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Research Article

Effect of Hot Rolling on Friction and Wear Characteristics of TiC Reinforced Copper-Based Metal Matrix Composites

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The current study examines the effect of titanium carbide reinforcement (TiC) on the tribological behavior of copper metal matrix composites. The stir-casting process followed by hot rolling was employed to fabricate the composite parts. Hot rolling was performed at 510°C temperature with a 90% reduction ratio. An optical microscope, scanning electron microscope with energy dispersion spectroscopy, and Brinell hardness tester were used to investigate the microstructure, reinforcement particle distribution, and hardness. The microstructural investigations witness the uniform distribution of titanium carbide reinforcing agents along with the excellent binding with the copper matrix. The hardness was improved with the addition of titanium carbide content in both casting and rolling specimens. Dry sliding friction and wear tests were employed on a pin-on-disk setup with load values ranging from 30 to 120 N and sliding velocity values ranging from 0.628–2.512 m/s. In both casting and rolling conditions, the composites have a less coefficient of friction and wear rate than the matrix element. Wear rates of the unreinforced and reinforced cast and hot rolled alloys were enhanced as load and sliding velocity was raised. The incorporation of titanium carbide lowered the coefficient of friction and wear rate. In comparison to the unreinforced cast and rolled alloys, the coefficient of friction and wear of cast and rolled copper metal matrix composites was significantly reduced. Scanning electron microscopy was employed to investigate the worn surfaces and wear debris to confirm the possible wear mechanisms.

1. Introduction

Copper metal matrix composites (CMMCs) are widely utilized in automobile sectors, aerospace applications, construction, and electronic industries. Copper metal matrix composites are essential due to properties such as reduced density, enhanced fatigue strength, higher hardness, and high strength-to-weight ratio. For the industrial usage of copper metal matrix composites, the development of these parameters is critical. Copper metal matrix composites are widely used due to their superior mechanical and physical properties. They were considered the most needed composites in many industrial sectors because of their lower density, increased hardness and strength, and enhanced wear properties. Due to growing demands, components used in advanced machines should have higher mechanical qualities. The reality that a manufactured product seems to be more resistive to the impact of different elements such as corrosion and wear has attracted the curiosity of a number of academicians and researchers. Copper's elastic modulus is lower, and its tensile characteristics are poor. The powder reinforcing agents have been added to improve the mechanical properties of pure copper. As per a few studies, introducing reinforcing agents as a hardening tool increased the mechanical properties of copper [1–5]. Copper metal matrix composites reinforced with powder reinforcing agents are well known for their remarkable tribological characteristics. Composites reinforcing with various influential ceramic powder particles, such as aluminum oxides (Al_2O_3), silicon carbides (SiC), silicon nitrides (Si_3N_4), boron carbides (B_4C), titanium diborides (TiB_2), carbon nanotubes (CNTs), molybdenum sulfides (MoS_2), and titanium carbides (TiC), have excellent wear characteristics, according to the majority of literature [6–12].

Mo and SiC were used as reinforcing agents to make copped metal matrix composites, and they found that increased weight percentage of reinforcements enhanced the mechanical and tribological performance of the composite structures produced [13]. Unique composite structures were developed by adding varied volume percentages of SiC reinforcement particles into an Al matrix which was reinforced with copper. They discovered that increasing reinforcement additions boosted the composite materials' properties [14]. As a result of the wear test carried out on the created composites, copper metal matrix composites reinforcing with varied quantities of molybdenum sulfides were developed, and they reported that, as the normal load is increased, the coefficient of friction declined and the wear resistance decreased. Several investigators are curious about this aspect, and they have claimed that it considerably enhances microstructural and wear properties [15]. Copper metal matrix composites reinforced with Be-Cr-C powdered reinforcement particles were developed and found that varying the reinforcement contents improved the microstructure, homogeneous dispersion, and tribological characteristics of the composite structures [16]. Copper-based composites with varying amounts of Gr and SiC were synthesized and discovered that increasing the reinforcement weight percentage improved the microstructural and wear performance [17]. SiC reinforcing agents into the copper-iron metal matrix in their research were incorporated, and it was discovered that the composite materials increased wear and corrosion resistance as an outcome [18]. Because of the dislocation strengthening, aluminium oxide powder reinforcing agents were introduced into the copper to increase mechanical characteristics. As a result, the hardness and strength of the copper metal matrix composite structures were found to be higher than that of pure copper [19]. The wear behavior of copper metal matrix composites reinforcing with three distinct reinforcing particles, such as aluminum oxide, boron carbide, and a combination of aluminum oxide and boron carbide, using friction stir processing, an intense plastic straining technique, was studied. They claimed that all the composite structures had better wear behavior than unreinforced composites and that the mixed composite structure had the best overall wear behavior [20]. Graphene reinforcing agents were added to the copper matrix in order to use it in electrical parts. They found that including graphene reinforcing agents increased the composites' mechanical and wear behavior at the same time [21]. The mechanical characteristics of Al matrix reinforcing with different weight percentages (3 percent, 6 percent, and 9 percent) of powdered reinforcements were studied [22]. The inclusion of 3 percent and 6 percent reinforcing agents increases the matrix's tensile strength, according to the researchers. However, after adding 9 percent reinforcing agents to the primary matrix, the tensile strength was reduced. The hardness of the composite structure, on the other side, was raised up to a 6 percent incorporation of reinforcing agents and then dropped as the reinforcement was added further (i.e., 9 percent). They eventually came to the conclusion that the optimal reinforcement content works as a strong force, pinning reinforcements to grain boundaries and opposing wear load during the wear test.

Besides, titanium carbide possesses exceptional microstructural and wear qualities. TiC offers a lot of potential as a wear-resistant replacement for ceramic components. Improper matrix and reinforcement mixing, ceramic dispersion, and interconnections between the two have all been reported in the traditional method of manufacturing metal matrix composites (MMCs), which is known as the stir casting technique [13]. Raising the volume percentages of Ti reinforcing agents in the base matrix improved the material's tribological and wear properties, as per the investigation of [23]. Furthermore, the element carbon has a lower density and so increases the local strength of the components in which they have been found. In research, composites with a Cu-carbide matrix were developed, and it was revealed that increasing the quantity of carbon reinforcement enhanced the composites' interfacial adhesion and boosted thermal conductivity. The friction stir processing method to produce the layer composites by drilling holes in the AA7XXX plates was used. As a result, the holes were supplied with Gr and TiC powder reinforcing agents, and the AA7XXX-based TiC-Gr composite structures were agitated and exposed to high levels of plastic strains by the nonconsumable revolving tool. The matrix element, which worked as a foundation for the interfacial adhesion of Gr-TiC reinforcing agents, is the most significant factor to consider when evaluating the wear performance of the composite [24].

The forming processes such as the blacksmithy and hot working techniques (rolling and extrusion) are the primarily used secondary operations for the preparation of metal matrix composites (MMC) due to their ability to prepare a variety of parts by various casting techniques. The forming methods enhance the mechanical strength and wear resistance of the composite parts by experiencing higher levels of plastic strains. Gr reinforcing composite structures were created by hot extruding method and the microstructural and physical characteristics were investigated. They concluded that the extruding leads to significant grain refining and uniform dispersion of reinforcing agents in the matrix element. They also stated that the high content of graphite reinforcements resulted in the enhancement of tensile properties [25]. The hot rolling secondary technique followed by stir casting was used to enhance the microstructure and mechanical behavior of the composites, and they reported that hardness was greatly enhanced as compared to cast composites [26]. Studies on copper metal matrix composites reinforced with TiC are rare in the literature studies, according to a review of the various literature sources. Hot rolling, on the contrary, is widely known for improving tribological performance. No research on the effects of hot rolling on titanium carbide reinforced copper composites has been found to the author's knowledge. As a result, the goal of this research is to make hybrid composites using powdered titanium carbide reinforcing agents in pure copper to improve wear performance. Titanium carbide was supplied to a pure copper substrate in various weight quantities (2.5–10% with a step of 2.5% to prepare four different composites for comparison purposes). This was accomplished by investigating the microstructure of copper metal matrix composite. The hardness and wear properties (wear rate and coefficient of friction) of the copper metal matrix composites were also investigated.

2. Experimental Procedure

2.1. Matrix and Reinforcements. In the current study, the composite structures were created with the stir-casting route. The copper in a sphere shape was chosen as the main matrix and was taken in commercial form with a purity of 99.5 percent. TiC was preferred to obtain good tribological properties such as less coefficient of friction and wear rate and strong interfacial adhesion between reinforcing agents and matrix elements. The reinforcement i.e., TiC, is hard and less dense than the copper matrix. Due to this superior characteristic of reinforcing agents, less dense copper metal matrix composites can be manufactured, and their wear properties can be improved. In the current study, powdered TiC reinforcing agents were chosen with a purity of 99 percent. Figure 1 presents the SEM and EDAX of TiC powder used in this investigation.

2.2. Preparation of Composites. The titanium carbide powder reinforcing agents were placed in a furnace at 110°C for a sufficient duration to eliminate the moisture content present in it. Later, the moisture-free powder reinforcing agents were placed on a weighing balance to measure the exact weight with a precision of 0.00001 g. The pure copper was heated to get the molten copper in a graphite crucible utilizing an electrical resistance furnace. Titanium carbide powdered reinforcements of size 26 μm to 65 μm was added to the molten copper matrix, and this molten metal was stirred with a TiO_2-coated stainless steel stirrer revolving at a speed of 100 rpm. A total of 4 different types of copper metal matrix composites were made with different weight percentages of TiC (2.5–10% with a step of 2.5% to prepare four different composites for comparison purposes) including pure copper and the sample's indexing, and different TiC weight percentages of the copper metal matrix composites are listed in Table 1. The copper-based composites with different weight percentages of TiC were continuously stirred for 3 minutes with an interval of 7 minutes. The composite mixtures were then kept at 1110°C and were injected into the preheated metal mold. The cast composite specimens were then sliced into the required sizes to undergoing them to the hot rolling process.

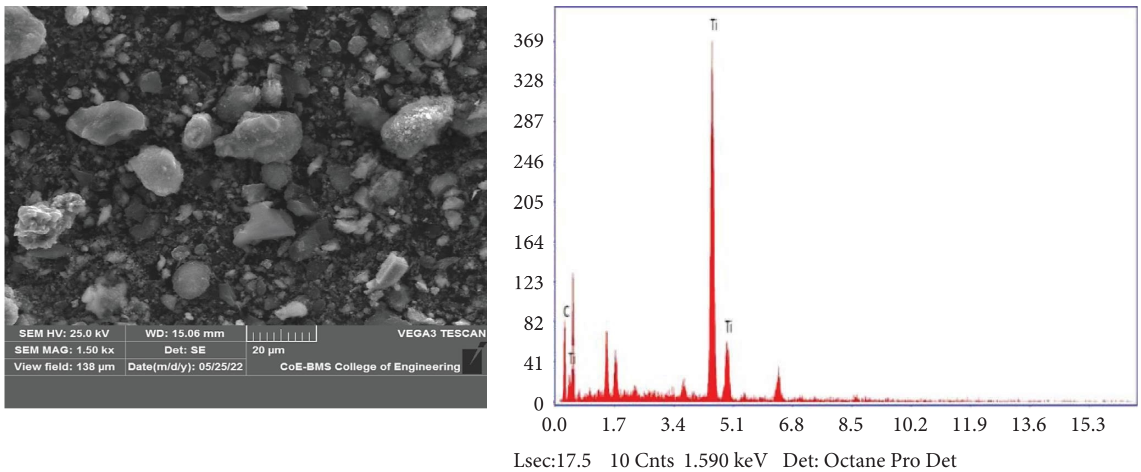
Prior to the hot rolling process, the cast composite parts and base metal were sectioned into specimens with dimensions of 50 mm × 50 mm × 10 mm and heated at 510°C for 1.5 hours in an electric furnace. Later, the hot rolling was carried out for cast copper-titanium carbide composite specimens with a two-high roller set up according to the predefined processing conditions to obtain better wear resistance. Figure 2 shows the photograph of the hot rolling facility used in this investigation. The processing conditions for the rolling process such as the temperature and duration of heat treatment between the two successive intermediate passes are 510°C and 60 min. To extract a hot rolling specimen with a 90% reduction, the heated specimens were subjected to rolling in a temperature-controlled chamber continuously with a 10% reduction on each and every pass till a sufficient thickness specimen was obtained. The hot rolling was performed with a constant strain rate of 7×10^3/s.

After two types of testing, specimens were made; one was from the stir casting technique, and another was from the hot rolling technique. Both cast and rolled copper metal matrix composites were investigated for microstructural analysis with an optical microscope and scanning electron microscope (SEM) with energy dispersion spectroscopy, hardness study with Brinell hardness test setup, wear behavior pin-on-disc machine, and fracture morphology using SEM.

2.3. Microstructural Studies. Prior to the fabrication of copper-based composites, the specimens of required dimensions were sectioned from the cast and rolled composites for the microstructural investigations with a wire-cut electric discharge machine (WC-EDM). The sliced specimen was then cold-mounted with cold setting die with cold setting resin mounting agents for enhanced gripping purposes during sample grinding. The mounted specimens were then well-ground with various grades of emery papers from 80 to 2000 grit sizes. After, the ground specimens were polished on a velvet cloth on a disc polishing setup with the alumina powder suspension to get a mirror finish. The specimen's polished surface was then kept under the force of a water stream to clean and wash out the foreign elements. The specimens were then dipped in Keller's reagent for a sufficient duration to reveal the different microstructural features. An optical microscope was chosen to study the etched specimens for microstructural features and particle distribution.

2.4. Hardness Analysis. The hardness was measured using the Brinell hardness test setup with a ball indentor of 1.25 mm radius. To obtain precise hardness values, the Brinell hardness test setup was used. The primary reason for performing the microhardness investigation is to obtain better hardness results by making good contact with both the copper matrix and TiC powder reinforcing agents. During hardness investigation, the specimens experienced an indent force of 100 kg for 15 sec. To minimize the errors in hardness values, for each specimen, six indents were given in different places on the specimen's area, and finally, the mean of five readings was taken.

2.5. Tribological Studies. The tribological properties (i.e., coefficient of friction (COF) and wear rate) were studied as per the ASTM-G99 standards using the pin-on-disc wear test setup, and the pictorial illustration of the wear test setup



(a) (b)

Figure 1: (a) SEM image and (b) EDS pattern of titanium carbide particles used in this investigation.

Table 1: Sample designation for alloy and composites.

Sample code	Weight percentage of reinforcements
Sample A	Cu 95500 alloy
Sample B	Cu 95500 + 2.5% TiC
Sample C	Cu 95500 + 5% TiC
Sample D	Cu 95500 + 7.5% TiC
Sample E	Cu 95500 + 10% TiC

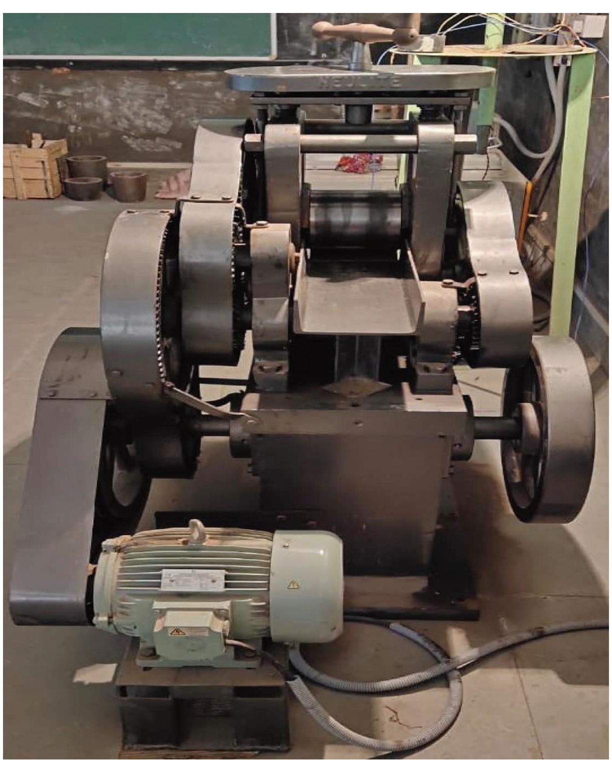


Figure 2: Photograph of hot rolling machine.

is shown in Figure 3. The wear load and sliding velocities for the wear test ranged from 30 N to 120 N and 0.628 m/s to 2.512 m/s. The photograph of the tribological test sample is displayed in Figure 4. The counterdisc was fabricated with EN-24 steel metal with a hardness value of 60 HRC, which was chosen as the counterplate. The specimens for the tribological characterizations were sliced to a length of 2.5 cm and a radius of 4 mm using a WC-EDM. The tribology investigation was carried out under ambient conditions for 0.5 hours. Prior to testing, all tribological samples were polished to a 1 μm finish and washed immediately to remove any foreign particles present on the specimen's surface. After the investigation, the test specimens were investigated under scanning electron microscope (SEM) for worn surface and wear debris morphologies.

3. Results and Discussion

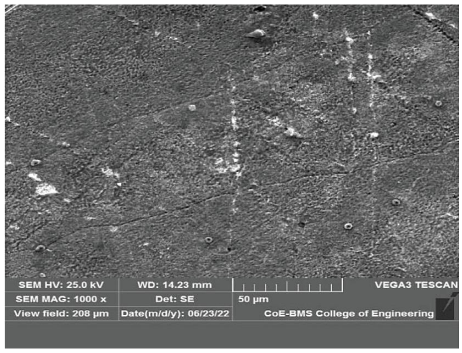
3.1. Microstructure. The SEM images of the stir casting and rolling copper metal matrix composites reinforced with varying weight percentages (2.5, 5, 7.5 percent, and 10 percent) of titanium carbide powder particles are represented in Figure 5. From Figure 5, it was identified that the dispersion of titanium carbide reinforcing agents was uniform throughout the copper matrix prior to the hot rolling method. The reinforcement dispersion in the copper matrix is one of the most important aspects of improving the

Figure 3: Photograph of pin-on-disc machine used for friction and wear test.

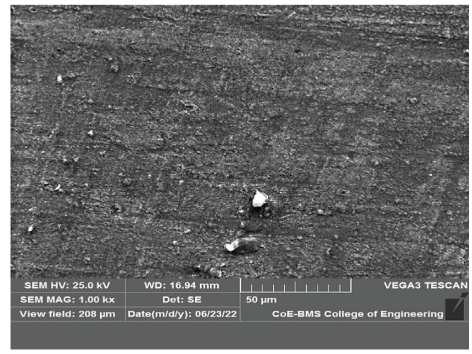
Figure 4: Photograph of friction and wear test specimen.

hardness and wear characteristics. The dispersion was clearly uniform, and the interface adhesion between the titanium carbide reinforcing agents and the copper matrix was robust. There is a formation of the dense structure prior rolling method and a final reduction in thickness, which is very much useful for improving the hardness and wear behavior. The size of the titanium carbide particles was reduced after the incorporation of further reinforcing agents (i.e., 10 percent), as shown in Figures 5(a) and 5(b). Generally, the stirrer serves as an object for reinforcement size reduction while stir casting. Because of the high volume percentages of reinforcing agents in 10% TiC reinforced copper composites, more numbers of reinforcements came in contact with the stirrer, and reinforcements collided with each other during stir casting resulting in the formation of fine TiC reinforcements, as shown in Figure 5(b). After hot rolling, the titanium carbide particles were further fragmented and resulted in the development of a very small size TiC particle, as shown in Figures 5(c) and 5(d). As the heavy rolling forces in every pass, the primary titanium carbide reinforcement phase was broken until the desired size of reinforcements was achieved, and these broken reinforcing agents of the primary phase elongated and oriented in the rolling direction. In comparison with five weight percent TiC copper-based composites (i.e., Sample 3), the size of the ten weight percent TiC copper-based composite (i.e., Sample g) was noticed to be very small because of the concentration of heavy rolling forces over the high weight percent of reinforcing agents, as shown in Figures 5(c) and 5(d).

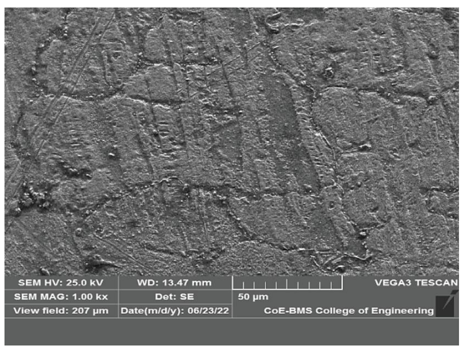
3.2. Hardness. Figure 6 shows the mean hardness readings of copper-based composites reinforcing with various weight quantities (0, 2.5, 5, 7.5, and 10 wt.%) of titanium carbide. It was identified that hardness was drastically increased after reinforcing with titanium carbide powder particles. In both casting and rolling circumstances, the reinforcing agents scattered in the copper matrix can withstand indenter load and have a higher hardness than unreinforced copper (i.e., Sample A). The hardness finding also confirmed that, as the reinforcement weight percentage increased, the hardness increased as well. The hardness of composites is affected by the high cohesiveness between the copper matrix and the titanium reinforcing agents. The studies on the wear behavior found that, as the weight percentage of reinforcing particles rises, the hardness value increases. However, we found that the hardness values of composite structures rise up to the specific content of reinforcing agents and then fall when more reinforcing agents are incorporated [13]. They also discovered that, after a specific weight content was reached, test samples enhanced with powder reinforcements had a negative impact on mechanical performance. Finally, they concluded that using powder reinforcing particles as a strengthening agent lowered the composite's plastic deformation resistance once the appropriate weight content was obtained.



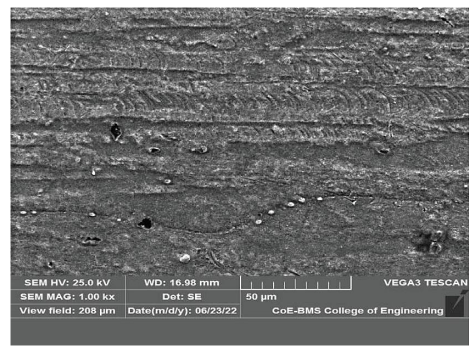
(a) SEM Images of cast Copper MMC with 5% TiC Reinforcement



(c) SEM Images of rolled Copper MMC with 5% TiC Reinforcement



(b) SEM Images of cast Copper MMC with 10% TiC Reinforcement



(d) SEM Images of rolled Copper MMC with 10% TiC Reinforcement

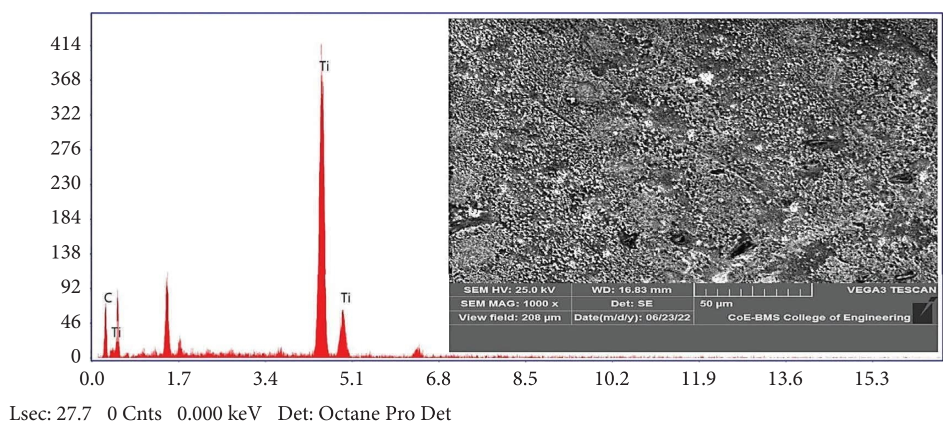


Figure 5: SEM of the cast and hot rolled copper-TiC composite showing the presence of TiC particles. (a) SEM images of cast copper MMC with 5% TiC reinforcement. (b) SEM images of cast copper MMC with 10% TiC reinforcement. (c) SEM images of rolled copper MMC with 5% TiC reinforcement. (d) SEM images of rolled copper MMC with 10% TiC reinforcement.

Hot rolling composites, on the other side, have significantly higher hardness than casting composites. As previously stated in microstructural investigations, the work hardening consequences caused during the rolling process result in the creation of dislocations, which serve as an obstacle to indent penetration, increasing the hardness of hot rolling specimens. Finally, in both casting and rolling conditions, Sample E (i.e., Cu with 10 wt.% TiC) has the higher hardness and Sample A (unreinforced pure copper) has the lower hardness. The Brinell hardness test results closely match the microstructural results.

3.3. Coefficient of Friction (COF). Figure 7 shows the COF comparison of casting and rolling samples prior to the wear testing for different titanium carbide weight percents (0%, 2.5%, 5%, 7.5%, and 10%) reinforced in the copper matrix constant processing conditions that were given in the experimental section. In the experimental description, when it comes to reinforced composites, a higher titanium carbide content results in a reduced coefficient of friction of samples. The composites containing 2.5, 5, and 7.5%, 10% titanium carbide reinforcements have less coefficient of friction in comparison with the specimen containing 2.5% titanium

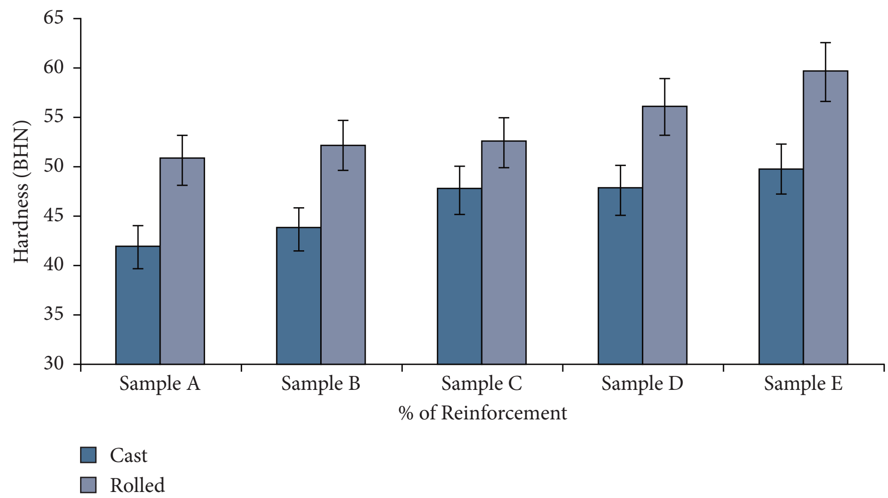


Figure 6: Comparison of BHN between as-cast and rolled specimens.

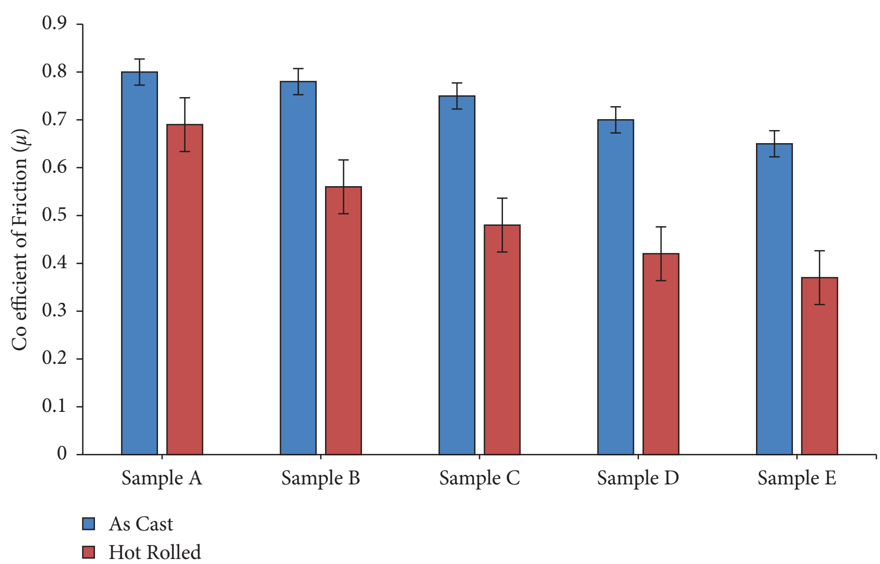


Figure 7: Effect of TiC content on COF of the cast and rolled composites.

carbide, regardless of processing parameters. By increasing the addition of titanium carbide particles to the copper matrix, the direct contact between the matrix and reinforcement particles will be reduced. The coefficient of friction of the specimens starts to decrease because of the less contacting region, and the specimen having 10% titanium carbide has a low coefficient of friction than other specimens because of the high concentration of titanium carbide particles. Because of the higher weight percentage of the titanium carbides, the specimen having 10 wt.% reinforcements showed less coefficient of friction for both as-cast and hot rolled samples, eliminating the direct contact with the harsh particles of the counter surface. Within the cast and rolled composites with varied reinforcing contents, the coefficient of friction of hot-rolled samples was less than stir-casting composites. This is because of enhanced titanium carbide particle dispersion. As mentioned in various studies, the homogeneous distribution of reinforcements increases the antifrictional qualities of composite parts. The low coefficient of friction in rolling samples is because of improved interface binding and increased reinforcement distribution. We reported that the extrusion process decreases the sample's wear and protects the teat area from damages in composites reinforced with silicon carbide particles [27–29].

Figure 8 depicts the frictional properties of cast and rolled Cu-based composites reinforced with different weight quantities of titanium carbides for varying wear loads of 30 N to 120 N achieved after the wear testing conducted at a fixed sliding velocity of 0.628 m/s. The coefficient of all specimens in stir casting and hot rolling rose constantly, while the wear load was increased from 30 N to 120 N, as displayed in Figure 8. Within the composite specimens, the specimens reinforced with high weight percentages of titanium carbides have a less coefficient of friction than samples reinforced with less weight percentages of titanium

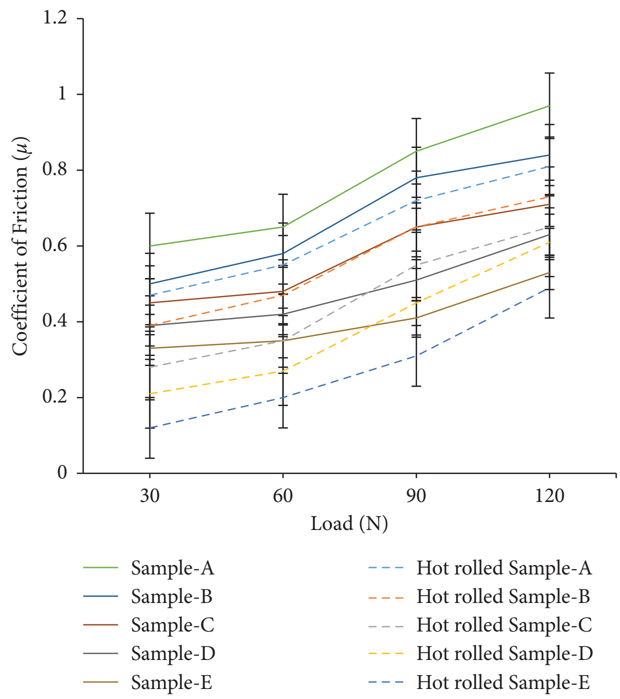


Figure 8: Effect of load on COF of the cast and rolled copper composites.

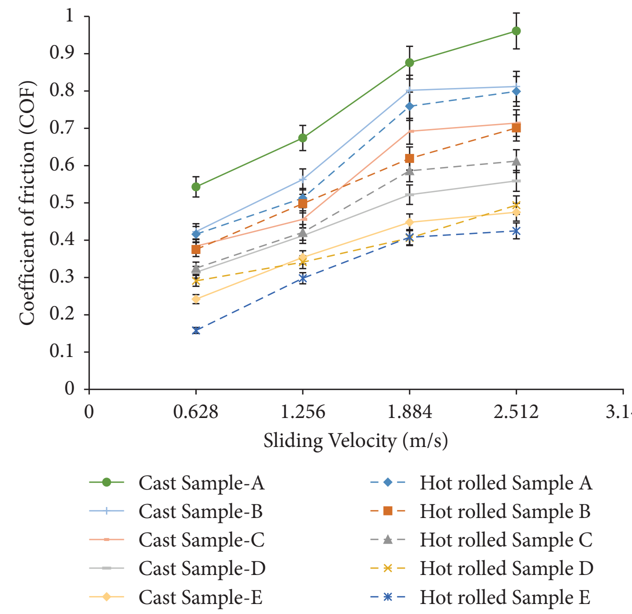


Figure 9: Effect of sliding velocity on COF of the cast and rolled copper composites.

carbides. The direct contact between harsh particles of the counterplate and big reinforcements with less TiC content composites resulted in an increase in the coefficient of friction and the COF increase in all other samples. The harsh particles of the counterplate plunge deeper into the surface of the samples as the wear load is raised, leading to a high coefficient of friction. In addition, the mechanical-mixed layer has a susceptibility to crack and shear at higher wear loads. It was also noticed from findings that, in comparison with rolling specimens, the coefficient of friction is high in casting specimens because of the high hardness and uniform dispersion of titanium carbide reinforcements in hot-rolling specimens.

The coefficient friction value of casting and rolling composites with a sliding velocity of 0.328 m/s to 2.5181 m/s after wear testing is performed at 20 N wear load is displayed in Figure 9. From Figure 9, it was identified that the coefficient of friction of all composites rises continuously as the sliding velocity was increased from 0.328 m/s to 2.5181 m/s. The coefficient of friction of casting composites having 2.5% TiC content is the highest; on the contrary, the coefficient of friction of casting composites having 10% TiC content is the lowest due to the incorporation of TiC particles, which improves the hardness. Moreover, adding titanium carbide particles reduces the contacting area between the sample and counterplate significantly. The coefficient of friction findings is affected by a reduced contacting area between the specimen and counterplate. The contacting area between the two contacting surfaces reduces as the titanium carbide particle weight percentage rose from 2.5 to 10%. Due to this, the composite having 10% TiC content has less coefficient of friction in both as-cast and hot rolled composites than composites having 2.5 to 7.5% TiC content. The frictional heat developed between the test sample and counterplate is greatly affected by the sliding velocity. The frictional heat developed at the counterplate softens the surface of the test specimen (i.e., pin), and the degree of softening of the sample's surface of the pin is influenced by the quantity of heat that is created by frictional force. The increase in the degree of softening is due to the increase in the depth of plunging off the harsh counter plate particles into the pin's surface. At a lower sliding velocity of 0.328 m/s, the pin's surface offered lesser friction heat, leading to less coefficient of friction. Increasing the sliding velocity results in a high amount of friction heat being developed on the pin's surface, leading to a high coefficient of friction and wear rate on the countersurface. It was also noticed in Figure 9 that, in comparison to casting samples, the coefficient of friction is less for hot-rolling composites because of higher hardness.

3.4. Wear Rate. Figure 10 shows the wear rate of the as-cast and hot-rolled composites tested at a constant wear load of 30 N load and sliding velocity of 0.328 m/s. The addition of TiC particles resulted in a lesser wear rate of the samples. The maximum wearing was observed for pure copper in both cast and hot-rolled conditions, while the addition of reinforcing agents drastically lowered the wear rate. In both composites, the composite having 2.5% TiC has a higher wear rate, while composites having 10% TiC has very less wear rates. Moreover, as TiC content rises, the wear rate lowers significantly and results in the composite having 10% TiC having the lesser wear rate. As mentioned in the previous analysis, decreased wear rate is linked to two factors: enhanced hardness and a reduced contacting area between

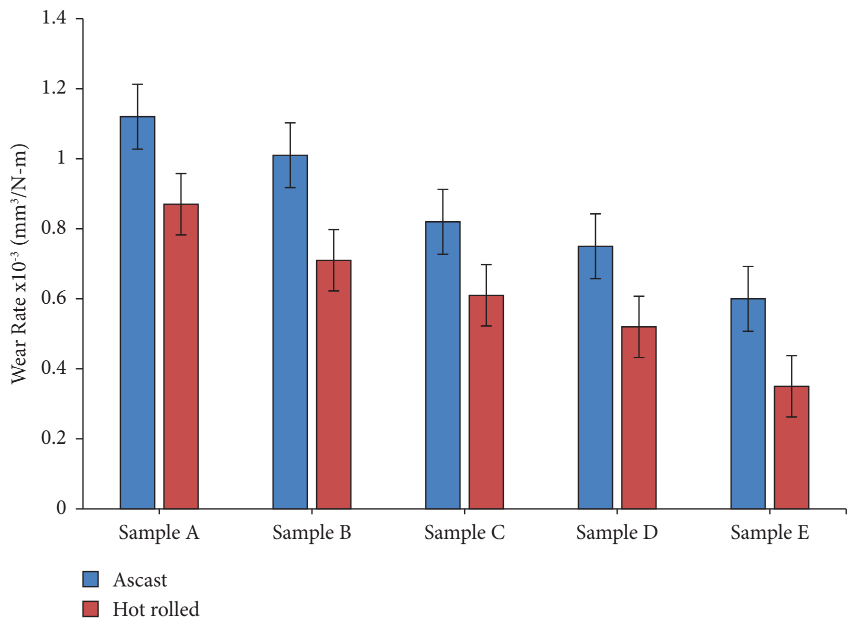


Figure 10: Effect of TiC content on the wear rate of the cast and rolled copper composites.

the test sample and counterplate. As an outcome, these harsh particles take on the major load, lowering the wear rate in the composites having 10% TiC. The severely strong TiC reinforcements chose to transfer their properties to the soft and ductile copper matrix which resulted in an increase in the hardness of the composites. The hardness is increased greatly in hot-rolled specimens as the enhanced binding and dislocation glide/climb prevention by the TiC reinforcing agents. Moreover, the reinforcing agents in the copper matrix function as barriers to dislocation movement and increase the stresses needed for dislocations glide/climb. The inclusion of reinforcing agents improved the mechanical performance of composite structures prior to hot rolling and led to improved wear performance. Within the composites, rolling composites have a significantly lesser coefficient of friction at different loads and sliding velocities, resulting in a lesser wear rate than cast composites.

Figure 11 depicts the wear properties of the as-cast and hot-rolled composites tested at different loading conditions (30 N to 120 N) and at a constant sliding velocity of 0.328 m/s. When it comes to both cast and rolled composites, composites containing 2.5% titanium carbide powder reinforcement have the maximum wear rates; on the contrary, composites having 10% titanium carbide powder reinforcements have the lesser wear rates. As the wear load rises up to 120 N, the wearing of both as-cast and hot-rolling composites is noticed to be dropped drastically. The titanium reinforcing agents are uniformly dispersed with enhanced interphase adhesion in composite specimens having 10% titanium carbide, resulting in greater hardness. The wear rate of the as-cast and hot-rolled composites is greatly affected by the increased hardness. The Archard formula, which measures that a material's hardness is inversely proportional to wear, will be utilized to obtain it. It was also identified from the results that, in comparison to rolling composites, the wear rate is greater in casting composites because of improved hardness and homogeneous dispersion of reinforcing agents in hot-rolling composites.

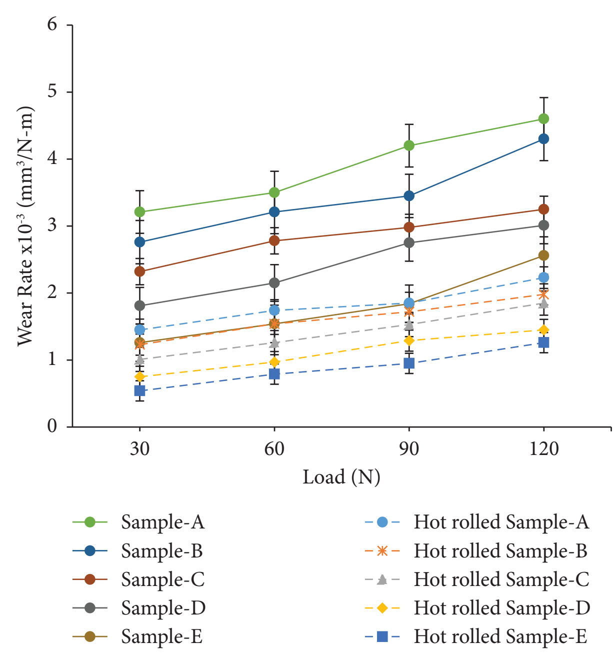


Figure 11: Effect of load on wear rate.

Figure 12 displays the wear properties of the as-cast and hot-rolled composites obtained prior to the wear testing conducted at a fixed wear load of 30 N and varying sliding velocities from 0.328 m/s–2.518 m/s. In both as-cast and hot-rolling composites, the composites with 2.5% titanium carbide powder particles have a greater wear rate than all other composites; on the contrary, the composites with 10% titanium powder reinforcing particles have a lesser wear rate than other composites. The increase of heat generation at

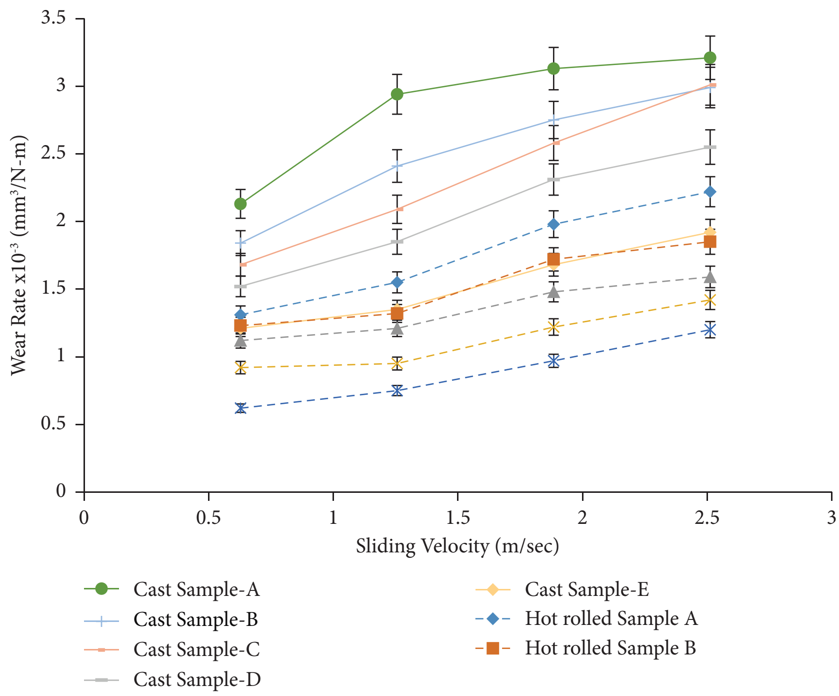


Figure 12: Effect of sliding velocity on wear rate.

contacting areas is responsible for the rise in wear rate as sliding velocity rises. The increase in heat generation in contacting area is the main reason for the rise in temperature. As an outcome, the pin's surface softens, increasing the wear resistance of casting and hot-rolling composites, irrespective of the processing route. Moreover, in the composite of 10% titanium powder reinforcements, the uniform dispersion of reinforcing agents with strong interface binding resulted in improved hardness. It is well known that the hardness of the materials is proportional to wear resistance, improving the hardness of casting composites and resulting in greater wear resistance. It was also noticed from the findings that, in comparison to casting composites, the wear resistance is higher in hot-rolling composites because of their greater hardness and uniform dispersion of reinforcing agents in hot-rolling composites. Finally, the results of the wear rate match with the results of the coefficient of friction as well as the microstructural and hardness results.

3.5. Worn-Out Surface Analysis. The SEM micrographs displayed in Figure 13 are of worn surface microstructures of casting composites having no reinforcing agents (Figures 13(a) and 13(c)) and 10% TiC reinforcements (Figures 13(b) and 13(d)), respectively, tested at two different wear loads (30 N and 120 N) and a constant sliding velocity of 0.328 m/s. Figures 13(a) and 13(c) shows that, at less wear load (30 N), the casting composites without reinforcing agents and with reinforcing agents display almost worn-out morphologies. In comparison with pure casting composites, the composites having reinforcing agents display slightly enhanced wear resistance due to the presence of reinforcing agents which can withstand the action of the counterplate over the composite's surface. The worn morphology of both samples includes abrasion and adhesion wear marks on the surface. As displayed in Figures 13(b) and 13(d), both casting composites fractured when the wear load was increased to 120 N, and the microstructure clearly witnessed higher worn out of composites in terms of the high density of abrasions and adhesions impressions because of the increase of heat generation between sample's surface and counterplate as an effect of high wear load. The SEM images displayed in Figures 13(e)–13(h) are of worn surface microstructures of the hot-rolling alloy having no reinforcing agents (Figures 13(e) and 13(g)) and 10% TiC reinforcements (Figures 13(f) and 13(h)), respectively, tested at two different wear loads (30 N and 120 N) and a constant sliding velocity of 0.628 m/s. The worn-out features of both pure and reinforcing composites show almost similar worn-out features at both wear loads. In comparison with the worn-out features composites tested at less load conditions (30 N), the wear resistance was slightly decreased for the composites tested at high load conditions (120 N). As a whole, the delamination wear was identified as the main wear mechanism in rolling samples.

The SEM images displayed in Figure 14 are of worn surface microstructures of casting composites having no reinforcing agents (Figures 14(a) and 14(c)) and 10% TiC reinforcements (Figures 14(b) and 14(d)), respectively, tested at two different sliding velocities (0.628 m/s and 2.518 m/s) and fixed wear load of 30 N. At lower sliding velocity (0.628 m/s), the alloy display (Figure 14(a)) more adhesion impressions and delaminations; on the contrary, the reinforcing composites (Figure 14(b)) display less adhesion impression and delaminations.

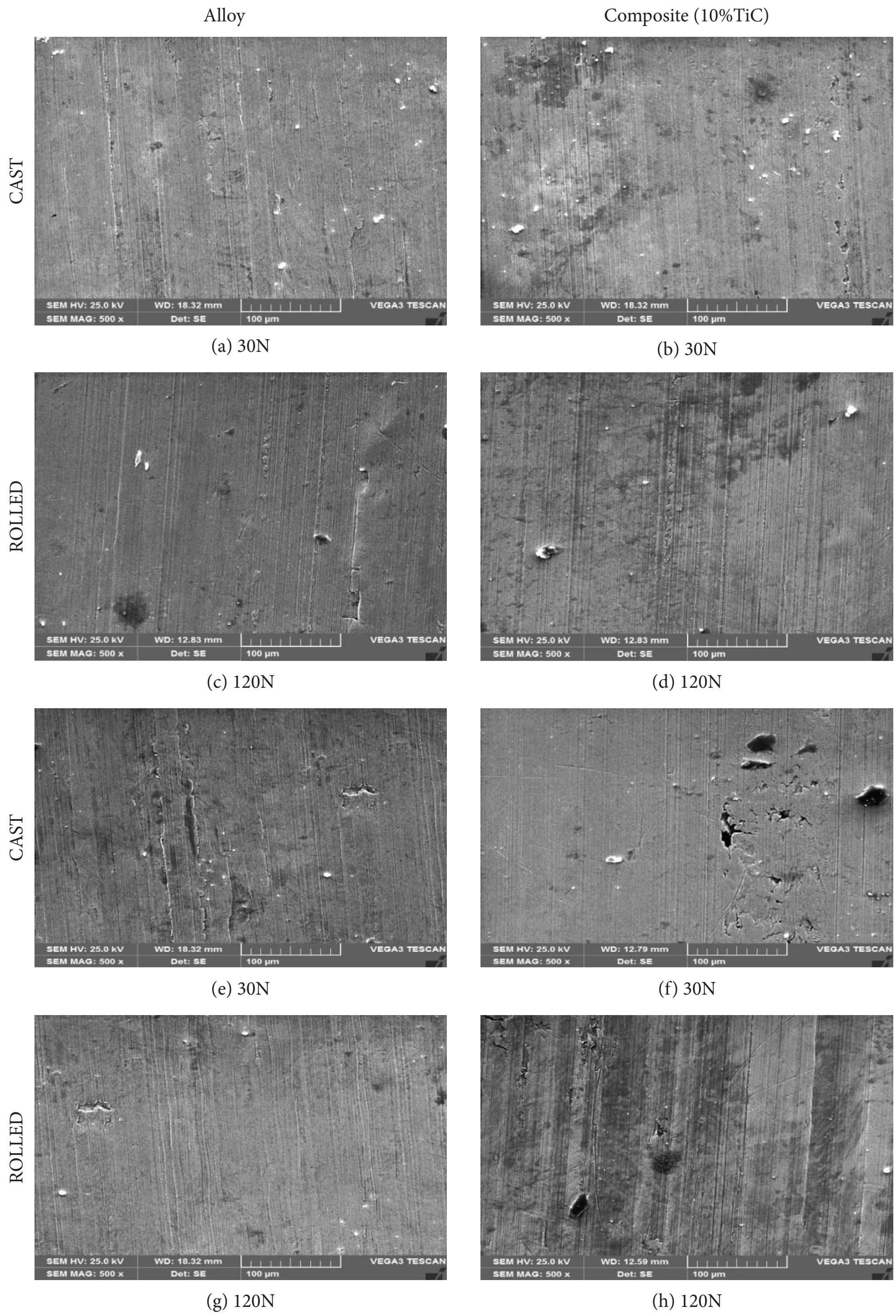


Figure 13: SEM of worn-out surfaces of the cast and rolled alloy and composites at different loads: (a) 30 N, (b) 30 N, (c) 120 N, (d) 120 N, (e) 30 N, (f) 30 N, (g) 120 N, and (h) 120 N.

At a higher sliding velocity (2.518 m/s), the fracturing tendency was improved and led to a slighter rise of adhesions and delaminations in the pure copper alloy (Figure 14(c)) and reinforcing copper composites (Figure 14(d)). The SEM images displayed in Figure 14 are of worn surface microstructures of hot-rolling composites having no reinforcing agents (Figure 14(e)) and 10% TiC reinforcements (Figure 14(f)), respectively, tested at two different sliding velocities (0.328 m/s and 2.518 m/s) and fixed wear load of 30 N. At lower sliding velocity (0.628 m/s), both pure (Figure 14(g)) and reinforcing composites (Figure 14(h)) display almost the same wear fracture features having

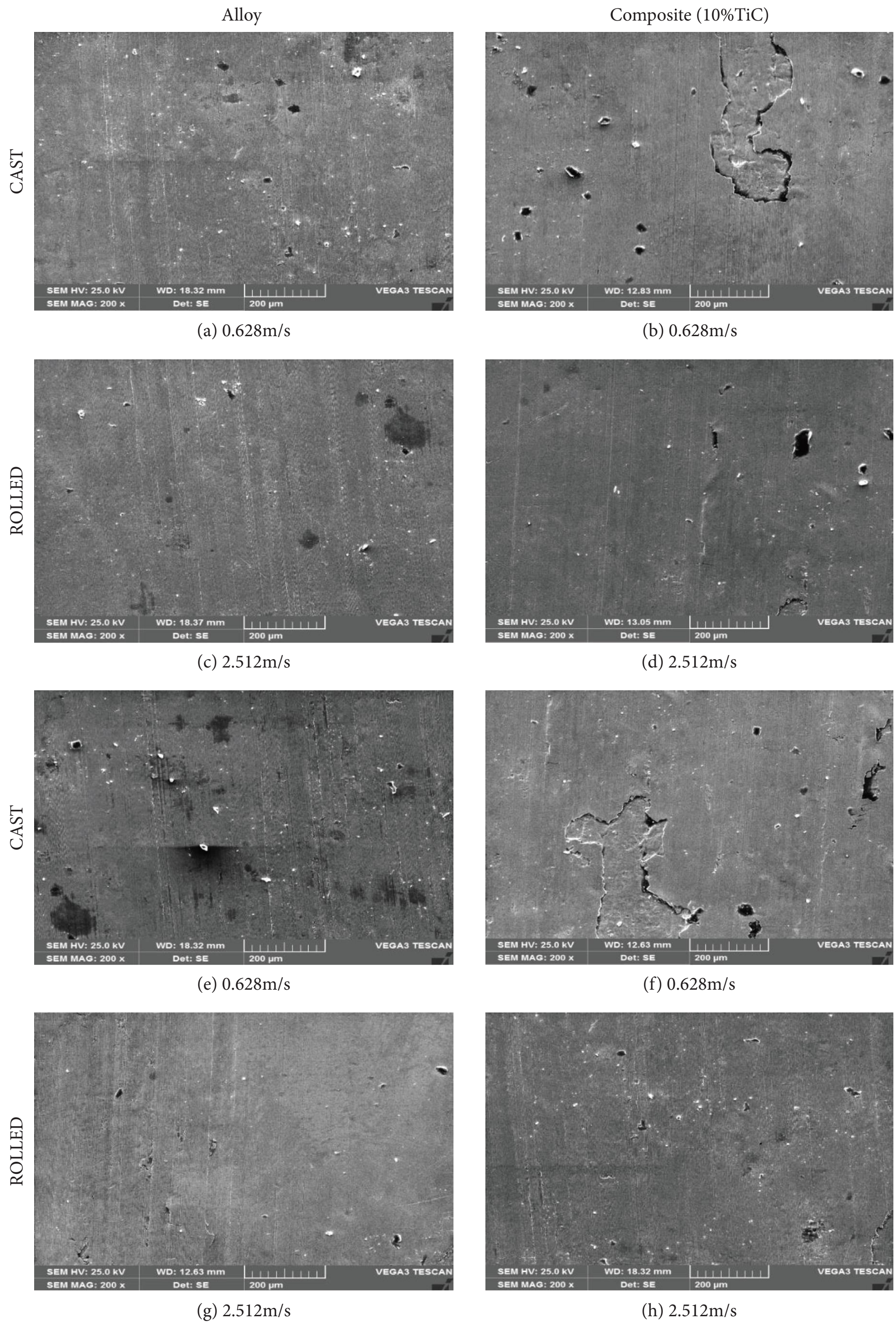


Figure 14: SEM of worn-out surfaces of the cast and rolled alloy and composites at different sliding velocities: (a) 0.628 m/s, (b) 0.628 m/s, (c) 2.512 m/s, (d) 2.512 m/s, (e) 0.628 m/s, (f) 0.628 m/s, (g) 2.512 m/s, and (h) 2.512 m/s.

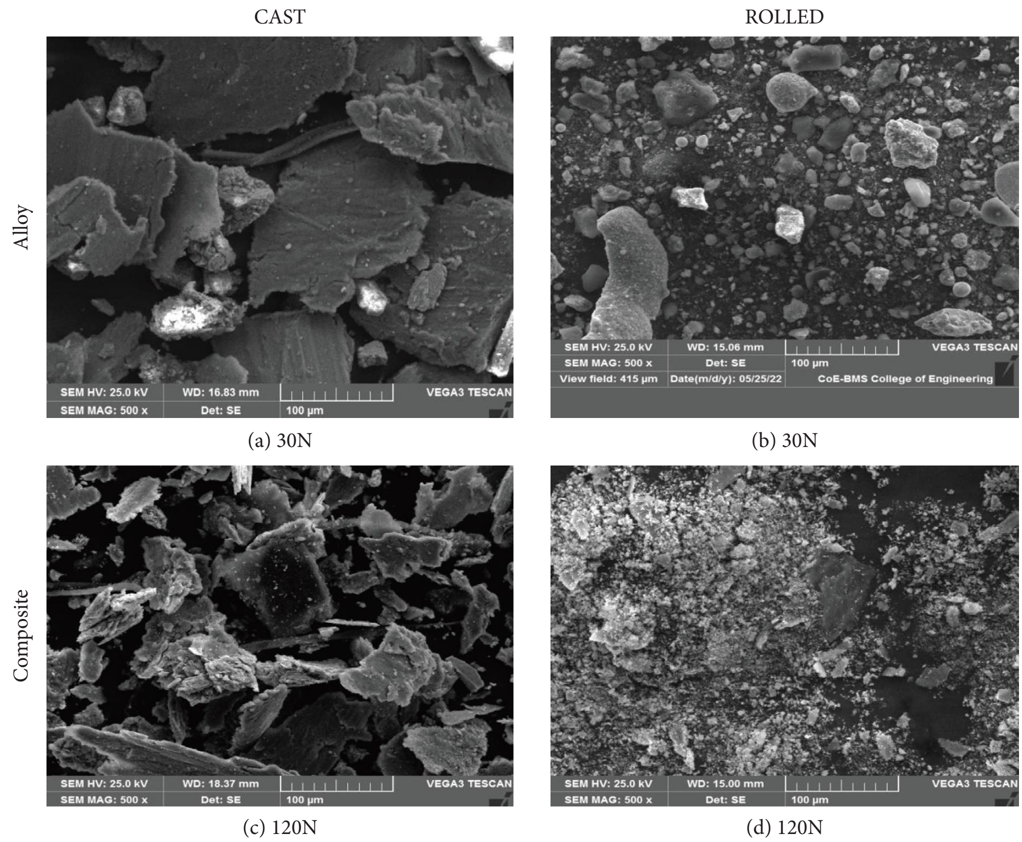


Figure 15: SEM of worn-out surfaces of the cast and rolled alloy and composites at different sliding velocities: (a) 30 N, (b) 30 N, (c) 120 N, and (d) 120 N.

delamination marks and adhesion impressions. At higher sliding velocity (2.518 m/s), both composite worn-out features include oxide particles, and other wear characteristics such as adhesions and delamination marks are identified to be the same as specimens examined at lower sliding velocity.

3.6. Worn Debris Analysis. The SEM micrographs displayed in Figure 15 are of worn debris microstructures of casting composites having no reinforcing agents (Figures 15(a) and 15(b)) and 10% TiC reinforcements (Figures 15(c) and 15(d)), respectively, tested at two different wear loads (30 N and 120 N) and a constant sliding velocity of 0.628 m/s. Figures 15(a) and 15(c) show the wear features of both alloy (Figure 15(a)) and reinforcing (Figure 15(c)) composite investigated at a lesser load (30 N), and the wear debris size of the two specimens were observed to be the same. In comparison with the lesser load circumstances, the size of the debris was grown for the specimens examined at a high wear load (120 N), as displayed in Figures 15(b) and 15(d). The increase in the wear load results in the growth of wear debris. Most of the debris formed was due to the delamination mechanism, so the material extracted was in the form of metallic layers. The preponderance of the delaminated debris's surface was covered in abrasion marks and microcracks. The wear debris features of all specimen debris were observed to be nearly identical regardless of the applied load, indicating that increasing the wear load had little effect on the size of the debris. Small fragmented oxide particles were seen on the surface of the wear debris, indicating an oxide wear mechanism. In both as-cast and hot-rolled composites, delamination plays a critical function in the metal removal of wear debris. Wear testing causes plastic deformation of both the counterplate and pin surfaces, as is well known. As the testing length and stress increase, fine microcracks emerge and grow in a sliding direction. These fractures expand and combine in the subsurface, leading to delaminations in the form of metallic layers in this specific area. The length of time it takes for the fracture to propagate determines the extent of the delaminated area.

4. Conclusions

In the current investigation, the copper-based metal matrix composites reinforced with the titanium carbide powder reinforcement particle were successfully fabricated, and we studied the microstructure, hardness, and tribological behavior with advanced characterization techniques, and the following conclusions were drawn.

(1) The microstructural findings revealed the homogeneous distribution of titanium carbide powder

reinforcements. Also, strong bonding was achieved between the copper matrix and reinforcements.

(2) The hardness was drastically increased in both casting and rolling samples due to the addition of titanium carbide reinforcing particles.

(3) In both casting and rolling composites, the coefficient of friction was measured to be less than unreinforced pure copper. The COF was increased with the rise in wear load and the sliding velocity in both conditions. In comparison to casting specimens, the COF was decreased for hot-rolling specimens.

(4) The wear rate was known to be raised with rising in wear load and sliding distance. On the other side, the casting specimens were found to have a higher wear rate than the hot-rolling specimens.

(5) The presence of homogeneously dispersed titanium carbide reinforcing agents with enhanced interphase adhesion is the primary reason for the lower wear rate in the reinforced copper composites than the pure copper.

(6) At lower wear loads and sliding velocities, the wear mechanism shows adhesion wear and abrasion wear, but at low wear loads and sliding velocities, delamination wear and oxidation wear are dominant.

(7) The growth of debris size reveals that higher shear strain that concentrates on the specimen's surface initiates and propagates the cracks into the subsurfaces, resulting in the removal of material in the form of metal sheets.

Data Availability

All data generated during this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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