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Research Article

Tensile and Wear Behaviour of Hybrid SiC-C Reinforced Epoxy Composites

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ABSTRACT

In this study, the wear and tensile behaviours of epoxy composites reinforced with SiC (silicon carbide) and C (carbon) were investigated. The influence of SiC and C reinforcement ratios and load parameters on the wear performance were systematically evaluated. The ultimate tensile load and deformation values were observed in neat epoxy samples. The incorporation of SiC and C particles adversely affected the tensile load of hybrid composite due to agglomeration of particles and weak bonding between filler and epoxy. When the SiC content was kept constant and the C content was increased, a noticeable improvement in the tensile load of the composite was observed. Conversely, when the C content was constant and SiC content was increased from 3% to 6%, the tensile load increased from 2053 N to 2409 N. Wear tests were conducted under two different loads (3N and 7N). The lowest coefficient of friction (COF) values were observed in epoxy composites reinforced with 6% SiC and 2% C due to protective layer formation on matrix surface by hard SiC particles and C particles. The addition of hard particles into the epoxy enhanced the wear performance of hybrid composites. SEM analysis of worn samples revealed that, surface deformations and material loss were more pronounced in the neat epoxy samples.

Introduction

Polymer epoxy resins are highly effective materials for use in different industrial applications due to low weight, low cost, and excellent mechanical characteristics [1-3]. Some of these industrial applications include coatings, sports equipment, aerospace and military components, electronics, automotive, and marine engineering. However, epoxy resins exhibit low wear resistance and possess a brittle nature. It is worth noting that reinforcing epoxy resin composites can significantly improve their mechanical characteristics such as hardness, fracture toughness, and wear performance [4,5]. Certain micro and nano particles can decrease the brittleness of epoxy resins and enhance their wear performance. Additionally, the size and shape (e.g., spherical or irregular) of the added particles can effect the overall behaviour of the polymer matrix [6,7]. Shen et al. investigated wear characteristics of PTFE reinforced SiO_2 epoxy composite. As a result, they observed the highest wear performance in epoxy composites containing optimum PTFE at the sliding distance of 1000m and 60N load [8]. Siddhartha et al. researched dry slide wear and mechanical properties of functionally graded epoxy composite reinforced with TiO_2 by taguchi design experimental approach. The lowest wear rates were obtained functionally graded epoxy composites reinforced with 20%-TiO_2. In addition, reinforcement of TiO_2 into obtained functionally graded epoxy composites established an increment at tensile modulus, flexural strength and impact strength [9]. Guermazi et al. described the production process and properties of glass, carbon and glass-carbon hybrid composites. The highest tensile strength, elastic modulus values were found at carbon laminated composites [10]. Babu et al. investigated wear performance of epoxy composite reinforced with debris powder. Epoxy composites reinforced with debris powder demonstrated low wear rates compared to neat composites [11]. Kanchanomai et al. investigated wear performance of epoxy composite reinforced with crushed silica particles. As a result, it was observed that when volume losses of composite increased the contact load increased too. Moreover at high sliding velocities abrasive wear and at high temperature epoxy–matrix deformations were determined [12]. Abenojar et al. studied wear and mechanical characteristics of silica reinforced composite. Mechanical and wear characteristics were effected with nano-SiO_2 reinforcement. As a result it was observed that silica reinforced epoxy nanocomposites showed reduced strength, hardness and Young's modulus values [13]. Nhuapeng et al. conducted mechanical performance of epoxy resin composites reinforced SiC nanowires. As a result, it was revealed that SiC nanowires enhanced mechanical performance of composite. The highest wear resistance values were obtained at epoxy resin composites reinforced 15% SiC nanowire. In addition tensile strength values of epoxy resin composites enhanced 341% approximately compared to neat epoxy resin composites [14]. Reinforcement of potassium titanate whisker was enhanced wear performance of resin composites and the lowest wear rate values, highest COF were observed in epoxy resin composites reinforced 15% potassium titanate whisker. Although strength and ductility values were exhibited increment by reinforcing [15]. Jagadeesh et al. examined hardness and tribological performance of thermoset and basalt-reinforced polymers. It was observed that hardness values of thermoset polymers were increased with basalt reinforcement and the optimum COF were found at basalt-reinforced polymers with 30% reinfircement ratio [16]. Mucha et al. searched effect of multiwall carbon nanotube on mechanical and wear performance of composites. It was observed that highest wear performance and tensile strength values with percentages between 0.25%-0.5% filled multiwall carbon nanotube between in epoxy resin composites [17]. Veena et al. investigated tribological performance of silica reinforced nanocomposites. Wear loss weights of unfilled and reinforced epoxy composites increased with increment of slide distance and load values. Silica reinforced epoxy nanocomposites revealed proof of mild abrasive wear because of hard ceramic reinforced particles [18]. Bobby and Samad investigated the wear performance of composites reinforced with nanoparticles. It was observed a considerable enhancement in wear behaviour of composites reinforced with particles to use many of tribological applications [19]. Abenojar et al. investigated wear characteristics of composite coated and reinforced with nano and micro ceramic particles. According to the wear test results the highest coefficient of friction values were found in coated epoxy resin composites [20]. Rong Lu et al. explored tribological and mechanical performance of composites reinforced with nano SiO_2 and TiO_2. As a result, it was proved that nano SiO_2 and TiO_2 can improve wear and mechanical features of composites [21]. Medina et al. analyzed tensile and toughness characteristics of epoxy resin reinforced with ZrO_2. It was determined that enhancement of tensile modulus, toughness by increment of ZrO_2 addition without lineal tendency [22]. Sakka et al. studied wear characteristics of epoxy resin reinforced with carbon nanotube and graphite. It was explored that optimum wear resistant results were found in epoxy resin reinforced with treated carbon nanotube [23]. Awwad et al. examined the impact of graphene platelets on wear and mechanical characteristics of composites. As a result, the increment impact of graphene platelets on stiffness, hardness and tribological performance and decrement influance of graphene platelets on tensile strength, strain and friction were observed [24]. Suresha et al. investigated mechanical and wear characteristics of carbon reinforced composite filled with graphite. It was observed that silane treated composites reinforced with graphite established enhanced wear, tensile strength and modulus, hardness values [25]. Suresha et al. investigated wear characteristics of composites. The lowest wear volume loss and ultimate tensile load and modulus were detected for nanocomposites at reinfoced higher than 5% organo-modified montmorillonite [26]. In a study conducted by Rout et al., the effect of SiC reinforcement on the sliding and erosive wear behavior of fiber-reinforced composites was investigated. It was found that the addition of SiC improved the wear resistance of the composites, while an increase in sliding velocity led to greater wear and material loss. Furthermore, it was reported that an increase in applied load resulted in a higher specific wear loss [27]. In another study, the wear resistance of composites obtained by placing SiC-reinforced epoxy plates between thin kraft papers was investigated. It was reported that composites with a high SiC content exhibited greater resistance to frictional forces, resulting in reduced wear loss. Furthermore, an increase in sliding velocity was noted to decrease the mass loss [28]. Li et al. investigated the mechanical and wear behaviors of carbon fiber-reinforced epoxy resin composites filled with SiC nanowires. They reported that the addition of SiC nanowires onto the carbon fibers enhanced the tensile and flexural strength of the hybrid composites. Furthermore, the SiC nanowires adhering to the surface of the carbon fibers provided mechanical interlocking, establishing a strong bond between the epoxy matrix and the fibers, which contributed to the improvement of wear resistance [29]. Apriliani et al. investigated the mechanical and wear characteristics of iron sand/epoxy composites reinforced with carbon powder. They found that the addition of carbon powder reduced the wear rate while increasing the flexural strength and hardness values of the composites [30].

A review of the existing literature reveals that studies investigating the combined use of SiC and C powder to enhance mechanical and wear properties are very limited. C powder possessing high chemical stability, good frictional performance, and favorable thermal properties [31,32] and SiC particles characterized by high hardness, high strength, and excellent impact and wear resistance, were used together to produce hybrid composite materials [33] to develop composites suitable for a wide range of applications in fields such as aerospace and energy.

The main purpose of the study is to reveal the influence of various reinforcements (SiC and C) and their contents (3% and 6%) on wear and tensile performance of epoxy resin. Tensile strength of neat samples and SiC and C particles reinforced composites at varying contents were determined, followed by an examination of their wear performance under different applied loads. Additionally, worn samples were evaluated utilizing Scanning Electron Microscopy (SEM) analysis.

Material and Method

The epoxy (ARC-152) and hardener (W-152) that had self curing property at room temperature for 24h were supplied by ARC Marin Ltd. Epoxy (ARC-152) was used, with tensile strength of 43.35 MPa, elastic modulus of 950 MPa, elongation of 6.5% [34]. SiC and C microparticles, with particle size of 75 and 150 µm respectively, were supplied by Ege Nanotek and KompozitShop. The weight ratio of epoxy (ARC-152) and hardener (W-152) was 4:1. The epoxy, hardener and particles was stirred by an ultrasonic bath device to disperse homogeneously the reinforcement particles (SiC and C) into the matrix. To prevent agglomeration of reinforcement particles, the mixing process with an ultrasonic bath device continued at a constant temperature for 1 hour. The manufacture process of epoxy composites performed by a contacting open mold without pressure, at room temperature. The mixtures prepared in the proportions (given in Table 1) were poured into the silicon mold. The epoxy composite samples were removed from the mold after 24h curing process at room temperature. Five various types of epoxy composites were produced as given in Table 1.

Table 1. Codes and content of epoxy composites.

Codes	Content of epoxy composite
Neat	Epoxy resin
2SiC-3C	Epoxy resin + 2% SiC + 3% C
2SiC-6C	Epoxy resin + 2% SiC + 6% C
3SiC-2C	Epoxy resin + 3% SiC + 2% C
6SiC-2C	Epoxy resin + 6% SiC + 2% C

The silicon mold prepared for the production of epoxy composites and the produced bone-shaped epoxy composite samples were shown in Figure 1.

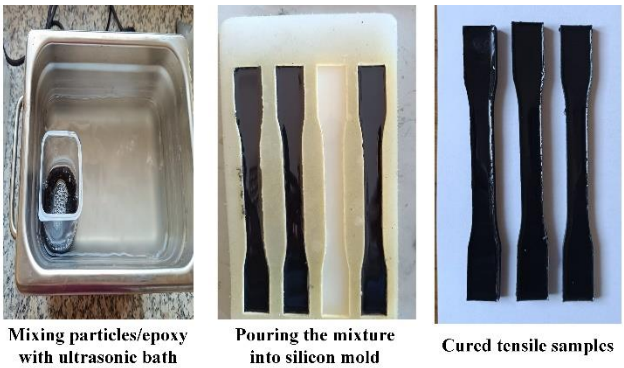

Figure 1. Silicon mold and bone-shaped epoxy composites.

Tensile tests were performed according to ASTM D638 test standard with crosshead speed of 1 mm/min by SHIMADZU AG-IC device. Wear tests were conducted under dry slide condition at room temperature utilizing the Turkyus brand pin on disk apparatus operating at constant 200 rpm rotational speed. Two different loads, 3N, 7N were performed during wear test. The effects of filler addition, filler content, and applied load on COF and wear rate were investigated. The wear testing apparatus used in the experiments is shown in Figure 2. For the tensile and wear tests, three samples were tested for each parameter, and the average of the obtained results was calculated.

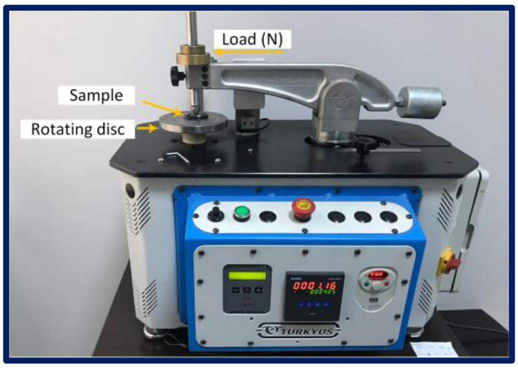

Figure 2. Wear device.

Results and Discussion

Tensile Test Results

Failure load (N) - displacement (mm) graphs of epoxy composites were given in Figure 3. Failure load values, displacements of epoxy composites and decrement ratios were given in Table 2.

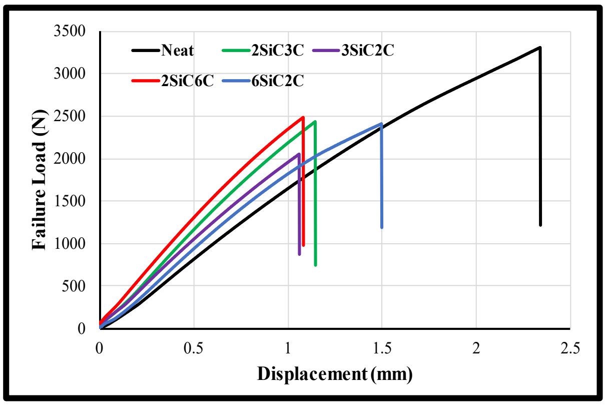

Figure 3. Failure load-displacement graphs of epoxy composites.

Table 2. Mechanical properties of epoxy composites.

Samples	Failure Load (N)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Displacement (mm)
Neat	3307	42.39	1273	2.344
2SiC-3C	2438	31.25	1918	1.146
2SiC-6C	2491	31.94	2070	1.080
3SiC-2C	2053	26.32	1754	1.059
6SiC-2C	2409	30.88	1450	1.497

The characteristic of failure load (N) - displacement (mm) curve of neat and hybrid SiC and C reinforced epoxy composites was approximately identical. As seen in Table 2 maximum tensile load was obtained at neat epoxy samples as 3307 N and minimum tensile load was found in 3SiC2C reinforced epoxy composites as 2053 N. Tensile load values and displacements of epoxy composites with SiC and C microparticles tend to decrease with different percentages of hybrid SiC and C reinforcement compared to neat epoxy samples. The decrease in tensile strength of the epoxy matrix composite with the addition of particles is attributed to the agglomeration of the added filler particles within the matrix and the weak bonding formed between the matrix and the particles. This phenomenon has been corroborated in similar studies [35,36]. In 3SiC2C and 6SiC2C hybrid reinforced epoxy composites, increasing the SiC microparticle reinforcement ratio also increased the tensile load values. Alaneme et al. observed increments in tensile strength with increasing SiC ratio in bamboo leaf ash particle reinforced aluminum matrix composites [37]. Suresha et al. produced hybrid carbon fiber and SiC reinforced epoxy composites and investigated the mechanical characteristics. Tensile load increment with the increasing of SiC reinforcement ratio in the composite matrix were discovered [38]. Tensile load values in 2SiC3C and 2SiC6C hybrid reinforced epoxy composites exhibited a slight increase tendency with increasing C particle reinforcement ratio. Zhou et al. increased tensile strength by increasing carbon nanotube reinforcement ratio in hybrid carbon nanotube and SiC filled composites [39]. In another study, Zhou et al. produced hybrid carbon nanotube and micro SiC filled AZ61 composites and observed increases in tensile strength with increasing carbon nanotube reinforcement ratio [40]. As seen in Table 2 maximum displacement was obtained in neat epoxy samples as 2.344 mm and minimum displacement was found in 3SiC2C hybrid reinforced epoxy composites as 1.059 mm. In 2SiC3C and 2SiC6C hybrid reinforced epoxy composites, as seen in Table 2, the increment of C particle reinforcement ratio from 3% to 6% increased the displacement values of epoxy composites. In 3SiC2C and 6SiC2C hybrid reinforced epoxy composite, as seen in Table 2, increment of SiC particle reinforcement ratio from 3% to 6% increased the displacement values of epoxy composites 41.4%. Alaneme et al. observed increments in displacement with increasing SiC ratio in bamboo leaf ash particle reinforced aluminum matrix composites [37]. Lv et al. observed decreases in displacements with increasing short carbon fiber reinforcement ratio in hybrid SiC and short carbon fiber-filled aluminum composites [41].

Wear Test Results

Figure 4 shows the variation of COF with applied load for neat epoxy samples, 3SiC2C and 6SiC2C samples over 200 m slide distance. It is detected that COF tends to decrease with increasing load for both neat and hybrid composites. For the neat epoxy samples, the COF decreased from 0.39 μ at a 3 N load to 0.33 μ when load was increased to 7 N, with addition of 3% SiC and 2% C particles to the epoxy matrix, the COF value at 3 N was found to decrease to 0.27 μ. When viscoelastic polymers come into contact with another material, heat is generated in the contact area, and this heat increases with higher contact loads. This results in softening of polymer, and transfer layer formation on counterface leads to a reduction in the COF [42]. These findings are consistent with those reported in similar studies [4,34].

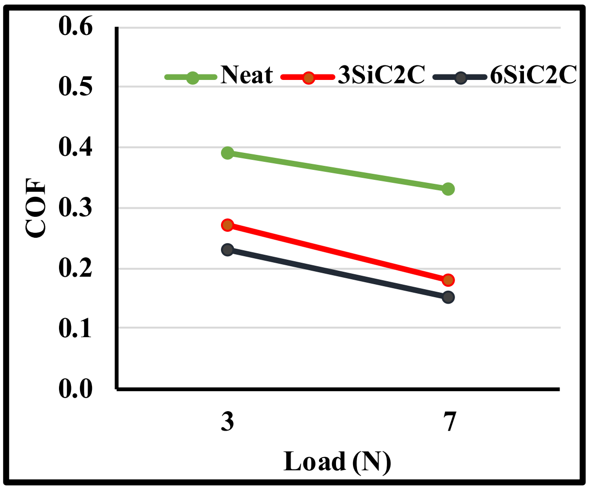

Figure 4. COF values of neat and hybrid composites depending on load.

Figure 5 illustrates variation in wear rates according to applied load and reinforcement content over 200 m sliding distance. For neat epoxy samples, wear rate increased from 2.40 mm^3/m at a 3 N load to 3.75 mm^3/m at 7 N. It was recognized that wear rate increased with the increment of load for all samples. The increment of wear loss with increment of load is a result of enhanced frictional heat, shear forces, and frictional thrust [44,45]. As the surface temperature rises and the matrix begins to soften, matrix degradation occurs under the influence of shear forces, leading to increased wear rates [45,46]. Adding of 3% SiC and 2% C particles decreased wear rate of hybrid composites from 2.40 mm^3/m to 1.06 mm^3/m at a 3 N load. This reduction in wear rate for hybrid composites is a result of protective layer formation on matrix surface by hard SiC particles and C particles, which limits the penetration of the counterface pin into the matrix [47]. Similarly, Suresha et al. stated that the inclusion of SiC particles to glass fiber reinforced composite improved wear resistance by enhancing interface adhesion between matrix and fiber [48]. Findings of Ji et al. are also consistent with these results [49]. When SiC reinforcement content in epoxy matrix was increased from 3% to 6%, the wear rate decreased from 1.60 mm^3/m to 0.93 mm^3/m under a 7 N load. Subbaya et al. examined effect of SiC filler content on wear performance of fiber reinforced composite and found that both presence and increased content of SiC improved the wear resistance. They concluded that existence of hard SiC particles within a ductile matrix enhances the overall matrix hardness, reducing the penetration of the counterface pin and thereby minimizing wear loss [50].

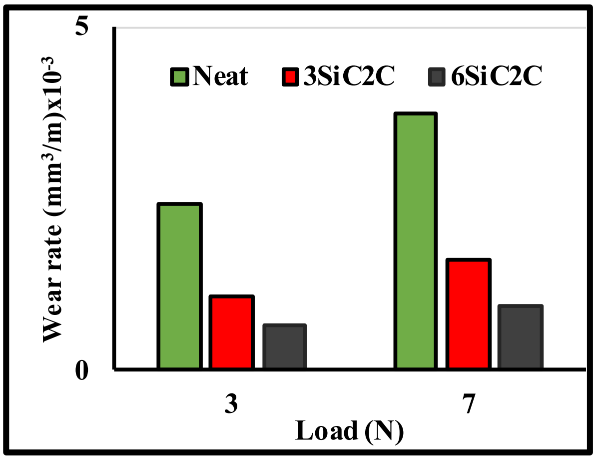

Figure 5. Wear rate values of neat and hybrid composites depending on load.

Wear Surface Morphology

Figure 6a presents worn surface morphology of the neat, 3SiC2C and 6SiC2C filled composites under a 3 N load. It was observed that the neat epoxy samples exhibited deep wear scars on their surface after wear test. In absence of hard filler particles, epoxy matrix could not withstand the applied load, resulting in more pronounced matrix detachments compared to the filled composites. As seen in Figure 6b, addition of 3% SiC and 2% C particles into the epoxy matrix significantly reduced plastic deformation. Matrix debris and surface pits became shallower, indicating improved surface integrity. The incorporation of SiC and C enhanced load-bearing capacity of matrix and acted as a protective barrier between abrasive pin and matrix, thereby enhancing wear resistance. Consequently, severely worn surface transformed into a relatively smoother morphology. In Figure 6c, increasing the SiC content from 3% to 6% further reduced matrix damage on the surface. The observed scratches and pit depths remained more superficial, indicating a decrease in wear loss with increasing SiC content. Moreover, microcrack formation was found to be less frequent at higher reinforcement levels. The enhanced interface adhesion between matrix and filler particles contributed to enhanced wear performance [51].

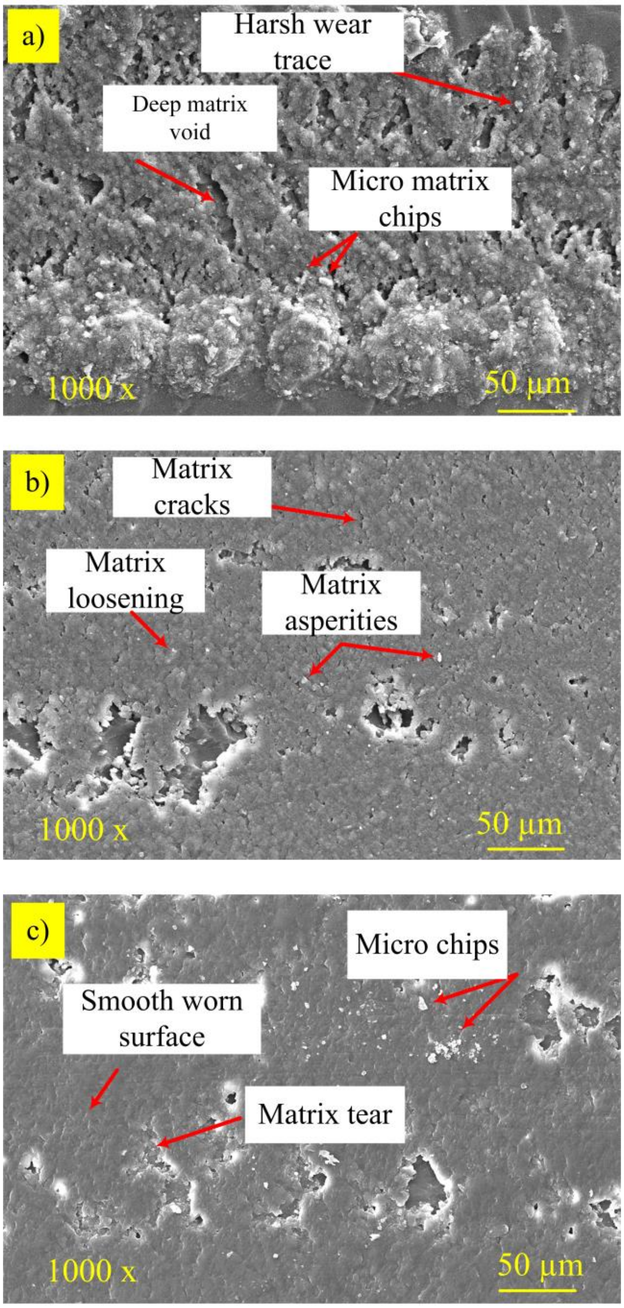

Figure 6. Morphology of worn surfaces a) Neat, b) 3SiC2C, c) 6SiC2C.

Conclusions

The primary objective of the study is to investigate tensile and tribological characteristics of composite produced by incorporating different types and proportions of fillers into epoxy resin. The neat epoxy samples indicated the highest tensile strength, reaching a maximum load of 3307 N, whereas the lowest tensile strength was obtained in the hybrid composites reinforced with 3SiC2C, with a value of 2053 N. Overall, the adding of SiC and C microparticles led to a noticeable reduction in both tensile load and displacement compared to the neat epoxy samples, with the extent of reduction dependent on the filler content. Tribological tests demonstrated that the neat epoxy samples exhibited the COF of 0.39 under a 3 N load, which decreased to 0.33 as the load increased to 7 N. The addition of 3% SiC and 2% C microparticles resulted in a pronounced reduction in COF, reaching 0.27 under a 3 N load, indicating the significant role of hard fillers in improving frictional performance. For the neat epoxy samples, the wear rate increased from 2.40 mm^3/m under a 3 N load to 3.75 mm^3/m at 7 N. It was noted that the neat epoxy samples showed deep wear trace on its surface following the wear test. Due to lack of hard filler microparticles, epoxy matrix was unable to resist the applied load, leading to more significant matrix detachments in comparison to the reinforced composites.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

Author contributions

The authors declare that they have contributed equally to the article.

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