hv. This increase in hardness proposes enhanced material flow and a more uniform distributions of reinforcement particles, lead to improved interfacial bonds between the matrix and reinforcements.

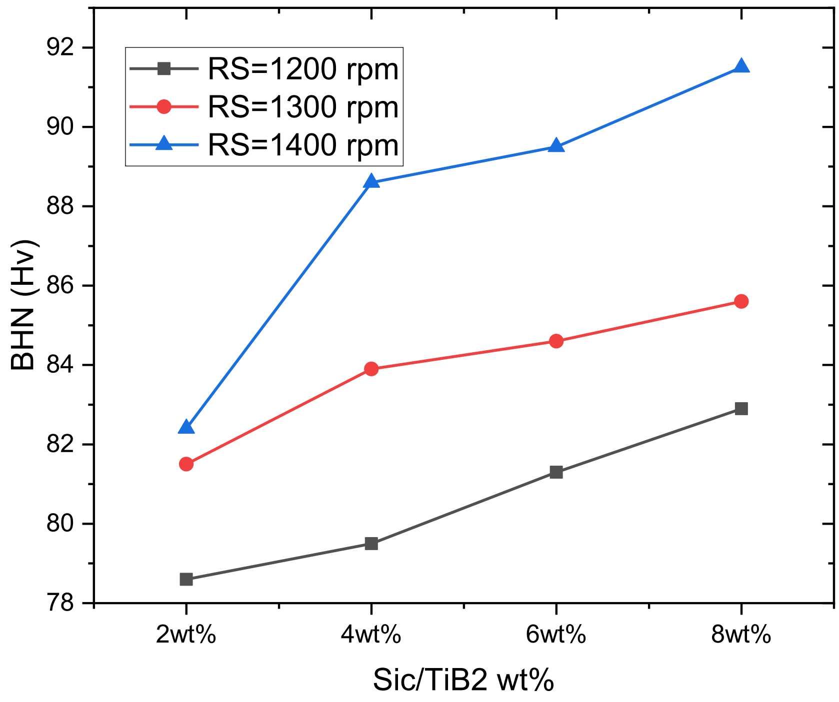


Figure. 3. Hardness results for different SiC/TiB2 wt%

Further increasing the RS to 1400 rpm with the same 8 wt% reinforcement, the BHN increased at 91.5 Hv. This significant increased in BHN can be attributed to the intensified stirring action, which not only augments the mechanical interlocking between the reinforcements and the matrix but also reduces porosity, resulting in a denser and stronger weld. This progressive rise in BHN with increasing rotational speed and constant reinforcement content demonstrates the high impact of parameters on the mechanical characteristics of joints. When both the weight percent of reinforcement and the tool rotational speed are optimized together, they can synergistically enhance the tensile strength. More reinforcement ensures a higher load-carrying capacity, while the increased tool speed ensures proper dispersion and grain refinement, maximizing the overall strength of the welded joint.

The lowest wear rate, recorded at 0.0489 mm^3/Nm, was achieved when the reinforcement content was maintained at 8 wt% and the rotational speed (RS) was set to 1200 rpm. This significant reduction in WRT can be attributed to the optimal interaction between the reinforcement particles (SiC/TiB_2) and the Al matrix, which enhances the material's resistance to wear.

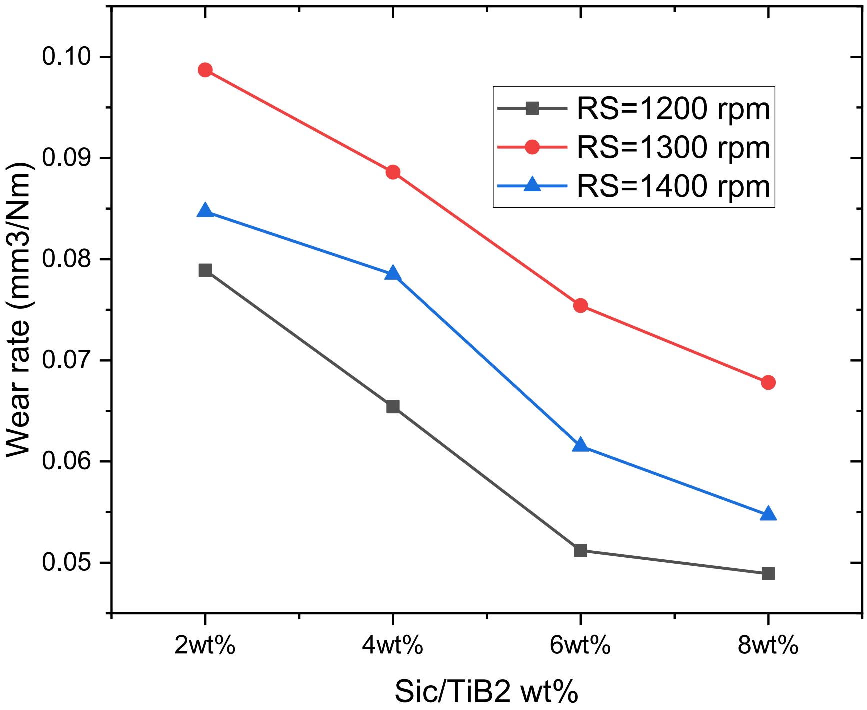


Fig. 4. Wear rate results for different SiC/TiB2 wt%

At 8 wt% reinforcement, the ceramic particles are more uniformly distributed, acting as a protective barrier that minimizes direct metal-to-metal contact during sliding. This leads to reduced material loss under applied load. Additionally, the rotational speed of 1200 rpm ensures efficient stirring, which helps embed the reinforcements more effectively within the matrix, thereby improving the overall mechanical integrity of the surface.

5. SEM analysis on fractured surfaces

The sem analysis are investigated for different tool rotational speed with 8 wt % of Sic/TiB2 reinforcement. From the Figure.5. High-magnification SEM pictures revealed a lot of dimples in the sheared section, which are typical features of ductile fracture.When observed under extreme magnification, the tensile cross-section displayed several tear edges and "cleavage-like" facets that were indicative of the quasi-cleavage fracture mechanism. Furthermore, it was evident that the dimple formation developed, exhibiting the traits of ductile fracture [19].

When the tool rotational speed is too low, there may not be enough heat generated to fully plasticize the material. This leads to poor material flow around the tool pin, resulting in voids or dimples at the centre of the weld zone where the material should consolidate.

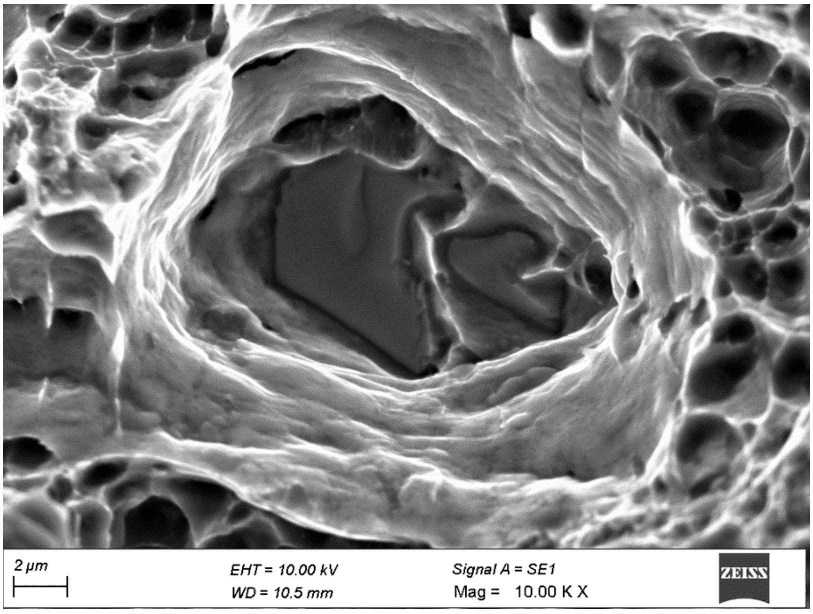


Fig. 5. SEM image for RS of 1200 rpm

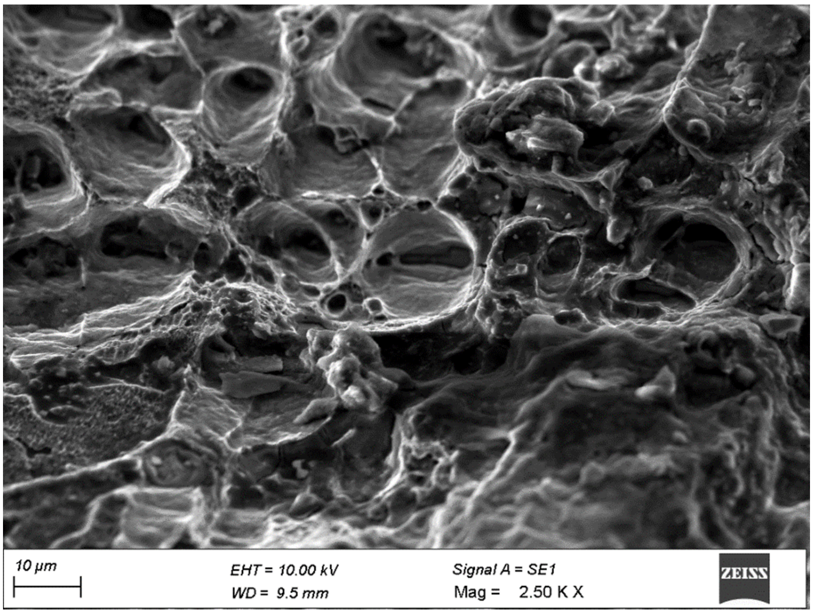


Fig. 6. SEM image for RS of 1300 rpm

From figure.6, there are uniform distribution orf reinforcement when tool rotational speed is equal to 1300 rpm this id due to A rotational speed of 1300 rpm provides effective stirring of the material, creating adequate mixing and breaking down any clumps or agglomerates of reinforcement particles. This leads to a homogeneous distribution of reinforcements within the matrix material. With proper rotational speed, issues like voids, dimples, or incomplete material consolidation are minimized, resulting in a smooth, uniform weld with an even distribution of reinforcement particles.

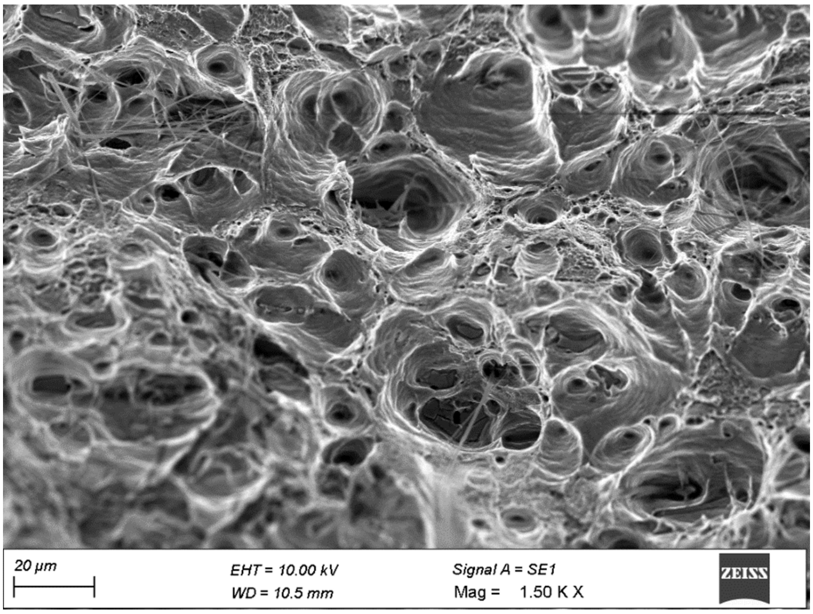


Fig. 7. SEM image for RS of 1400 rpm

From figure.7 there are micro dimples produced when tool rotational speed is equal to 1400 rpm. At 1400 rpm, the stirring action becomes more aggressive, which can cause turbulent flow of the material in the stir zone. This turbulence may result in uneven particle distribution and entrapment of air or other voids, creating micro dimple and Rapid material flow at higher speeds can disrupt the smooth flow of particles, leading to the formation of small discontinuities such as micro dimples or voids in the weld nugget.

6. Conclusion

Friction Stir Welding (FSW) process was conducted on dissimilar alloys AA8014 and AA2024, with a focus on analyzing mechanical properties such as tensile strength, hardness, and wear rate. . The influence of SiC/TiB2 nanoparticles, with weight percentages ranging from 2 to 8 wt%, was examined on the mechanical properties. The results indicated that increasing the rotational speed to 1400 rpm while maintaining the reinforcement at 8 wt%, the UTS peaked at 239.4 MPa and BHN of 91.5Hv . When both the weight percent of reinforcement and the tool rotational speed are optimized together, they can synergistically enhance the tensile strength. More reinforcement ensures a higher load-carrying capacity, while the increased tool speed ensures proper dispersion and grain refinement, maximizing the overall strength of the welded joint and The lowest wear rate, recorded at 0.0489 mm^3/Nm, was achieved when the reinforcement content was maintained at 8 wt% and the rotational speed (RS) was set to 1200 rpm and SEM analysis of the fractured surfaces revealed that micro dimples were produced at this higher rotational speed of 1400 rpm.

References

1. Y. Su, X. Yang, D. Wu, T. Meng, W. Li, W. Feng, W. Zhao, and A. Vairis, J. Mater. Res. Technol. **27**, 490 (2023)
2. Z. Guo, T. Ma, X. Yang, J. Tao, J. Li, W. Li, and A. Vairis, Mater. Sci. Eng. A **872**, 144991 (2023)
3. S. Suresh, K. Venkatesan, and E. Natarajan, J. Nanomater. **2018**, 1 (2018)
4. M. Barmouz, P. Asadi, M. K. Besharati Givi, and M. Taherishargh, Mater. Sci. Eng. A **528**, 1740 (2011)
5. M. Paidar and M. L. Sarab, J. Mech. Sci. Technol. **30**, 365 (2016)
6. A. K. Sahoo and V. Patel, Mater. Today Proc. **41**, 145 (2021)

7. S. Kim, J. Hong, Y. Joo, and M. Kang, J. Manuf. Process. **82**, 860 (2022)
8. S. V.Gosavi and M. D.Jaybhaye, Mater. Today Proc. **72**, 719 (2023)
9. S. Hassanifard, A. Ghiasvand, and A. Varvani-Farahani, J. Mater. Eng. Perform. **31**, 1781 (2022)
10. A. M. Hassan, M. Almomani, T. Qasim, and A. Ghaithan, Mater. Manuf. Process. **27**, 1419 (2012)
11. Sachinkumar, M. Nagamadhu, R. I. Badiger, and K. Anand Babu, Mater. Today Proc. **45**, 115 (2021)
12. J. A. Österreicher, C. Pfeiffer, G. Kunschert, T. Weinberger, C. M. Schlögl, W. Suppan, and K. M. Radlmayr, J. Adv. Join. Process. **9**, 100213 (2024)
13. D. Pal, S. Vijayakumar, T. V. J. Rao, and R. S. R. Babu, Mater. Today Proc. **62**, 1995 (2022)
14. H. P. Pydi, A. P. Pasupulla, S. Vijayakumar, and H. A. Agisho, Mater. Today Proc. **51**, 728 (2022)
15. S. Vijayakumar, S. Anitha, R. Arivazhagan, A. D. Hailu, T. V. J. Rao, and H. P. Pydi, Adv. Mater. Sci. Eng. **2022**, 1 (2022)
16. R. Kesharwani, K. K. Jha, M. Imam, C. Sarkar, and I. Barsoum, Heliyon **10**, e25449 (2024)
17. S. Vijayakumar, S. Manickam, S. Seetharaman, T. V. J. Rao, D. Pounraj, and H. P. Pydi, Adv. Mater. Sci. Eng. **2022**, 1 (2022)
18. S. Jain and R. S. Mishra, Silicon **14**, 10741 (2022)
19. B. Yuan, D. Liao, W. Jiang, H. Deng, G. Li, and J. Gu, J. Mater. Res. Technol. **23**, 4642 (2023)