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Short Carbon Fiber-Reinforced Epoxy Tribomaterials Self-Lubricated by Wax Containing Microcapsules

The effects of wax lubricant filled microcapsule content on the tribological properties of epoxy composites without or with 8 wt.% short carbon fibers (SCFs) were systematically investigated. The core percentage of the microcapsules used in this study was about 70 wt.%. The tribological results clearly showed that the friction and wear of the epoxy composites without or with SCFs tested against a 6 mm steel ball significantly decreased with increased microcapsule content from 2.5 to 10 wt.% as a result of the increased amount of released wax lubricant to lubricate rubbing surfaces. The epoxy composites with 8 wt.% SCFs exhibited the lower friction and wear than the ones without SCFs due to the combined lubricating effects of SCFs and released wax lubricant and the improved mechanical strength of the composites. It can be concluded that the higher microcapsule content gives rise to the lower friction and wear of the epoxy composites as the epoxy composites with 8 wt.% SCFs have the better tribological performance than the ones without SCFs. [DOI: 10.1115/1.4028752]

Keywords: epoxy, wax microcapsules, SCF, friction, wear

1 Introduction

Polymers are widely used for engineering applications due to their relatively low cost, ease-of-processing, acceptable thermal and environmental resistances, and recyclability [1]. However, polymers have poor wear resistance and short running life when they are applied in tribological applications under heavy duty. Therefore, it is important to improve the wear resistance of polymers for successful tribological applications [2].

Polymer composites have been greatly interested for tribological applications, since the specific development of polymer composites based on conventional polymers can achieve desired properties even with a small amount of fillers [3–6]. The wear resistance of polymer composites has been improved by reinforcements and solid/liquid lubricants [7]. Incorporation of reinforcements, such as fibers and tubes, enhances the wear resistance of polymer composites by improving their mechanical properties [8–11]. Solid reinforcements cannot always give desired properties of polymer composites due to their several drawbacks such as their difficult dispersion and processing, relatively high prices, and so on. The use of liquid lubricants, such as liquid paraffin, during tribological test improves the wear resistance of polymer composites by lubricating rubbing surfaces [12]. External lubrication degrades materials by absorption and osmosis of lubricants into the materials and limits the application of the materials [12,13]. In addition, the use of liquid lubricants for external lubrication is not suitable for oil-sensitive materials or oil-contamination free environment [14]. Guo et al. [13] reported that incorporation of microencapsulated oil in epoxy matrix gave rise to ultra-low friction and wear during wear test due to the sustainably released lubricant from broken microcapsules to lubricate rubbing surfaces. Recently, Khun et al. [15] reported that microencapsulation of wax lubricant was an effective way to dramatically lower the friction of silicone composites than that of the neat silicone. They also found that epoxy composites containing microencapsulated mixture of multiwalled carbon nanotubes (MWCNTs) and wax lubricant exhibited the dramatically lower friction and wear than neat epoxy due to the combined lubricating effects of MWCNTs and released wax lubricant [7]. Moreover, Khun et al. [16] revealed that the higher wax lubricant filled microcapsule content or incorporation of larger microcapsules resulted in the lower friction and wear of epoxy composites due to the larger amount of released wax lubricant during wear test. However, incorporation of microcapsules significantly reduces the mechanical properties of polymer composites, such as hardness and elastic modulus, as a result of the much lower mechanical strength of microcapsules than that of polymer matrix [7,13,14,16]. Therefore, it is importantly necessary to improve the mechanical strength of polymer composites while maintaining their relatively low friction and wear for oil and gas applications (e.g., flexible risers) where high mechanical strength, low friction, and excellent wear resistance are crucial. SCFs can be considered as one of the most popular candidates for the development of

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high strength polymer composites because of their high surface-to-volume ratio, outstanding thermal and mechanical properties, and good dispersion in polymer matrices [17–19]. Moreover, SCFs can serve as a solid lubricant to lubricate rubbing surfaces for friction reducing applications [19–24]. Zhang et al. [25] reported that epoxy composites reinforced with combined multi-scale fillers of carbon nanofibers and microsized SCFs exhibited much higher modulus, strength, and fracture toughness than the ones reinforced solely with either nano- or microfillers. Khun et al. [19] found that the incorporation of SCFs was an effective way to improve the mechanical and tribological properties of epoxy composites with an optimized content of about 8 wt.% SCFs for the best results. Therefore, it is expected that additional incorporation of 8 wt.% SCFs in microencapsulated wax containing epoxy composites would be a possible way to develop novel epoxy composites with higher mechanical strength and better tribological performance, which has not been reported yet and needs to be systematically investigated.

In this study, the effects of wax lubricant filled microcapsule content on the mechanical and tribological properties of the epoxy composites without or with 8 wt.% SCFs were systematically investigated. The mechanical and tribological properties of the epoxy composites were measured using micro-indentation and ball-on-disk microtribological tests, respectively.

2 Experimental Details

2.1 Materials. Bisphenol F epoxy resin, Epolam 5015 (Axson, France), and the related aliphatic amine hardener, Hardener 5015 (Axson, France) were used as epoxy matrix. Urea, formaldehyde, resorcinol, ammonium chloride (NH_4Cl), and sodium hydroxide (NaOH) were purchased from Sigma-Aldrich (Singapore). The surfactant, ethylene maleic anhydride copolymer (EMA), was purchased from MP Biomedicals. The wax lubricant, Episole B2538 with 14–17 carbon atoms in its chain, was ordered from Epichem Internatioinal Pte. Ltd. (Singapore). All the chemicals were used as received unless otherwise specified. The average diameter and length of the SCFs (M-2007 S, Kreca) used were about 14.5 μm and 90 μm, respectively.

2.2 Sample Preparation. The wax lubricant, Episol B2538, was encapsulated by poly(ureaformaldehyde) (PUF) shell using the similar procedure as stated in references [7,16,26–28]. Briefly, 30 g wax was charged into a beaker with liquid mixture consisting of 100 ml deionized (DI) water, 25 ml of an aqueous solution containing 2.5 wt.% EMA, 2.5 g urea, 0.25 g resorcinol, and 0.25 g NH_4Cl at 400 rpm by a mechanical stirrer (Caframo, Model: BDC6015). The beaker was placed in a water bath with temperature controlled by a programmable hotplate (hotplate digital aluminum 230). The pH of the mixture was adjusted to 3.5 using 1 M NaOH solution. After emulsification for about 10 min, 6.3 g of an aqueous solution containing 37 wt.% formaldehyde was slowly added into the mixture. Later, the beaker was covered with aluminum foil and the temperature of the water bath was heated up to the target temperature of 55 °C at a ramp rate of 35 °C/h. After reaction at 55 °C for about 4 h, the encapsulation process was stopped and the achieved microcapsules were filtered and washed using DI water. The microcapsules were air-dried at room temperature (RT ~ 22–24 °C) for about 24 h.

First, Epolam 5015 and hardener 5015 were mixed at the recommended ratio of 100:30 for about 10 min. The mixture was evacuated for about 15 min to completely remove air-bubbles and then molded in Teflon molds for pure epoxy samples. For the epoxy composite samples with 8 wt.% SCFs, the degassed epoxy resin was mixed with SCFs at different concentrations in a glass beaker placed in a water bath at 60 °C and mechanically stirred at 1500 rpm for 30 min [19]. After degassing for 15 min in a vacuum oven, the hardener was added in the mixture followed by hand stirring for 10 min and degassing for another 15 min. The well mixed resin was then slowly poured into Teflon mold. For the epoxy composite samples with different microcapsule contents, wax lubricant filled microcapsules were well dispersed into the degassed mixture at different contents for about 5 min. The mixture was evacuated for 15 min to remove trapped air-bubbles before they were molded in Teflon molds. For the epoxy composite samples with a mixture of 8 wt.% SCFs and wax lubricant filled microcapsules, wax lubricant filled microcapsules were well dispersed into the degassed mixture with the fixed amount of 8 wt.% SCFs and the final mixture was evacuated for 15 min to remove air bubbles for molding in Teflon molds. After that, all the samples were cured at RT for 24 h and then at an elevated temperature of 60 °C for another 3 h in an oven (Binder, Model: V53).

2.3 Characterization. The core content of the microcapsules was characterized by thermogravimetric analyzer (TGA) (AutoTGA 2950HR). In all the TGA tests, 10–30 mg powder samples were placed in a platinum pan and heated at a ramp rate of 10 °C/min under N_2 atmosphere.

The surface morphology and topography of the samples were studied using scanning electron microscopy (SEM, JEOL-JSM-5600LV and JOEL JSM-7600 F) and surface profilometry (Talyscan 150, Taylor Hobson) with a diamond stylus of 4 μm in diameter. For SEM measurement, the samples were coated with a gold layer to avoid charging. Three measurements on each sample were carried out to get an average root-mean-squared surface roughness, R_q.

The hardness of the samples was measured using a micro-indenter (micro-CSM) with a pyramidal shaped diamond tip of 20 μm in diameter. The indentation test was performed in a load control mode with a total load of 3 N. In each indentation test, the loading and unloading rates and dwelling time at the peak load were 6 N/min, 6 N/min, and 5 s, respectively. The average hardness of the samples was taken from 16 indentation measurements carried out at different locations on each sample [29].

The tribological properties of the samples were investigated using a ball-on-disk microtribolometer (CSM) by sliding them against a Cr6 steel ball of 6 mm in diameter in a circular path of 2 mm in radius for about 60,000 laps at a sliding speed of 4 cm/s under a normal load of 6 N. All the samples were polished using 1200 grit papers prior to tribological test to stabilize the surface conditions. Two to three measurements per sample were carried out to get an average friction coefficient. The widths and depths of wear tracks of the samples were measured using surface profilometry to get average wear width and depth with four measurements per wear track.

3 Results and Discussion

Figure 1(*a*) shows the overview of the wax lubricant filled microcapsules with 209 ± 32 μm in diameter calculated based on at least 50 individuals. Figure 1(*b*) shows the surface morphology of the single microcapsule on which the cottonlike features caused by the precipitation of PUF nanoparticles are observed. In addition, the microcapsules consist of smooth inner wall (Figs. 1(*c*) and 1(*d*)) due to the deposited PUF with low molecular weight at the early stage of the process and rough outer shell (Figs. 1(*a*)–1(*d*)) formed by the deposited PUF nanoparticles (Fig. 1(*c*)) thereafter. The microcapsules have a very dense inner wall with a uniform thickness of about 217 ± 36 nm as shown in Fig. 1(*d*).

Figure 2 shows the TGA curves of the pure wax, microencapsulated wax, and pure PUF shell material. It is estimated that the core percentage of the synthesized microcapsules is about 70 wt.%.

Figure 3 shows the R_q values of the polished epoxy composites without or with 8 wt.% SCFs as a function of microcapsule content. The R_q value of the neat epoxy is about 0.3 μm. The incorporation of 8 wt.% SCFs in the epoxy apparently gives rise to the larger R_q value of about 0.6 μm due to the protruded SCFs above the surface and SCF debonded sites on the surface caused by the

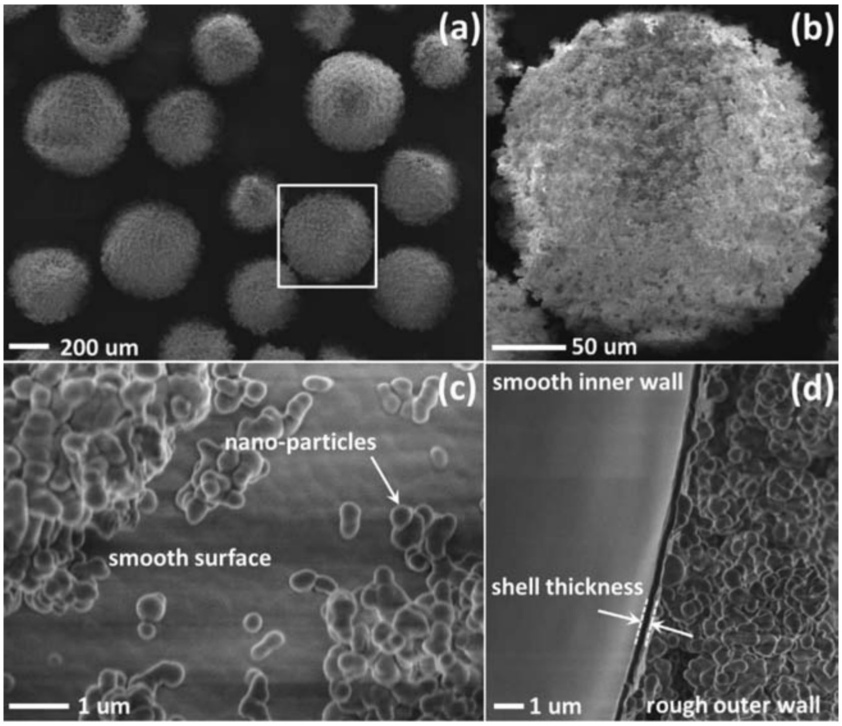


Fig. 1 (*a*) Overview of synthesized microcapsules containing Epiwax B2538. (*b*) Surface morphology, (*c*) enlarged surface morphology, and (*d*) cross-sectional morphology of a single microcapsule.

mechanical polishing [19]. The incorporation of 2.5 wt.% microcapsules in the epoxy significantly increases the R_q value to about 19.8 μm due to single holes on the surface left by the rupture of microcapsules during the mechanical polishing. The increased microcapsule content to 10 wt.% further increases the R_q value of the epoxy composite without SCFs to about 31.8 μm as a result of the increased number of ruptured microcapsules [7,14]. It is consistently found that the increased microcapsule content from 2.5 to 10 wt.% apparently increases the R_q value of the epoxy composites with 8 wt.% SCFs from about 5.7 to 9.5 μm due to the increased number of ruptured microcapsules. As shown in Fig. 3, the R_q values of the microcapsule containing epoxy composites with 8 wt.% SCFs are significantly smaller than those of the ones without SCFs because the presence of SCFs on the surface apparently lessens the rupture of microcapsules by preventing the surface wear during the mechanical polishing.

Figure 4 shows the surface morphologies of the microcapsule containing epoxy composites without or with 8 wt.% SCFs. Figure 4(*a*) shows the surface morphology of the neat epoxy on which abrasive lines caused by the mechanical polishing are apparently found. The surface morphology of the epoxy composite with 8 wt.% SCFs (Fig. 4(*b*)) confirms that the SCF debonded sites on the surface of the epoxy composite are responsible for its larger R_q value compared to that of the neat epoxy. As shown in Fig. 4(*c*), the mechanical polishing ruptures the microcapsules and leaves them as single holes on the surface of the epoxy composite with 2.5 wt.% microcapsules, which are responsible for the much larger R_q value of the epoxy composite than that of the epoxy. Comparison of Figs. 4(*c*) and 4(*d*) shows that the increased microcapsule content to 10 wt.% increases the number of single holes on the surface of the epoxy composite due to the increased number of ruptured microcapsules during the mechanical polishing. It is consistently found that the increased microcapsule content from 2.5 to 10 wt.% consistently increases the number of

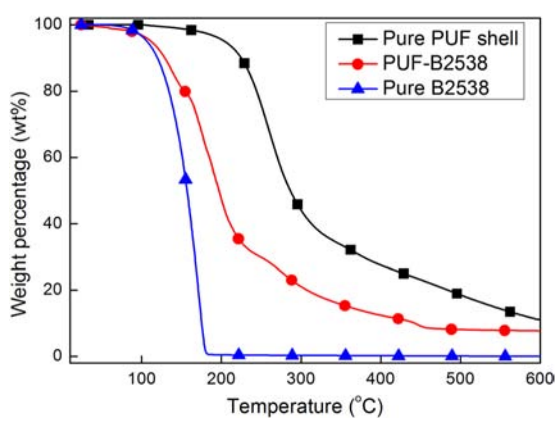


Fig. 2 TGA curves of pure Epiwax B2538, microencapsulated Epiwax B2538, and pure PUF shell

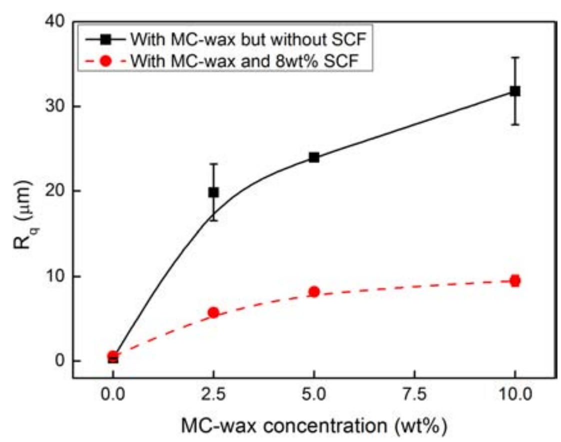


Fig. 3 Root-mean-squared surface roughnesses, R_q, of polished epoxy composites without or with 8 wt.% SCFs as a function of wax lubricant filled microcapsule content

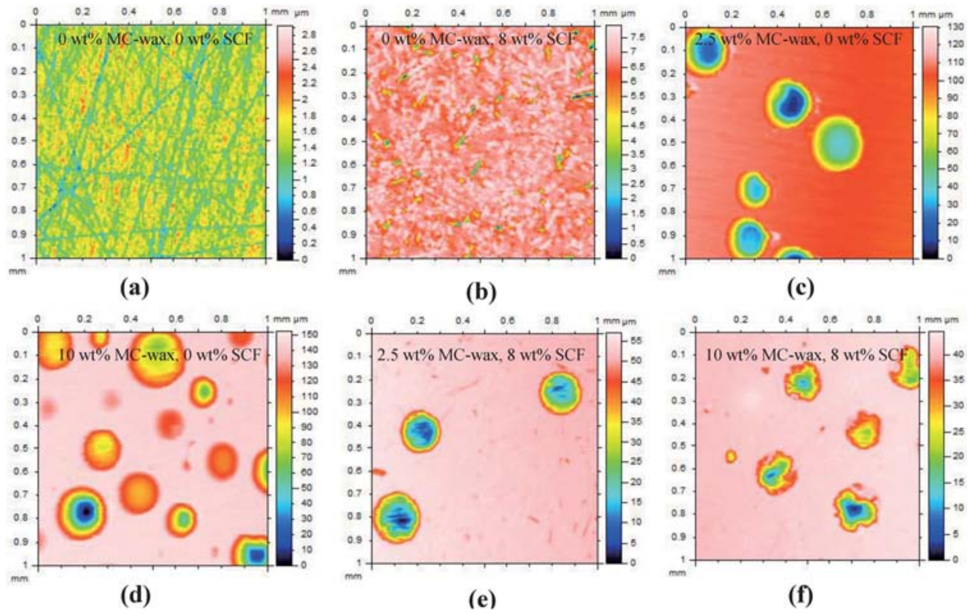


Fig. 4 Surface morphologies of polished (*a*) epoxy and epoxy composites (*b*) with 8 wt.% SCFs, with (*c*) 2.5 and (*d*) 10 wt.% wax lubricant filled microcapsules and with mixtures of (*e*) 8 wt.% SCFs and 2.5 wt.% wax lubricant filled microcapsules, and (*f*) 8 wt.% SCFs and 10 wt.% wax lubricant filled microcapsules

single holes on the surface of the epoxy composite with 8 wt.% SCFs as shown in Figs. 4(*e*) and 4(*f*). However, the microcapsule containing epoxy composites with 8 wt.% SCFs (Figs. 4(*e*) and 4(*f*)) have the smaller number of single holes on the surfaces than the ones without SCFs (Figs. 4(*c*) and 4(*d*)), which confirms that the existence of SCFs on the surface apparently lessens the rupture of microcapsules.

Figure 5 presents the hardnesses of the epoxy composites without or with 8 wt.% SCFs as a function of microcapsule content. The hardness of the neat epoxy is about 286 MPa and the incorporation of 8 wt.% SCFs in the epoxy increases the hardness to about 373 MPa as a result of the much higher rigidity of the SCFs than that of the epoxy matrix [19]. The incorporation of 2.5 wt.% microcapsules significantly decreases the hardness of the epoxy composite without SCFs to about 198 MPa due to the much lower hardness of the microcapsules than that of the epoxy matrix. The increased microcapsule content to 10 wt.% further decreases the hardness of the epoxy composite to about 91 MPa [7,11,14,16,30,31]. The increased microcapsule content from 2.5 to 10 wt.% consistently decreases the hardness of the epoxy composites with 8 wt.% SCFs from about 373 to 241 MPa. It is clearly seen in Fig. 5 that the microcapsule containing epoxy composites with 8 wt.% SCFs have the much higher hardnesses than the ones without SCFs, which indicates that the incorporation of 8 wt.% SCFs in the epoxy composites significantly improves the hardness of the composites.

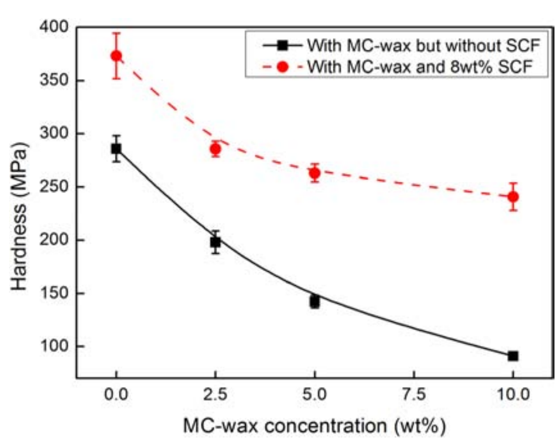
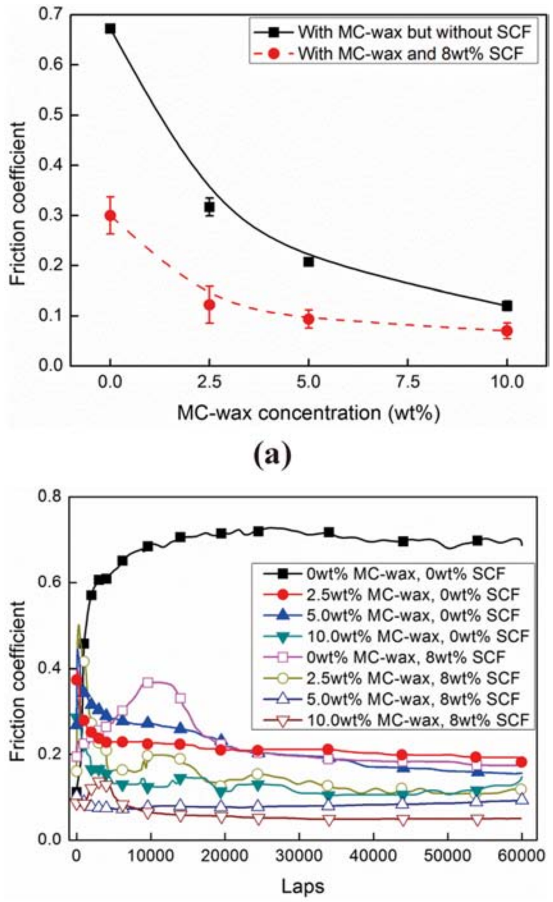


Fig. 5 Hardnesses of epoxy composites without or with 8 wt.% SCFs as a function of wax lubricant filled microcapsule content

The tribological properties of the microcapsule containing epoxy composites without or with 8 wt.% SCFs were systematically investigated by sliding them against a Cr6 steel ball for about 60,000 laps at a sliding speed of 4 cm/s under a normal load of 6 N and their mean friction coefficients are presented in Fig. 6(*a*). The friction coefficient of the neat epoxy is about 0.67. It is known that an incorporation of SCFs in an epoxy matrix can give rise to a lower friction via the solid lubricating effect of the SCFs [19–24]. In addition, the existence of SCFs on the surface can result in a lower friction by preventing the removal of surface materials and lessening a direct contact between two rubbing surfaces to subsequently weaken an effective interfacial shear strength between them [32,33]. Released SCFs to an interface between two rubbing surfaces during wear test can also give a lower friction by serving as spacers to lessen a direct contact between them and freely rolling or sliding under a lateral force [7,19,34]. It is therefore clear that the incorporation of 8 wt.% SCFs gives rise to the lower friction coefficient (about 0.3) of the epoxy composite than that of the neat epoxy as found in Fig. 6(*a*).

The incorporation of 2.5 wt.% microcapsules results in the lower friction coefficient (about 0.32) of the epoxy composite without SCFs than that of the neat epoxy as found in Fig. 6(*a*) because the released wax lubricant via the rupture of microcapsules lubricates the rubbing surfaces and lessens the direct solid–solid contact between them [7,13–16]. Therefore, the increased microcapsule content to 10 wt.% further decreases the friction coefficient of the epoxy composites without SCFs to about 0.12 due to the increased amount of released wax lubricant.

In Fig. 6(*a*), the increased microcapsule content from 2.5 to 10 wt.% consistently decreases the friction coefficient of the epoxy composites with 8 wt.% SCFs from about 0.12 to 0.07 because the more release of wax lubricant results in the more effective self-lubricating of the composites. During the wear test, the existence of SCFs on the surfaces lowers the friction of the epoxy composites via the solid lubricating and free-rolling effects



(b)

Fig. 6 Friction coefficients of epoxy composites without or with 8 wt.% SCFs, slid against a Cr6 steel ball of 6 mm in diameter in a circular path of 2 mm in radius for about 60,000 laps at a sliding speed of 4 cm/s under a normal load of 6 N, as functions of (*a*) wax lubricant filled microcapsule content and (*b*) the number of laps

of the SCFs while the released wax lubricant helps to lubricate the rubbing surfaces and lessen the direct solid–solid contact between them. As a result, the combined lubricating effects of the SCFs and released wax lubricant effectively lower the friction of the microcapsule containing epoxy composites with 8 wt.% SCFs than that of the ones without SCFs, as found in Fig. 6(*a*), although the incorporation of 8 wt.% SCFs apparently lessens the rupture of microcapsules embedded in the epoxy composites during the wear test.

The effect of surface roughness on the friction of the epoxy composites should be taken into account, since a rougher surface can give a higher friction via mechanical interlocking between two mating surface asperities [35–38]. The significantly lower friction of the epoxy composite with 8 wt.% SCFs than that of the neat epoxy (Fig. 6(*a*)) cannot be correlated to its slightly larger R_q value (Fig. 3), which indicates that the surface roughnesses of the epoxy and composite with 8 wt.% SCFs do not significantly influence their friction. In Fig. 3, the R_q values of the microcapsule containing epoxy composites without or with 8 wt.% SCFs dramatically increase with increased microcapsule content. However, no correlation between the increased R_q value (Fig. 3) and decreased friction coefficient (Fig. 6(*a*)) of the epoxy composites clearly indicates that the surface roughness of the epoxy composites does not have a significant influence on their friction in terms of mechanical interlocking because the larger number of ruptured microcapsules gives rise to the larger R_q value of the composites without resulting in the stronger mechanical interlocking between the two mating surfaces.

Normally, a larger contact between two rubbing surfaces can give a higher friction via a higher interfacial shear strength between them [35–38]. Therefore, the lower hardness of a polymer can result in a higher friction by causing a larger contact between the polymer and counter ball during sliding [7,39]. Therefore, the improved hardness of the epoxy composite associated with the incorporation of 8 wt.% SCFs (Fig. 5) is one of the reasons lowering the friction of the composite than that of the neat epoxy via the reduced contact area between the steel ball and composite (Fig. 6(*a*)). It is consistently found that the higher hardness of the microcapsule containing epoxy composites with 8 wt.% SCFs than that of the ones without SCFs gives rise to their lower friction due to their reduced contact with the steel ball in addition to the combined lubricating effects of SCFs and released wax lubricant. However, the decreased hardness of the microcapsule containing epoxy composites without or with 8 wt.% SCFs with increased microcapsule content from 2.5 to 10 wt.% (Fig. 5) cannot be correlated to their decreased friction (Fig. 6(*a*)) because the presence of released wax lubricant on the surfaces suppresses the influence of the mechanical strength of the composites on their friction.

Figure 6(*b*) illustrates the friction coefficients of the microcapsule containing epoxy composites without or with 8 wt.% SCFs as a function of the number of laps. Although the neat epoxy exhibits the relatively high and stable friction during the entire sliding, the incorporation of 8 wt.% SCFs significantly decreases the friction of the epoxy composite throughout the wear test. The incorporation of 2.5 wt.% microcapsules dramatically decreases the friction of the epoxy composite without SCFs during the entire sliding due to the effective lubricating effect of released wax lubricant. The increased microcapsule content to 10 wt.% further depresses the trend of friction coefficient versus laps of the epoxy composite as a result of the increased amount of released wax lubricant. As the epoxy composites with 8 wt.% SCFs consistently have the lower trends of friction coefficient versus laps for the higher microcapsule contents, the friction coefficients of the microcapsule containing epoxy composites with 8 wt.% SCFs with respect to the number of laps are relatively lower than those of the ones without SCFs as found in Fig. 6(*b*). It can be deduced that the increased microcapsule content decreases the friction coefficients of the epoxy composites without or with 8 wt.% SCFs throughout the wear test as the microcapsule containing epoxy composites with 8 wt.% SCFs exhibit the lower friction than the ones without SCFs.

Figure 7 presents the wear widths and depths of the epoxy composites without or with 8 wt.% SCFs as a function of microcapsule content. The incorporation of 8 wt.% SCFs dramatically decreases the wear width and depth of the epoxy composite than those of the neat epoxy due to the solid lubricating and free-rolling effects of the SCFs in addition to the improved mechanical strength of the composite. The incorporation of 2.5 wt.% microcapsules dramatically decreases the wear width and depth of the epoxy composite without SCFs than those of the neat epoxy due to the effective lubricating effect of released wax lubricant. The increased microcapsule content to 10 wt.% further decreases the wear width and depth of the epoxy composites via the increased amount of the released wax lubricant. The microcapsule containing epoxy composites with 8 wt.% SCFs also consistently exhibit decreases in the wear width and depth with increased microcapsule content from 2.5 to 10 wt.% as a result of the decreased wear of the composites. It can be clearly seen in Fig. 7 that the microcapsules containing epoxy composites with 8 wt.% SCFs have the significantly lower wear than the ones without SCFs due to the combined lubricating effects of SCFs and released wax lubricant and the improved mechanical strength of the composites. It is clear that the higher microcapsule content results in the lower friction and wear of the epoxy composites without or with 8 wt.% SCFs as the microcapsule containing epoxy composites with 8 wt.% SCFs

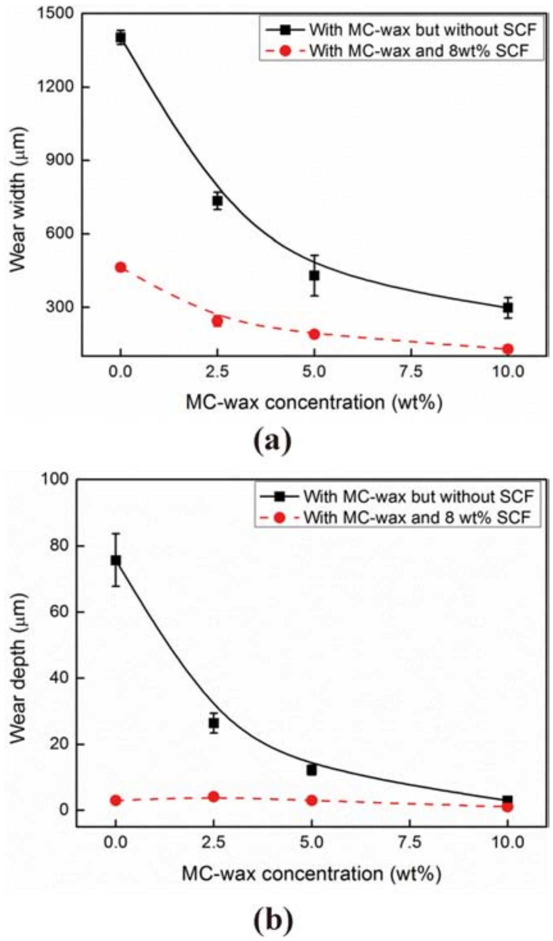


Fig. 7 Wear widths and depths of epoxy composites without or with 8 wt.% SCFs, tested under the same conditions as described in Fig. 6, as a function of wax lubricant filled microcapsule content

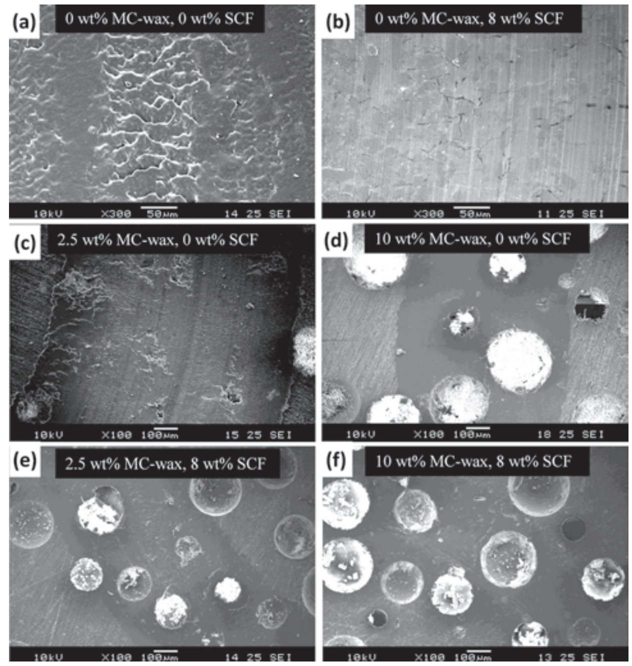


Fig. 8 SEM micrographs showing surface morphologies of worn (*a*) epoxy and epoxy composites (*b*) with 8 wt.% SCFs, with (*c*) 2.5, and (*d*) 10 wt.% wax lubricant filled microcapsules and with mixtures of (*e*) 8 wt.% SCFs and 2.5 wt.% wax lubricant filled microcapsules, and (*f*) 8 wt.% SCFs and 10 wt.% wax lubricant filled microcapsules, tested under the same conditions as described in Fig. 6

exhibit the better tribological performance than the ones without SCFs.

After the tribological test, the surface morphologies of the worn samples were observed using SEM. Figure 8(*a*) shows the surface morphology of the epoxy on which microwave features are apparently found. During the wear test, the repeated sliding of the steel ball induces cyclic stress concentration in front of it so that the resulted surface fatigue results in initiation of minute cracks perpendicular to the sliding direction and propagation of the cracks into the subsurface [7,14,16,19,40,41]. As a result, the formation of a network of microcracks causes microwave features on the wear track of the epoxy (Fig. 8(*a*)). Such microwave features are not found on the wear track of the epoxy composite with 8 wt.% SCFs as shown in Fig. 8(*b*), which indicates that the incorporation of 8 wt.% SCFs effectively suppresses the surface fatigue of the composite due to the lessened direct contact between the steel ball and composite associated with the existence of the SCFs on the surface and the solid lubricating and free-rolling effects of the SCFs. However, interfacial cracks between the SCFs and epoxy matrix (Fig. 8(*b*)) reveal that the repeated sliding of the steel ball still results in the surface fatigue and the subsequent formation of the interfacial cracks through debonding between the SCFs and epoxy matrix [19]. Abrasive lines on the surface of the epoxy composite with 8 wt.% SCFs (Fig. 8(*b*)) indicate that the wear of the epoxy composite is attributed to the abrasive wear even under the solid lubricating effect of the SCFs.

The surface morphology of the epoxy composite with 2.5 wt.% microcapsules exhibits the localized removal of materials caused by the rupture of microcapsules and the surface fatigue, as found in Fig. 8(*c*), although the incorporation of 2.5 wt.% microcapsules significantly reduces the friction and wear of the epoxy composite (Figs. 6 and 7). The incorporation of 10 wt.% microcapsules apparently lowers the surface wear and suppresses the surface fatigue of the epoxy composite than that of 2.5 wt.% microcapsules, as found in Figs. 8(*c*) and 8(*d*), because the higher amount of released wax lubricant results in the more effective lubricating effect and the lower direct solid–solid contact between the steel ball and composite [7,14–16]. The surface wear of the microcapsule containing epoxy composites with 8 wt.% SCFs (Figs. 8(*e*) and 8(*f*)) is much lower than that of the ones without SCFs (Figs. 8(*c*) and 8(*d*)) due to the combined lubricating effects of SCFs and released wax lubricant. However, the increased microcapsule content to 10 wt.% slightly decreases the surface wear of the microcapsule containing composites with 8 wt.% SCFs (Figs. 7, 8(*e*), and 8(*f*)) because the hindered surface wear of the epoxy composites associated with the incorporation of SCFs results in the controlled release of wax lubricant.

Comparison of Figs. 8(*c*) and 8(*e*) clearly shows that the additional incorporation of 8 wt.% SCFs apparently lowers the surface wear and fatigue of the microcapsule containing epoxy composite due to the combined lubricating effects of SCFs and released wax lubricant and the improved mechanical strength of the composite. Although the both epoxy composites without and with 8 wt.% SCFs have the same content of 2.5 wt.% microcapsules, the microcapsule containing epoxy composite with 8 wt.% SCFs (Fig. 8(*c*)) obviously has the larger number of ruptured microcapsules on the surface than the one without SCFs (Fig. 8(*e*)) because the presence of SCFs on the surface effectively lessens the surface wear of the epoxy composite and subsequently reduces the production of wear debris that fill and cover the ruptures during the sliding. The SEM observation clearly shows that the higher microcapsule content or the incorporation of SCFs gives rise to the lower surface wear and fatigue of the epoxy composites as the epoxy composites have the much better tribological performance than the neat epoxy.

4 Conclusions

In this study, the mechanical and tribological properties of the epoxy composites without or with 8 wt.% SCFs were systematically investigated with respect to wax lubricant filled microcapsule content. The hardness of the epoxy composites without or with 8 wt.% SCFs decreased with increased microcapsule content from 2.5 to 10 wt.% as a result of the much lower hardness of the microcapsules than that of the epoxy matrix. The epoxy composites with 8 wt.% SCFs had the higher hardnesses than the ones without SCFs due to the much higher rigidity of the SCFs than that of the epoxy matrix. The tribological results clearly showed that the higher microcapsule content resulted in the lower friction and wear of the epoxy composites without or with 8 wt.% SCFs via the higher amount of released wax lubricant to lubricate the rubbing surfaces. The microcapsule containing epoxy composites with 8 wt.% SCFs exhibited the lower friction and wear than the ones without SCFs due to the combined lubricating effects of SCFs and released wax lubricant and the improved mechanical strength of the composites. The SEM observation revealed that the higher microcapsule content or the incorporation of SCFs significantly suppressed the surface fatigue of the epoxy composites. It can be concluded that the higher microcapsule content gives rise to the lower hardness but the better tribological performance of the epoxy composites without or with 8 wt.% SCFs as the additional incorporation of 8 wt.% SCFs improves the both mechanical and tribological properties of the epoxy composites.

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