



Article

Friction Stir Processed AA5754- Al_2O_3 Nanocomposite: A Study on Tribological Characteristics

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Abstract: This study investigates the tribological properties of an AA 5754 aluminum alloy composite reinforced with the nanopowder of Al_2O_3 , fabricated using the friction stir processing (FSP) technique with blind holes. The aim is to analyze the effects of varying the tool rotational speed (rpm) and blind hole diameter on the wear and friction behavior of the produced composite. A pin-on disk test is conducted under dry conditions and room temperature to assess the tribological properties against steel. Scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS) is employed to examine the worn and wear surfaces of the produced composites post test. The results indicate that increasing the applied load results in a decrease in the coefficient of friction (COF), with values ranging from 0.775 to 0.852 for 10 N and 0.607 to 0.652 for 20 N. Moreover, the wear rate diminishes with higher Al_2O_3 content and optimal FSP tool rotation (1280 rpm). Hardness analysis reveals variations between 33–42 HV and 35–39 HV, influenced by nanoparticle distribution. The composite demonstrates superior wear resistance compared to raw AA5754 aluminum due to its reinforced nature. However, high FSP tool rotation rates lead to abrasive wear and surface cracks. These findings offer insights into optimizing FSP parameters to enhance the tribological performance of nano-reinforced aluminum alloys.

Keywords: surface composites; friction stir processing; Al_2O_3 particles; wear resistance; coefficient of friction



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1. Introduction

Recently, several researchers have been interested in the study of metal–ceramic composites to develop the properties of the composites to serve specific applications. Composite materials are gaining popularity due to their superior mechanical properties [1–3]. Metal matrix composites (MMCs) with suitable additions are usually used to improve the thermal expansion coefficient and mechanical properties, and these composites are used as alternatives to the conventional materials [4,5]. Good corrosion resistance, high thermal conductivity, and an adequate strength-to-weight ratio have made aluminum alloys very popular structural materials. Yet, their tribological applications have been restricted by their relatively poor wear resistance, such as in bearings, gears, and sliding components [6]. Therefore the use of ceramic particles, such as aluminum oxide (Al_2O_3) and silicon carbide (SiC), as reinforcements to form aluminum matrix composites has been studied [7,8].

There are several ways to add reinforcement material including atmosphere plasma spray, friction stir processing (FSP), and compocasting techniques [9–11]. FSP is a simple technique used in solid-state process to add reinforcement material which depends on mechanical action and lower heat generation than the melting point of the base metal to

mix the reinforced material with the base metal. The reinforced material via FSP is usually put in the base metal either in a longitudinal groove or by surface reservoir patterns called blind holes. Moreover, studying the microstructure and tribological behavior of these new compounds is of great importance for evaluating their resistance against external loads or stresses; for example, Nabi et al. [12] discussed the wear behavior of Al 5052 alloys reinforced with NiTi using the longitudinal groove method for additional reinforcement. The powder was put in a square groove (2×2 mm), parallel to the welding direction. They observed that increasing the number of processing passes from one to four enhanced the mixing and wear resistance of the aluminum surface. Furthermore, the addition of NiTi reduced the coefficient of friction by 17% and 15% under different loads.

Qu et al. [8] used two reinforcement nanomaterials of Al_2O_3 and SiC to improve the surface of aluminum 6061-T651. They used various surface reservoir patterns for additional reinforcement materials. They highlighted the potential of FSP to enhance the performance of aluminum alloys for applications requiring high strength and toughness. Mehta and Vishvesh [13] compared two strategies, blind straight slot and blind zigzag holes, for additional reinforcement ceramic powder B4C to enhance the wear resistance of AA 6061. Pin-on-disk wear testing showed that the best specimen from the slot method had an 86.14% reduction in wear, and the hole method had an 87.43% reduction compared to the base metal. Vignesh et al. [14] examined the impact of various FSP parameters, including tool rotational speed, welding rate, and tool shoulder diameter, on both the microstructure and wear resistance of an AA 5083 aluminum alloy. Their findings revealed that the extent of dispersion and partial dissolution of phase β - Al_2Mg_3 was contingent upon the strain rate and thermal cycles, which, in turn, were influenced by the process parameters.

Gangil et al. [15] discussed the fabrication and tribological behavior of surface composites made from an AA7050-T7451 alloy using FSP. They prepared a homogeneous mixture composed of ceramics and metal particles by weight ratios. The findings demonstrate that inadequate bonding between the reinforcement–matrix leads to a significant decrease in both strength and wear characteristics. Yadav et al. [11] studied the tribological behavior of AA5083 reinforced by Al_2O_3 for surface composites fabricated using FSP under different heat input conditions, represented by the combination of tool rotational speed and traverse speed. They evaluated the wear resistance of the composites against a steel ball under different loads, 5 N, 10 N, and 20 N. The composites fabricated under high heat conditions showed superior wear resistance compared to those fabricated under low heat conditions.

Girish and Anandakrishnan [16] discussed the optimization of dry sliding wear parameters, such as load levels, sliding velocity, and sliding distance, for AA7075 processed using friction stir recursion. The observations were made using electron microscopy, and the optimization was conducted using the Taguchi experimental design. The main effect plot suggested that the wear rate could be minimized by applying a load: a sliding velocity and a sliding distance that were 9.81 N, 2 m/s, and 2000 m, respectively. Mazaheri et al. [17] improved wear and corrosion resistance for the surface of AZ31 bars by the FSP technique. The reinforcement powder used pure ZrO_2 nanopowder with almost an average diameter of 30–40 nm. They used the blind hole technique to add the powder in the base metal. They found that a friction stir tool with threaded pins led to significant grain refinement and homogenous dispersion. Moreover, FSP and nanoparticle additions enhance the hardness and wear resistance of the processing samples and reduce the friction coefficient.

Sahu et al. [18] studied the wear behavior of the AZ31 reinforced by three volume fractions of Al particles 3%, 6%, and 9%. Optical microscopy, FESEM, a 3D profilometer, and a ball-on-disc tribometer were used to evaluate the behavior of samples regarding wear mechanisms and the coefficient of friction. They found that the best results of grain refinement, mechanical properties, phase distribution, and wear resistance were given at 6% Al alloying. Mir et al. [19] investigated the influence of friction stir welding (FSW) parameters on the surface properties, wear resistance, and mechanical properties of AA2024-T3 and 304 stainless steel. They found that the tool rotational speed was the most impact factor for enhancing wear resistance, which led to an ultrafine grain structure in the stir

zone. Park et al. [20] studied the effects of FSW on 2 mm thick S45C steel due to its potential applications in various industries. The study conducted a comparative analysis, with a specific focus on wear resistance, microstructural changes, and mechanical properties. They found that FSW not only improved the wear resistance but also enhanced the mechanical properties of carbon steel joints, particularly at temperatures below the melting point. This improvement was a result of the high strain rate, which caused dislocation and subsequently led to grain refinement within the stir zone. One of the most important considerations in the excessive use of the reinforcement material is that it can wear the welding tool.

Zuo et al. [21] conducted a study on the increment of tool wear during the friction stir welding (FSW) process. High-speed steel pins, both with and without AlCrN coating, were utilized in the experiments. They proposed a novel method to calculate tool wear based on hydrodynamic pressure. The study revealed that the presence of hard particles in particle-reinforced aluminum composites resulted in a shortened tool life. Additionally, it was found that the initial application of AlCrN coating reduced the wear rate and extended the tool life. However, once the coating wore off, the wear rate increased significantly. Tiwari et al. [22] created cemented carbides by varying the cobalt content and utilizing medium and ultrafine tungsten carbide particles. Their objective was to assess the mechanical characteristics, microstructure, and effectiveness of these carbides in the friction stir welding of high-strength low-alloy steel. The researchers discovered that incorporating ultrafine WC powder into a medium-grain carbide matrix enhanced the mechanical properties and wear resistance of the cemented carbide tools.

Based on the above studies, there is a gap in the literature regarding the specific effects on the tribological behavior in the Al_2O_3 -reinforced aluminum alloy AA5754. For this reason, this study aims to address this research gap by investigating the wear behavior and coefficient of friction in the Al_2O_3 -reinforced aluminum alloy AA5754 after friction stir processing (FSP).

2. Materials and Methods

2.1. Raw Materials

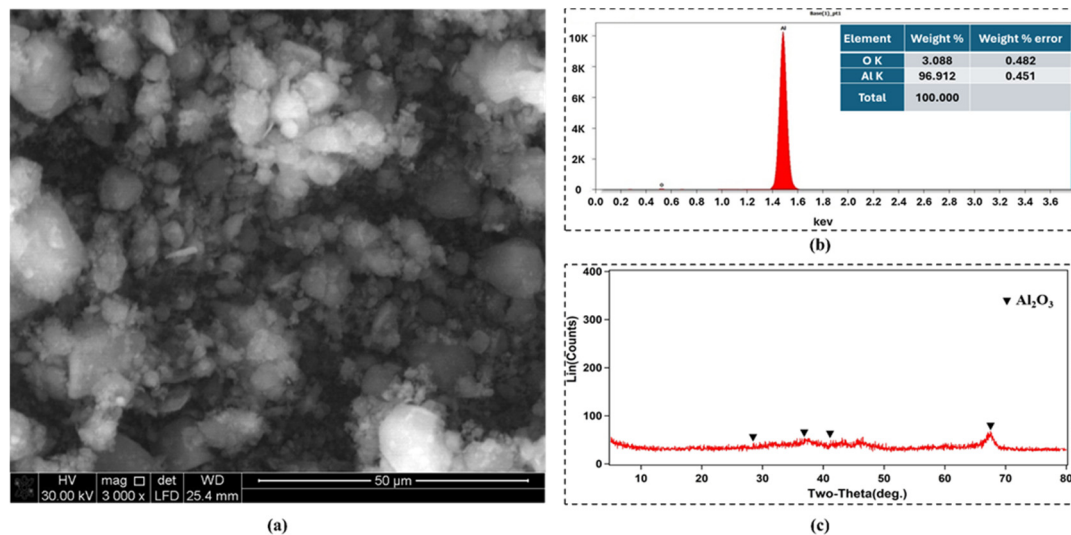
An AA5754 aluminum alloy reinforced by Al_2O_3 nanoparticles exhibits enhanced mechanical properties, including increased hardness and tensile strength, making it suitable for high-stress applications. This composite material demonstrates improved wear resistance and durability, which is advantageous for automotive components. Additionally, the uniform distribution of Al_2O_3 nanoparticles within the AA5754 matrix contributes to its superior thermal stability and corrosion resistance. In the experimental investigation, the AA5754 aluminum alloy, sourced locally, served as the primary matrix material with a thickness of 3 mm. The chemical composition of this alloy was determined from provided data sheets, meticulously outlined in Table 1. Precision cutting via a hydraulic shearing machine yielded rectangular pieces measuring 160×200 mm, enabling controlled experimentation. Comprehensive mechanical property data collected in a laboratory setting are detailed in Table 2. To augment the alloy's characteristics, Al_2O_3 nanoparticles were deliberately chosen as additives to craft a nanocomposite material. The average size of these Al_2O_3 particles was confirmed at 1000 nm, factoring in any potential agglomeration effects. The morphology of these particles is visually captured in Figure 1a via scanning electron microscope (SEM) imaging, while further characterization is provided through energy dispersive X-ray (EDX) and X-ray diffraction analysis (XRD) results in Figures 1b and 1c, respectively.

Table 1. Chemical composition of AA 5754 aluminum alloy.

Element	Mn	Fe	Si	Cr	Mg	Zn	Ti	Cu	Al
wt.%	0.5	0.4	0.4	0.3	2.6:3.6	0.2	0.15	0.1	Balance

Table 2. Mechanical properties of AA 5754 aluminum alloy.

Properties	Value
Proof stress (0.2%)	267 MPa
Ultimate tensile strength (UTS)	463 MPa
Elongation at break (%)	35
Strength coefficient (K)	1096 MPa
Strain hardening exponent (n)	0.39
Hardness Vickers (HV)	37 ± 2

**Figure 1.** (a) SEM image, (b) EDX and (c) XRD results of Al₂O₃ particles.

2.2. Composite Preparation

In the experimental procedure for fabricating aluminum matrix composites via FSP, the initial steps involved drilling the surface of the AA5754 aluminum alloy. This preparatory stage was crucial for the subsequent composite production. The holes were drilled strategically in a linear pattern at the matrix's center, ensuring consistency and uniformity in the fabrication process. Each hole was standardized to a depth of 1.5 mm, with a linear separation of 10 mm between them. This meticulous arrangement provided precise control over the composite formation, facilitating an accurate analysis of the resulting effects (see Figure 2a). The diameter of the blind hole was intentionally kept smaller than the FSP tool pin diameter to ensure the proper distribution of the reinforced particles within the forming area. Similarly, the distance between blind holes was maintained smaller than the diameter of the tool shoulder to ensure the effective distribution of supported material along the welding line. These specific parameters were chosen in this study for optimal results.

To explore the impact of varying Al₂O₃ weight percentages on composite properties, four different hole diameters were selected: 0 mm, 1 mm, 1.5 mm, and 2 mm. The 0 mm diameter hole represented the baseline condition, where the FSP of the aluminum matrix occurred without incorporating any powder additives (refer to Figure 2b). Following this, the effects of FSP process parameters were assessed by adjusting the tool rotational speed. Three rotational speeds—910, 1280, and 1700 rpm—were systematically tested to evaluate their influence on the composite's characteristics. Throughout the FSP process, parameters such as tool traveling speed, plunge depth, and tilt angle were maintained constant at 29 mm/min, 0.15 mm, and 2 degrees, respectively. The use of a specialized tool with a 12 mm shoulder diameter, featuring a square pin measuring 4 mm in area and 2.5 mm in length, ensured precise and controlled processing, facilitating the comprehensive analysis of experimental outcomes (see Figure 2b).

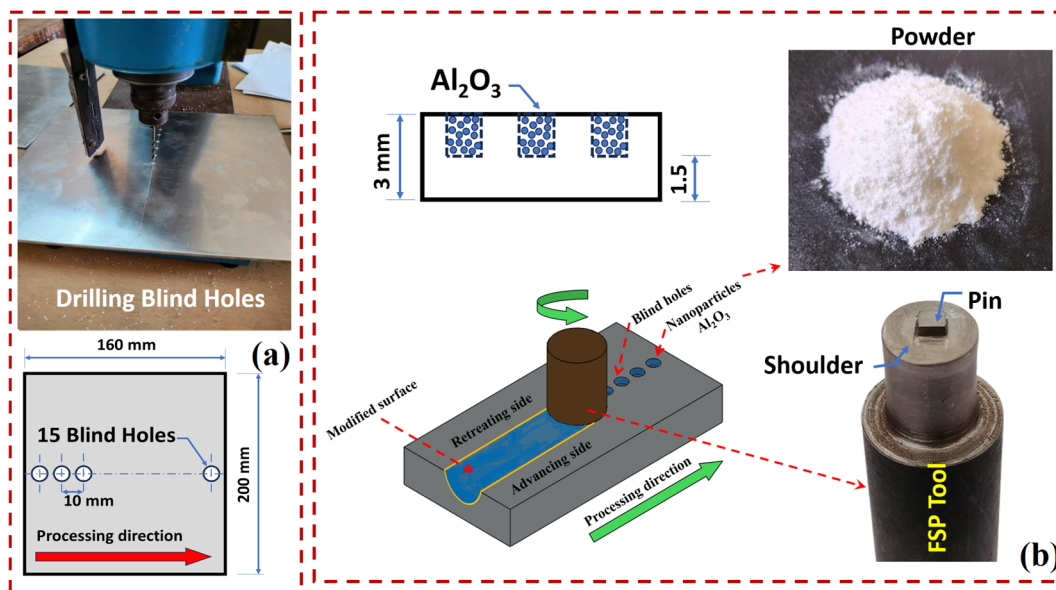


Figure 2. (a) Drilling holes on aluminum matrix, (b) Al₂O₃ powder placements in aluminum matrix, and used FSP tool.

To enhance the sample analysis, each case is assigned a unique number determined by the rotational velocity and hole diameter using the FSP tool. Table 3 displays the conditions and names of all samples.

Table 3. Sample names and test conditions.

Rotational Velocity	Name	State	Nanopowder Amount (g)
910 rpm	A0	Processing without powder	0
910 rpm	A1	Hole diameter 1 mm	0.070
910 rpm	A2	Hole diameter 1.5 mm	0.157
910 rpm	A3	Hole diameter 2 mm	0.280
1280 rpm	B0	Processing without powder	0
1280 rpm	B1	Hole diameter 1 mm	0.070
1280 rpm	B2	Hole diameter 1.5 mm	0.157
1280 rpm	B3	Hole diameter 2 mm	0.280
1700 rpm	C0	Processing without powder	0
1700 rpm	C1	Hole diameter 1 mm	0.070
1700 rpm	C2	Hole diameter 1.5 mm	0.157
1700 rpm	C3	Hole diameter 2 mm	0.280

2.3. Friction Test

The wear test of the samples was performed applying pin-on-disk wear equipment at room temperature as depicted in Figure 3a. A carbon steel disc counterface with an outer diameter of 185 mm and a surface roughness (Ra) of $1.2 \pm 0.15 \mu\text{m}$ was employed. The wear tests were conducted under different normal loads of 10 and 20 N, with a sliding speed of 0.8 m/s. The rates of wear were determined by weighting the resulting debris after the sliding of 144 m. The coefficient of friction was estimated by the measured friction torque during sliding. To determine the weight loss, a digital electronic balance was employed to weight the specimens before and after the wear test. The difference between the two weights represented the wear rate. Throughout the wear test, the friction force was continuously recorded at one-millisecond intervals using a calibrated data logger connected to a load cell with a capacity of 40 kg and a PC laptop. The coefficient of friction (COF) was calculated by dividing the friction force by the applied load.

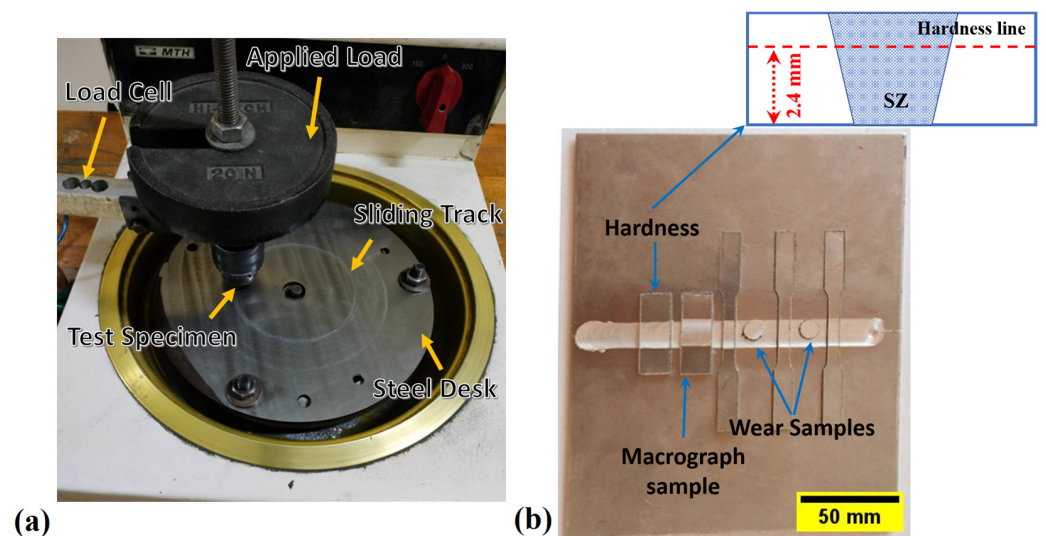


Figure 3. (a) The used pin-on-disk setup in this study. (b) Microhardness and metallography samples.

An optical microscope was used in the comprehensive assessment of welding defects within the welding zone, as well as to evaluate the areas of the Stir Zone (SZ) and Heat-Affected Zone (HAZ). Two types of optical microscope were used; the first one was a Stereo optical microscope connected to Leica DMC 2900 (Nanotechnology, Al Bustan Street, Sheikh Zayed City, 6 October City, Egypt) to evaluate the areas of the Stir Zone (SZ) and Heat-Affected Zone (HAZ) and the second was a light optical microscope (LECO LX 31) connected to a Pax-Cam camera (Tabbin Institute for Metallurgical Studies, 5 Rd.215 Wadi Degla, Maadi, Cairo, Egypt). This microscope enables the precise scrutiny of the weld structure and the identification of potential defects such as porosity, cracks, or inclusions. The microhardness samples underwent testing using a Vickers micro-hardness tester, Model No. 1600-4981 (Faculty of Technology and Education, Beni-Suef University, Beni-Suef, Egypt). Following the guidelines outlined in ASTM E384-99, the Vickers microhardness test was conducted on various welding zones, applying a 300 g testing load for a duration of 15 s (refer to Figure 3b).

3. Results and Discussions

3.1. Composite Analysis

The cross-sectional analysis of all composites produced by FSP is illustrated in Figure 4. The caption of each composite condition is presented in the image. Upon an initial inspection, the resulting composite exhibits a clear division into two distinct regions: a central white area and a surrounding light-brown region. This division suggests the presence of varied microstructural compositions within the joint zone, likely influenced by the FSP process [23,24]. The distribution and shape of the produced composite at the center of samples are not similar. It can be seen that with different FSP parameters, the size and shape of central composite changes. Further analysis reveals notable alterations in microstructure and coloration within the central composite, indicative of changes in material properties resulting from the FSP process. Specifically, the incorporation of Al_2O_3 nanoparticles into the aluminum matrix has led to the formation of a reflective region, visible under optical microscopy, underscoring the interaction between the nanoparticles and the matrix. Detailed information regarding the produced composite can be found in a previous study by the authors and is beyond the scope of this research. The primary focus here lies on investigating the effects of FSP parameters on the distribution of Al_2O_3 nanoparticles on the aluminum matrix and their tribological characteristics.

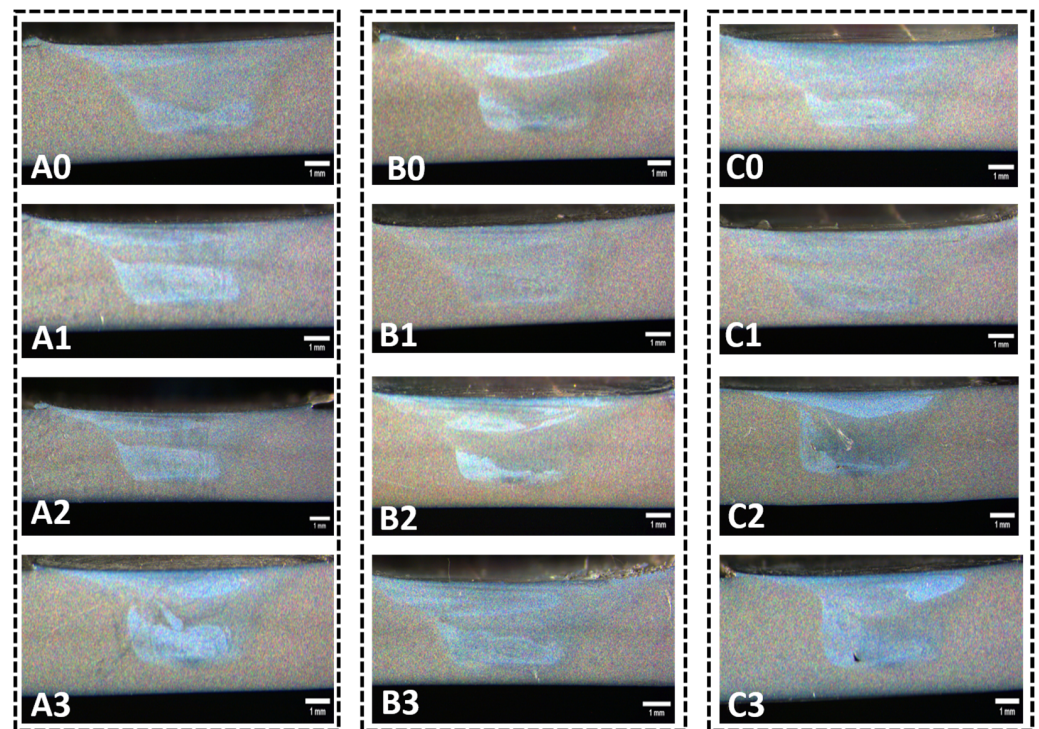


Figure 4. Cross-section view of produced composites with various FSP parameters.

3.2. Coefficient of Friction

Figure 5a presents a sample graph depicting the coefficient of friction for the C1 sample, obtained under applied loads of 10 N and 20 N. Meanwhile, Figure 5b illustrates the mean coefficient of friction for the produced composites under multiple loads, specifically 10 N and 20 N, while maintaining a sliding velocity of 0.8 m/s. The A terms in the graph present the raw AA5754 aluminum alloy results.

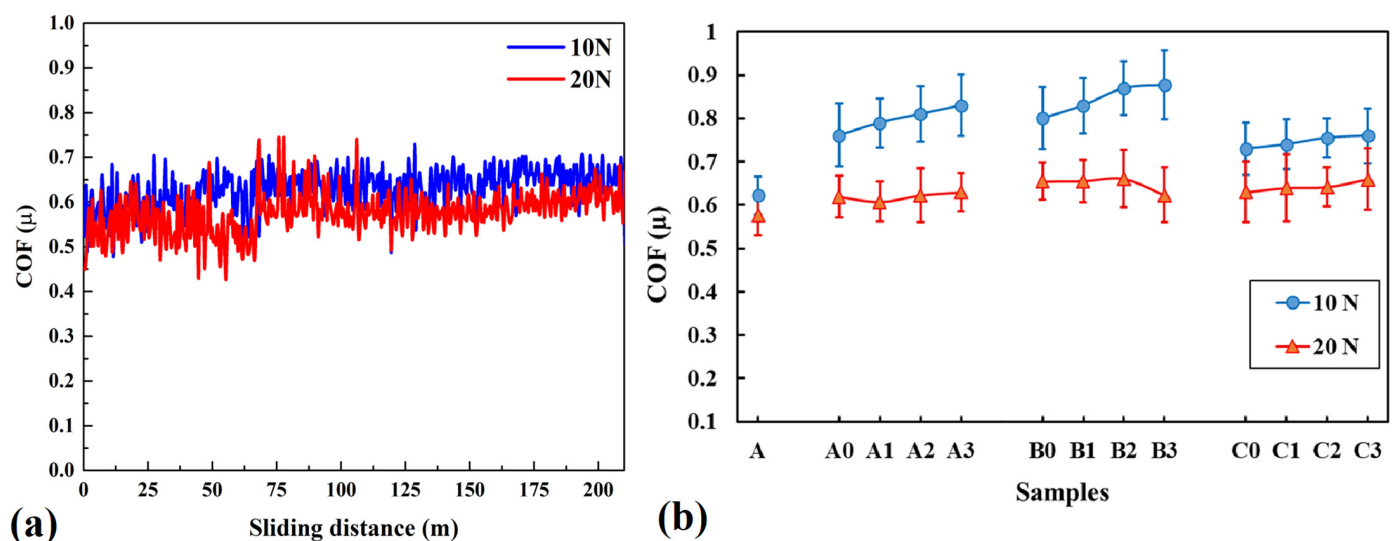


Figure 5. (a) COF graph of sample C1, (b) COF of various samples at different loads.

The observed trend reveals that as the applied load increases, there is a corresponding decrease in the coefficient of friction. This phenomenon can be attributed to the greater indentation depth of the pin into the sample as the load rises. Moreover, it can be inferred that an increase in the content of Al_2O_3 leads to a reduction in the coefficient of friction across the samples. This reduction in friction coefficient is primarily attributed to the behav-

ior of the Al_2O_3 nanoparticles during sliding action. As the composite undergoes sliding, the Al_2O_3 nanoparticles are drawn out from the AA5754 aluminum alloy sheet and migrate to the connecting surfaces. This migration and subsequent presence of Al_2O_3 nanoparticles at the contact interfaces contribute to a decrease in the coefficient of friction [25]. The decline in the friction coefficient with increasing Al_2O_3 content can be linked to the inherent properties of Al_2O_3 nanoparticles within the structure. The presence of these hard particles effectively reduces frictional resistance, thereby influencing the overall friction behavior of the composite.

The pin-on disk test conducted in this study yielded insightful results regarding the friction coefficients (COFs) across different scenarios. Firstly, the COF ranged from 0.866 to 0.607, indicating significant variations in frictional behavior among the tested conditions. The COF for case B0 was the highest recorded in the study, reaching 0.866, surpassing both A0 and C0, and standing out as the maximum COF observed. This trend persisted across different applied loads, with B0 consistently exhibiting higher COF values compared to A0 and C0. Upon further analysis of the A series, it was observed that the COF increased with the concentration of Al_2O_3 . The average COF for 10 N was between 0.775 and 0.812 and the average COF for 20 N was between 0.607 and 0.652. This phenomenon suggests that lower tool rotation rates might contribute to nanoparticle agglomeration, consequently leading to an increase in the COF. As the applied load increased within this series, there was a corresponding rise in the COF, indicating a direct relationship between load and friction. In contrast, the B series exhibited the highest COF among all samples. The average COF for 10 N was between 0.809 and 0.851 and the average COF for 20 N was between 0.623 and 0.655. The COF in this series escalated with increasing applied loads, indicating a significant influence of the load on frictional behavior. This trend suggests that the materials in the B series may possess characteristics or interactions that exacerbate friction under higher loads. Conversely, the C series composites demonstrated the lowest COF values among all samples. The average COF for 10 N was between 0.748 and 0.756 and the average COF for 20 N was between 0.635 and 0.655. Notably, the average COF in the C series was approximately 10% lower than in other cases. This indicates that the composition or structure of the C series materials may possess properties conducive to reducing friction.

3.3. Wear Rate

Figure 6 illustrate, the wear rate of the AA 5754 sheet matrix and the AA 5754 sheet reinforced by Al_2O_3 nanoparticle at different loads (10 and 20 N) with a velocity of 0.8 m/s and speed of 150 rpm. Usually, increasing the applied load raises the sliding wear rate as a result of the higher penetration of indenters in the specimens, which enables higher metal removal rates [26]. However, with the rise in Al_2O_3 content, the wear rate decreases. This observation highlights the large dependence of wear properties of the AA 5754 sheet with Al_2O_3 particles. Also, wear resistance is enhanced due to the addition of hard ceramic Al_2O_3 nanoparticles to the soft aluminum sheet. This improved resistance of wear is because of the greater hardness obtained (in comparison to the AA 5754 sheet) as a result of the better bonding between the AA 5754 sheet with Al_2O_3 particles and the presence of Al_2O_3 nanoparticles that have a good load-bearing capacity. The wear rate changes for all specimens as a function of Al_2O_3 nanoparticle content under a constant sliding velocity of 0.8 m/s and applied loads. We can conclude that the AA 5754 sheet exhibits an extremely higher wear rate than AA 5754 sheet with Al_2O_3 nanoparticles. The A terms in the graph present the raw AA5754 aluminum alloy results. The addition of Al_2O_3 to the soft AA 5754 sheet is very effective in decreasing its sliding wear rate due to the addition of Al_2O_3 nanoparticles increasing the hardness of the AA 5754 sheet. Also, the sliding wear rate of the AA 5754 sheet with Al_2O_3 increased, as a result of the increase in the surface temperature under high sliding velocity, which helps to soften the surface, leading to more damage of the surface and subsurface.

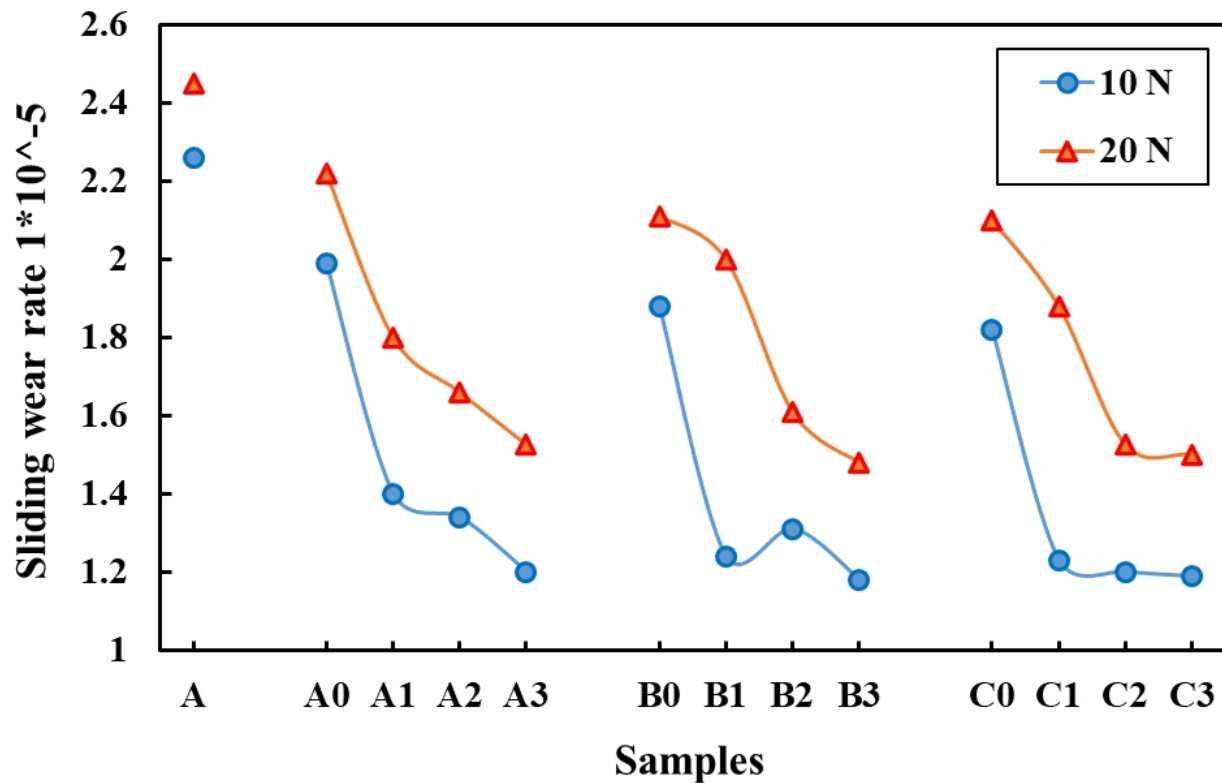


Figure 6. Wear rate of various samples at different loads.

Analyzing the wear rate results for the A, B, and C series at different applied loads reveals interesting trends and insights. Let us first examine the trends based on applied loads; the wear rates across all series (A, B, and C) tend to decrease as the concentration of Al_2O_3 nanoparticles increases. Within each series, there is a noticeable decrease in wear rates as the concentration of Al_2O_3 increases. For instance, comparing A0 to A3, B0 to B3, and C0 to C3, we observe this trend consistently. However, there are slight fluctuations in wear rates within each series, suggesting nuanced effects of other factors such as material composition and processing conditions. The wear rates for each series under an applied load of 10 N follow a similar pattern, with slight variations depending on the specific series and concentration. Similar to the trends observed at 10 N, the wear rates generally decrease with increasing Al_2O_3 concentrations across all series. Within each series, there is again a noticeable decrease in the wear rate as the concentration of Al_2O_3 increases, although the magnitude of the decrease varies. Comparing the wear rates at 20 N to those at 10 N, it can be seen that the wear rates generally increase with higher applied loads, which is expected due to the higher stresses experienced by the materials under greater loads. Despite the overall increase in wear rates at 20 N compared to 10 N, the relative trends within each series remain consistent, with higher Al_2O_3 concentrations generally associated with lower wear rates.

The A series consistently exhibits higher wear rates compared to the B and C series across all concentrations of Al_2O_3 . This suggests that the material composition or structure of the A series (a prepared composite with 910 rpm tool velocity) may be less effective in resisting wear compared to the B and C series. Within each series, the wear rates generally decrease as the concentration of Al_2O_3 increases, indicating the beneficial effects of Al_2O_3 nanoparticles in reducing wear. The B series shows relatively lower wear rates compared to the A series but slightly higher wear rates compared to the C series, suggesting intermediate wear resistance. The C series (a prepared composite with 1700 rpm tool velocity) consistently demonstrates the lowest wear rates among all series, indicating superior wear resistance compared to the A and B series. Similar to the trends at 10 N, the A series still exhibits higher wear rates compared to the B and C series, albeit with

increased magnitudes due to the higher applied load. The wear rates across all series increase compared to those at 10 N, reflecting the expected increase in wear under higher loads. Despite the increase in wear rates, the relative trends within each series remain consistent, with higher Al_2O_3 concentrations associated with lower wear rates. The C series continues to demonstrate the lowest wear rates, indicating its superior wear resistance, even under higher applied loads.

3.4. Hardness Analysis

The hardness analysis provided valuable insights into the material properties of the produced nanocomposite samples [27–29]. Comparing the FSP sample (Figure 7a) with the C3 composite (Figure 7b) as a sample highlighted the impact of nanoparticles on these properties.

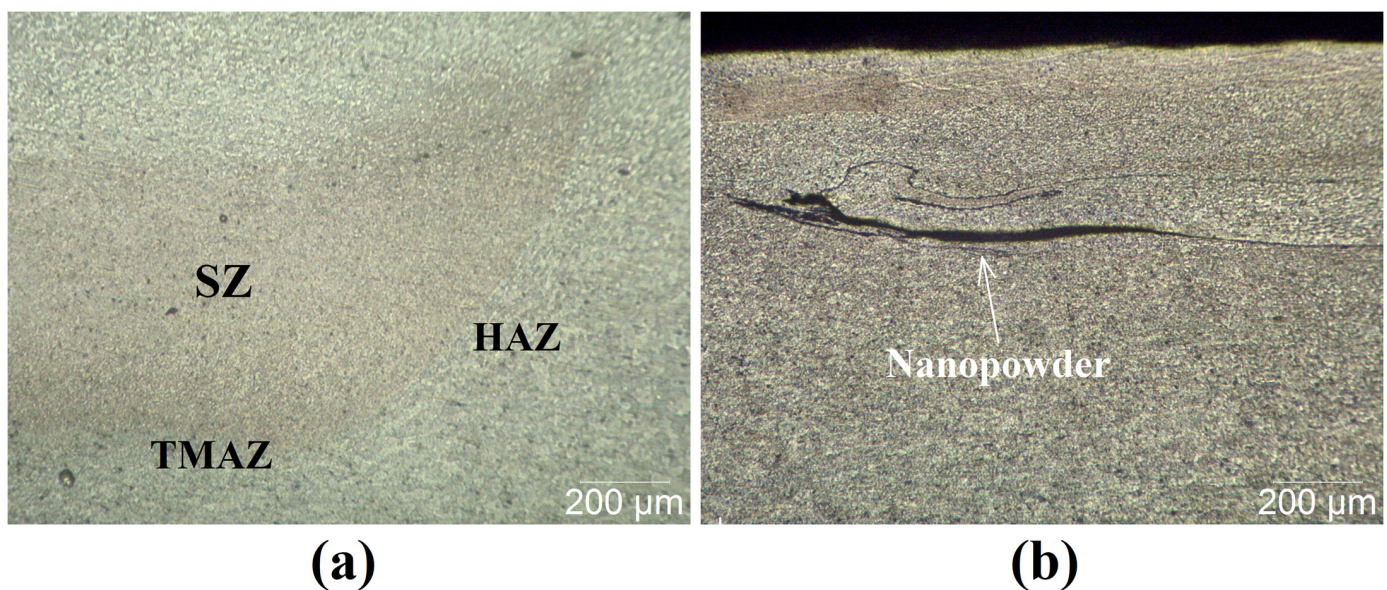


Figure 7. (a) FSP zone and (b) produced composite at C3 case.

The dispersion of nanoparticles within the composite influenced its tribological properties. The hardness values for the upper sections of the A, B, and C series are depicted in Figure 8a, Figure 8b, and Figure 8c, respectively. This method allowed for an assessment of the horizontal hardness variation in the composite's top surface. The results showed an average hardness at the composite center of 42 HV, 41 HV, 39 HV, and 33 HV for samples A0, A1, A2, and A3, respectively. An inverse correlation was observed between hole diameter (amount of Al_2O_3) and composite hardness, with larger hole diameters resulting in decreased hardness at a tool speed of 910 rpm. Similarly, for B series samples, the average hardness values were 39 HV, 42 HV, 44 HV, and 46 HV for samples B0, B1, B2, and B3, respectively, with the highest hardness observed in sample B3. Notably, the average hardness in the B series was higher than in the A series, and increasing hole diameters correlated with increased hardness. The key difference between the A and B series was the FSP tool rotation. The conclusion can be drawn that a tool velocity of 1280 rpm leads to a more homogeneous dispersion of nanoparticles and increased composite hardness compared to the A series. Alternatively, increasing the tool velocity during FSP reduces microstructure size and enhances hardness. In contrast, C series samples exhibited lower hardness values, with average readings of 39 HV, 38 HV, 36 HV, and 35 HV for samples C0, C1, C2, and C3, respectively. These findings indicate a detrimental effect of FSP tool rotation on hardness, resulting in the softening of the nanocomposite. The hardness analysis revealed variations in material hardness across different processing conditions, with low and very high rotational velocities leading to decreased hardness due to nanoparticle distribution.

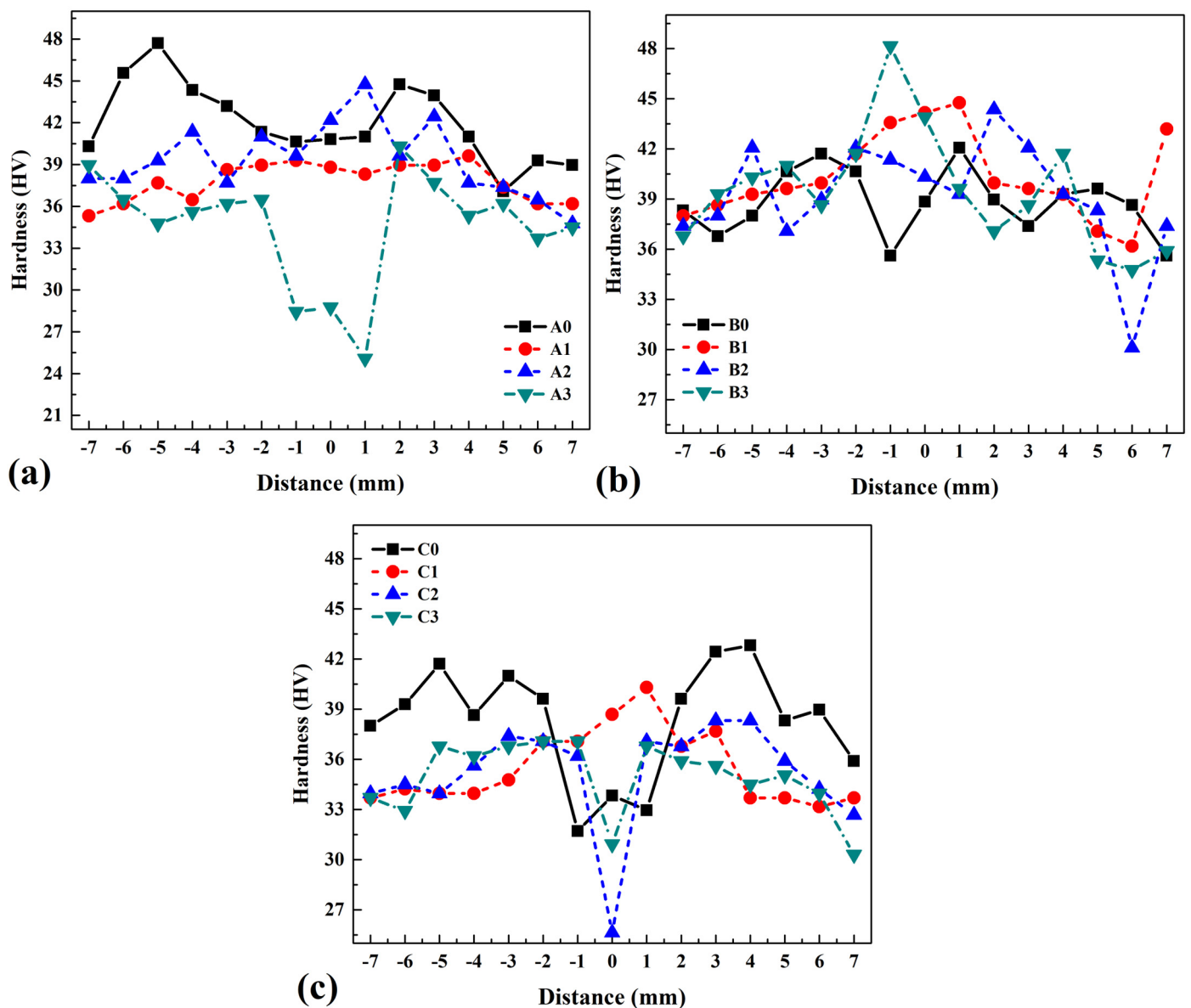


Figure 8. Hardness profile of (a) A-series, (b) B-series, and (c) C-series.

3.5. Worn Surface Analysis

Figure 9a–c depict field SEM images of the worn surfaces of the produced composite for raw AA5754 aluminum alloy (A), B2, and C3 particle samples, subjected to an applied load of 20 N and a sliding velocity of 0.8 m/s. Deeper and continuous furrows, parallel to the sliding direction, are evident on the surfaces. These images feature both low and high magnifications of the worn surfaces. The results reveal abrasive wear and galling effects on the composite surface after testing the A sample. Additionally, high-magnification images of the worn surface in the raw AA5754 aluminum alloy (A) sample indicate the agglomeration of wear debris and galling effects. Abrasive wear occurs when a hard surface slides against a softer surface, resulting in material removal through plowing, cutting, or scratching. This phenomenon is facilitated by relative motion between two surfaces, with particles trapped between them acting as abrasives, leading to material removal from both AA5754 aluminum alloy and steel surfaces. Conversely, galling represents a more severe form of adhesive wear, arising when AA5754 aluminum alloy and steel disk surfaces slide against each other under pressure, resulting in material transfer between surfaces. This transfer can lead to localized adhesion, cold welding, and subsequent material tearing

from one or both surfaces. Abrasive wear is also observed in the B2 and C3 cases, with surface cracks evident in the C3 case. Based on the produced composite, it can be inferred that the quantity of nanoparticles and FSP parameters for distribution play a crucial role in the tribological properties of the produced composite. Higher quantities of Al_2O_3 and increased tool rotational velocity result in decreased tribological properties of the produced composite, as evidenced by the comparison between the B2 and C3 cases.

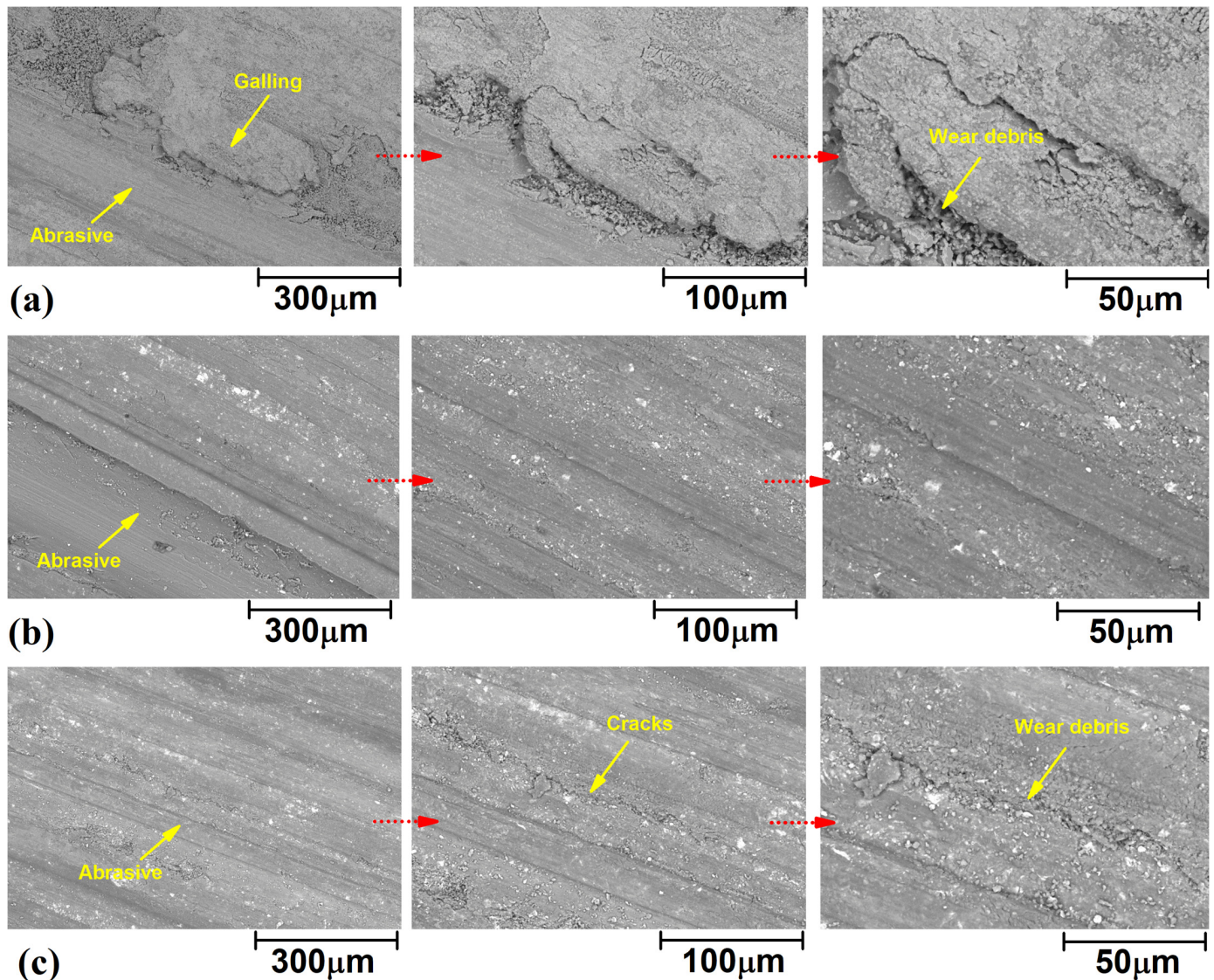


Figure 9. SEM image of worn surface of (a) raw AA5754 aluminum alloy (A), (b) B2, and (c) C3 samples.

The high-magnification SEM image from Sample B2, depicted in Figure 10, provides insightful observations. In the B2 case, the presence of nanoparticles is distinctly discernible, shedding light on a potential deficiency in the reinforcement of the aluminum matrix. The SEM analysis reveals the presence of agglomerated Al_2O_3 nanoparticles on the surface, with detectable concentrations predominantly observed in the flat areas of the worn surface. However, notably absent are these particles from the edges of the worn surface. Despite the application of a higher quantity of Al_2O_3 during the FSP process, resulting in larger holes within the material, the utilization of a 1280 rpm FSP tool facilitates a more uniform dispersion of nanoparticles within the matrix. However, this observation also suggests a limitation in the distribution process at this rotational velocity. Although the nanoparticles

are better distributed compared to other cases, the overall effectiveness in reinforcing the aluminum matrix is still hindered to some extent. Further investigation into optimizing the FSP parameters is warranted to overcome these limitations and enhance the intended strengthening effect of the Al_2O_3 nanoparticles within the composite material.

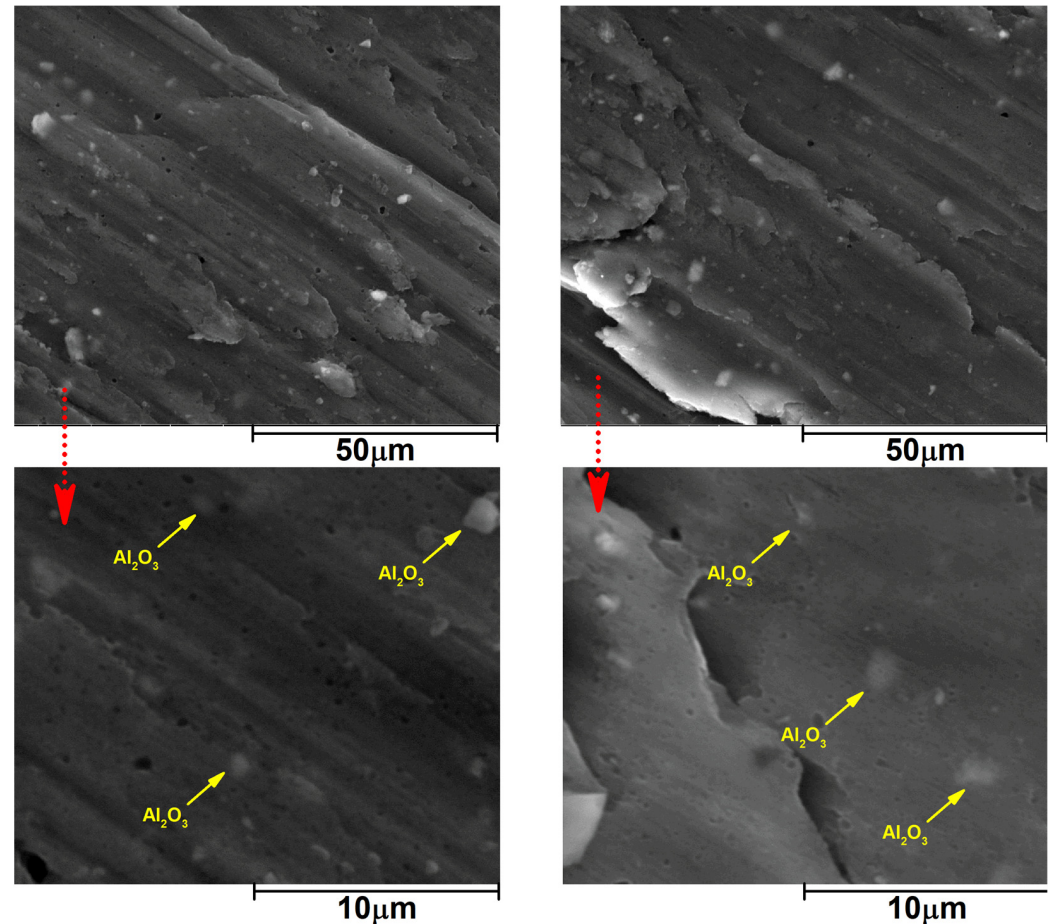


Figure 10. High-magnification SEM image of worn surface of Sample B2.

The high-magnification SEM image from Sample C3 is depicted in Figure 11. Conversely, the C3 case exhibits a contrasting phenomenon, characterized by a significant presence of shiny zones. This phenomenon suggests that the 1700 rpm tool rotation can potentially lead to the agglomeration of particles. The agglomeration, in turn, may diminish the strengthening properties of Al_2O_3 within the aluminum matrix, thereby compromising the overall structural integrity. This observation underscores the critical role of FSP parameters, such as rotational velocity, in achieving the desired dispersion and reinforcement of nanoparticles within the composite matrix. Further investigation into optimizing these parameters is warranted to enhance the mechanical properties and performance of the nanocomposite material. The agglomeration of Al_2O_3 nanoparticles on the abrasive surface can enhance the abrasive wear resistance of the reinforced aluminum alloy. The nanoparticles act as hard particles that can withstand abrasive forces, thereby reducing material loss due to abrasion. Although the nanoparticles are not directly located at the crack edge in the B2 sample, their presence on the abrasive surface can indirectly inhibit crack propagation. Further analysis of these light points, along with different areas of the aluminum matrix, is presented in Figure 12 through the EDS point analysis for case C3.

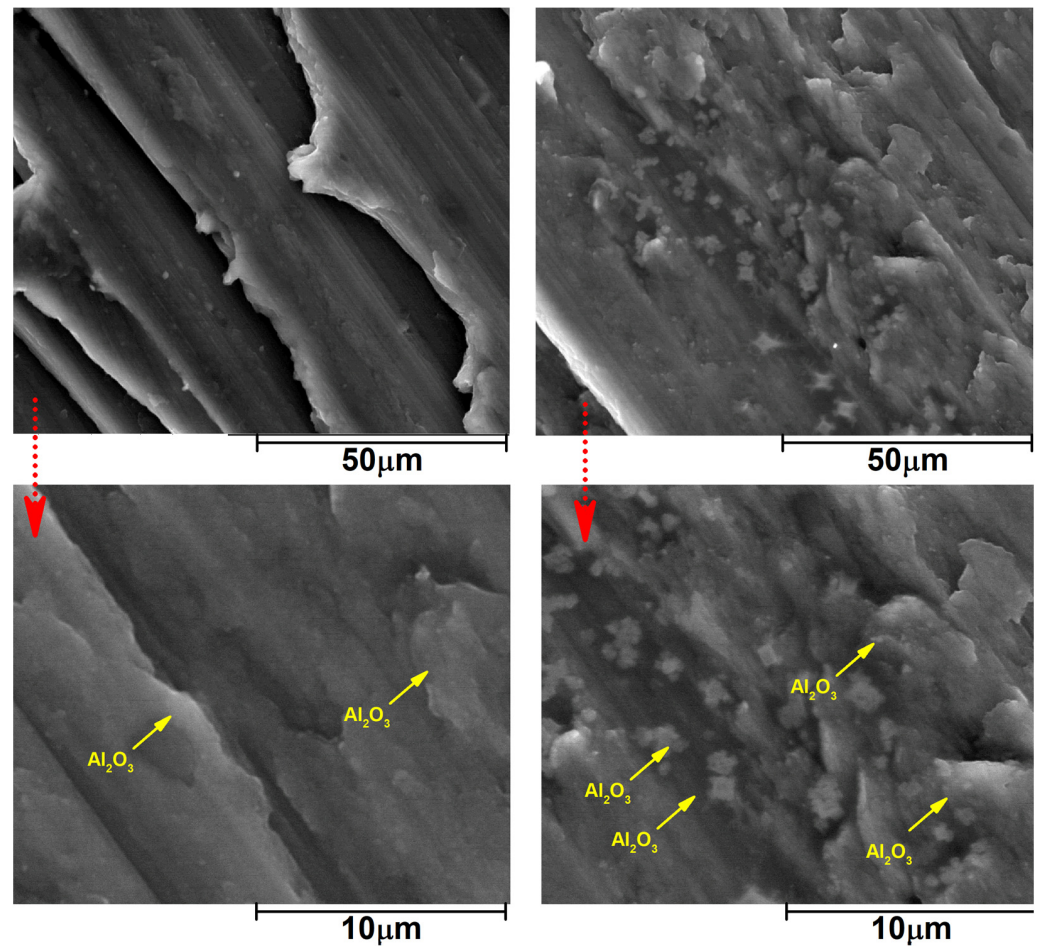


Figure 11. High-magnification SEM image of worn surface of Sample C3.

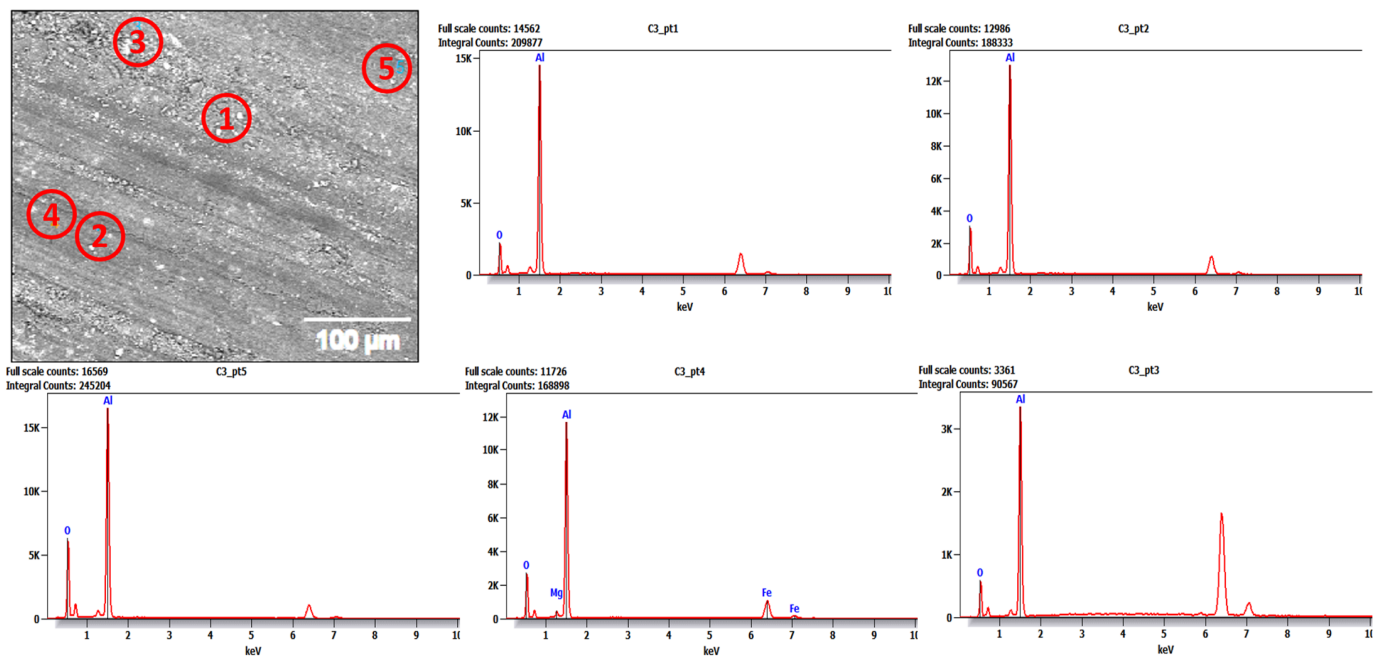


Figure 12. EDS point analysis of worn surface of C3 samples.

By reinforcing the aluminum matrix, the nanoparticles may provide additional support to resist crack growth, thereby prolonging the fatigue life of the material. But, by increasing

FSP tool rotation, this behavior may act in the opposite way. This means that over-stirring action at high rotation leads to over-agglomeration that leads to a decrease in the resistance effects of Al_2O_3 nanoparticles in contact with steel. On the other hand, the absence of nanoparticles at the crack edge may result in a localized stress concentration. Without the reinforcement provided by the nanoparticles, the crack edge may experience higher stress levels, potentially leading to accelerated crack propagation and reduced material durability. The EDS map analyses of both the AA5754 aluminum alloy (A) and Sample C3 are illustrated in Figures 13 and 14, respectively.

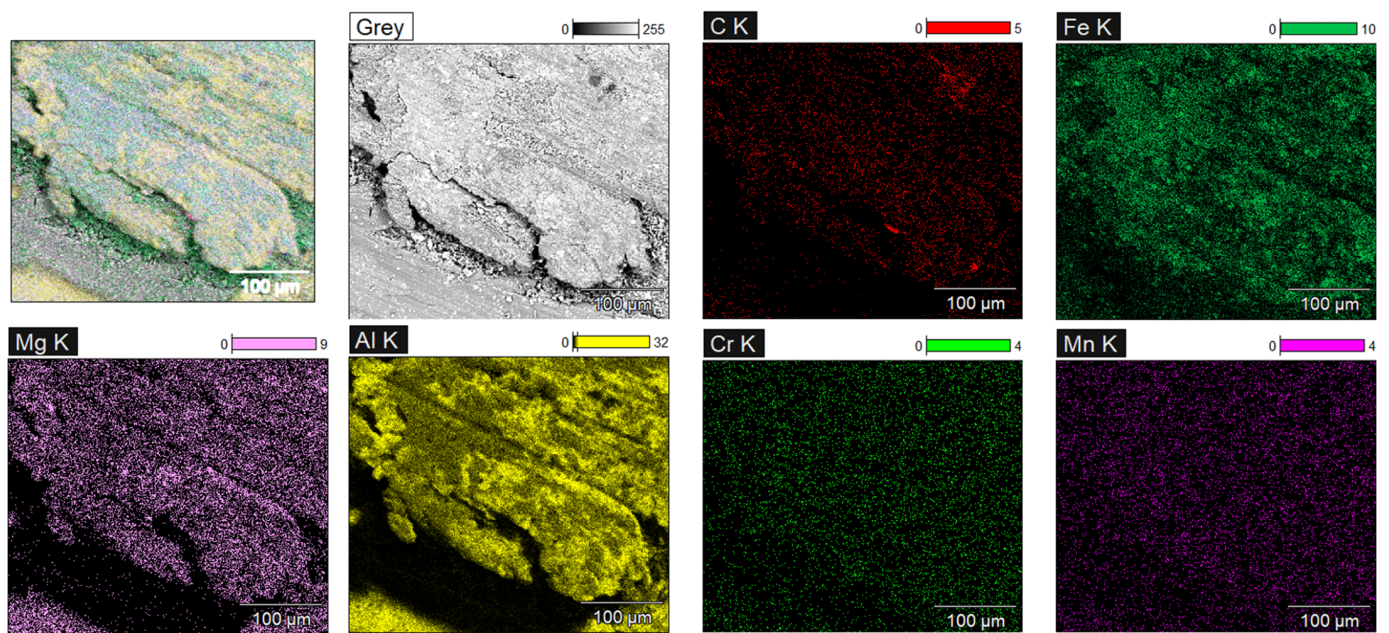


Figure 13. EDS map analysis of worn surface of raw AA5754 aluminum alloy (A) samples.

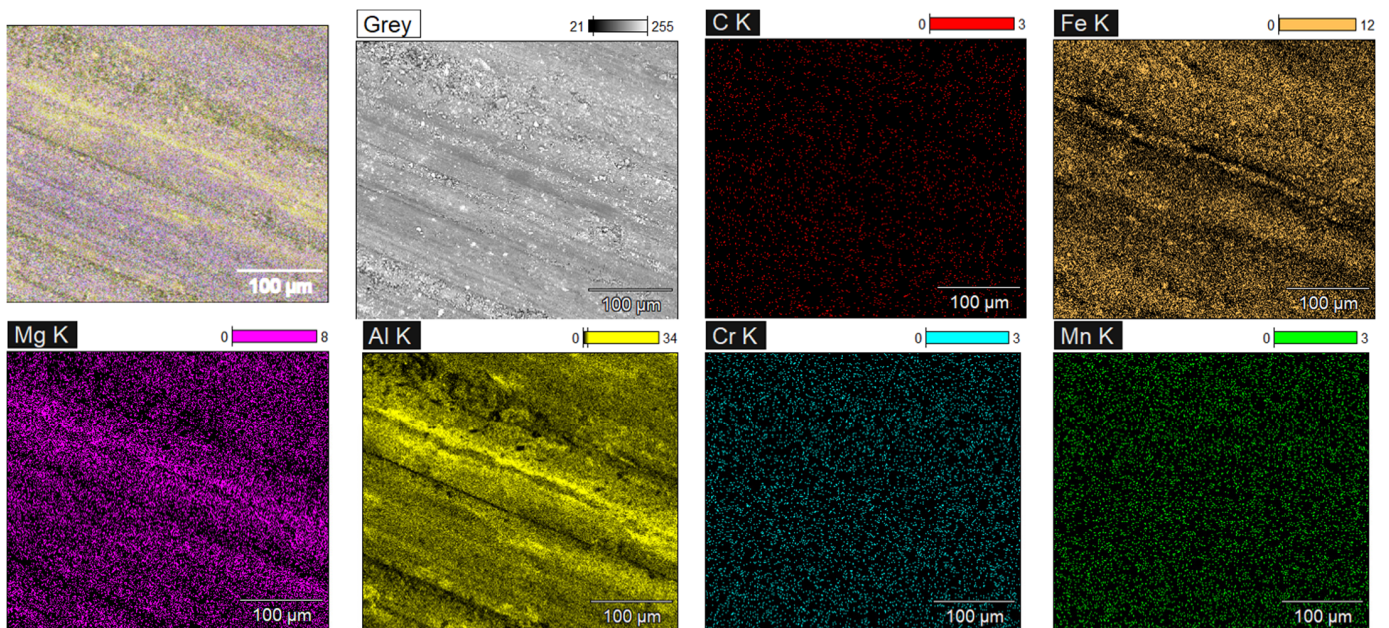


Figure 14. EDS map analysis from worn surface of C3 samples.

These analyses shed light on the distribution of alloy elements on the worn surface, revealing the significant influence of FSP parameters on the tribological properties of the produced composite. The main elements in the worn surface were carbon (C), iron (Fe),

magnesium (Mg), aluminum (Al), chromium (Cr), and manganese (Mn). The EDS element maps from the surfaces of Samples A and C3 consist of the mentioned elements.

Figure 13 showcases several finer aluminum particles, likely debris, that were detached during the wear process. In AA 5754 sheet materials, the wear surface exhibits narrower and shallower furrows, with minimal grain stripping. The distribution of AA 5754 elements depicted in Figure 13 suggests that, during the pin-on-disk test, the absence of Al_2O_3 nanoparticles has a significant impact on the tribological properties of the aluminum alloy. The hardness of the AA5754 aluminum alloy (A) sample was much lower than the steel disk used for this tribotest due the galling effect and debris detected on the worn surface.

In contrast, Figure 14 reveals distinct grooves and ridges running parallel to each other in the sliding direction, indicating a smooth distribution of Al_2O_3 nanoparticles on the surface. There is no alloy element concentration or debris on the C3 sample. This result indicated the effects of the added Al_2O_3 nanoparticles on the surface tribological properties of the produced composite against hard materials like steel.

This observation implies the chemical stability of the produced composite during the wear test. The presence of such well-defined features underscores the importance of appropriate FSP parameters in ensuring the uniform dispersion and structural integrity of the composite material.

4. Conclusions

This study delves into the tribological characteristics of an Al_2O_3 -AA5754 aluminum alloy composite, fabricated through friction stir processing in contact with steel. The investigation considers the effects of FSP parameters and applied loads on the properties of this composite. The key findings are succinctly outlined below:

1. The average coefficient of friction (COF) under a 10 N load ranged from 0.775 to 0.852, while under a 20 N load, it varied between 0.607 and 0.652. The rotational velocity of the FSP tool influences the distribution of nanoparticles and the tribological behavior of the composite. Notably, an increase in the applied load correlates with a decrease in the COF of the produced composite.
2. The average wear rate of the Al_2O_3 -AA5754 aluminum alloy composite was lower under a 10 N load compared to a 20 N load. Additionally, an increase in the quantity of Al_2O_3 resulted in a decrease in the wear rate. Furthermore, the optimal tool rotation observed in this study was 1280 rpm, yielding the composite with the lowest wear rate.
3. The hardness analysis revealed that the average hardness of the produced composite was 33–42 HV at 910 rpm, 39–46 HV at 1280 rpm, and 35–39 HV at 1700 rpm, respectively. The distribution of nanoparticles by the FSP tool significantly influences the hardness and wear properties of the composite, with changes in surface hardness attributed to the distribution process during composite production.
4. The primary wear mechanisms observed in raw AA5754 aluminum after testing were abrasive and galling, with wear colonies evident on the surface. In contrast, the produced composite exhibited improved wear mechanisms compared to the AA5754 aluminum alloy, indicating greater strength in this tribological test scenario. Notably, higher FSP tool rotation rates resulted in abrasive wear and surface cracks, while at 1280 rpm, the produced composite predominantly exhibited abrasive wear.

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