



Article

Effect of Hybrid Addition of Boron Nitride and Vanadium Carbide on Microstructure, Tribological, and Mechanical Properties of the AA6061 Al-Based Composites Fabricated by FSP

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Abstract: This work investigates the impact of friction stir processing (FSP) on the microstructure and mechanical characteristics of AA 6061 alloy and its composites, which are strengthened with boron nitride nanoparticles and vanadium carbide microparticles. Composite samples were created using different proportions of reinforcing particles, including mono and hybrid composites. The efficacy of FSP as a technological method for enhancing the grain size of AA 6061 alloy and its composites has been proven. Adding reinforcing particles led to enhanced grain refinement, especially when using VC particles, which demonstrated greater efficacy than BN particles; thus, mono composite AA6061/VC shows the highest percentage reduction (94.29%) in grain size. Hybrid composites with a higher concentration of VC particles exhibited a more symmetrical microhardness profile. The microhardness of hybrid composites with a larger concentration of VC particles (40 vol.%BN + 60 vol.%VC) shows the most significant enhancement, with an increase of 51.61%. The Young's and shear modulus of all composite samples processed by (FSP) had greater values than the wrought AA 6061 alloy. The investigated composite samples, especially 60% BN and 40% VC, enhanced the tribological properties of AA6061 and reduced the wear rate by about 52%. The observed characteristics may be due to BN and VC particles in the hybrid compost. This is because these particles effectively prevent grain elongation and inconsistent movement. This is because reinforcing particles can be tailored to have specific properties for specific applications.

Keywords: FSP; hybrid composite; wear; mechanical properties; grain refinement



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1. Introduction

Aluminum alloys are widely used in many applications due to their outstanding characteristics, such as their superior strength-to-weight ratio, corrosion resistance, and efficient thermal and electrical conductivity [1–4]. However, some materials' hardness and limited wear resistance may limit their applicability under specific conditions [5]. Incorporating ceramic nanoparticles that fit aluminum tendons using FSP represents a promising strategy for advancing high-performance composites. It offers many possible applications. These composites show improved mechanical and microstructural characteristics, such as increased strength and stiffness [6–8]. The single or mono composite aluminum matrix, reinforced with a singular type of particles, represents a composite material wherein a single variety of ceramic nanoparticles is dispersed within an aluminum alloy matrix via FSP [9–11]. This particular composite has several advantages over conventional composite

materials. These advantages include a simpler fabrication process and the ease of fabricating mono composites, unlike hybrid composites that incorporate different types of ceramic nanoparticles [12,13].

Furthermore, using a singular sort of ceramic nanoparticle offers enhanced control over the qualities of the composite material. This includes but is not limited to its strength, hardness, and resistance to wear [14]. Numerous researchers have investigated the impact of BN nanoparticles on aluminum alloy composites [15–18]. Consequently, it has been demonstrated that incorporating BN nanoparticles through FSP leads to notable enhancements in these composites' mechanical and thermal characteristics. The incorporation of BN particles into composite materials leads to increased strength and stiffness characteristics [19]. BN particles affected the thermal and electrical conductivity of two aluminum ligand composites [20]. The increased performance may result from the reinforcement of BN particles, which results in increased strength and stiffness within the composite matrix [21]. Incorporating VC nanoparticles has yielded notable enhancements in the characteristics of aluminum alloy composites produced using friction stir processing (FSP), which enhanced grain size refinement and promoted the dispersion of reinforcement particles. [22,23]. Hybrid reinforcements have been employed in friction-stir composites to improve the surface characteristics of the aluminum matrix [24]. Hybrid nanocomposites have been employed to enhance the surface characteristics of materials by integrating ceramic nanoparticles into an aluminum matrix. Hybrid nanocomposites can be created using boron nitride and vanadium carbide nanoparticles in the composite matrix [25]. FSP has promoted the incorporation and dispersion of various reinforcing particles with different properties and morphologies, allowing hybrid nanocomposites to be fabricated without limitations [26,27]. Therefore, from the previous investigation, there is a lack of studies referring to incorporating BN and VC as a hybrid composite; this research endeavor will serve as the inaugural investigation into the ramifications of integrating both BN and VC particles into AA6061 aluminum alloy. The study will examine mono and hybrid composites, with varying proportions of the hybrid particles. This will facilitate a more comprehensive understanding of the impacts of these particles on the characteristics of AA6061 aluminum alloy.

Moreover, this research will employ a diverse range of methodologies to assess the microstructure and properties of the composites. These methodologies encompass optical and scanning electron microscopy (SEM) and mechanical testing. This will facilitate a more comprehensive understanding of the correlation between the microstructure and properties of the composites.

2. Materials and Methods

The selection of AA6061 rolled plates as the primary matrix in this study was based on its wide range of practical applications and chemical composition, as outlined in Table 1. Nanoceramic reinforcements in the form of BN nanoparticles and VC microparticles were utilized to strengthen the surface of the base alloy. The selection of the reinforcing nanoparticles was based on their capacity to augment the qualities of wear resistance and hardness. The observed physical similarity between these two types of particles is due to the same chemical composition and crystal structure. Both VC and BN offer outstanding characteristics such as high stiffness and inertia, and hexagonal boron nitride (h-BN), with a hardness typically around 2.4 GPa and VC hardness of 28 GPa, respectively. Figure 1 shows the transmission electron microscope images (TEM), JEM-F200, Jeol Ltd., Tokyo, Japan. The TEM analysis demonstrated that the average particle size of the BN and VC is 600 nm and 800 nm, respectively. This makes it a concept for reinforcing particles in composite materials to generate hybrid composite forms using the corresponding volume fraction ratio. This study investigates two mono composites with 100% Al/VC and 100% Al/BN and three hybrid composites with varying compositions of vanadium carbide (VC) and boron nitride (BN): hybrid composite 1 consists of 40% VC and 60% BN, hybrid composite 2 contains 60% VC and 40% BN, and hybrid composite 3 is composed of 50% VC and 50% BN. A

recent study indicates that combining two distinct sources of reinforcement, such as VC and BN, yields a more potent and efficient reinforcement effect than using a single reinforcing element. The volume fraction (V_f) was determined using the following equation:

$$V_f = (V_{np}/V_c) \times 100\%$$

where

V_f is the volume fraction of nanoparticles (%)

V_{np} is the total volume of nanoparticles (mm^3)

V_c is the total volume of the composite (mm^3)

Given the dimensions of the processed composites ($100 \text{ mm} \times 8 \text{ mm} \times 8 \text{ mm}$) and the holes (2 mm diameter, 3 mm depth), with a 3 mm spacing between holes, the calculated V_{np} is 585.34 mm^3 . This results in a V_f of approximately 9.15%:

$$V_f \approx (585.34 \text{ mm}^3 / 6400 \text{ mm}^3) \times 100\% \approx 9.15\%$$

Table 1. Chemical composition of the wrought alloy AA6061.

Element	Mg	Mn	Si	Fe	Cu	Zn	Al
Wt. %	0.71	0.36	0.43	0.83	0.25	0.19	remain

The production of the nanocomposite surface on aluminum plates was achieved by applying the FSP. Before this step, the aluminum plates underwent preparation and cutting procedures with a milling machine. This process resulted in forming a sequence of holes arranged in a linear configuration, as illustrated in Figure 2. The process of incorporating reinforcing nanoparticles into the cavity of the holes was conducted using two separate situations. The second scenario examined the impact of modifying the proportion of reinforcement particles in the hybrid composite matrix. The ceramic particle hybrids underwent a comprehensive blending and agitation process before integrating into the underlying matrix.

The FSP involves the utilization of a rotating tool to generate friction and heat at the interface of two solid materials, enabling their combination. The material is softened by the heat generated from friction, but it does not reach the necessary temperature for melting. Figure 3 illustrates the use of a friction stir tool to fabricate a composite sheet. Heat is generated when there is friction between the shoulder and the workpiece surface. The pin carefully stirs the malleable substance, resulting in a seamless blend. The thermal scan in the figure reveals that the temperature achieved through the FSP reached a maximum of 521°C .

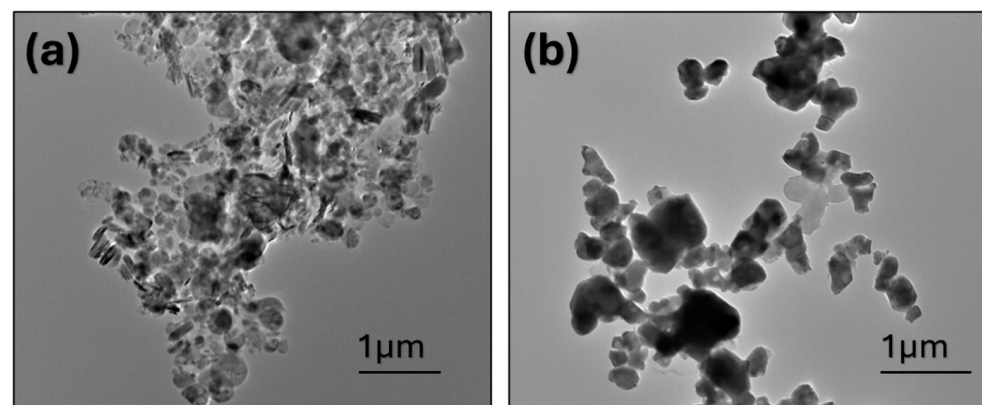


Figure 1. TEM images of the investigated reinforcement particles (a) BN, (b) VC.

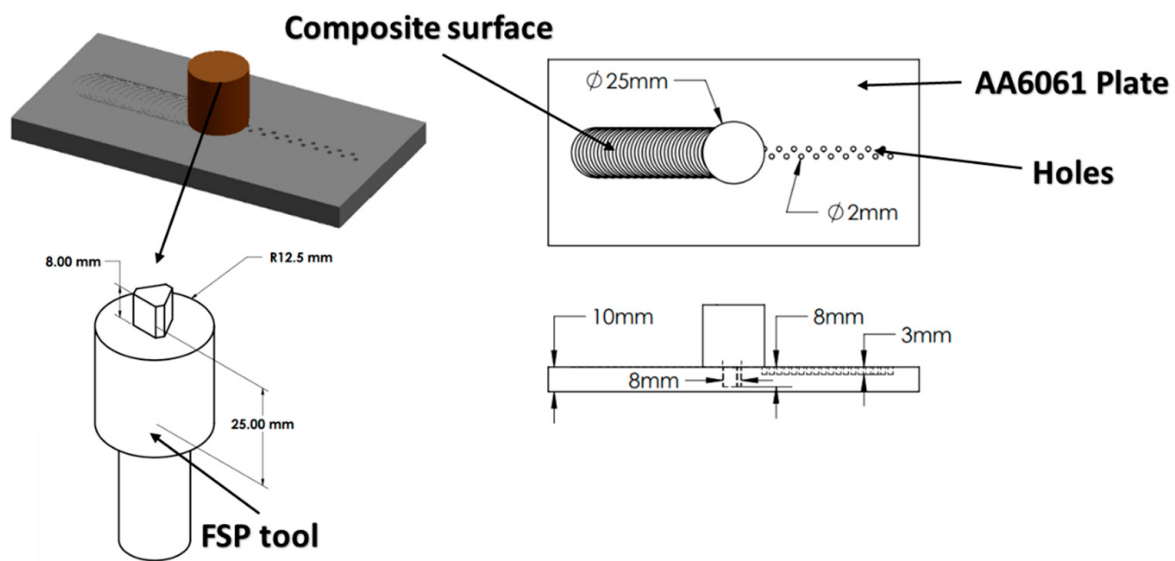


Figure 2. Friction stir process schematic drawing and design.

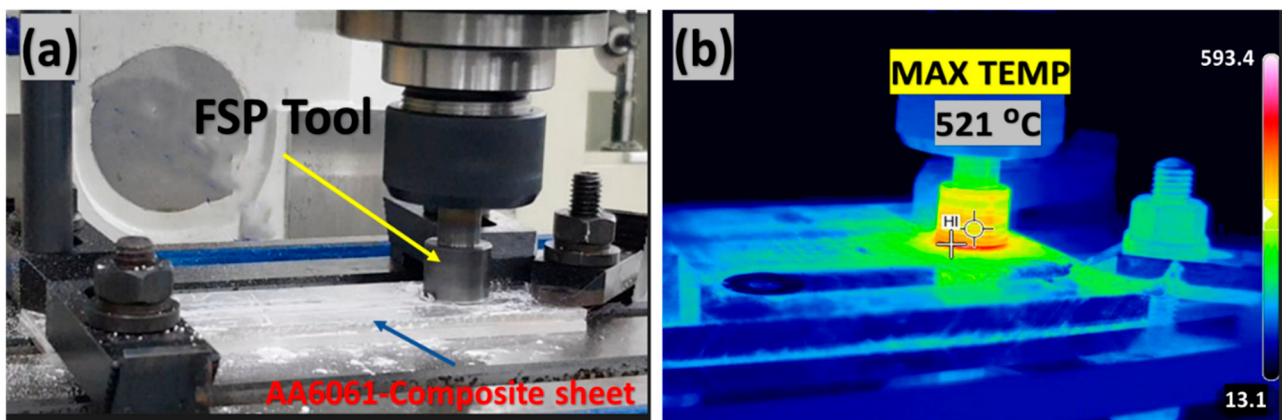


Figure 3. Manufacturing the composite sheet using FSP: (a) typical FSP process using a milling machine, (b) a thermal image during the manufacturing process.

Moreover, the hybrid material is evenly distributed and incorporated into the mixture before inserting into the cavities of the primary matrix. The methodology for testing an automatic milling machine that meets the specified parameters is as follows: tool rotation speed of 1125 revolutions per minute (rpm), linear travel speed of 30 (mm/min), and a constant tilt angle of 3° . The shoulder has a diameter of 25 mm and a special pine profile obtained from a triangular, polygonal profile with chamfered edges and a depth of 6 mm. Triangular, polygonal profiles are often chosen for FSP ferrules due to their perforation and satisfactory soldering quality.

2.1. Mechanical Properties Test

The pulse–echo method (ultrasonic digital signal processing) tests the sintered samples' mechanical properties. This approach allowed us to measure how fast ultrasonic longitudinal waves (VL) and shear waves (VS) moved through the material. With these speeds (VL and VS), we figured out Lamé's constants, as explained in earlier studies [28]. Then, we used Lamé's constants to work out several key elastic moduli of the sintered samples: longitudinal modulus, Young's modulus, shear modulus, and bulk modulus, the exact formulas used for these calculations in the research [29,30].

2.2. Microstructure Analysis

The assessment of the microstructure of friction stir processed (FSP) welds was conducted using optical microscopy (OM) and scanning electron microscopy (SEM). Optical microscopy (OM) was performed using an Olympus BX51 microscope produced in the United States to fully understand the microstructure. The grain size measurement in the FSPed samples was conducted utilizing the linear intercept approach. In this particular approach, a sequence of lines was systematically delineated across the microstructure image, and afterward, the number of grain boundaries intersected by each line was quantified [31]. Calculating the average grain size involved dividing the cumulative number of grain boundaries by the aggregate length of the lines drawn.

2.3. Microhardness Test

The Vickers microhardness profiles were determined by measuring the Vickers microhardness throughout all processing zones. The ZwickRoell microhardness tester was utilized to conduct Vickers microhardness tests in accordance with the ASTM E-384-17 standard. The applied force during the test was 100 g force, and the test duration was 10 s. A minimum of ten hardness measurements were recorded at each specified site.

2.4. Wear Test

The wear test was conducted using a pin-on-disk tribometer, a widely used instrument for assessing the wear resistance of materials. The check methodology employed became the weight loss method, which includes measuring the load of the pin before and after the test to determine the cloth loss due to wear. The wear test was utilized using the following parameters: load of 0.2 bar, speed of 265 RPM, and total time of 10 min.

3. Results and Discussions

3.1. Microstructure Observation

Figure 4 illustrates a notable disparity in grain size between the AA6061 base alloy and the stirred zone after the implementation of the FSP. The base alloy has an average grain size of 210 μm , whereas the stirred zone displays a refined grain with an average size of 13 μm . The observed decrease in grain size can be ascribed to the dynamic recrystallization phenomenon. During FSP, the material changes its crystal structure due to intense plastic deformation, which results in smaller grains. We expect this grain size reduction in the stirred zone to improve the material's mechanical properties, making it stronger, more flexible, and less prone to fatigue. This happens because smaller grains are less likely to have structural flaws, such as dislocations and grain boundaries. Flaws in a material can become starting points for cracks. As a result, materials with smaller grain sizes tend to be tougher and more resistant to fatigue. The presented figure also illustrates the disparity in grain shape between the base alloy and the stirred zone. The grains present in the base alloy exhibit equiaxed morphology, indicating that their diameters are about equivalent in all directions. In contrast, the grains within the stirred zone exhibit elongation along the path of the FSP tool. Figure 4 shows the grain size distribution in the SZ of the manufactured composites, Al/BN, Al/VC, and hybrid Al/50%BN + 50%VC. The Al/BN composite exhibits the narrowest distribution of grains about the mean, while the other composites exhibit close distribution about the average grain size. The narrow distribution of grains about the mean reflects the uniformity of equiaxed grains in the stirred zone of the manufactured composites. The sample designated as hybrid composite 50%BN_50%VC has the most significant role of refined grain, measuring 94.3%, as shown in Figure 5.

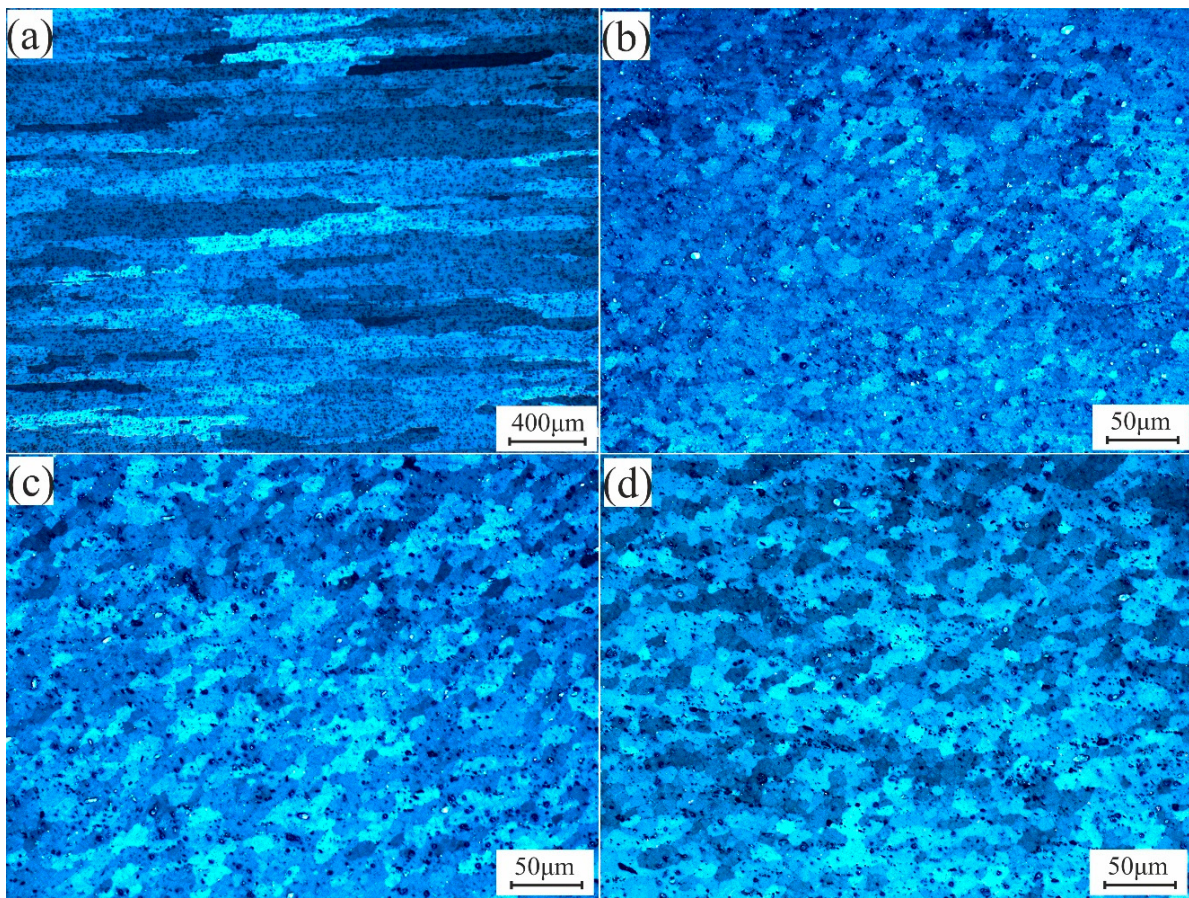


Figure 4. Optical micrographs showing the grain structure of (a) AA 6061 base alloy and (b) the refined grain structure in the stirred zone after friction stir processing (FSP), (b) Al/BN, (c) Al/VC, and (d) hybrid Al/50%BN + 50%VC.

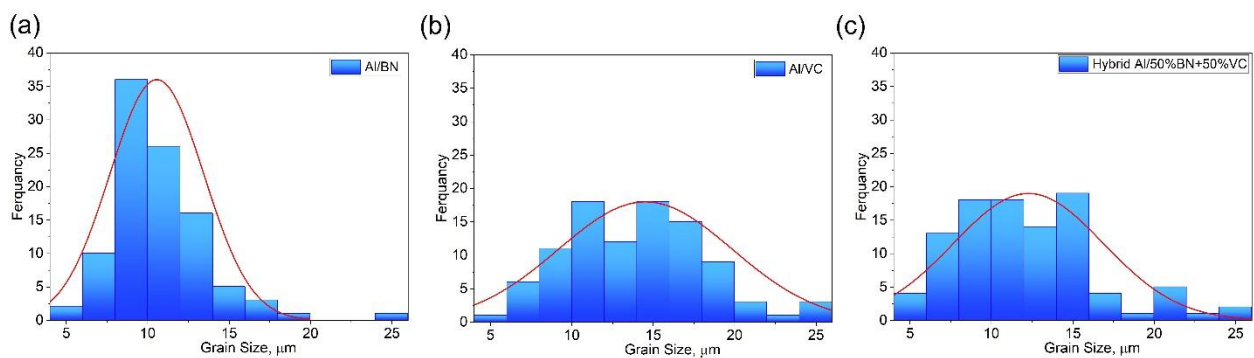


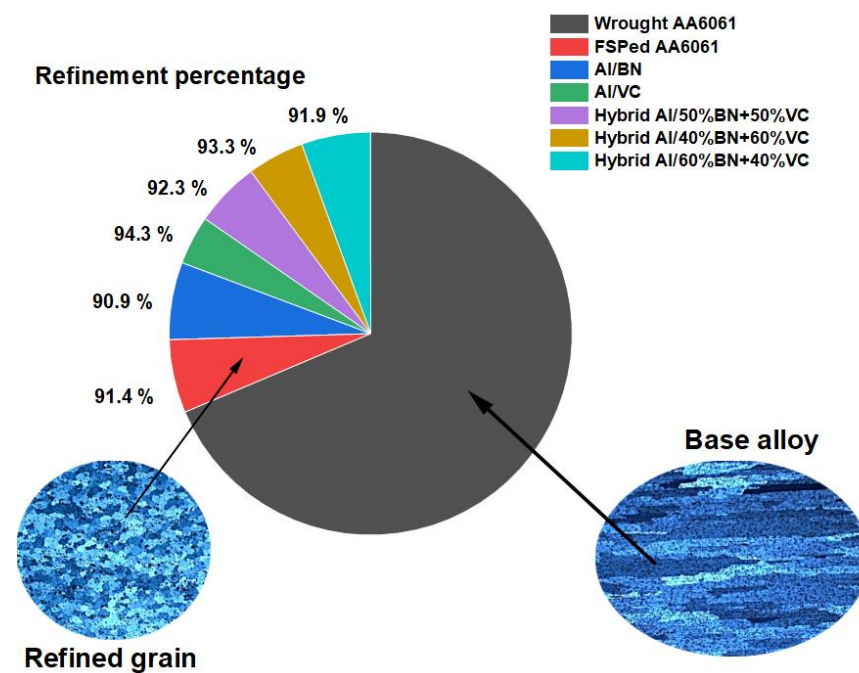
Figure 5. Grain size distribution of the manufactured composites in the stirred zone: (a) Al/BN, (b) Al/VC, and (c) hybrid Al/50%BN + 50%VC.

Table 2 shows the values of the average grain size and the standard deviation of the normal distribution of the grains about the mean for the manufactured composites. The manufactured composites exhibit significant differences in standard deviations; for example, the grain size distribution is narrow for the Al/BN composite with the lowest standard deviation. The other composites have a close grain size distribution; however, the hybrid Al/50%BN + 50%VC composite has a lower standard deviation of 4.6 μm .

Table 2. The average grain size and the standard deviation of grain distribution of the manufactured composites.

	Al/BN	Al/VC	Hybrid Al/50%BN + 50%VC
Average grain size, μm	10.5 ± 2	14.5 ± 5	12.3 ± 4
Standard deviation, mm	2.9	5.3	4.6

The probable cause of this effect is the composition of the 50%BN_50%VC hybrid composite, which combines BN and VC particles. This combination appears more effective in inhibiting grain development throughout the FSP process. Adding reinforcing particles can make the grains even smaller and boost the material's mechanical properties. Notably, the hybrid composite 50%BN_50%VC and 40%BN_60%VC samples show bigger drops in grain size than the mono composite BN and mono composite VC samples. Further enhancement was observed with the addition of BN and VC, with Al/VC showing the highest refinement at 94.3%. Hybrid combinations of BN and VC also proved effective, particularly Al/40%BN + 60%VC with 93.3% refinement, as shown in Figure 6. The pie chart visually represents these data, where larger slices correspond to higher refinement percentages, confirming the positive correlation between processing technique/additives and grain refinement.

**Figure 6.** Percentage of grain refinement due to friction stir processing (FSP) in AA 6061 alloy and its composites.

The SEM image shown in Figure 7 is for the more detailed study of BN and VC, which are uniformly dispersed particles that fit well into the AA6061 matrix like any other organically formed hybrid composite. As described earlier, the homogeneous distribution of reinforcing particles throughout the composite is important when seeking better mechanical properties. That makes it so the particles will not agglomerate (or group up). It was attributed to the manufacturing method used for fabricating composite material, which used reinforcement particles to be uniformly dispersed in a matrix. Figure 7c shows the effectiveness of the FSP process in homogenizing the hybrid particles inside the composite matrix. Figure 8a shows the agglomerate clusters of BN particles in the hybrid AA6061/60%BN + 40%VC, while Figure 8b shows the homogeneous distribution of the hybrid AA6061/50%BN + 50%VC. The methodology above can effectively disperse rein-

forcement particle clusters, facilitating a homogeneous matrix distribution. The uniform dispersion of reinforcing particles presents a multitude of benefits. The initial approach to improving the mechanical characteristics of the composite involves the introduction of supplementary barriers to impede crack propagation [32].

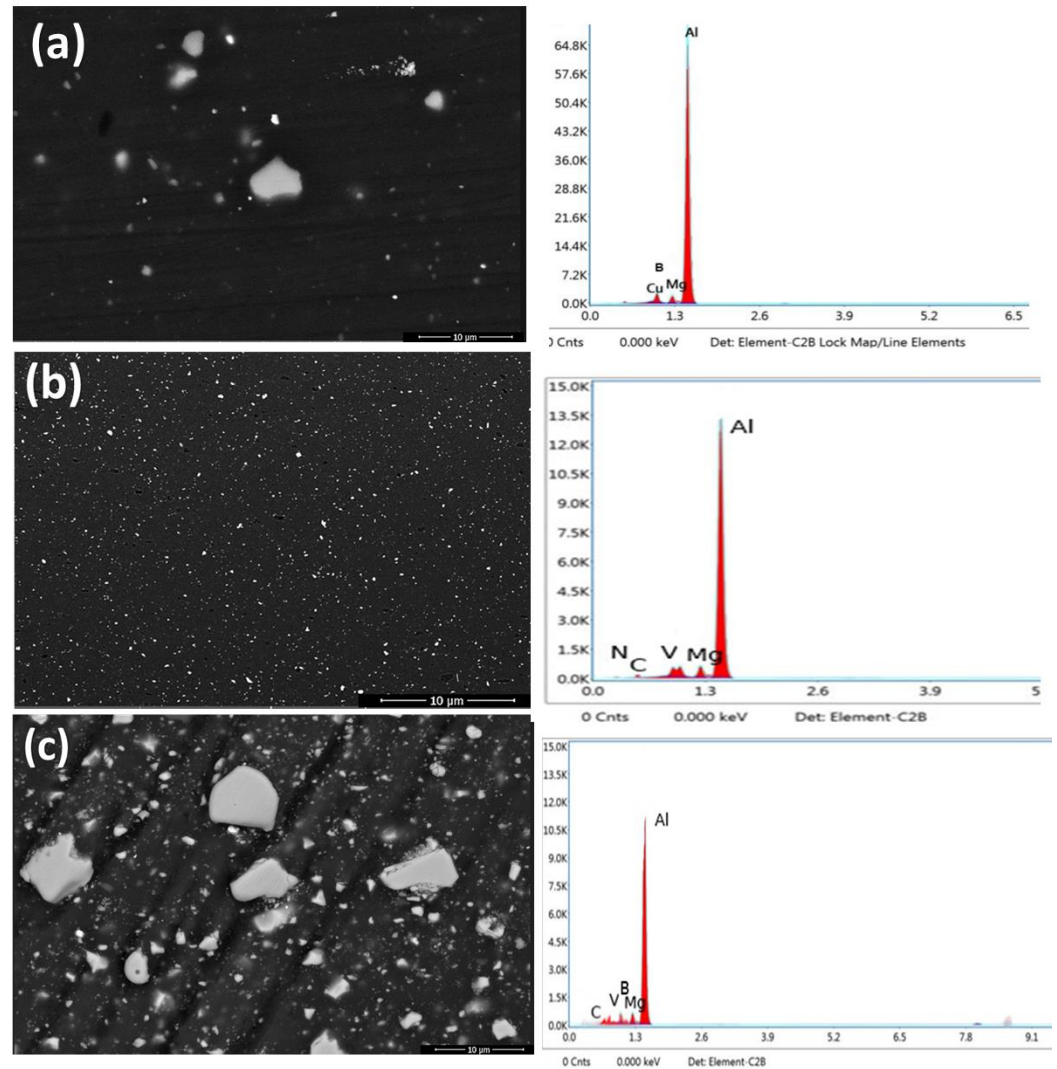


Figure 7. (SEM) images of hybrid composite samples containing (a) AA6061/BN mono composite, (b) AA6061/VC mono composite, and (c) hybrid composite AA6061/40%BN + 60%VC.

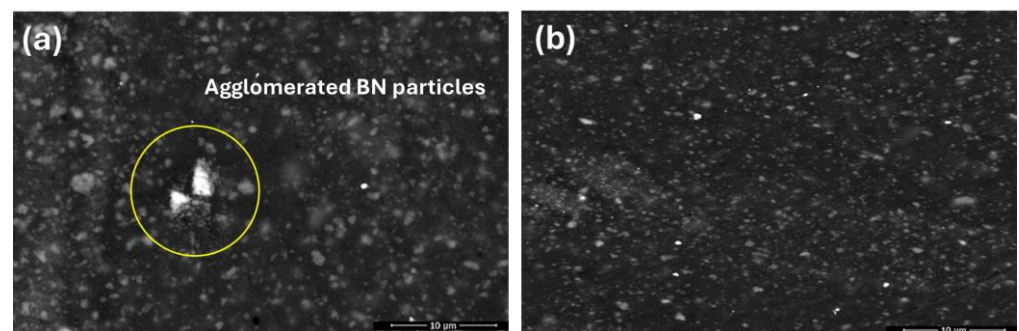


Figure 8. (SEM) images of hybrid composite samples containing (a) 60% BN + 40%VC, (b) hybrid composite AA6061/50%BN + 50%VC.

The distribution of reinforcement particle stitches after FSP is closely related to the characteristics of these nanoparticles. Differently distributed hard reinforcement particles, such as VC and soft reinforcement particles (BN), are presented in this study. VC particles were discovered at the surface or just below the second layer of the FSP-processed specimen. Because the particles were so hard, they could not move fully into the matrix, and similarly, they were partially inhibited by stirring and cracks sticking out onto part surfaces. The exudation of the particles from the matrix is sometimes added by leaving a large void visible at the surface level. The particles were exposed on the surface or second layer of the FSP-processed specimen through this void. However, the VC and BN particles were well distributed inside the nugget zone of the FSP-processed specimen. The observation was that their particle size became finer than before the FSP was conducted. This was due to the particle fragmentation that took place during FSP. This act is important in cases of hard reinforcement particles since the hard particles can cause tool fracture during FSP. The tool fracture will damage the surface texture of the welds, leading to a need to polish the surface texture and poor wear resistance. No surface void was observed for the VC particles. This was considered an improvement gained by FSP in the wear resistance of the FSP-processed specimen.

3.2. Bulk Density Observation

The density of all samples subjected to (FSP) exhibits a marginal increase compared to the wrought AA 6061 alloy, except for the mono composite Al/BN, which demonstrates a slightly lower density. The theoretical densities of the VC and BN are 5.77 g/cm^3 and 2.27 g/cm^3 , respectively. Thus, reinforcing particles, especially VC, increase material density in the AA 6061 alloy. The Al/VC mono composite shows the highest density among the tested specimens, as shown in Figure 9. The observed rise in density can be attributable to the reinforcing particles' higher density than the AA 6061 alloy. It is vital to acknowledge that the density of a substance is only one contributing element that influences its characteristics. The role of other elements, such as the composition and dispersion of the reinforcing particles, should also be considered. Hence, it is imperative to consider all of these elements while designing and developing materials with the intended qualities. The FSP technique demonstrates its applicability in the fabrication of AA 6061 alloy and its composites, offering diverse densities. The density of the material can be modified by manipulating the composition and quantity of the reinforcing particles employed.

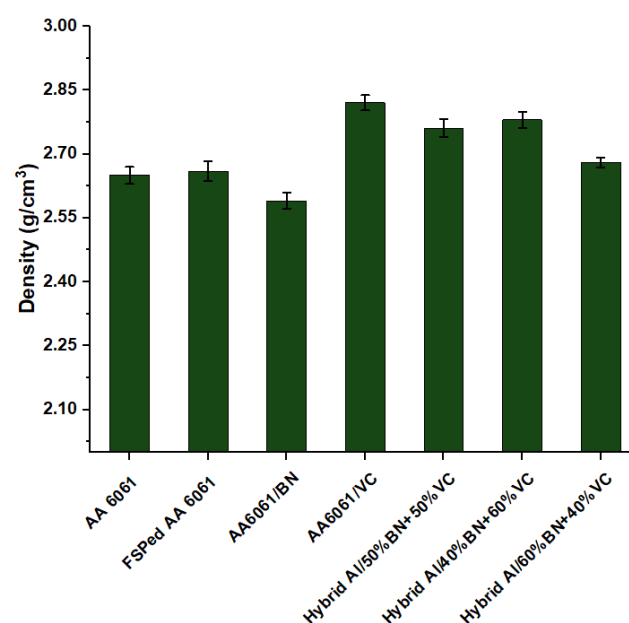


Figure 9. Bulk density values of the investigated samples.

3.3. Microhardness Profile

Figure 10 shows the investigated sample's microhardness profile; thus, all composite samples' microhardness is higher than that of the wrought AA 6061 alloy. This is due to the presence of reinforcing particles in the composite samples. Figure 10a shows the microhardness comparison of wrought AA 6061, FSPed AA 6061, and AA 6061 reinforced with various BN and VC composites. The addition of BN and VC generally increases the microhardness, with hybrid composites showing the highest values. Figure 10b shows the microhardness profiles across the stir zone of friction stir processed AA 6061 and its composites. All composites exhibit a significant increase in microhardness within the stir zone compared to the base AA 6061. Hybrid composites demonstrate a more comprehensive and uniform hardness distribution across the stir zone.

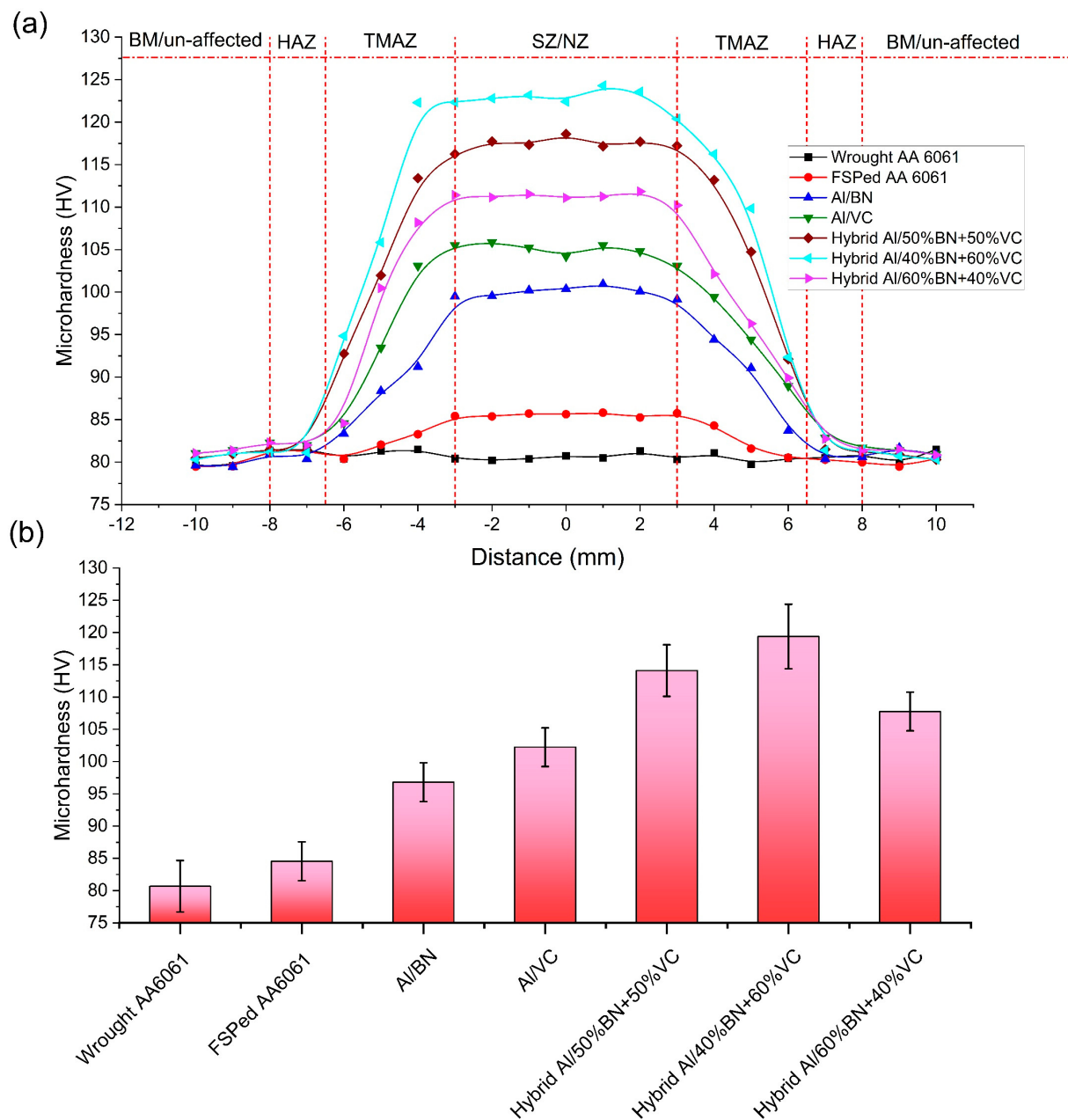


Figure 10. Microhardness behavior (a) AVG microhardness value in the stirred zone; mechanical properties: (b) profile of the base metal, mono composite, and hybrid composite samples fabricated through friction stir processing (FSP).

The microhardness of all composite samples decreases with increasing distance from the composite surface. This is because the grain size of the composite material increases with increasing distance from the composite surface. The hybrid composite samples have the highest microhardness values. The hybrid composite samples contain BN and VC particles, which can effectively hinder grain growth and dislocation movement. The microhardness profile of the 40%BN_60%VC hybrid composite is more symmetrical than the microhardness profile of the other composite samples. This may occur because the 40%BN_60%VC has a higher percentage of VC particles, which are more evenly distributed in the matrix. The microhardness profiling results show that the FSP process can produce AA 6061 and composites with various microhardness values. The microhardness of the material can be tuned by adjusting the type and amount of auxiliary particles' force used. The microhardness profile results significantly impact the design and development of AA6061 ligands and composites. For example, the results suggest that hybrid compost containing equal amounts of BN and VC particles can fabricate materials with higher hardness values. Additionally, the results indicated that hybrid compost with more VC particles could produce materials with a more symmetrical microhardness profile. Therefore, the microhardness profile results can be used to design and develop AA 6061 alloy and its composites with the desired mechanical properties for specific applications.

3.4. Mechanical Properties

Figure 11 demonstrates the significant impact of FSP and reinforcing particles (BN and VC) on the mechanical properties of AA6061 aluminum alloy. FSP alone slightly increased both Young's modulus (by 1%) and shear modulus, while the addition of BN and VC led to substantial improvements, particularly with Al/VC, which showed a 34.4% increase in Young's modulus and a 34.1% increase in shear modulus compared to the wrought alloy. Combining BN and VC, hybrid composites offered a balance of properties, with Al/40%BN + 60%VC exhibiting the highest values among the hybrid combinations. Figure 10a displays the Young's modulus of all composite samples. The mono and hybrid composites have a higher magnitude than the wrought AA 6061 alloy. The observed outcomes can be ascribed to the incorporation of reinforcing particles inside the composite samples. The hybrid composite samples have the highest Young's modulus values. The likely reason for this phenomenon can be traced to hybrid composite samples of BN and VC particles. It is hypothesized that these particles have improved capacities to hinder both the formation of grains and the movement of dislocations. The Young's modulus of the mono composite containing VC particles is greater than that of the BN particles. The hybrid composite sample, consisting of equal parts boron and vanadium 50%BN_50%VC, demonstrates a greater Young's modulus value in comparison to the hybrid composite samples composed of 40%BN_60%VC and 60%BN_40%VC. The observed phenomena can be ascribed to the equilibrated composition of the 50%BN_50%VC hybrid composite, where an equivalent ratio of BN and VC particles is present. It is considered that this well-balanced composition has a stronger inhibitory effect on the growth of grains and the movement of dislocations. The Young's modulus of a material is a crucial property that affects its stiffness and ability to withstand deformation. Therefore, Young's modulus results can be applied in developing and improving AA 6061 alloy and its composites, allowing for achieving desired rigidity and durability levels customized for specific uses. The results suggest hybrid composite samples with equal amounts of BN and VC particles can generate materials demonstrating the highest modulus values. Figure 11b indicates that hybrid composite specimens with a higher concentration of VC particles lead to increased shear modulus. Nevertheless, this mechanical characteristic improvement may be followed by a decrease in malleability. The results of the shear modulus measurements suggest that the FSP process is effective in manufacturing AA 6061 alloy and its composites, showing a wide range of shear modulus values.

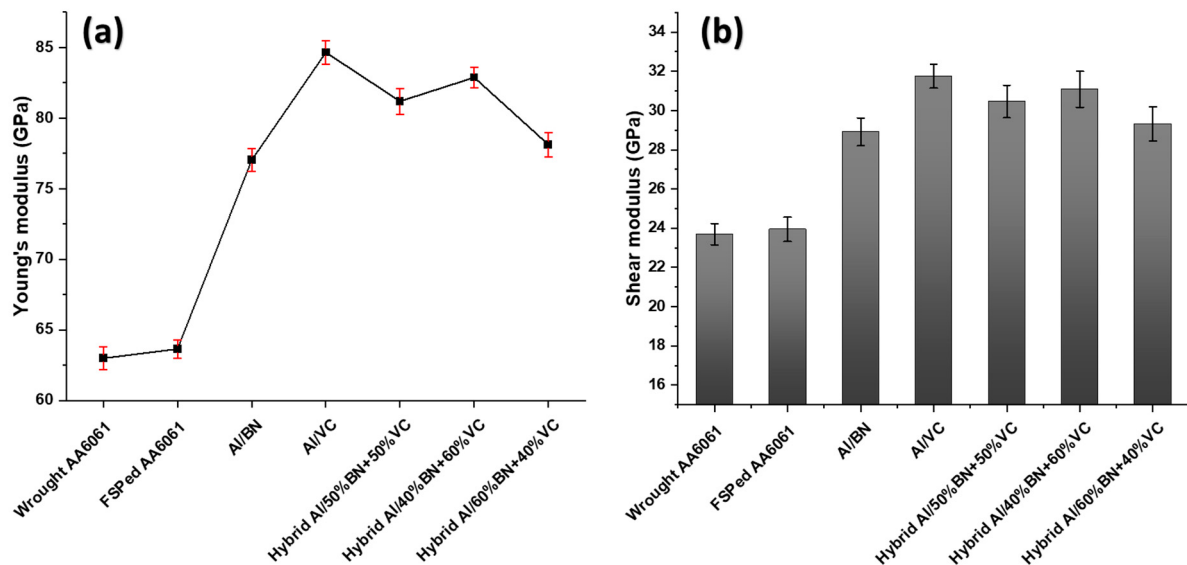


Figure 11. Mechanical properties: (a) Young's modulus of AA 6061 alloy and its composites with different reinforcement percentages, (b) influence of shear modulus on AA 6061 alloy and its composites.

3.5. Wear Results

The analysis of the wear rate data reveals that incorporating reinforcing particles, either BN or VC, enhances the wear resistance of the base material, wrought AA6061. This enhancement is evident in the reduction of wear rates for both individual particle additions and hybrid compositions. Notably, the Al/BN sample exhibits the most substantial improvement, with a 76.19% reduction in wear rate compared to the baseline, as shown in Figure 12. Boron nitride possesses exceptional lubricity, significant hardness, and commendable heat stability. These characteristics provide an efficient deterrent to deterioration. Its composition, akin to graphite, facilitates effortless ring and sliding, diminishing friction and, consequently, wear. Vanadium carbide exhibits significant hardness and wear resistance but to a lesser degree than boron nitride. It is recognized for its robustness and capacity to endure elevated temperatures, enhancing wear performance relative to the base alloy. The notable reduction in wear rate for the Al/BN composite (from around 0.06 g/min to around 0.01 g/min) underscores the considerable enhancement in wear resistance attributable to the incorporation of BN. This significant decrease indicates that BN efficiently safeguards the aluminum matrix from wear. Al/VC demonstrates a decreased wear rate (about 0.04 g/min), corroborating the beneficial effect of VC.

Nonetheless, the enhancement is less significant than with BN, suggesting that VC provides somewhat worse wear resistance. Hybrid composites, comprising both BN and VC, demonstrate intermediate wear rates, reinforcing the notion that BN significantly contributes to improved wear resistance. This improvement can be attributed to the increased hardness, compressive strength, Young's modulus, and grain refinement resulting from adding BN particles.

In contrast, the FSPed AA6061 sample shows a slight increase in wear rate, indicating that the FSP technique may not be effective in improving the wear resistance of AA6061. The hybrid composites, combining BN and VC particles, also demonstrate significant improvements in wear resistance, with the hybrid Al/60%BN + 40%VC sample achieving a 52.38% reduction in wear rate. This suggests that the combination of BN and VC particles can synergistically enhance the wear resistance of AA6061.

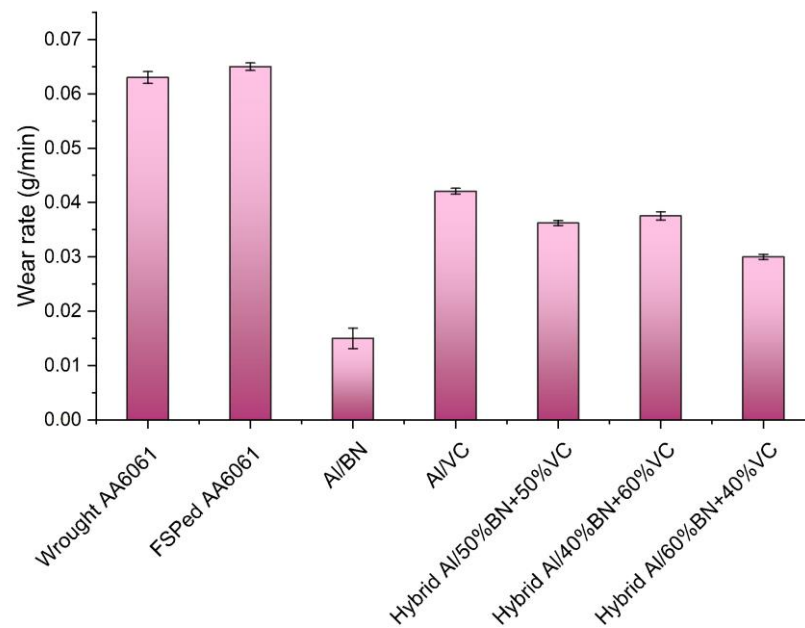


Figure 12. The wear rate behavior of the investigated sample using the weight loss method.

Based on the data represented in Figure 13, it can be observed that all composite samples demonstrate improvements in all measured properties when compared to the base AA6061 alloy. The most consistent improvement in all composite types was seen with a reduction in grain size. Averaging more than 90%, hybrid composites generally show significant improvements in hardness, compressive stress, and Young's modulus compared to mono composites. The 40%B_60%VC hybrid composite had the most critical enhancements in hardness (51.61%), compressive stress (28.21%), and Young's modulus (31.57%) compared to other composites. However, determining the most suitable composite material depends on the specific application terms. For example, achieving maximum hardness is the most important thing; the 40%BN_60%VC hybrid composite is considered the most suitable choice. The 40%BN_60%VC or 50%BN_50%VC hybrid composite option is recommended for applications requiring high Young's modulus and overall improvement. Incorporating hybrid composites containing BN and VC particles significantly enhances the wear resistance of AA6061. Notably, the hybrid composite with 60% BN and 40% VC demonstrates a substantial improvement of 52.38% in wear resistance. This enhancement can be attributed to the combined positive effects of BN and VC particles, contributing to improved hardness, compressive strength, Young's modulus, and grain refinement. The hybrid composite's superior performance in wear resistance highlights its potential for applications where material durability under wear and tear is critical.

According to the current work and previous investigations mentioned in the literature, many attempts have been made to improve the properties of AA6061 aluminum alloy by compositing it with hard particles. The current work shows that FSP is an effective method for improving the properties of AA6061 aluminum alloy. The addition of BN and VC particles to AA6061 aluminum alloy resulted in a significant improvement in hardness. The most improvement was observed in the composite reinforced with 40% BN and 60% VC hybrid composite, with a 51.61% increase in hardness. Hybrid composites also showed a considerable gain in wear resistance with a 52.38% reduction in wear rate, particularly in the hybrid Al/60%BN + 40%VC sample. Previous studies have also shown that adding reinforcing particles to AA6061 aluminum alloy can improve its hardness. For example, one study showed that the microhardness and Rockwell hardness of AA6061 base alloy increased by 17.02% and 33.80%, respectively, with the addition of 2.5 wt% CeO₂ [33]. Another study showed that the hardness of AA6061 aluminum alloy was significantly improved by up to 5 wt% of SiC particles [34]. The current work and previous

studies suggest that adding reinforcing particles to AA6061 aluminum alloy can enhance its properties [35]. The most significant improvement in hardness was observed in the current work, which used a hybrid composite of 40% BN and 60% VC. This suggests that using a hybrid composite of BN and VC particles may be more effective than using a single reinforcing element.

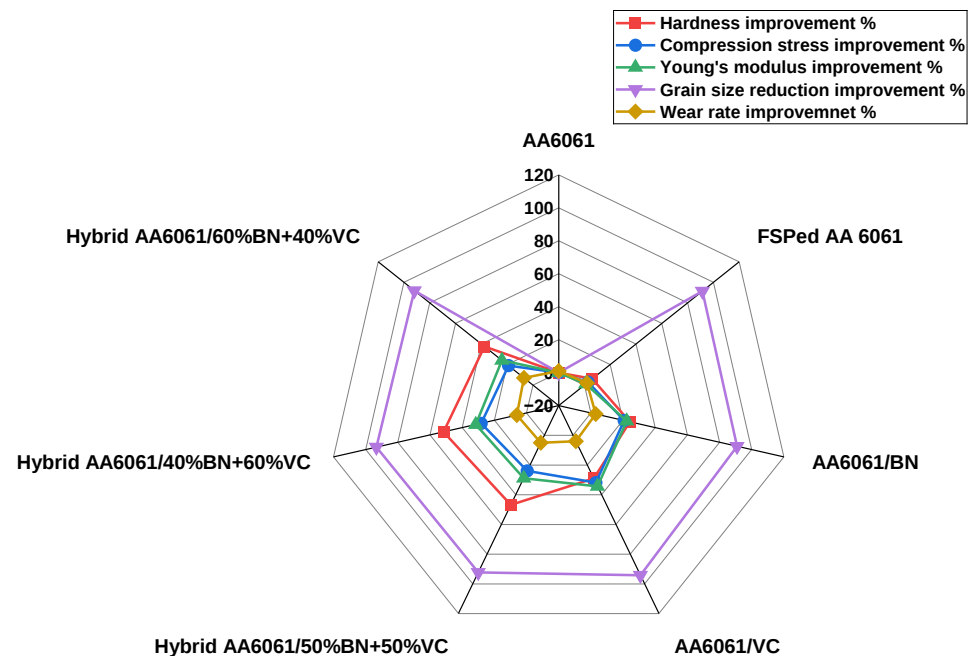


Figure 13. The radar plot shows the comparative performance of AA6061 and its composites.

4. Conclusions

This study investigated the effect of friction stir processing (FSP) on AA6061 aluminum alloy and its composites reinforced with BN and VC particles. The results showed that FSP is an effective method for the preparation of AA6061 grain size, which was reduced by more than 90% on average across all mix types. VC addition had a positive effect on grain refinement, with VC particles shown to be significantly more effective than BN effects on grain growth, which were inhibited for FSP. Hybrid composites typically combining BN and VC particles showed significant improvements in hardness, tensile stress, and Young's internal modulus compared to mono composites; for example, the 40%BN_60%VC hybrid composite showed substantial increases in terms of hardness (51.61%), compressive stress (28.21%), and Young's parameter (31.57%) compared to other composites. Hybrid composites also showed significant improvement in wear resistance for the hybrid Al/60%BN + 40%VC sample. The incorporation of the AA6061 alloy with the reinforcement particles led to a significant improvement in the hardness of all the manufactured composites. The highest hardness enhancement was obtained in the composite reinforced with hybrid 40% BN and 60% VC. A remarkable 52.38% reduction in wear rate was obtained. The findings indicated that adding hybrid composites containing BN and VC fragments could significantly increase the mechanical properties and wear resistance of AA6061. The selection of the most appropriate composite, whether 40%BN_60%VC or 50%BN_50%VC composite, depends on the needs of the specific application through factors such as desired stiffness and Young's modulus, and improvement occurs upon consideration of all technical factors.

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