

Exploring Microstructural, Interfacial, Mechanical, and Wear Properties of AlSi7Mg0.3 Composites with TiMOVWCr High-Entropy Alloy Powder

Shashi Prakash Dwivedi,^{*} Shubham Sharma,^{*} Changhe Li, Yanbin Zhang, Rajesh Singh, Abhinav Kumar, Fuad A. Awwad,^{*} M. Ijaz Khan, and Emad A. A. Ismail^{*}

Cite This: *ACS Omega* 2024, 9, 18813–18826

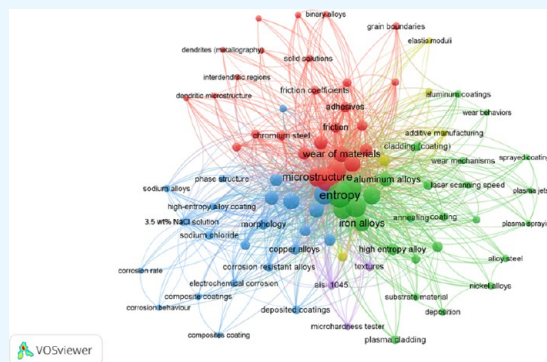
Read Online

ACCESS |

Metrics & More

Article Recommendations

ABSTRACT: This study explored the impact of varying weight percentages of TiMoVWCr high-entropy alloy (HEA) powder addition on A356 composites produced using friction stir processing (FSP). Unlike previous research that often focused on singular aspects, such as mechanical properties, or microstructural analysis, this investigation systematically examined the multifaceted performance of A356 composites by comprehensively assessing the microstructure, interfacial bonding strength, mechanical properties, and wear behavior. The study identified a uniform distribution of TiMoVWCr HEA powder in the composition A356/2%Ti2%Mo2%V2%W2%Cr, highlighting the effectiveness of the FSP technique in achieving homogeneous dispersion. Strong bonding between the reinforcement and matrix material was observed in the same composition, indicating favorable interfacial characteristics. Mechanical properties, including tensile strength and hardness, were evaluated for various compositions, demonstrating significant improvements across the board. The addition of 2%Ti2%Mo2%V2%W2%Cr powder enhanced the tensile strength by 36.39%, while hardness improved by 62.71%. Similarly, wear resistance showed notable enhancements ranging from 35.56 to 48.89% for different compositions. Microstructural analysis revealed approximately 1640.59 grains per square inch for the A356/2%Ti2%Mo2%V2%W2%Cr processed composite at 500 magnifications. In reinforcing Al composites with Ti, Mo, V, W, and Cr high-entropy alloy (HEA) particles, each element imparted distinct benefits. Titanium (Ti) enhanced strength and wear resistance, molybdenum (Mo) contributed to improved hardness, vanadium (V) promoted hardenability, tungsten (W) enhanced wear resistance, and chromium (Cr) provided wear resistance and hardness. Anticipating the potential applications of the developed composite, the study suggests its suitability for the aerospace sector, particularly in casting lightweight yet high-strength parts such as aircraft components, engine components, and structural components, underlining the significance of the investigated TiMoVWCr HEA powder-modified A356 composites.



1. INTRODUCTION

High-entropy alloys (HEAs) have emerged as promising reinforcement materials in composite applications, particularly when combined with aluminum matrices. HEAs are unique materials composed of multiple elements in near-equiatomic proportions, leading to exceptional mechanical, thermal, and functional properties compared with traditional alloys. When integrated as reinforcements in aluminum-based composites, HEAs contribute to a wide array of enhancements.¹ The addition of titanium (Ti), molybdenum (Mo), vanadium (V), tungsten (W), and chromium (Cr) elements to aluminum alloy through friction stir processing (FSP) yields multifaceted benefits. Individually, Ti enhances strength and corrosion resistance, Mo contributes to improved toughness, V enhances hardenability, W imparts superior wear resistance, and Cr provides corrosion resistance and hardness. When combined in high-entropy alloy (HEA) formation by using FSP, these

elements synergize to create a unique microstructure with enhanced mechanical properties. The FSP technique ensures a fine and uniform distribution of these elements, resulting in improved hardness, tensile strength, and wear resistance in the aluminum alloy. The HEA composition, derived through FSP, thus delivers a composite material that excels in diverse applications due to its heightened mechanical performance and durability.^{2,3}

Received: October 8, 2023

Revised: January 9, 2024

Accepted: January 12, 2024

Published: April 17, 2024



The incorporation of TiMoVWCr high-entropy alloy (HEA) powder reinforcement into A356 composites holds significant promise, marked by enhanced mechanical properties and multifaceted performance improvements.⁴ The A356 composites exhibit substantial increases in tensile strength, hardness, and wear resistance after the addition of a TiMoVWCr HEA powder. This points to the potential for manufacturing advanced materials with superior structural integrity and durability.^{5–7} The significance of A356 composites with TiMoVWCr HEA powder reinforcement extends to their potential applications across diverse industries. In aerospace engineering, these composites can find utility in casting crucial components, such as engine parts and structural elements. The combination of lightweight properties and heightened strength makes them particularly attractive for aircraft applications, where material efficiency is paramount.^{8,9} Moreover, the improved wear resistance positions these composites for applications in various industrial settings, such as manufacturing machinery components, where resistance to abrasion and fatigue is essential. The ability to tailor the composition of A356 composites with TiMoVWCr HEA reinforcement allows for customization, catering to specific requirements in sectors ranging from automotive manufacturing to marine engineering.^{10,11}

The friction stir processing (FSP) technique has emerged as a transformative method for developing aluminum-based composites. FSP involves using a rotating tool to stir and consolidate materials in the solid state, facilitating the incorporation of reinforcement materials into an aluminum matrix.^{12,13} This innovative process eliminates the melting and solidification associated with traditional methods, preserving the material's integrity and producing a fine, homogeneous microstructure.^{12,15} In the context of aluminum-based composites, FSP enables the uniform distribution of reinforcing elements, such as nanoparticles, fibers, or alloys, within the aluminum matrix.^{16–19} This leads to enhanced mechanical properties, improved wear resistance, and increased strength without sacrificing the inherent lightweight nature of aluminum.^{20,21} The FSP technique offers precise control over the composite's microstructure and properties, making it a promising approach for tailoring materials to specific applications in industries ranging from aerospace to automotive and beyond.²²

Li et al.²³ fabricated a Ni–Cu composite interlayer on the A356 aluminum alloy solid insert using chemical nickel-plating and electro-coppering technology. This aimed to mitigate the formation of brittle phases and enhance the shear strength in the A356 aluminum/AZ91D magnesium bimetal produced through compound casting. The study on the Ni–Cu composite interlayer's impact on microstructure, mechanical properties, and corrosion resistance revealed effective suppression of brittle Al–Mg intermetallic compounds (IMCs). The interlayer reduced the interface thickness from 1400 to 40 μm , resulting in a remarkable 20.3% increase in shear strength compared to the bimetal without the Ni–Cu composite interlayer. Qin et al.²⁴ investigated the impact of sintering temperature on microstructure and damping capacity in multilayer 316L stainless steel hollow spheres/A356 alloy composites reinforced by NiTi alloy sheets. Experiments reveal that the sintering temperature significantly influences composite properties. Notably, composites sintered at 640 °C exhibit the lowest density ($2.42 \pm 0.21 \text{ g/cm}^3$) and the highest porosity ($43.1 \pm 2.1\%$). The remaining NiTi alloy sheets at

this temperature contribute to a higher plateau stress ($125.06 \pm 2.27 \text{ MPa}$) and loss factor (0.032 ± 0.006), showcasing the crucial role of sintering conditions in composite behavior. Pandey et al.²⁵ synthesized the A356–K2ZrF6 composite via in situ reaction, confirmed by X-ray diffraction (XRD) analysis showing the successful formation of Al3Zr reinforcement. Microstructure examinations revealed uniform dispersion of blocky-shaped Al3Zr particles, enhancing tensile strength but reducing elongation in the A356/Al3Zr composite. Lu et al.²⁶ fabricated 3D-SiCp/A356 composites, featuring an interpenetrating microstructure, through pressure infiltration of the A356 alloy into a 3D-SiC ceramic preform. The thermal expansion coefficient of the SiC/A356 composite with oxidized SiC particles was lower than that of the unoxidized counterpart, showing maxima at 420 and 350 °C. Overburning at 565 °C led to a rapid decrease in the thermal expansion coefficient in the A356 matrix. Niu et al.²⁷ delved into the microstructural evolution and mechanical properties of the T6-treated A356–0.3 wt % Ce–1.5 vol % TiCN composite. Compared to the T6-treated A356 alloy, the composite exhibits notable grain refinement and eutectic Si modification effects, akin to the T6-treated A356–0.3 wt % Ce alloy. Significantly, in situ-reinforced (Al,Si)₃(Ti,Ce) precipitates were identified in the T6-treated A356–0.3 wt % Ce–1.5 vol % TiCN composite. Mazaheri et al.²⁸ produced an A356/Cr3C2–NiCr surface composite, through high-velocity oxy-fuel and postfriction stir processing treatment, that exhibited improved mechanical and tribological properties. Uniaxial tensile test results revealed that friction stir processing enhanced the yield strength and ultimate tensile strength. The four-pass friction stir processed composite demonstrated approximately 53 and 22% higher YS and UTS than the base material. Teng et al.²⁹ explored the impact of continuous rheological extrusion with Al–5Ti–0.6C– α Ce alloy addition on the mechanical properties of the A356 alloy. As the Ce content increased (0–2.0 wt %), the α -Al grain size and coarse needlelike phase length varied nonmonotonically. Optimal refinement occurred at 1.0 wt % Ce, yielding enhanced tensile strength, yield strength, and elongation: 290.45 MPa, 238.27 MPa, and 2.80%, respectively.

While the utilization of high-entropy alloys (HEAs) as reinforcements in aluminum-based composites has gained attention, there is a notable research gap regarding the specific influence of varying weight percentages of TiMoVWCr HEA powder on the microstructure, interfacial bonding strength, mechanical properties, and wear behavior of A356 composites fabricated by using the friction stir processing (FSP) technique. Existing studies often focus on a single aspect, such as mechanical properties or microstructural analysis, without systematically investigating the comprehensive effects of HEA content variation on the multifaceted performance of A356 composites fabricated through FSP.

This research addresses a significant gap in the current literature by systematically examining the effect of different weight percentages of TiMoVWCr HEA powder on a range of properties, such as the microstructure, interfacial bonding strength, mechanical behavior, and wear resistance of A356 composites fabricated via FSP. The novelty lies in the holistic approach, elucidating the interplay between the HEA content and composite properties, which is crucial for optimizing material performance. This study's comprehensive nature contributes to a deeper understanding of HEA powder-reinforced A356 composites, providing valuable insights for

designing advanced materials tailored to specific engineering applications. By bridging this research gap, this study paves the way for the development of more efficient and durable aluminum-based composites with wide-ranging industrial significance.

2. MATERIALS AND METHODS

2.1. Matrix Material. A356, an aluminum–silicon casting alloy, exhibits a melting point of approximately 557–610 °C, making it suitable for casting processes. It features a moderate hardness, typically about 59 HV on the Vicker scale. The tensile strength of A356 was around 231.45 MPa, providing a balance of strength and formability. With a density of about 2.68 g/cm³, A356 is lightweight yet sturdy. In terms of wear resistance, A356 demonstrates good performance, particularly when reinforced or modified, making it suitable for applications where durability and resistance to wear and deformation are essential.

2.2. Reinforcement Materials. Figure 1 shows the powder XRD of ball-milled TiMoVWCr HEA's powder.

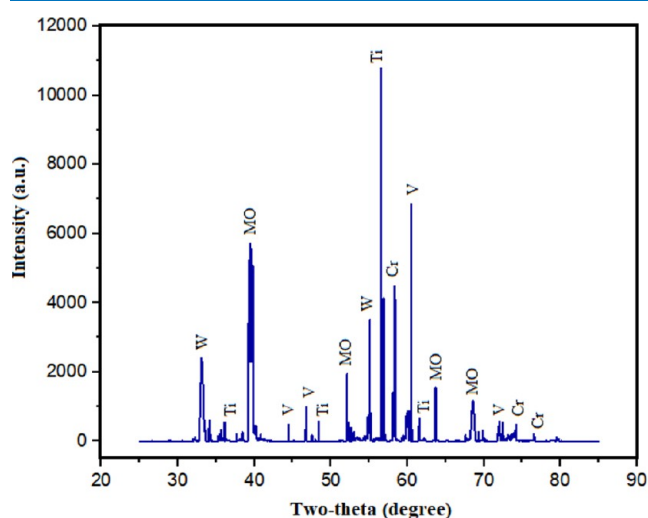


Figure 1. Powder XRD of ball-milled TiMoVWCr HEA powder.

Incorporating TiMoVWCr high-entropy alloy (HEA) powder as reinforcement with aluminum offers a novel approach to enhancing the properties of aluminum-based composites. These HEA particles, with their unique multicomponent composition, bring forth a synergistic combination of mechanical strength, thermal stability, and wear resistance. When dispersed within the aluminum matrix, TiMoVWCr HEA powder contributes to improved tensile strength, hardness, and overall mechanical performance. This reinforcement strategy also enhances interfacial bonding, mitigating potential weaknesses at the matrix–particle interface. The HEA's high thermal stability ensures the retention of properties at elevated temperatures, making it particularly suitable for applications requiring thermal resistance.¹ Moreover, the incorporation of TiMoVWCr HEA powder presents an avenue for tailoring the composite's performance through variation in particle content. This innovative approach holds promise in sectors such as aerospace, automotive, and engineering, where lightweight materials with enhanced mechanical and thermal characteristics are in high demand.² Figure 2a–e shows the photograph of Ti powder, Mo powder, V powder, W powder, and Cr powder, respectively.

The experimental procedure for ball-milling involved the meticulous blending of titanium (Ti), molybdenum (Mo), vanadium (V), tungsten (W), and chromium (Cr) powders. The powders were subjected to a ball-milling process, in which mechanical alloying occurred. This process was extended for 100 h, ensuring thorough mixing and homogenization of the individual metallic components. The ball-milling was conducted with a ball-to-powder ratio (BPR) of 1:5, signifying the optimal proportion of milling balls to powder mass. This carefully orchestrated milling procedure aimed to facilitate the creation of a well-integrated HEA powder, harnessing the synergies of Ti, Mo, V, W, and Cr powders for enhanced structural and mechanical properties. The scanning electron microscopy (SEM) image of the ball-milled TiMoVWCr high-entropy alloy (HEA) powder revealed a distinct powder morphology (Figure 2f). These particles exhibited a fine and homogeneous distribution, showcasing their microcrystalline nature. The surface appeared to be characterized by irregular shapes and sizes, indicative of mechanical milling-induced deformation and fragmentation. The microstructure hinted at the alloy's potential for enhanced mechanical properties, making it a promising candidate for various advanced applications in materials science and engineering.

2.3. Experimental Procedure. In the preparation for the friction stir processing (FSP) of the A356 aluminum alloy, a systematic approach was undertaken. The alloy, initially in the form of 100 mm × 50 mm × 10 mm pieces, underwent precise cutting to ensure appropriateness for the FSP process, as depicted in Figure 3. Achieving a uniform distribution of TiMoVWCr high-entropy alloy (HEA) powders was crucial, and they were meticulously spread over the groove of the A356 alloy. The specific parameters used for the FSP process include details such as a 6 mm pin diameter, 0° tool tilt angle, threaded tool profile, 25 mm/min transverse speed, 1020 rpm rotational speed, 3 mm pin length, 20 mm shoulder diameter, and H13 tool steel as the chosen tool material. These carefully selected parameters played a crucial role in the success of the FSP process on the A356 aluminum alloy with TiMoVWCr HEA powders, resulting in a well-prepared composite sample. The subsequent step involved the setup of a vertical milling machine outfitted with a carefully chosen FSP tool. To fine-tune the FSP tool's performance, rotational speed and traverse rate adjustments were made based on a combination of preliminary tests and insights drawn from relevant literature. Ensuring the stability of the composite sample during processing, a suitable fixture was installed, following established guidelines.^{2,6} The composite sample was securely positioned within this fixture on the milling machine. Upon initiation of the milling machine, the FSP process commenced, and stringent control was exerted over the process parameters to prevent any potential material degradation due to excessive heating.¹³ Following completion of the FSP process, the composite sample was handled with care and removed from the fixture. To allow for a controlled cooldown, the sample was left to naturally reach room temperature.¹⁴

The selection of specific weight percentages for titanium (Ti), molybdenum (Mo), vanadium (V), tungsten (W), and chromium (Cr) in composite compositions was a crucial aspect determined through pilot run investigations. The aim was to enhance the mechanical and wear properties of the composite material. In the initial exploration, a total weight percent addition of 10 wt % was targeted, with various combinations detailed in Table 1. During the experimentation,

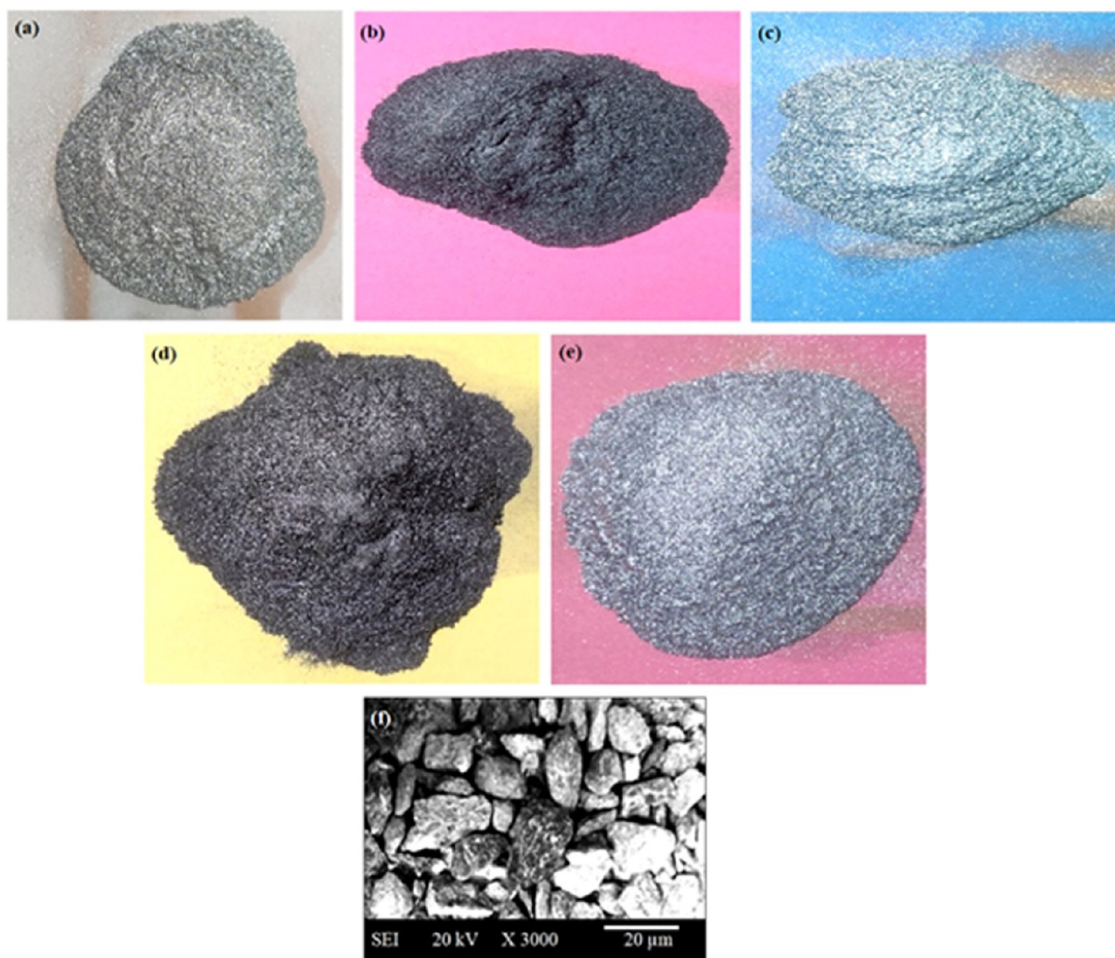


Figure 2. (a) Ti powder, (b) Mo powder, (c) V powder, (d) W powder, (e) Cr powder, and (f) SEM image of ball-milled TiMoVWCr HEA powder.

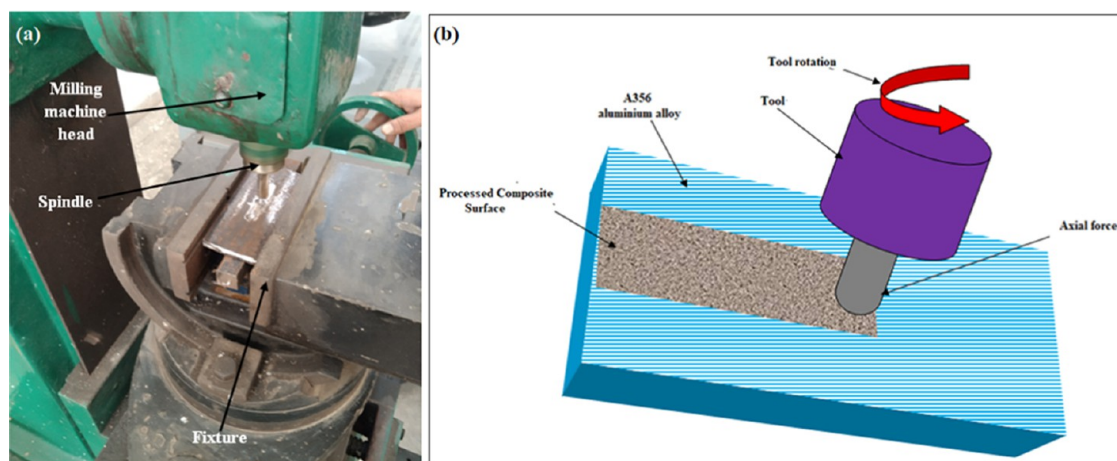


Figure 3. (a) Vertical milling machine for FSP setup and (b) composite development process.

it was observed that maintaining an 8% total weight percent combination with equal weight percentages for Ti, Mo, V, W, and Cr (1.6% each) resulted in undesired agglomeration and porosity. Conversely, a 12% total weight percent combination with equal weight percentages (2.4% each) led to nonuniform distribution and the emergence of cracks within the composite structure. However, a balance was achieved when the total weight percent combination was 10% with equal weight

percentages for Ti, Mo, V, W, and Cr (2% each), demonstrating a uniform distribution. Taking these findings into consideration, we made the decision to maintain the total weight percent of reinforcement at 10% (as indicated in Table 1). It was noteworthy that this choice was informed by the observed uniform distribution at this composition. Further, in Section 3, the internal rational weight percentages of each element are discussed in detail, highlighting their individual

Table 1. Composite Compositions

sample no.	base material (matrix material)	Ti (wt %)	Mo (wt %)	V (wt %)	W (wt %)	Cr (wt %)	composition	rationale selection
1	A356	2.0%	2.0%	2.0%	2.0%	2.0%	A356/2%Ti2%Mo2%V2%W2%Cr	adding 2 wt % each of Ti, Mo, V, W, and Cr to Al aims to identify the individual effects of these elements, achieving a balanced enhancement in aluminum composite properties
2	A356	4.0%	1.5%	1.5%	1.5%	1.5%	A356/4%Ti1.5%Mo1.5%V1.5%W1.5%Cr	incorporating 4% Ti, 1.5% each of Mo, V, W, and Cr into Al emphasizes assessing the heightened impact of titanium on the properties of the aluminum composite
3	A356	1.5%	4.0%	1.5%	1.5%	1.5%	A356/1.5%Ti4%Mo1.5%V1.5%W1.5%Cr	introducing 1.5% Ti, 4% Mo, 1.5% each of V, W, and Cr into Al emphasizes evaluating the amplified influence of molybdenum on aluminum composite properties
4	A356	1.5%	1.5%	4.0%	1.5%	1.5%	A356/1.5%Ti1.5%Mo4%V1.5%W1.5%Cr	incorporating 1.5% each of Ti, Mo, W, and Cr with 4% V into Al emphasizes discerning the heightened impact of vanadium on the aluminum composite properties
5	A356	1.5%	1.5%	1.5%	4.0%	1.5%	A356/1.5%Ti1.5%Mo1.5%V4%W1.5%Cr	introducing 1.5% each of Ti, Mo, V, and Cr with 4% W into Al focuses on isolating and understanding the elevated impact of tungsten on composite properties
6	A356	1.5%	1.5%	1.5%	1.5%	4.0%	A356/1.5%Ti1.5%Mo1.5%V1.5%W4%Cr	incorporating 1.5% each of Ti, Mo, V, and W with 4% Cr into Al emphasizes discerning the heightened impact of chromium on the aluminum composite properties

effects on the composite material. This detailed analysis provided insight into the nuanced interplay of Ti, Mo, V, W, and Cr, laying the foundation for a comprehensive understanding of the composite material's behavior and performance.

2.4. Material Testing. The evaluation of A356 composites with TiMoVWCr HEA powder reinforcement employed a meticulous approach, utilizing advanced testing techniques and standardized procedures. A computerized universal testing machine played a central role in conducting tensile tests on composite samples with specified parameters, including gauge length, maximum extension, specimen diameter, and strain rate, ensuring a standardized and controlled testing environment.

The parameters of this machine (Figure 4a) encompassed essential aspects such as gauge length (25–50 mm), maximum extension (5 mm), specimen diameter (0.5–30 mm), and strain rate (10^{-4} – 10^{-1} s⁻¹). These parameters ensure a standardized and controlled environment for the tensile testing, allowing for precise determination of mechanical properties.^{13,14} The ASTM E8 standard facilitates tensile testing. Samples, with a 36 mm gauge length and 6 mm gauge diameter, undergo evaluation to determine mechanical properties like yield strength (Figure 5a). Hardness testing, a key aspect of material characterization, was conducted on a dedicated machine following ASTM E92—Standard Test Methods (Figure 5b). Moreover, wear testing was conducted according to the ASTM G99—Standard Test Method, utilizing a pin-on-disc apparatus (Figure 4b). This method enabled the evaluation of wear resistance under controlled conditions, providing valuable insights into the practical performance of A356 composites. The wear behavior testing involved specific conditions, including a sliding speed of 2 m/s, a 1000 N force, and a sliding distance of 1000 m.

3. RESULTS AND DISCUSSION

3.1. Microstructural Observation. Figure 6 shows the macrostructure image of the composite material. The macrostructure of an A356-based composite reinforced with a titanium–molybdenum–vanadium–tungsten–chromium high-entropy alloy (2%Ti2%Mo2%V2%W2%Cr HEA) powder exhibited remarkable attributes of porosity-free and crack-free surfaces (Figure 6a). The A356/2%Ti2%Mo2%V2%W2%Cr composite material, resulting from the incorporation of the HEA reinforcement within the A356 aluminum matrix, showed exceptional structural integrity and enhanced mechanical properties. The crack-free surface indicated meticulous attention to homogeneity and interfacial bonding between the matrix and reinforcement phases.¹⁵ This macrostructural configuration culminated in a composite material with an improved load-bearing capacity, thermal stability, and wear resistance. The reinforcement of A356 with the TiMoVWCr HEA powder not only preserved the alloy's inherent lightweight properties but also imparted added strength and durability. The porosity-free and crack-free macrostructure served as a testament to the synergy between innovative processing methodologies and material design strategies, setting the stage for the utilization of this composite in demanding engineering applications that demand high performance and reliability.²

Figure 7 shows the microstructure of an A356-based composite reinforced with TiMoVWCr HEA powder. The microstructure of an A356-based composite reinforced with a

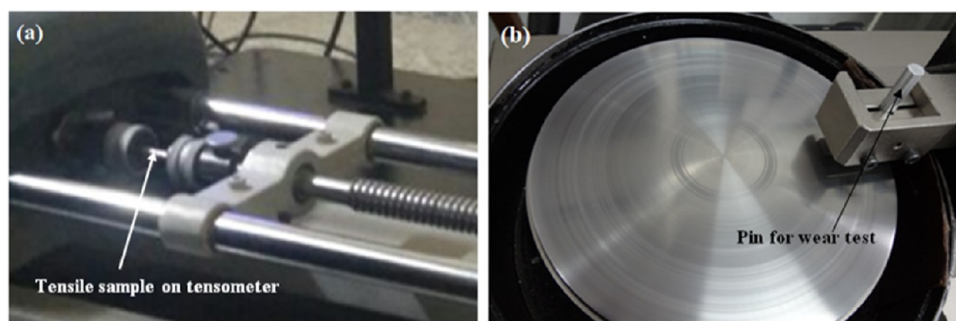


Figure 4. (a) Tensometer for tensile testing and (b) pin-on-disc apparatus.

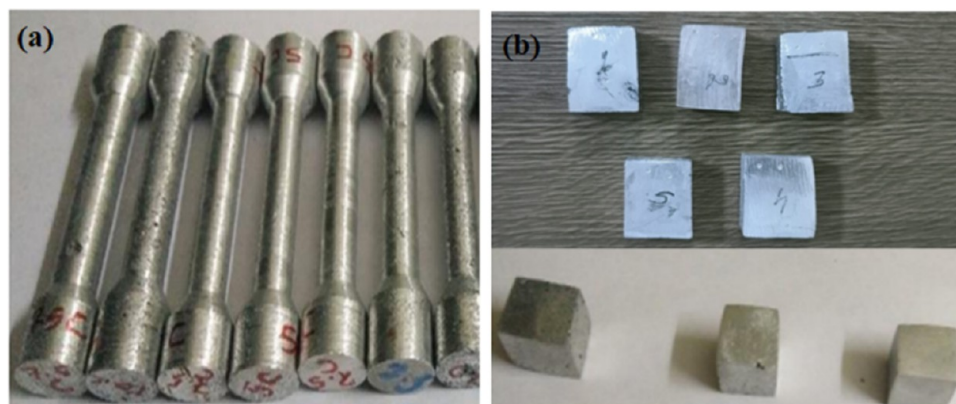


Figure 5. Samples photographs: (a) tensile samples and (b) hardness samples.

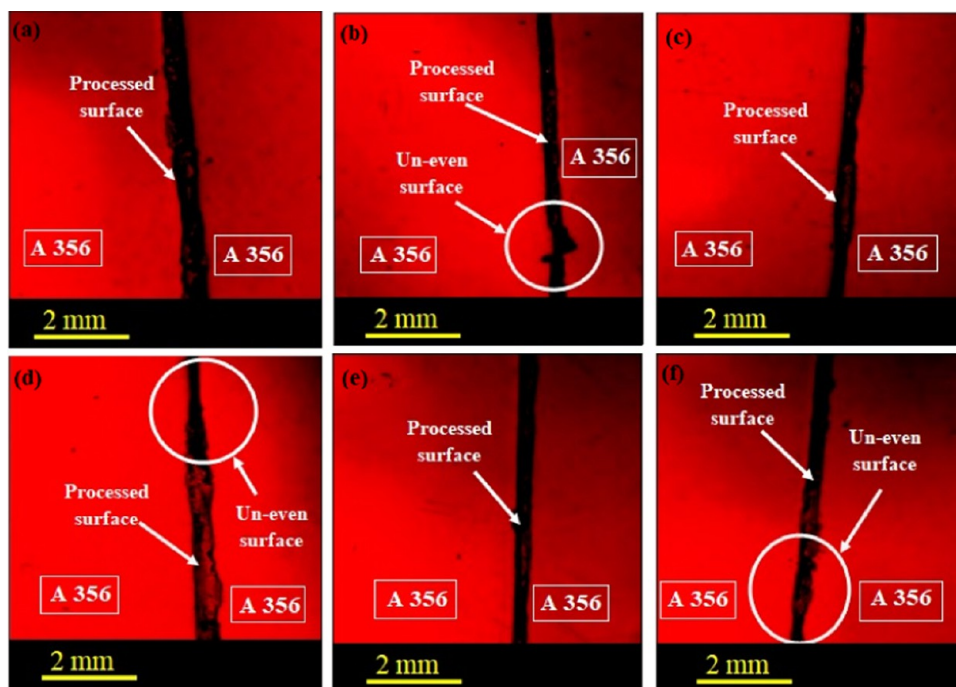


Figure 6. Macrostructure image: (a) A356/2%Ti2%Mo2%V2%W2%Cr, (b) A356/4%Ti1.5%Mo1.5%V1.5%W1.5%Cr, (c) A356/1.5%Ti4%Mo1.5%V1.5%W1.5%Cr, (d) A356/1.5%Ti1.5%Mo4%V1.5%W1.5%Cr, (e) A356/1.5%Ti1.5%Mo1.5%V4%W1.5%Cr, and (f) A356/1.5%Ti1.5%Mo1.5%V1.5%W4%Cr.

titanium–molybdenum–vanadium–tungsten–chromium high-entropy alloy (2%Ti2%Mo2%V2%W2%CrHEA powder), fabricated using the friction stir processing (FSP) technique, displays a strikingly uniform distribution of reinforcement particles within the aluminum matrix while showcasing an

absence of porosity, as shown in Figure 8. This microstructural refinement achieved through FSP attested to the efficacy of this solid-state processing method in creating mechanically robust and defect-free composite materials. The FSP technique involved the localized heat generated by a rotating tool to

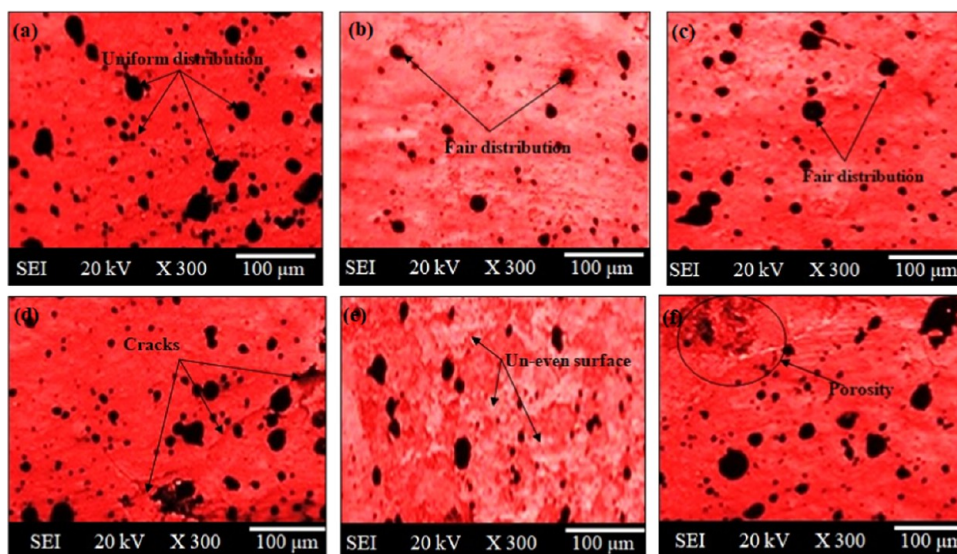


Figure 7. SEM image: (a) A356/2%Ti2%Mo2%V2%W2%Cr, (b) A356/4%Ti1.5%Mo1.5%V1.5%W1.5%Cr, (c) A356/1.5%Ti4%Mo1.5%V1.5%W1.5%Cr, (d) A356/1.5%Ti1.5%Mo4%V1.5%W1.5%Cr, (e) A356/1.5%Ti1.5%Mo1.5%V4%W1.5%Cr, and (f) A356/1.5%Ti1.5%Mo1.5%V1.5%W4%Cr.

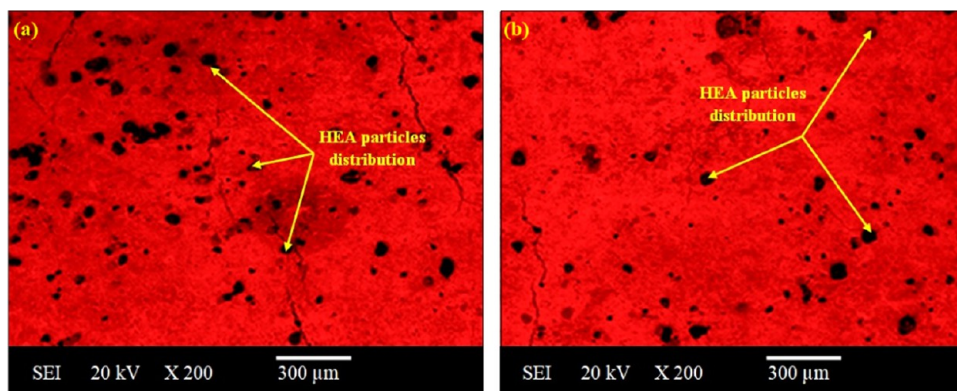


Figure 8. (a, b) HSEM image of A356/2%Ti2%Mo2%V2%W2%Cr.

soften and blend the composite's constituents. This controlled plastic deformation led to a homogenized distribution of the HEA reinforcement within the A356 matrix. The absence of porosity in the microstructure was attributed to the combination of the FSP's mechanical agitation and the solid-state nature of the process, which suppressed the formation and entrapment of gas bubbles.⁶ The uniform dispersion of the HEA reinforcement augmented the composite's mechanical properties, enhancing its load-bearing capacity, tensile strength, and wear resistance. The absence of porosity further contributed to the material's structural integrity, minimizing potential sites for crack initiation.²¹ Manocherian et al.³⁰ developed an A356 aluminum alloy-based surface composite reinforced with 2.5, 5, and 7.5 vol % nanolayered Ti_3AlC_2 MAX phase particles using friction stir processing (FSP). Microstructural analysis through optical microscopy (OM) and scanning electron microscopy (SEM) revealed refined structures, reduced porosity, and modified dendrites and silicon particles. These improvements contributed to increased microhardness and tensile strength values in the fabricated surface composites.

The interfacial bond strength between the matrix and the titanium–molybdenum–vanadium–tungsten–chromium

high-entropy alloy (TiMoVWCr HEA powder) reinforcement in an A356-based composite, fabricated using the friction stir processing (FSP) technique for A356/2%Ti2%Mo2%V2%W2%Cr, is shown in Figure 9. FSP promoted the formation of a robust and coherent interface through mechanical mixing and localized plastic deformation. During FSP, the rotating tool exerted shear forces and generated heat that facilitated diffusion of atoms at the interface. This phenomenon promoted atomic bonding between the matrix and the HEA reinforcement, resulting in a metallurgically coherent and mechanically sound interface. The solid-state nature of FSP ensured that interfacial bonding occurred without the complications of fusion-based methods, such as porosity or detrimental phase changes.¹⁴ The strong interfacial bond effectively transferred mechanical loads between the matrix and the reinforcement, minimizing stress concentration and preventing premature failure. This bond contributed significantly to the composite's enhanced mechanical properties, such as improved tensile strength, hardness, and overall structural integrity.²¹ The uniform distribution of the HEA particles within the matrix further augmented load distribution and reinforced the composite's performance.

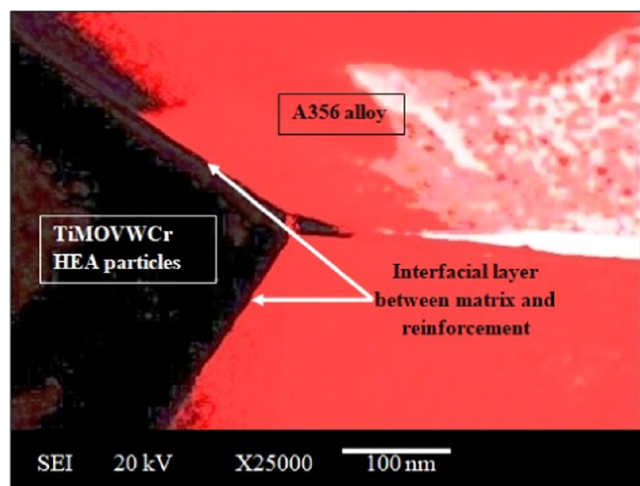


Figure 9. Interfacial layer of the matrix and TiMoVWCr powder for the A356/2%Ti2%Mo2%V2%W2%Cr processed surface with FSP.

3.2. Number of Grains. The A356-based composite reinforced with the titanium–molybdenum–vanadium–tungsten–chromium high-entropy alloy (TiMoVWCr HEA), fabricated by using the friction stir processing (FSP) technique, displayed a controlled and refined grain structure. The number of grains (n) was observed by

$$n = 2^{(G-1)} \quad (1)$$

where eq 1 relates to the number of grains (n) to the grain size number (G) according to ASTM standards. It signifies a geometric progression in grain count based on grain size.

$$G = [-6.644\log_{10}(l_\alpha)] - 3.28 \quad (2)$$

where

$$l_\alpha = \frac{V_{\alpha}(L_T)}{N_\alpha}$$

Here, eq 2 represents a grain size estimation model. In this equation, l_α is calculated as the product of V_{α} (fraction of the volume of the α phase), L_T (length or magnification of the test line), and N_α (number of intercepted grains). This equation is employed to determine the grain size (G) in materials, providing an analytical tool for evaluating the microstructure based on the volume fraction and characteristics of the α phase.

Now

$$l_\alpha = \frac{0.56 \times (487/500)}{96}$$

$$l_\alpha = 0.0056$$

Now again G from eq 2

$$G = [-6.644\log_{10}(0.0056)] - 3.28$$

$$G = 11.68$$

Now from eq 1

$$n = 2^{(11.68-1)}$$

$$n = 2^{(10.68)}$$

$$n = 1640.59$$

The number of grains was found to be about 1640.59 for the A356/2%Ti2%Mo2%V2%W2%Cr processed composite per square inch at 500 magnifications. FSP's mechanical stirring and localized heat input contributed to optimizing the number of grains and grain size within the composite material (Figure 10). The FSP process induced recrystallization and grain

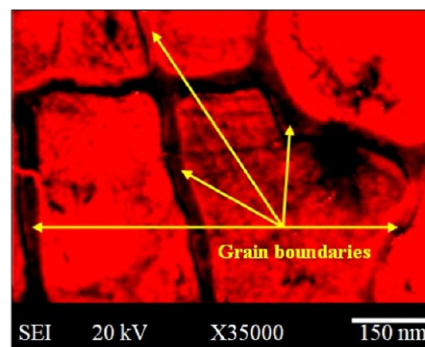


Figure 10. Developed grain boundaries for the A356/2%Ti2%Mo2%V2%W2%Cr composite.

refinement due to dynamic deformation and thermal cycles. This resulted in a higher number of smaller grains compared with conventionally processed materials. The uniform distribution of the HEA reinforcement further influenced the grain growth behavior, ensuring that the reinforcement particles acted as nucleation sites for new grains, promoting a fine-grained microstructure.^{13,14} The smaller grain size enhanced the composite's mechanical properties by impeding dislocation movement, thereby increasing its strength and hardness. Additionally, the increased grain boundaries contributed to improved wear resistance.¹⁶

3.3. Mechanical Behavior. The incorporation of titanium–molybdenum–vanadium–tungsten–chromium high-entropy alloy (TiMoVWCr HEA powder) reinforcement into A356 aluminum alloy using the friction stir processing (FSP) technique has a pronounced impact on the tensile strength of the composite material (Figure 11a). Tensile strength values of A356 after the addition of 2%Ti2%Mo2%V2%W2%Cr, 4%Ti1.5%Mo1.5%V1.5%W1.5%Cr, 1.5%Ti4%Mo1.5%V1.5%W1.5%Cr, 1.5%Ti1.5%Mo4%V1.5%W1.5%Cr, 1.5%Ti1.5%Mo1.5%V4%W1.5%Cr, and 1.5%Ti1.5%Mo1.5%V1.5%W4%Cr were improved 36.39, 31.68, 33.84, 34.56, 33.26, and 30.24%, respectively. The HEA's unique mechanical properties and the FSP's processing benefited synergistically, contributing to this enhancement. The presence of a TiMoVWCr HEA powder reinforcement introduced high-strength characteristics to the composite. The reinforcement's uniform dispersion within the A356 matrix effectively impeded dislocation motion during deformation, resulting in improved tensile strength. Additionally, the HEA's inherent resistance to deformation assisted in load-bearing, augmenting the composite's overall structural integrity. The FSP technique further reinforced the tensile strength improvement. FSP promoted an optimized distribution of HEA particles, leading to effective load transfer and stress distribution.^{14,21} The mechanical mixing and localized heat input during FSP also refined the microstructure, creating finer grains that enhanced the composite's strength. Collectively, the addition of TiMoVWCr HEA powder reinforcement through FSP yielded a composite material with a substantially elevated tensile strength.

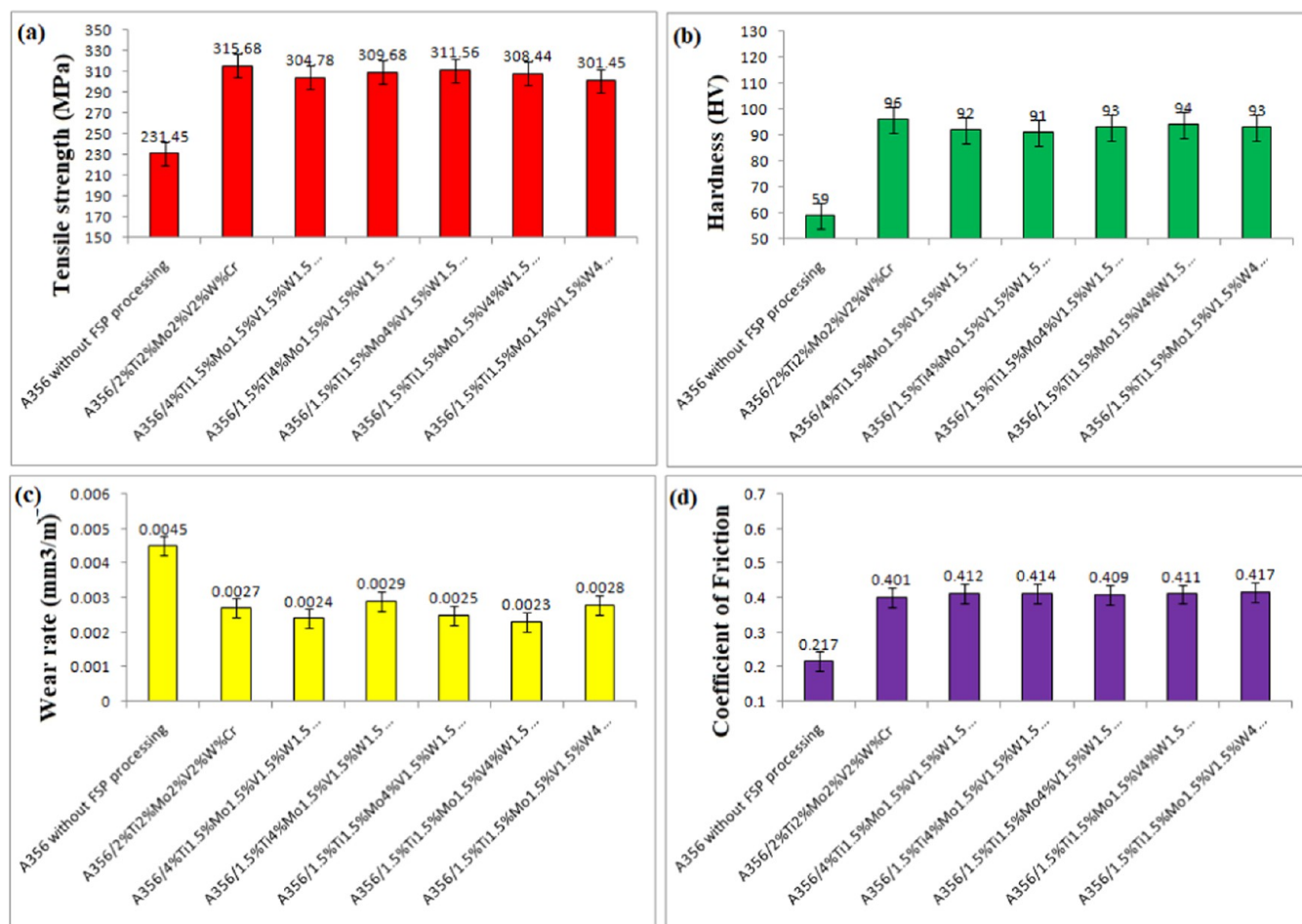


Figure 11. Behavior of composite: (a) tensile strength, (b) hardness, (c) wear, and (d) friction.

The integration of titanium–molybdenum–vanadium–tungsten–chromium high-entropy alloy (TiMoVWCr HEA powder) reinforcement into A356 aluminum alloy, facilitated by the friction stir processing (FSP) technique, triggered a significant augmentation in the material's hardness (Figure 11b). Hardness values of A356 after the addition of 2%Ti2%Mo2%V2%W2%Cr, 4%Ti1.5%Mo1.5%V1.5%W1.5%Cr, 1.5%Ti4%Mo1.5%V1.5%W1.5%Cr, 1.5%Ti1.5%Mo4%V1.5%W1.5%Cr, 1.5%Ti1.5%Mo1.5%V4%W1.5%Cr, and 1.5%Ti1.5%Mo1.5%V1.5%W4%Cr were improved 62.71, 55.93, 54.24, 57.63, 59.32, and 57.63%, respectively. The inherent hardness of the TiMoVWCr HEA powder, characterized by its high strength and superior mechanical properties, fortified the composite. The uniform dispersion of HEA particles throughout the A356 matrix, achieved through FSP, generated a composite material with an enhanced load-bearing capacity and resistance to deformation. The interaction of HEA particles with the matrix not only acted as a barrier to dislocation motion but also effectively reinforced the material, leading to an overall increase in hardness. FSP further contributed to the hardness improvement by refining the microstructure of the composite. The mechanical mixing and localized heat generated by the FSP tool resulted in smaller grain sizes, which were associated with increased hardness.²¹ The presence of fine-grained regions led to enhanced strength and hardness due to the grain boundary strengthening mechanism. Manocherian et al.³⁰ detailed the surface reinforcement of A356 aluminum alloy with 2.5, 5, and

7.5 vol % nanolayered Ti_3AlC_2 MAX phase particles. The A356–7.5 vol % Ti_3AlC_2 surface composite exhibited notable improvements, with microhardness and tensile strength values rising to approximately 87 HV and 184 MPa, compared to the as-received alloy's 68 HV and 112 MPa. Daneshifar et al.³¹ employed friction stir processing (FSP) to add Mg to an Al–Si cast eutectic alloy, investigating the formation of Mg_2Si using various analysis techniques. Findings demonstrate FSP's effectiveness in producing an Al/ Mg_2Si composite, with the composite's hardness moderately improving ($\sim 15\%$) compared to the FSP-based alloy. Maharishi et al.³² focused on aluminum alloy 356, blended with zirconium silicate (ZrSiO_4) particles at various fractions (0, 3, 5, and 8 wt %). Stir casting facilitated sample preparation. SEM images of ZrSiO_4 particles were captured to assess their size and shape. Tensile, compression, and hardness tests, conducted following ASTM standards, indicated that the AA356 + 5 wt % ZrSiO_4 composition exhibited superior tensile strength (169.29 MPa) compared to the other compositions.

3.4. Wear and Friction Behavior. The wear behavior of materials is a critical factor in determining their suitability for various applications, particularly in industries in which mechanical components are subjected to friction and abrasion. In this study, the addition of the titanium–molybdenum–vanadium–tungsten–chromium high-entropy alloy (TiMoVWCr HEA powder) to A356-based composites through the friction stir processing (FSP) technique has garnered significant attention due to its potential to enhance wear

resistance as shown in Figure 11c,d. Results showed that the wear resistance of the A356 alloy after the addition of 2%Ti2%Mo2%V2%W2%Cr, 4%Ti1.5%Mo1.5%V1.5%W1.5%Cr, 1.5%Ti4%Mo1.5%V1.5%W1.5%Cr, 1.5%Ti1.5%Mo4%V1.5%W1.5%Cr, 1.5%Ti1.5%Mo1.5%V4%W1.5%Cr, and 1.5%Ti1.5%Mo1.5%V1.5%W4%Cr improved by about 40, 46.67, 35.56, 44.44, 48.89, and 37.78%, respectively. The addition of the 2%Ti2%Mo2%V2%W2%CrHEA powder through FSP offered the advantage of achieving a homogeneous distribution of the HEA particles within the A356 matrix, minimizing the risk of segregation and improving overall material integrity. This resulted in enhanced hardness, reduced friction, and increased resistance to abrasive wear. However, the success of this approach relied on careful parameter optimization during the FSP process to avoid potential drawbacks such as porosity and microstructural defects. Here, the FSP technique was a solid-state processing method that involved the rotation of a nonconsumable tool in contact with the base material, generating heat and causing plastic deformation.^{13,14} This process led to the incorporation of the TiMoVWCr HEA powder into the A356 matrix, forming a composite with a potentially enhanced wear resistance. The microstructural changes induced by FSP, such as refined grains and the distribution of the HEA particles, contributed to improved mechanical properties and wear performance. Satyanarayana et al.³³ investigated the impact of wear parameters on friction performance in A356 aluminum–graphite/granite particle-reinforced metal matrix hybrid composites. Varying weight proportions of reinforcements were mixed at 2 and 4 wt %. Wear rate and friction were monitored during dry sliding tests at different loads, track diameters, and sliding times. The study revealed that sliding time (48.51%) was the most influential factor, followed by load (21.93%), and weight percentage of graphite and granite dust particles (7.01%) in the coefficient of friction for the hybrid composite. Hemanth et al.³⁴ conducted a study on A356 aluminum alloy metal matrix composites (MMCs) reinforced with fused silica particles. Fabrication involved sand molds with metallic and nonmetallic chills, dispersing 3–12 wt % fused silica (50–100 μm) into the matrix. The resulting composites were examined for their microstructure, strength, hardness, and wear behavior. Microstructural analysis showed good bonding and a uniform dispersoid distribution. Strength, hardness, and wear resistance increased up to 9 wt % additions, with copper chill exhibiting superior performance due to its high volumetric heat capacity.

The examination of wear surface morphology is a crucial aspect of understanding the performance of materials in abrasive environments. SEM image of the wear surface of A356-based composites after 2%Ti2%Mo2%V2%W2%Cr HEA powder incorporation through FSP provided a visual representation of the material's response to abrasive forces (Figure 9). This image revealed the intricate details of the surface topography, including features such as cracks, debris, wear tracks, and the distribution of HEA particles.^{35–37} The microstructural change induced by FSP was evident in the SEM images. The high rotational and traverse speeds of the FSP tool led to severe plastic deformation and heat generation, causing the HEA particles to be incorporated into the A356 matrix.³⁸

Upon careful examination of the A356/2%Ti2%Mo2%V2%W2%Cr composite processed surface using friction stir processing (FSP), notable features of adhesive wear and grooves became apparent (Figure 12). Adhesive wear, a

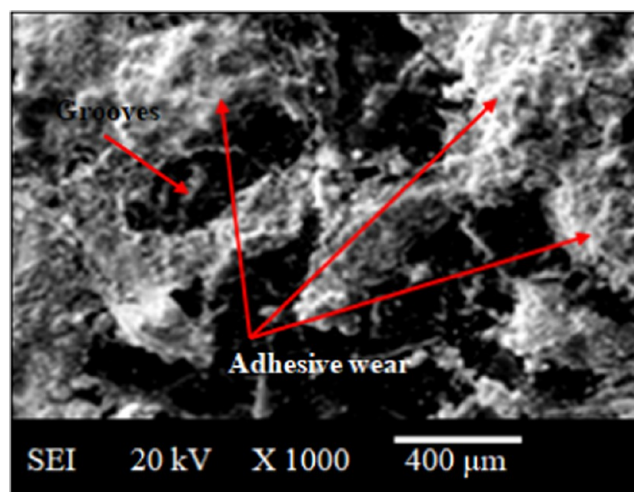


Figure 12. Wear surface SEM image of the A356/2%Ti2%Mo2%V2%W2%Cr processed surface with FSP.

common tribological phenomenon, was characterized by the transfer of material from one surface to another due to frictional forces.^{40–42} In this case, the interaction between the composite and its surroundings resulted in observable adhesive wear, indicating dynamic material transfer and contact. The presence of grooves on the processed surface further accentuated the mechanical and tribological alterations induced by FSP.^{43–45} Grooves, likely formed during the frictional stirring process, was attributed to the complex interaction between the rotating tool and the composite material. The creation of grooves reflected the localized plastic deformation and material displacement caused by the high mechanical forces involved in FSP.^{46–49}

3.5. XRD Observation. Figure 13 shows the XRD analysis of the A356/2%Ti2%Mo2%V2%W2%Cr composite processed with FSP. When a 2%Ti2%Mo2%V2%W2%Cr high-entropy alloy (HEA) powder was added onto A356 alloy, the formation of various phases involving α aluminum (α -Al), titanium (Ti), molybdenum (Mo), vanadium (V), tungsten (W), and chromium (Cr) was anticipated. The α -Al is a common

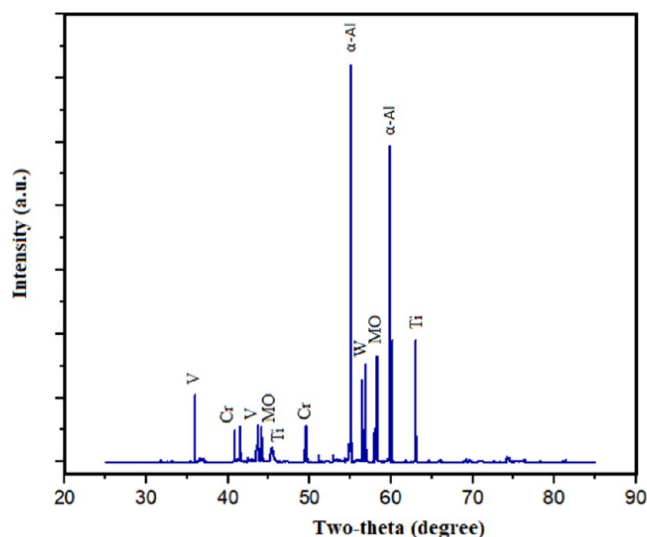


Figure 13. XRD analysis of the A356/2%Ti2%Mo2%V2%W2%Cr composite processed with FSP.

phase in aluminum alloys, forming the base matrix.^{50–52} Here, it provided the alloy's mechanical properties and formed the structure for reinforcement. The α -Al contributed to the alloy's ductility and formability, making the composite easier to process and shape.^{53–55} Ti enhanced the mechanical strength and corrosion resistance of the composite due to its high strength-to-weight ratio and excellent oxidation resistance.^{56–58} Ti also contributed to the composite's thermal stability, allowing it to retain its mechanical properties at elevated temperatures.^{59,60} Mo's high melting point and thermal stability enhanced the composite's performance at elevated temperatures, making it suitable for applications in high-temperature environments.^{61,62} Mo added strength and hardness to the composite, improving its overall mechanical properties. The V contributed to increased strength and toughness in the composite, making it useful for applications requiring high mechanical performance.^{63,64} The V also acted as a grain refiner, leading to finer microstructures and improved mechanical properties. W's high density and exceptional strength contributed to the composite's ability to withstand heavy loads and mechanical stress.^{65–67} Cr's corrosion resistance helped protect the composite from environmental degradation, especially in harsh and corrosive conditions. These elements, when incorporated as phases or components within a composite, led to a combination of enhanced mechanical properties, wear resistance, and other tailored characteristics.^{68,69}

All in all, the incorporation of TiMoVWCr high-entropy alloy (HEA) powder reinforcement into A356 composites holds significant promise, marked by enhanced mechanical properties and multifaceted performance improvements.^{70–72} The A356 composites exhibit substantial increases in tensile strength, hardness, and wear resistance after the addition of TiMoVWCr HEA powder. The significance of A356 composites with TiMoVWCr HEA powder reinforcement extends to their potential applications across diverse industries. In aerospace engineering, these composites can find utility in casting crucial components like engine parts and structural elements. The ability to tailor the composition of A356 composites with TiMoVWCr HEA reinforcement allows for customization, catering to specific requirements in sectors ranging from automotive manufacturing to marine engineering.^{73,74}

Hence, the FSP technique has emerged as a transformative method for developing aluminum-based composites. FSP involves using a rotating tool to stir and consolidate materials in the solid state, facilitating the incorporation of reinforcement materials into an Al matrix.^{75,76} This leads to enhanced mechanical properties, improved wear resistance, and increased strength without sacrificing the inherent lightweight nature of aluminum.⁷⁶ The FSP technique offers precise control over the composite's microstructure and properties, making it a promising approach for tailoring materials to specific applications in industries ranging from aerospace to automotive and beyond.⁷⁷

4. CONCLUSIONS

This study focused on investigating the impact of varying weight percentages of TiMoVWCr high-entropy alloy (HEA) powder on the microstructure, interfacial bonding strength, and mechanical and wear behavior of A356 composites produced through the friction stir processing (FSP) technique. The incorporation of 2% each of Ti, Mo, V, W, and Cr in A356

resulted in refined grain structures, improved HEA particle dispersion, and minimized defects. This composition exhibited strong interfacial adhesion that is crucial for effective load transfer. Mechanical properties, such as tensile strength and hardness, showed notable enhancements of 36.39 and 62.71%, respectively. Wear resistance, influenced by TiMoVWCr HEA powder weight percentages, reached optimal levels with 2% each of Ti, Mo, V, W, and Cr. The unique properties of HEA, coupled with the improved matrix, contributed to the enhanced wear resistance. XRD analysis confirmed the presence of α -aluminum (α -Al), titanium (Ti), molybdenum (Mo), vanadium (V), tungsten (W), and chromium (Cr) phases in the A356/2%Ti2%Mo2%V2%W2%Cr composite, providing a comprehensive understanding of its structural composition. This research underscores the tailored optimization of composite properties through strategic HEA incorporation, offering valuable insights into advanced materials engineering.

AUTHOR INFORMATION

Corresponding Authors

Shashi Prakash Dwivedi – Lloyd Institute of Engineering & Technology, Greater Noida 201306 Uttar Pradesh, India; Email: spdgbl@gmail.com

Shubham Sharma – School of Mechanical and Automotive Engineering, Qingdao University of Technology, 266520 Qingdao, China; Department of Mechanical Engineering, Lebanese American University, 1102-2801 Beirut, Lebanon; Faculty of Mechanical Engineering, Opole University of Technology, 45-758 Opole, Poland; Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura 140401 Punjab, India; orcid.org/0000-0002-1120-8451; Email: shubham543sharma@gmail.com, shubhamsharmacsircrli@gmail.com

Fuad A. Awwad – Department of Quantitative Analysis, College of Business Administration, King Saud University, Riyadh 11587, Saudi Arabia; Email: fawwad@ksu.edu.sa

Emad A. A. Ismail – Department of Quantitative Analysis, College of Business Administration, King Saud University, Riyadh 11587, Saudi Arabia; Email: emadali@ksu.edu.sa

Authors

Changhe Li – School of Mechanical and Automotive Engineering, Qingdao University of Technology, 266520 Qingdao, China

Yanbin Zhang – School of Mechanical and Automotive Engineering, Qingdao University of Technology, 266520 Qingdao, China

Rajesh Singh – Uttarakhand Institute of Technology, Uttarakhand University, Dehradun 248007, India; Department of Project Management, Universidad Internacional Iberoamericana, Campeche C.P. 24560, Mexico

Abhinav Kumar – Department of Nuclear and Renewable Energy, Ural Federal University Named After the First President of Russia, 620002 Ekaterinburg, Russia

M. Ijaz Khan – Department of Mechanical Engineering, Lebanese American University, 1102-2801 Beirut, Lebanon; Department of Mechanics and Engineering Science, Peking University, Beijing 100871, China

Complete contact information is available at:
<https://pubs.acs.org/10.1021/acsomega.3c07837>

Author Contributions

S.P.D.: Conceptualization, methodology, formal analysis, investigation, writing—original draft preparation; S.S.: conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, writing—review and editing, supervision, project administration, funding acquisition; C.L.: formal analysis, writing—review and editing, supervision, project administration; Y.Z.: formal analysis, writing—review and editing, supervision, project administration; R.S.: formal analysis, writing—review and editing, supervision, project administration; A.K.: formal analysis, writing—review and editing; F.A.A.: formal analysis, writing—review and editing, funding acquisition; M.I.K.: formal analysis, writing—review and editing, funding acquisition; E.A.A.I.: formal analysis, writing—review and editing, funding acquisition.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was supported by project number RSPD2024R576, King Saud University, Riyadh, Saudi Arabia.

REFERENCES

- (1) Zheng, Z. G.; Chen, X. L.; Wang, H. Y.; Da, S.; Wang, G.; Qiu, Z. G.; Zeng, D. C.; Xia, Q. B. Giant magnetocaloric effects of MnNiSi-based high-entropy alloys near room temperature. *J. Alloys Compd.* **2023**, 966, No. 171483.
- (2) Dwivedi, S. P.; Sharma, S. Synthesis of high entropy alloy AlCoCrFeNiCuSn reinforced AlSi7Mg0.3 based composite developed by solid state technique. *Mater. Lett.* **2024**, 355, No. 135556.
- (3) Dwivedi, S. P.; Yadav, A. K.; Saxena, A.; Dwivedi, V. K. Tribomechanical, physical and thermal behaviour of Al/Si₃N₄ composite with and without the addition of Cu, Ni and Cr entropy elements. *Proc. Inst. Mech. Eng., Part E* **2023**, No. 09544089231189663.
- (4) Dwivedi, S. P.; Sharma, S. Effect of CeO₂–Ni addition on the behavior of AZ91–A356 based composite fabricated by friction solid state technique. *Mater. Chem. Phys.* **2024**, 311, No. 128551.
- (5) Verma, S. K.; Dwivedi, V. K.; Dwivedi, S. P. Effect of spent alumina catalyst and date palm fiber ash addition in the development of aluminum based composite. *Proc. Inst. Mech. Eng., Part C* **2023**, No. 09544062231214021.
- (6) Dwivedi, S. P.; Sharma, S. Effect of Ni addition on the behavior of dissimilar A356-AZ91/CeO₂ aluminum-magnesium based composite fabricated by friction stir process technique. *Compos. Interfaces* **2023**, 1–26.
- (7) Dwivedi, S. P.; Chaudhary, V.; Sharma, S.; Sharma, S. Ultrasonic vibration effect in the development of Al/CCLW/alumina metal matrix composite to enhance mechanical properties. *Proc. Inst. Mech. Eng., Part E* **2023**, No. 09544089231200467.
- (8) Dwivedi, S. P. Development and characterization of grinding sludge-reinforced aluminum-based composite by friction stir process technique *World J. Eng.* **2023**, Vol. ahead-of-print No. ahead-of-print.
- (9) Radhakrishnan, S.; Khan, A.; Dwivedi, S. P.; et al. Studies on mechanical, thermal, and water immersion of plant and animal wastage nanofiller-based bio-fiber-reinforced composites. *Biomass Convers. Biorefin.* **2023**, 1–22.
- (10) Dwivedi, S. P.; Selvaprakash, S.; Sharma, S.; Kumari, S.; Saxena, K. K.; Goyal, R.; Iqbal, A.; Djavanroodi, F. Evaluation of various properties for spent alumina catalyst and Si₃N₄ reinforced with PET-based polymer composite. *Mech. Adv. Mater. Struct.* **2023**, 1–11.
- (11) Dwivedi, S. P.; Sharma, S.; Krishna, B. V.; Sonia, P.; Saxena, K. K.; Iqbal, A.; Djavanroodi, F. Effect of the addition of TiB₂ with waste glass powder on microstructure, mechanical and physical behavior of PET-based polymer composite material. *Mech. Adv. Mater. Struct.* **2023**, 1–10.
- (12) Dwivedi, S. P.; Chaudhary, V.; Sharma, S. Effect of the Addition of Waste Glass Powder along with TiC as Reinforcement on Microstructure, Wettability, Mechanical and Tribological Behavior of AZ91D Magnesium Based Alloy. *Int. J. Metalcast.* **2023**, 1–14.
- (13) Dwivedi, S. P.; Kumar, I.; Sehgal, S.; Gupta, N.; Saxena, K. K. Development of dissimilar AA2014 and AA2024 based composite with nano-Si₃N₄ reinforcement by friction stir process technique. *J. Adhes. Sci. Technol.* **2023**, 1–17.
- (14) Dwivedi, S. P.; Sharma, S.; Li, C.; Zhang, Y.; Kumar, A.; Singh, R.; Eldin, S. M.; Abbas, M. Effect of nano-TiO₂ particles addition on dissimilar AA2024 and AA2014 based composite developed by friction stir process technique. *J. Mater. Res. Technol.* **2023**, 26, 1872–1881.
- (15) Miniappan, P. K.; Marimuthu, S.; Kumar, S. D.; Gokilakrishnan, G.; Sharma, S.; Li, C.; Dwivedi, S. P.; Abbas, M. Mechanical, fracture-deformation, and tribology behavior of fillers-reinforced sisal fiber composites for lightweight automotive applications. *Rev. Adv. Mater. Sci.* **2023**, 62, No. 20230342.
- (16) Rajkumar, G.; Saravanan, M.; Bejathin, A. B. H.; Sharma, S.; Dwivedi, S. P.; Kumar, R.; Singh, S. Parametric Optimization of Powder-Mixed EDM of AA2014/Si₃N₄/Mg/Cenosphere Hybrid Composites Using Fuzzy Logic: Analysis of Mechanical, Machining, Microstructural, and Morphological Characterizations. *J. Compos. Sci.* **2023**, 7, No. 380.
- (17) Kumar, S.; Dang, R.; Manna, A.; Kumar Dhiman, N.; Sharma, S.; Dwivedi, S. P.; Kumar, A.; Li, C.; Tag-Eldin, E. M.; Abbas, M. Optimization of chemical treatment process parameters for enhancement of mechanical properties of Kenaf fiber-reinforced polylactic acid composites: A comparative study of mechanical, morphological and microstructural analysis. *J. Mater. Res. Technol.* **2023**, 26, 8366–8387.
- (18) Wei, H.; Ge, H.; Zhao, T.; Sharma, S.; Petru, M.; Dwivedi, S. P.; Kumar, A.; Abbas, M. Vanadium dioxide thin films-assisted terahertz meta-surface for simultaneous absorption, polarization conversion bi-functional switching, and wavefront operation. *Results Phys.* **2023**, 53, No. 106970.
- (19) Kumar, R.; Sharma, S.; Singh, J. P.; Gulati, P.; Singh, G.; Dwivedi, S. P.; Li, C.; Kumar, A.; Tag-Eldin, E. M.; Abbas, M. Enhancement in wear-resistance of 30MNCRB5 boron steel-substrate using HVOF thermal sprayed WC–10%Co–4%Cr coatings: a comprehensive research on microstructural, tribological, and morphological analysis. *J. Mater. Res. Technol.* **2023**, 27, 1072–1096.
- (20) Kumar, S.; Dang, R.; Manna, A.; et al. Effect of chemically treated kenaf fiber on the mechanical, morphological, and microstructural characteristics of PLA-based sustainable bio-composites fabricated via direct injection molding route. *Biomass Convers. Biorefin.* **2023**, 1–17.
- (21) Dwivedi, S. P.; Sharma, S. Development and characterization of Cu-Ni–Al₂O₃ surface composite developed by friction stir process technique. *Mater. Today Commun.* **2023**, 37, No. 107399.
- (22) Radhakrishnan, S.; Krishna, J. S.; Dwivedi, S. P.; et al. Experimental investigation of mechanical and physical properties of coconut shell and eggshell filler-based bio-fiber reinforced epoxy hybrid composites. *Biomass Convers. Biorefin.* **2023**, 1–13.
- (23) Li, G.; Jiang, W.; Guan, F.; Zhu, J.; Zhang, Z.; Fan, Z. Microstructure, mechanical properties and corrosion resistance of A356 aluminum/AZ91D magnesium bimetal prepared by a compound casting combined with a novel Ni–Cu composite interlayer. *J. Mater. Process. Technol.* **2021**, 288, No. 116874.
- (24) Qin, R.; Guo, C.; Jiang, F.; Li, Y.; Cao, M.; Guo, D. Effect of sintering temperature on microstructure characteristics and damping capacity of multilayer 316L stainless steel hollow spheres/A356 alloy composites reinforced by NiTi alloy sheets. *Mater. Sci. Eng., A* **2022**, 860, No. 144321.
- (25) Pandey, P.; Sankant, P.; Uthaisangsuk, V. Structure-mechanical property relationships of in-situ A356/Al₃Zr composites. *Mater. Sci. Eng., A* **2023**, 866, No. 144673.
- (26) Lu, J.; Wang, J.; Lin, Y.; Zheng, K.; Tian, Z.; Han, P. The influence of particle surface oxidation treatment on microstructure

and mechanical behavior of 3D-SiCp/A356 interpenetrating composites fabricated by pressure infiltration technique. *J. Mater. Res. Technol.* **2023**, *24*, 8984–8996.

(27) Niu, G.; Wang, J.; Li, J.; Ye, J.; Mao, J. Characterization of in-situ reinforced (Al,Si)₃(Ti,Ce) precipitates in T6 treated A356–0.3wt.%Ce–1.5 vol %TiCN composite and its effects on mechanical properties. *Mater. Charact.* **2022**, *185*, No. 111756.

(28) Mazaheri, Y.; Malmir, R.; Jalilvand, M. M.; Sheikhi, M.; Heidarpour, A. Mechanical properties and tribological performance of A356/Cr3C2–NiCr surface composite developed by high-velocity oxy-fuel and post friction stir processing treatment. *Surf. Interfaces* **2022**, *28*, No. 101627.

(29) Teng, D.; Zhang, G.; Zhang, S.; Li, J.; Guan, R. Response of mechanical properties of A356 alloy to continuous rheological extrusion Al–5Ti–0.6C–xCe alloy addition upon different Ce contents. *J. Mater. Res. Technol.* **2023**, *27*, 209–224.

(30) Manochehrian, A.; Heidarpour, A.; Mazaheri, Y.; Ghasemi, S. On the surface reinforcing of A356 aluminum alloy by nanolayered Ti₃AlC₂MAX phase via friction stir processing. *Surf. Coat. Technol.* **2019**, *377*, No. 124884.

(31) Daneshifar, M. H.; Papi, A.; Alishahi, M. Fabrication of Al–Si/Mg₂Si in-situ composite by friction stir processing. *Mater. Lett.* **2021**, *282*, No. 128832.

(32) Maharishi, M. D.; Moshi, A.; Marcel, A. M. M.; Hariharasakthisudhan, P.; Rajan, B. S. Investigation on the Mechanical Behaviour of Aluminium Alloy 356 – Zirconium Silicate Metal Matrix Composites (AA356–ZrSiO₄ MMCs). *Silicon* **2022**, *14*, 11731–11739.

(33) Satyanarayana, T.; Rao, P. S.; Krishna, M. G. Influence of wear parameters on friction performance of A356 aluminum – graphite/granite particles reinforced metal matrix hybrid composites. *Heliyon* **2019**, *5* (6), No. e01770.

(34) Hemanth, J. Abrasive and slurry wear behavior of chilled aluminum alloy (A356) reinforced with fused silica (SiO₂p) metal matrix composites. *Composites, Part B* **2011**, *42* (7), 1826–1833.

(35) Feng, Y.; Pan, R.; Zhou, T.; Dong, Z.; Yan, Z.; Wang, Y.; Chen, S.; Chen, S. Direct joining of quartz glass and copper by nanosecond laser. *Ceram. Int.* **2023**, *49* (22), 36056–36070.

(36) Chen, R.; Zhao, B.; He, T.; Tu, L.; Xie, Z.; Zhong, N.; Zou, D. Study on coupling transient mixed lubrication and time-varying wear of main bearing in actual operation of low-speed diesel engine. *Tribiol. Int.* **2024**, *191*, No. 109159.

(37) Wang, N. X.; Wang, Y. S.; Zheng, K.; Zhi, J. Q.; Zhou, B.; Wu, Y. X.; Yu, S. W.; et al. Achieving CVD diamond films on Mo_{0.5}(TiZrTaW)_{0.5} highly concentrated alloy for ultrastrong corrosion resistance. *Surf. Coat. Technol.* **2023**, *466*, No. 129620.

(38) Liao, D.; Zhu, S.; Keshtegar, B.; Qian, G.; Wang, Q. Probabilistic framework for fatigue life assessment of notched components under size effects. *Int. J. Mech. Sci.* **2020**, *181*, No. 105685.

(39) Niu, X.; Zhu, S.; He, J.; Liao, D.; Correia, J. A. F. O.; Berto, F.; Wang, Q. Defect tolerant fatigue assessment of AM materials: Size effect and probabilistic prospects. *Int. J. Fatigue* **2022**, *160*, No. 106884.

(40) Yuhua, C.; Yuqing, M.; Weiwei, L.; Peng, H. Investigation of welding crack in micro laser welded NiTiNb shape memory alloy and Ti6Al4V alloy dissimilar metals joints. *Opt. Laser Technol.* **2017**, *91*, 197–202.

(41) Fu, Z. H.; Yang, B. J.; Shan, M. L.; Li, T.; Zhu, Z. Y.; Ma, C. P.; Gao, W.; et al. Hydrogen embrittlement behavior of SUS301L–MT stainless steel laser-arc hybrid welded joint localized zones. *Corros. Sci.* **2020**, *164*, No. 108337.

(42) Zhu, Z. Y.; Liu, Y. L.; Gou, G. Q.; Gao, W.; Chen, J. Effect of heat input on interfacial characterization of the butter joint of hot-rolling CP–Ti/Q235 bimetallic sheets by Laser + CMT. *Sci. Rep.* **2021**, *11* (1), No. 10020.

(43) Zhu, Q.; Chen, J.; Gou, G.; Chen, H.; Li, P. Ameliorated longitudinal critically refracted—Attenuation velocity method for

welding residual stress measurement. *J. Mater. Process. Technol.* **2017**, *246*, 267–275.

(44) Chen, Y.; Sun, S.; Zhang, T.; Zhou, X.; Li, S. Effects of post-weld heat treatment on the microstructure and mechanical properties of laser-welded NiTi/304SS joint with Ni filler. *Mater. Sci. Eng., A* **2020**, *771*, No. 138545.

(45) Zhu, S.; Zhu, J.; Ye, S.; Yang, K.; Li, M.; Wang, H.; He, J. High-entropy rare earth titanates with low thermal conductivity designed by lattice distortion. *J. Am. Ceram. Soc.* **2023**, *106* (10), 6279–6291.

(46) Wang, K.; Zhu, J.; Wang, H.; Yang, K.; Zhu, Y.; Qing, Y.; He, J.; et al. Air plasma-sprayed high-entropy (Y_{0.2}Yb_{0.2}Lu_{0.2}Eu_{0.2}Er_{0.2})–3Al₂O₃ coating with high thermal protection performance. *J. Adv. Ceram.* **2022**, *11* (10), 1571–1582.

(47) He, H. T.; Fang, J. X.; Wang, J. X.; Sun, T.; Yang, Z.; Ma, B.; Chen, H.; Wen, M. Carbide-reinforced Re_{0.1}Hf_{0.25}NbTaW_{0.4} refractory high-entropy alloy with excellent room and elevated temperature mechanical properties. *Int. J. Refract. Met. Hard Mater.* **2023**, *116*, No. 106349.

(48) Fang, J. X.; Wang, J. X.; Wang, Y. J.; He, H. T.; Zhang, D. B.; Cao, Y. Microstructure evolution and deformation behavior during stretching of a compositionally inhomogeneous TWIP–TRIP canton-like alloy by laser powder deposition. *Mater. Sci. Eng., A* **2022**, *847*, No. 143319.

(49) Wang, H.; Huang, Z.; Zeng, X.; Li, J.; Zhang, Y.; Hu, Q. Enhanced Anticarbonization and Electrical Performance of Epoxy Resin via Densified Spherical Boron Nitride Networks. *ACS Appl. Electron. Mater.* **2023**, *5* (7), 3726–3732.

(50) Yang, S.; Zhang, Y.; Sha, Z.; Huang, Z.; Wang, H.; Wang, F.; Li, J. Deterministic Manipulation of Heat Flow via Three-Dimensional-Printed Thermal Meta-Materials for Multiple Protection of Critical Components. *ACS Appl. Mater. Interfaces* **2022**, *14* (34), 39354–39363.

(51) Yang, C.; Yin, C.; Wu, Y.; Zhou, Q.; Liu, X. Atomic insights into the deformation mechanism of an amorphous wrapped nanolamellar heterostructure and its effect on self-lubrication. *J. Mater. Res. Technol.* **2023**, *26*, 4206–4218.

(52) Zhou, C.; Ren, Z.; Lin, Y.; Huang, Z.; Shi, L.; Yang, Y.; Mo, J. Hysteresis dynamic model of metal rubber based on higher-order nonlinear friction (HNF). *Mech. Syst. Signal Process.* **2023**, *189*, No. 110117.

(53) Wang, H.; Wang, F.; Qian, D.; Chen, F.; Dong, Z.; Hua, L. Investigation of damage mechanisms related to microstructural features of ferrite-cementite steels via experiments and multiscale simulations. *Int. J. Plast.* **2023**, *170*, No. 103745.

(54) Li, Y. T.; Jiang, X.; Wang, X. T.; Leng, Y. X. Integration of hardness and toughness in (CuNiTiNbCr)_{Nx} high entropy films through nitrogen-induced nanocomposite structure. *Scr. Mater.* **2024**, *238*, No. 115763.

(55) Li, Y. T.; Chen, X. M.; Zeng, X. K.; Liu, M.; Jiang, X.; Leng, Y. X.; et al. Hard yet tough and self-lubricating (CuNiTiNbCr)_{Cx} high-entropy nanocomposite films: Effects of carbon content on structure and properties. *J. Mater. Sci. Technol.* **2024**, *173*, 20–30.

(56) Zhang, D.; Shi, D.; Wang, F.; Qian, D.; Zhou, Y.; Fu, J.; Jiang, S.; et al. Electromagnetic shocking induced fatigue improvement via tailoring the α -grain boundary in metastable β titanium alloy bolts. *J. Alloys Compd.* **2023**, *966*, No. 171536.

(57) Jiang, X. J.; Bao, S. J.; Zhang, L. W.; Zhang, X. Y.; Jiao, L. S.; Qi, H. B.; Wang, F. Effect of Zr on microstructure and properties of TC4 alloy fabricated by laser additive manufacturing. *J. Mater. Res. Technol.* **2023**, *24*, 8782–8792.

(58) Zhang, H.; Xiao, Y.; Xu, Z.; Yang, M.; Zhang, L.; Yin, L.; Cai, X.; et al. Effects of Ni-decorated reduced graphene oxide nanosheets on the microstructural evolution and mechanical properties of Sn–3.0Ag–0.5Cu composite solders. *Intermetallics* **2022**, *150*, No. 107683.

(59) Hu, J.; Yang, K.; Wang, Q.; Zhao, Q. C.; Jiang, Y. H.; Liu, Y. J. Ultra-long life fatigue behavior of a high-entropy alloy. *Int. J. Fatigue* **2024**, *178*, No. 108013.

(60) Yang, Z.; Tang, B.; Qiu, Y.; Wu, J.; Wei, W.; Huang, X.; Luo, X.; Wu, G. Measurement of transient temperature using laser-induced

breakdown spectroscopy (LIBS) with the surface temperature effect. *J. Anal. At. Spectrom.* **2023**, 38 (10), 1952–1961.

(61) Xie, B.; Li, H.; Ning, Y.; Fu, M. Discontinuous dynamic recrystallization and nucleation mechanisms associated with 2-, 3- and 4-grain junctions of polycrystalline nickel-based superalloys. *Mater. Des.* **2023**, 231, No. 112041.

(62) Gao, S.; Li, H.; Huang, H.; Kang, R. Grinding and lapping induced surface integrity of silicon wafers and its effect on chemical mechanical polishing. *Appl. Surf. Sci.* **2022**, 599, No. 153982.

(63) Zhao, Y. Understanding and design of metallic alloys guided by phase-field simulations. *npj Comput. Mater.* **2023**, 9 (1), No. 94.

(64) Guo, Q.; Hou, H.; Pan, Y.; Pei, X.; Song, Z.; Liaw, P. K.; Zhao, Y. Hardening-softening of Al_{0.3}CoCrFeNi high-entropy alloy under nanoindentation. *Mater. Des.* **2023**, 231, No. 112050.

(65) Wang, J.; Pan, Z.; Wang, Y.; Wang, L.; Su, L.; Cuiuri, D.; Zhao, Y.; Li, H. Evolution of crystallographic orientation, precipitation, phase transformation and mechanical properties realized by enhancing deposition current for dual-wire arc additive manufactured Ni-rich NiTi alloy. *Addit. Manuf.* **2020**, 34, No. 101240.

(66) Fu, A.; Liu, B.; Liu, B.; Cao, Y.; Wang, J.; Liao, T.; Liu, Y.; et al. A novel cobalt-free oxide dispersion strengthened medium-entropy alloy with outstanding mechanical properties and irradiation resistance. *J. Mater. Sci. Technol.* **2023**, 152, 190–200.

(67) Meng, B.; Wang, J.; Chen, M.; Zhu, S.; Wang, F. Study on the oxidation behavior of a novel thermal barrier coating system using the nanocrystalline coating as bonding coating on the single-crystal superalloy. *Corros. Sci.* **2023**, 225, No. 111591.

(68) Dikshit, M. K.; Singh, S.; Pathak, V. K.; Saxena, K. K.; Agrawal, M. K.; Malik, V.; Salem, K. h.; Khan, M. I. Surface characteristics optimization of biocompatible Ti6Al4V with RCCD and NSGA II using die sinking EDM. *J. Mater. Res. Technol.* **2023**, 24, 223–235.

(69) Sehar, B.; Waris, M.; Gilani, S.; Ansari, U.; Mushtaq, S.; Khan, N.; Jameel, M.; Khan, M.; Bafakeeh, O.; Eldin, S. The Impact of Laminations on the Mechanical Strength of Carbon-Fiber Composites for Prosthetic Foot Fabrication. *Crystals* **2022**, 12, No. 1429.

(70) Singh, B.; Kumar, I.; Saxena, K.; Mohammed, K.; Khan, M.; Ben Moussa, S.; Abdullaev, S. A future prospects and current scenario of aluminium metal matrix composites characteristics. *Alexandria Eng. J.* **2023**, 76, 1–17.

(71) Kumar, M. S.; Sathisha, N.; Manjnatha, S.; et al. Fatigue surface analysis of AL A356 alloy reinforced hematite metal matrix composites. *Biomass Convers. Biorefin.* **2023**, 1–13.

(72) Ganeshkumar, S.; Kumar, A.; Maniraj, J.; Suresh Babu, Y.; Ansu, A. K.; Goyal, A.; Kareem Kadhim, I.; Saxena, K. K.; Prakash, C.; Altuijri, R.; Ijaz Khan, M.; Hassan, A. M. Exploring the potential of nano technology: A assessment of nano-scale multi-layered-composite coatings for cutting tool performance. *Arabian J. Chem.* **2023**, 16 (10), No. 105173.

(73) Shahid, M.; Javed, H. M. A.; Ahmad, M.; Qureshi, A.; Khan, M.; Alnuwaiser, M.; Ahmed, A.; Khan, M.; Eldin, S.; Shahid, A.; Rafique, A. A Brief Assessment on Recent Developments in Efficient Electrocatalytic Nitrogen Reduction with 2D Non-Metallic Nanomaterials. *Nanomaterials* **2022**, 12, No. 3413.

(74) Kiranakumar, V.; Thejas, R.; Naveen, S.; Khan, M.; Prasanna, G.; Reddy, S.; Oreijah, M.; Guedri, K.; Bafakeeh, O.; Jameel, M. A review on electrical and gas-sensing properties of reduced graphene oxide-metal oxide nanocomposites. *Biomass Convers. Biorefin.* **2022**, 1–11.

(75) Kumar, R.; Dwivedi, R.; Arya, R.; Sonia, P.; Yadav, A.; Saxena, K.; Khan, M.; Sana, B. M. Current Development of Carbide Free Bainitic and Retained Austenite on Wear Resistance in High Silicon Steel. *J. Mater. Res. Technol.* **2023**, 24, 9171–9202.

(76) Prasanthi, P. P.; Kumar, M.; Mallampati, S.; Madhav, V.; Saxena, K.; Mohammed, K.; Khan, M.; Upadhyay, G.; Eldin, S. Mechanical Properties of Carbon Fiber Reinforced with Carbon Nanotubes and Graphene Filled Epoxy Composites: Experimental and Numerical Investigations. *Mater. Res. Express* **2023**, 10, No. 025308.

(77) Vemanaboina, H.; Babu, M. M.; Prerana, I. C.; Gundabattini, E.; Yelamasetti, B.; Saxena, K. K.; Agrawal, M. K.; et al. Evaluation of residual stresses in CO₂ laser beam welding of SS316L weldments using FEA. *Mater. Res. Express* **2023**, 10 (1), No. 016509.