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EFFECT OF REINFORCING POLYMERS BY SILICON CARBIDE NANOFIBERS ON FRICTION AND WEAR

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ABSTRACT

The present study aims to investigate the effect of silicon carbide nanofibers (SiCNF) of 0.1, 0.3, 0.5, 0.7 and 1.0 wt. % contents reinforcing polymethyl methacrylate (PMMA) and epoxy on the tribological behavior of the composites when applying normal loads of 5N, 10N and 15N to a tapered outer race of bearing 30203 rotating against the mentioned composites. The hardness of composites is measured by Shore D Durometer on surfaces of specimens. Friction coefficient of SiCNF/PMMA and SiCNF/Epoxy composites is measured through the monitored rotating test rig at room temperature.

Based on the experiments, results display that there is no apparent improvement in hardness of PMMA filled by SiCNF while of epoxy composites slightly increases by adding SiCNF. Friction coefficient of PMMA composites minimum values are detected at 0.7 wt. % SiCNF, 0.7 wt. % and 1.0 wt. % for 5N, 10N and 15N respectively. The minimum values of epoxy composites friction coefficient are detected at 0.5 wt. % SiCNF content for 5N and 10N, while for 15N appears at 0.5 wt. %. Minimum scar width occurs in SiCNF/PMMA composites at 0.7 wt. % content for 10N and 15N, white it occurs at 0.3 wt. % for 5N normal load. Minimum scar width occurs in epoxy composites at 0.3 wt. % SiCNF for all applied loads.

KEYWORDS

Silicon carbide nanofiber, reinforcement, polymethyl methacrylate, epoxy, composites, hardness, wear scar, friction coefficient, normal load, bearing steel.

INTRODUCTION

Composite materials are known to have high specific modulus, high specific strength, high resistance to corrosion, low weight and can be tailored to meet specific purpose, which give them advantage over traditional materials such as metals and ceramics, [1]. Polymer matrix composites (PMCs) are commonly used nowadays in industrial applications such as bearing materials can used in fishing boats, brake pads materials, flooring materials and so on, [2]. They have wide range of applications in aerospace, marine, automotive, biomedical, defense, offshore drilling, leisure goods and low-

pressure pipes, [3]. Further approaches in designing polymeric composites in order to operate under low friction and low wear against steel counterparts are described, [4]. Due to the great changes in technology that occurred in the last century, a larger number of components fabricated in engineering polymers and composites have been used; substituting the most traditional metals in diverse applications, attaining in many cases better advantages as reduction of maintenance costs, save in weight and higher freedom for designing. Some examples of applications can be cited as: self-lubricant bearings, plain bearings, linear guides, mechanical seals, bushings, bearings cages, transporting belts, gears, and pulleys. These components are in turn more required in the aspects of mechanical resistance, fatigue strength and resistance to wear, [5]. Due to their versatile properties combined with a favorable strength-to-weight ratio, polymer composites find numerous applications in industry, [6]. To further improve their performance, new matrix and reinforcing materials are required. The control of the nanostructure and the addition of nanoparticles to polymers have led to structural and functional property enhancements in a number of polymeric systems as a material answer to continuous requirements from advanced industrial sectors, [7].

PMMA is one of the most widely used industrial polymeric materials and still remains an active material for research at the cutting edges of science. Because of its good biocompatibility, reliability, dimensional stability, absence of taste, odor, tissue irritation and toxicity, [8], teeth adhesion, [9], insolubility in body fluids, relative ease of manipulation, good aesthetic appearance, [10], and color stability, [11], PMMA based materials are widely used as biomaterials. Nowadays, PMMA finds applications not only in dentistry but also in areas such as transparent glass substitutes, interior design, transparent dielectric films, [12], acrylic paints, [13], and microcellular foams, [14]. **Still, one of the most attractive applications of PMMA based materials is in various biomedical applications such as intraocular lenses, [15], and bone cement in orthopedic surgery, [16]. The properties of acrylic PMMA are mentioned in details, [17]. Wear generally originates from damage induced by rubbing bodies due to repeated applications of mechanical, impact and other kinds of forces, [18]. Therefore, the surface loses mechanical cohesion and debris is formed that is dislodged from the contact zone. Many wear mechanisms have been proposed, [18], e.g., abrasive, adhesive, fatigue, corrosive, erosive and delamination, which show the complexity of the wear phenomena. Wear debris can also be generated by material transfer from one surface to another. Wear of polymers is affected by many intrinsic and extrinsic factors, such as surface roughness, contact kinematics, material nature, mechanical, physical and chemical properties of interacting bodies, testing environment, etc. In general, depending on the molecular and internal structural organizations, polymers have lower multiple transition temperatures and thermal conductivity than metals. Hence, the energy consumed in the processes of friction and wear can lead to softening, melting, oxidation or pyrolysis on the surface of the polymer and its relevant wear debris significantly affects the wear and friction performance, [19]. It is necessary to understand the interaction between two mating surfaces so as to demonstrate completely the tribological performance.**

Scratching is an alternative to conventional wear testing to evaluate the tribological properties of polymers. In the scratch test, a hard indenter is pressed onto the material under load and moves relative to the material; and scratch resistance is given by its ability to withstand mechanically induced surface damage under those conditions. Unlike an indentation process where the normal load is uniformly distributed beneath the indenter, scratching involves a high-friction-induced sliding process, [20]. The indenter is fully supported by the specimen in the front and only partially by recovered material in the rear-half. The extent of recovery again depends on the stress-relaxation characteristics of the material in the contact zone. The scratch process is also divided into two stages where the first stage involves indenting the specimen until a specified load (which is a dynamic process) and then the second stage involves the sliding of the indenter on the sample surface (which is a quasi-static process).

Different types of testing methods are developed over the last few decades to measure the resistance to scratching in polymers and these include: Ford five finger test, Taber scratch tester, instrumented indentation test, DIN abrasion, and recently, depth-sensing instruments capable of scratching at nano-level on different materials. Available scratch testing techniques for polymers were reviewed, [21], currently and it was noted that a scratch test employing a linear load increase method provides sufficient repeatability of the test data. Scratch performance of polymers is determined by the material properties, test environment, and the stress field due to the scratching process.

The most common types of material damage during scratching for (a) ductile, (b) ductile and brittle, (c) brittle and (d) elastomeric responses, [22]. In addition, the surface tension of polymers has also been shown to play a role in influencing the scratch resistance., [23] The relation of surface tension, residual scratch depth, penetration depth, static and dynamic friction for fluoropolymer filled epoxy was reported. They demonstrated that increasing the surface tension, friction, penetration and residual depths were also increased.

In the present work, the effect of reinforcing PMMA by SiCNF on the tribological behavior of the composites when sliding against bearing steel has been investigated.

EXPERIMENTAL

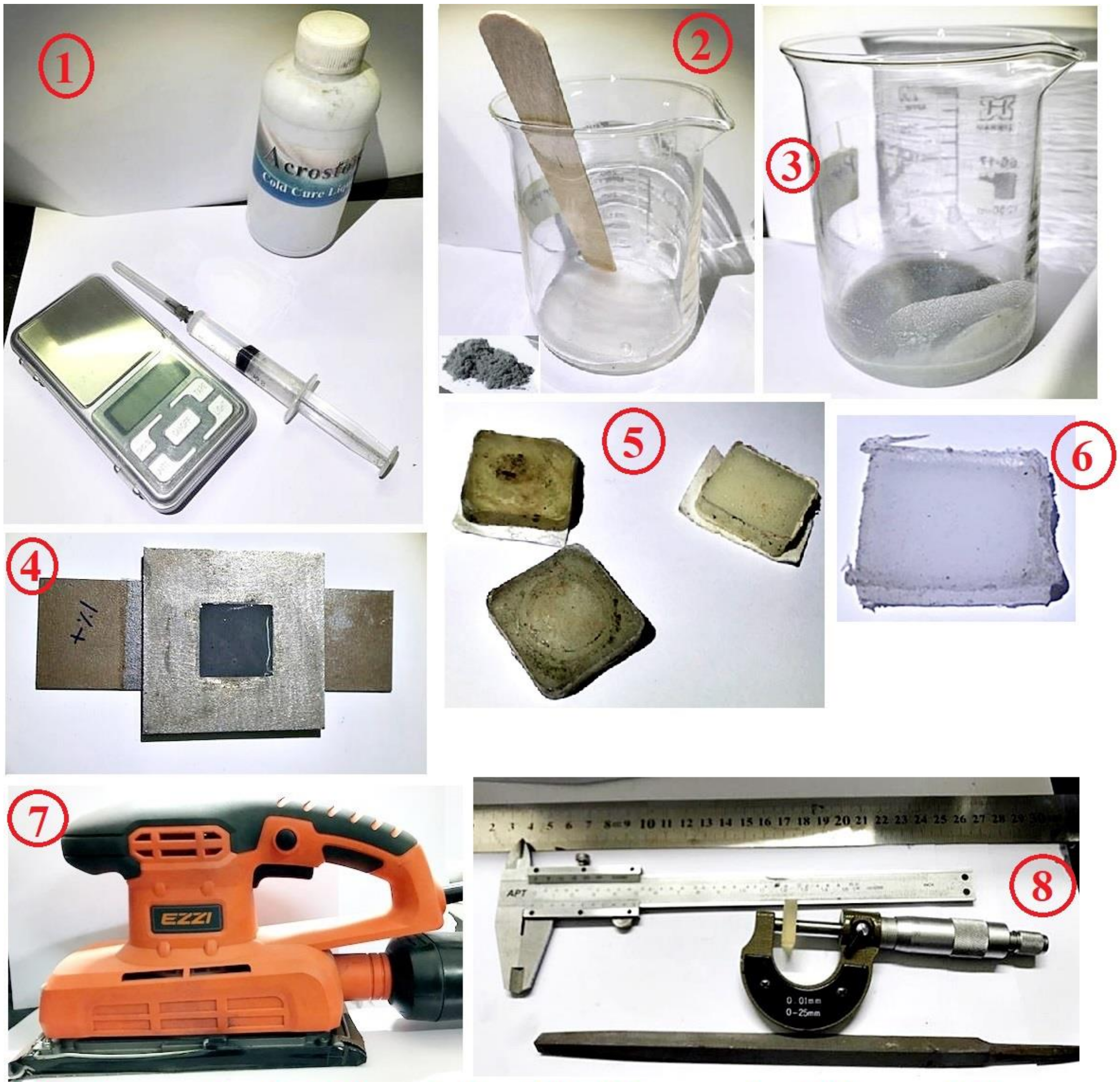
Materials

Experiments of this study had been carried out on test specimens composed of polymethyl methacrylate (PMMA) and epoxy as matrix materials and reinforced by silicon carbide nanofiber (SiCNF). PMMA and epoxy had been used as cold cured resins.

Preparation of Test Specimen

Figure 1 shows the test specimens preparation procedure that had been fabricated from cold cured PMMA (as received) by mixing powder and liquid according to recommended mixing percentages in a glass beaker to avoid undesired chemical reactions. SiCNF had been added, and then mixed with the compound for 30 seconds in room temperature before pouring into the mold of dimensions of 20 × 20 × 3 mm. After

curing, the sample had been ejected, its dimensions had been confirmed, residues had been removed and adhered to a steel strip as shown in Fig. 2. The same methods had been applied to epoxy sampling while mixing had been done in paper beakers as recommended and silicon carbide nanofibers had been added to total compound by weight with the same percentages, procedure shown in Fig. 3.



1-Mixing powder-liquid by weight, 2-Defining required fillers weight,
3- Mixing PMMA with SiC fibers, 4- Pouring mixture in die,
5- Examples of rejected samples, 6- Undesired residues,
7- Automatic sander for removing residues & softening ,
8- Specimen dimension confirmation

Fig. 1 PMMA composite specimen preparation

1- Mixing epoxy components by weight & defining required SiCNF weight,
2- Mixing SiCNF with epoxy by weight,
3- Mixed composite before molding,
4- SiCNF/epoxy composite in die before curing,
5- Examples of rejected samples
6- Jig for residues removal & smoothening
7- Automatic sander for residues removal
8- Specimen dimension confirmation

Fig. 2 Epoxy composite specimen preparation procedure

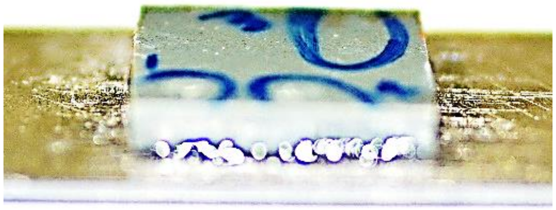


Fig. 3 Test specimen of a cold cured composite adhered to holder strip.

Test Method

Hardness Test

Shore D Durometer instrument was used to measure hardness of specimens' surfaces, as durometer measures material's resistance to permanent indentation, it was used to measure in the upright position towards specimen surface.

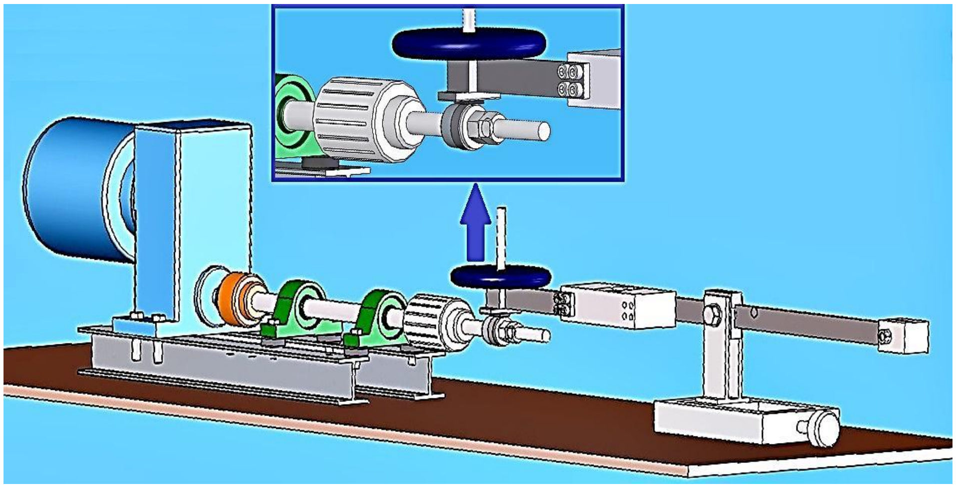


Fig. 4 Details of the test rig.

Friction Test

Evaluation of the friction coefficient of composite specimens was done by using tribometer tester to monitor friction force though subjecting specimens to different normal loads while a tapered ring rotating towards them. Friction force readings average was taken from 60 readings during one-minute test. Test rig shown in Fig. 4 consists of a variable speed gearmotor rotating a shaft with chuck which holds a small shaft with fixed tapered outer race of bearing 30203, the tapered outer race rotates against specimens held by clamps and subjected to normal loads. For each normal load, the friction coefficient is determined by the relationship:

$$\mu = F / N \qquad [8]$$

Where μ is the friction coefficient, F is the friction force and N is the normal load. Experiments were carried out with the parameters of 200 rpm, normal loads of 5N, 10N and 15N and test duration of one-minute for each load per sample.

RESULTS AND DISCUSSION

Hardness

Figure 5 shows the effect of silicon carbide nanofibers content (SiCNF) on the hardness of cold curing PMMA. There is no apparent improvement of PMMA hardness noticed with the increase of silicon carbide nanofibers.

Figure 6 shows the hardness enhancement occurred in epoxy composited with the increase of silicon carbide nanofibers (SicNF) content. This improvement in hardness might be due to the strength increase and Young's modulus of adding silicon carbide nanofibers.

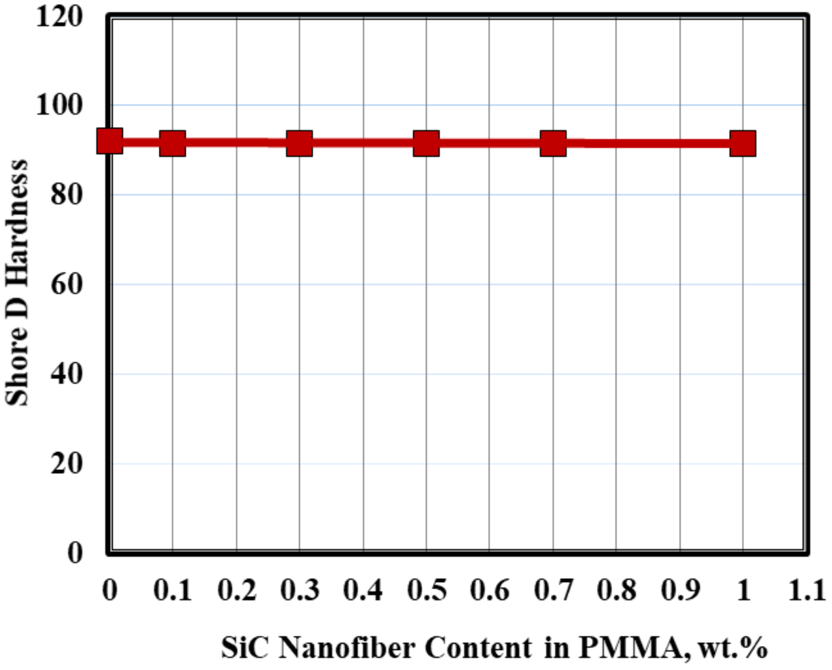


Fig. 5 Effect of SiCNF content on the surface hardness of SiCNF/PMMA composites.

Friction

Figures 7 and 8 show the effect of silicon carbide nanofiber (SiCNF) on the friction coefficient (μ) of composites. For PMMA composites, in figure 5 it can be noticed that when applying a normal load of 5N to PMMA composites, the friction coefficient tends to increase with adding SiCNF while the minimum value of friction coefficient was for the pure PMMA sample, then 0.7 wt. % of SiCNF and the highest value friction coefficient value was at 0.3 wt. %. When a normal load of 10N was applied, the friction coefficient showed the minimum value at the pure PMMA sample, then 0.7 wt. % of SiCNF, and the highest friction coefficient value was at 0.1 wt. %. The same behavior was observed when applied 15N normal load and also showed the minimum value at the pure PMMA, while next was second lowest value at 0.7 wt. % and the highest value was at 0.1 wt. % SiCNF. The increasing friction coefficient behavior might be attributed to the abrasive action of SiCNF and strengthening the polymeric matrix as well as increasing the shear strength. It was noticed that the overall friction coefficient behavior tended to decrease when the normal loads increased. This can be explained by the correlation between contact area and load, as increasing the normal load applied, the contact area increases, hence the interacting surfaces produce particles work as a medium decreasing the friction coefficient.

Figure 8 reveals the friction coefficient behavior with increasing the content of SiCNF reinforcing epoxy specimens. When epoxy composites were applied to 5N normal load during experiment, friction coefficient showed the minimum value at pure epoxy specimen then the next lowest value at 0.3 wt. % SiCNF while the highest value was at 0.7 wt. % content. For experiments performed under normal load of 10N, the minimum friction coefficient value was at 0.3 wt. % SiCNF content and the maximum value was at

0.7 wt. %. For 15N normal load tests, the minimum values of epoxy composites were at 0.5 wt. % and 0.3 wt. % respectively and both values were lower than the friction coefficient value showed by pure epoxy samples, while the maximum friction coefficient value was shown at epoxy composite with 1.0 wt. % of SiCNF content. The friction coefficient overall behavior tended to decrease with increasing the normal load applied to epoxy composites samples, as it could be because fragmentation occurred when contact area increased because of load increase, as those fragments could work as a third body medium worked on decreasing the overall friction coefficient behavior than the lower applied loads.

Wear scar width in the current study is alternatively representing wear. The correlations observed between scar width and silicon nanofiber (SiCNF) content respecting different applied loads are shown in Figs. 9 and 10 for PMMA composites and epoxy composites respectively. Figure 9 shows PMMA composite with a 0.3 wt. % SiCNF content shows the minimum scar width when applied to 5N normal load, while the widest scar appears at 0.5 wt. %. For 10N normal load, the minimum scar width is at pure PMMA sample, then 0.7 wt. % and the maximum scar is 1.0 wt. %. Maximum scar width at 15N normal load can be observed at 1.0 wt. % and the minimum scar width appears at 0.1 wt. % SiCNF. The minimum value, observed at 5 N load of PMMA reinforced by 0.3 wt. % SiCNF, may be attributed to increase of wear resistance gained by composite, while the maximum value of scar width occurred in PMMA composite and applied to 10 N load appears at 1.0 wt. % SiCNF due to wear increase as result of the decrement of PMMA and SiCNF. Inhomogeneous dispersion may play a role in scar increase.

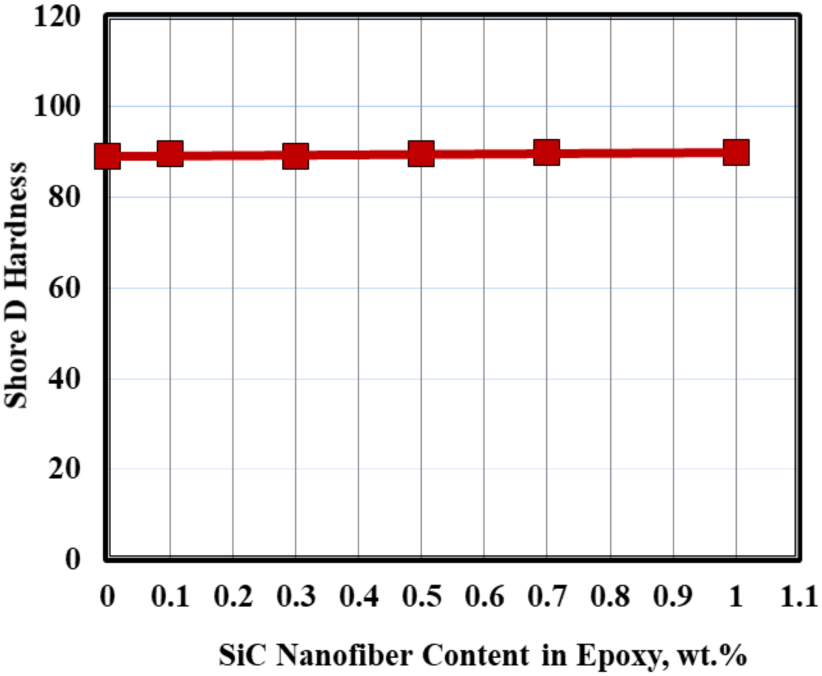


Fig. 6 Effect of SiCNF content on the surface hardness of SiCNF/Epoxy composites.

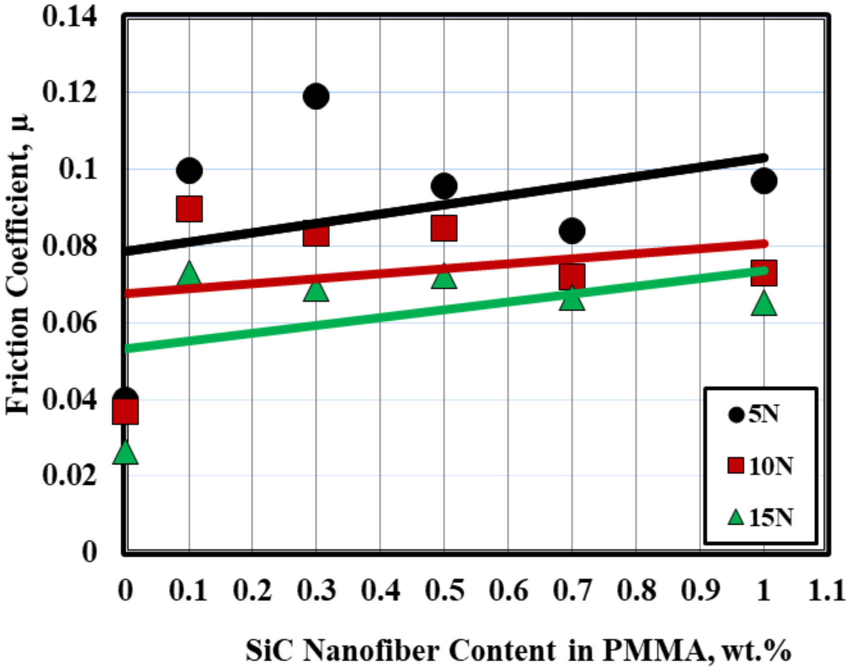


Fig. 7 Effect of SiCNF content on the friction coefficient of SiCNF/PMMA composites.

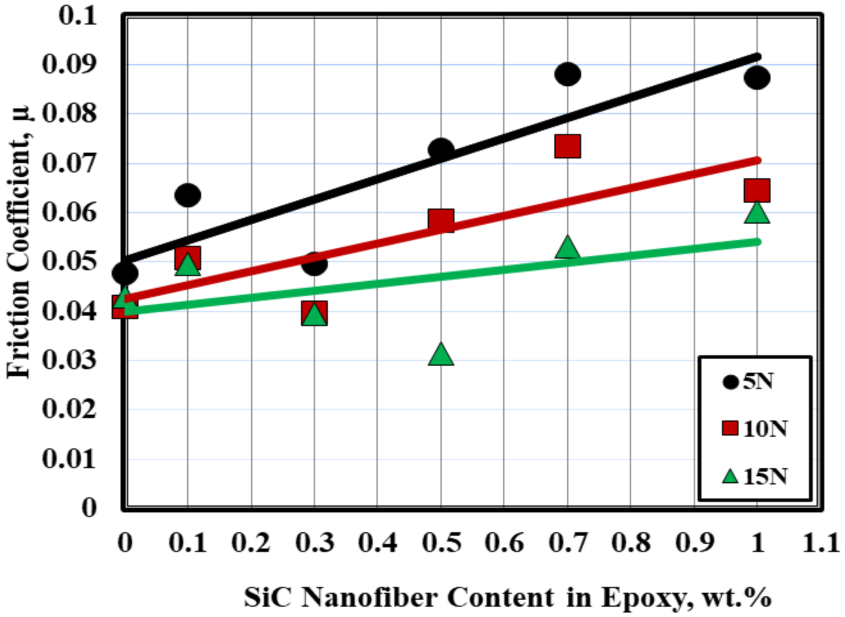


Fig. 8 Effect of SiCNF content on the friction coefficient of SiCNF/Epoxy composites.

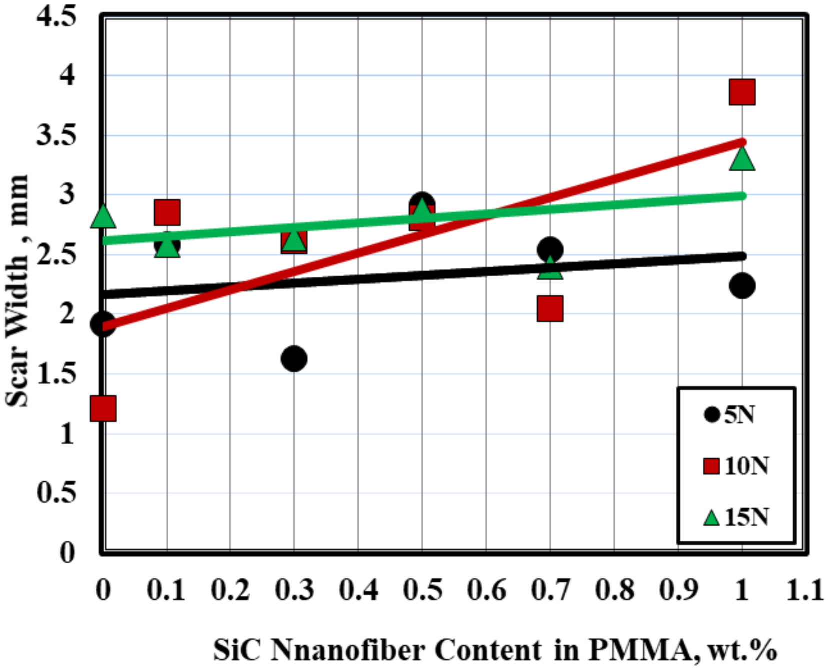


Fig. 9 Effect of SiCNF content on the scar width of SiCNF/PMMA composites.

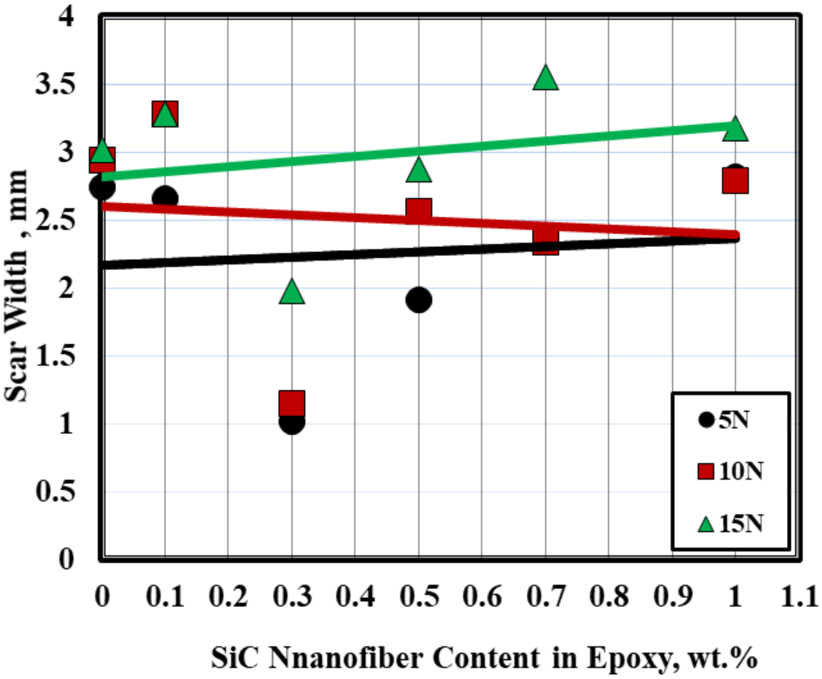


Fig. 10 Effect of SiCNF content on the scar width of SiCNF/Epoxy composites.

Figure 10 shows the relationship between wear scar width and silicon carbide nanofiber of different weight contents reinforcing epoxy at different values of normal loads. For 5 N normal load, the minimum scar width value appears at 0.3 wt. % SiCNF, which is the same percentage of SiCNF showed minimum scar width for 10N and 15N. This behavior could be attributed to the increase of wear resistance gained by composite while adding 0.3 wt. % SiCNF to epoxy, as it seems to be the best gained cohesion of epoxy and SiCNF content. The maximum scar width value occurred in epoxy composites for 10N appears at 0.1 wt. % SiCNF. For normal load of 5N is at 1.0 wt. % and for 15N at 0.7 wt. %, which might be explained that at those loads, the high content of SiCNF wear might be increased due agglomeration of SiCNF inside the epoxy matrix.

CONCLUSIONS

Based on the experimental results of this study, the following points can be concluded:

1. There is no apparent improvement in hardness of PMMA filled by SiCNF.

2. Hardness of epoxy composites slightly increases by adding SiCNF.

3. Friction coefficient of PMMA composites tends to decrease with increasing normal load, while minimum values are detected at 0.7 wt. % SiCNF, 0.7 wt. % and 1.0 wt. % for 5N, 10N and 15N respectively.

4. Friction coefficient of epoxy composites tends to decrease with the increase of normal load, while the minimum values for epoxy composites are detected at 0.5 wt. % SiCNF content for 5 N and 10 N, while for 15 N it appears at 0.5 wt. %.

5. Minimum scar width occurs in SiCNF/PMMA composites at 0.7 wt. % content for 10 N and 15 N, while it occurs at 0.3 wt. % for 5 N normal load.

6. Minimum wear scar width occurs in epoxy composites at 0.3 wt. % SiCNF for all applied loads.

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