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Dry sliding wear of epoxy/cenosphere syntactic foams

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ABSTRACT

Dry sliding wear behavior of epoxy matrix syntactic foams filled with 20, 40 and 60 wt% fly ash cenosphere is reported based on response surface methodology. Empirical models are constructed and validated based on analysis of variance. Results show that syntactic foams have higher wear resistance than the matrix resin. Among the parameters studied, the applied normal load (F) had a prominent effect on wear rate, specific wear rate (w_s) and coefficient of friction (μ). With increasing F, the wear rate increased, whereas w_s and μ decreased. With increase in filler content, the wear rate and w_s decreased, while the μ increased. With increase in sliding velocity as well as sliding distance, the wear rate and w_s show decreasing trends. Microscopy revealed broken cenospheres forming debris and extensive deformation marks on the wear surface.

1. Introduction

Lightweight polymer matrix composites offer advantage of high specific strength and stiffness, which are important for weight sensitive structures. Hollow particle filled porous composites, called syntactic foams, are a class of particulate composites that are finding applications in marine and aircraft structures due to their lightweight combined with high damage tolerance, capability of keeping damage localized and possibility of simultaneously tailoring a variety of mechanical and thermal properties [1,2]. Increasing use of syntactic foams in automotive and aerospace applications requires understanding their tribological properties. Although detailed studies on wear behavior of metal matrix syntactic foams are available [3–6], similar studies on polymer matrix syntactic foams are relatively scarce [7–9]. In addition, due to a large number of parameters involved in wear testing, a clear understanding of structure–property correlations requires considerable additional effort.

Inclusion of organic and inorganic fillers, and fibers of glass, carbon and aramid improves the wear performance of polymers, for example, see [10,11]. It has been reported that addition of nano Al_2O_3, SiC, CuO, TiO_2, ZnO and ZrO_2 can improve the wear resistance of polymers [12–17]. The micro and nanoscale particles used to improve mechanical properties can also improve the wear resistance [14,18]. There is a significant interest in finding lighter weight and lower cost fillers to reduce the overall density and cost of the composites, while improving their tribological properties. One of the low cost fillers is fly ash, which is obtained as a waste by-product from thermal power plants [19,20]. Finding applications for this waste material can also help environment. Fly ash contains hollow microspheres called cenospheres, which primarily consist of silica and alumina [21,22]. Cenospheres have been dispersed in different matrices like cement, polyester and epoxy resins for producing syntactic foams [23,24]. Low cost of cenospheres can make syntactic foams economical [25] while improving the mechanical and thermal characteristics.

Considerable differences are likely in the tribological properties and wear mechanisms of composites containing hollow particles compared to those reinforced with solid particles. Partial wear can open up the void enclosed inside the hollow particles, where debris can accumulate. Thin walls of hollow particles may shear off easily. Therefore, detailed investigations of hollow particle filled composites are desired to understand the mechanisms of wear and damage. Some of the existing studies on metal matrix

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syntactic foams have touched upon these issues. The craters on the specimen surface due to the breakage of cenospheres were found to play a significant role in the dry sliding wear process in Al/cenosphere syntactic foams [3].

Table 1 summarizes the studies found in the literature where cenosphere filled polymer matrix composites are studied for tribological properties [8,9,26–28]. Wear behavior of cenosphere filled vinyl ester and polyester matrix syntactic foams has been reported [7–9]. Chauhan et al. [8] studied the friction and wear characteristics of vinyl ester/cenosphere syntactic foams under dry sliding conditions for different cenosphere sizes, applied loads and sliding speeds. It was found that the submicron and micro-sized cenospheres are capable of improving mechanical properties and wear resistance of syntactic foams. Chand et al. [26] studied the abrasive wear behavior of silane treated low density polyethylene (LDPE)/cenospheres syntactic foams and found that 10 wt% of cenospheres was optimum to obtain high mechanical and tribological properties.

In the existing literature, no methodical work is found on wear of epoxy/cenosphere syntactic foams, which is the focus of this work. Tribological behavior is investigated by conducting experiments on Pin-on-disc tribometer. Further, based on the experimental values, response surface methodology (RSM) based models of wear rate, specific wear rate (wear rate per unit load) and coefficient of friction (COF) are developed with reduced number of experiments using full factorial design (FFD). These models are used for interpolation between the scarce experimental data to capture the trend. Later, the ANOVA scheme is used which allows conducting experiments to investigate the independent effect of each parameter on the response. These empirical models are useful in observing the overall trend. This experimental design scheme allows the study of interactions among the process parameters. Table 1 also shows that all the studies on vinyl ester matrix syntactic foams have used cenospheres without any surface treatment or compatibilization. In order to directly compare the results of the present study on epoxy–cenosphere composite with the existing observations, no surface treatment is applied to cenospheres used in the present work. However, it is recognized that alteration of cenosphere surface compatibility or change in the particle-matrix interfacial strength may affect the result on wear properties, which may be focus of the future studies. The effects of sliding velocity, normal load, sliding distance and filler content on friction and sliding wear are analyzed.

2. Response surface methodology

RSM is an accumulation of mathematical and statistical techniques for building empirical models. RSM has been widely used in wear studies [29–31]. In this methodology, the objective is to optimize a response (output variable), which is influenced by several independent input variables [29–31]. Using FFD, the

Table 1
Literature review on cenosphere filled syntactic foams. Untreated cenospheres are used in all studies except for the one marked with *.

Ref.	Matrix	Particle properties	Wear parameters	Results
[8]	Vinylester	Φ=2 μm, 900 nm and 400 nm ρ_c=0.4–0.6 g/cm^3 R=2, 6, 10 wt%	L=5, 10, 15, 20, 25 km N=10, 70 N v=1.9, 5.7 m/s	1. The submicron sized particles are more effective in improving the wear resistance as compared to the microsized particles. 2. Composites with 6 wt% submicron sized particles have the lowest specific wear rate. 3. The highest wear rate is observed at N=10 N, v=1.9 m/s, Φ=2 μm. Lowest wear rate is at N=70 N, V=1.9 m/s and Φ=400 nm. 4. 400 nm diameter cenospheres are most effective in reducing COF and specific wear rate.
[9]	Polyester	Φ=900 nm, ρ_c=0.67 g/cm^3; Φ=600 nm, ρ_c=0.65 g/cm^3; Φ=300 nm, ρ_c=0.64 g/cm^3 R=10 wt%	L=1, 2, 3, 4 km v=1.57, 2.62, 3.66, 4.71 m/s N=10, 20, 30, 40 N	1. 300 nm size cenospheres filled composite shows high wear resistance. 2. The COF and specific wear rate of neat polyester are higher compared to submicron size cenosphere particulate-filled composites. 3. COF and specific wear rate of cenosphere-filled composites decrease with increase in normal load and sliding velocity but increase with sliding distance.
[26]	LDPE	Φ < 355 μm* R=10, 15, 20 wt%	N=10 N v=0.314, 0.628, 0.942 m/s Contact pressure × v=0.062, 0.124, 0.187 MPa m/s	1. Wear rate increases with the increase in speed and weight concentration of cenospheres when applied load and sliding duration are kept constant. 2. Abrasive wear resistance of LDPE cenosphere composite is greatly increased on silane treatment of cenospheres. 3. 10 wt% silane treated LDPE/cenosphere composite showed the highest wear resistance.
[27]	Vinylester	R=40, 50 wt%	N=5, 7.5, 10 N v=0.2 m/s Radial distance (35, 30, 25 mm) ω=50, 65, 80 rpm	1. Unfilled resin had a 443%, 535% and 751% higher weight loss compared to the 40% composites at all applied normal loads. 2. Wear of resin increased with the sliding distance. 3. The COF of composites was lower than that of neat resin. 4. Syntactic foam containing 40% particles had had a lower weight loss, linear wear and a COF compared to the 50% composites. 5. The optimum combination of strength and higher energy absorption of 40% composites made them more wear resistant than the 50% composites.
[28]	Vinylester	Φ=2 μm, 900 nm and 400 nm ρ_c=0.4–0.6 g/cm^3 R=10 wt%	N=10, 40, 70 N ω=300, 600, 900 rpm L=2, 4, 6 km	1. The submicron sized particles are more effective in improving the wear resistance than the microsized particles. 2. Load and filler content have 75.33% and 13.23% contribution on COF. 3. Applied load is an important parameter for specific wear rate.

Φ=particle diameter, ρ_c=particle density, R=particle content.
L=Sliding distance, v=speed, N=Normal load, ω=rpm.