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Tribological properties of epoxy nanocomposites III. Characteristics of transfer films

Li Chang [a,c], Zhong Zhang [b,*], Lin Ye [c], Klaus Friedrich [a]

[a] Institute for Composite Materials, University of Kaiserslautern, 67663 Kaiserslautern, Germany
[b] National Center for Nanoscience and Technology, No. 2, 1st North Street Zhongguancun, 100080 Beijing, PR China
[c] Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia

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Abstract

The multiple parts of this study are intended to experimentally and analytically elaborate the tribological properties of epoxy nanocomposites, reinforced by short carbon fibres (SCF), nano-TiO_2 particles, polytetrafluorethylen (PTFE) powders and graphite flakes, in order to understand the role of fillers in modifying the wear behaviour of the materials. In this part, the influences of two solid lubricants, PTFE and graphite, were studied and compared. The transfer films established with two lubricants in sliding wear of epoxy nanocomposites against metallic counterparts were characterised under different sliding conditions. The morphology of transfer films was examined using scanning electronic microscopy (SEM), while their mechanical properties were investigated using micro-hardness tests. A method was proposed to determine the thickness of transfer films based on micro-indentation. The role of transfer films in dissipation of frictional heating was also studied. Epoxy nanocomposites containing both PTFE powders and graphite flakes showed a synergised effect in wear performance, especially under very severe wear conditions.

Keywords: Epoxy nanocomposite; PTFE; Graphite; Transfer film; Wear; Micro-hardness

1. Introduction

Over the past decades, polymer composites have been increasingly applied as structural materials in the aerospace, automotive and chemical industries, providing lower weight alternatives to traditional metallic materials. A number of these applications are tribological components such as gears, cams, bearings and seals, where the self-lubrication of polymers is of special advantage. One of the features that make polymer composites so promising in industrial applications is the possibility of tailoring their properties with special fillers. The fundamental understanding of synergy in tribological performance among various functional fillers is essential for successful applications. Our previous studies [1–3], investigated wear behaviours and fibre removal mechanisms of epoxy nanocomposites composed of short carbon fibres, nano-TiO_2, PTFE powders and graphite flakes. PTFE powders and graphite flakes are widely used to reduce both the frictional coefficient and wear rate of polymeric composites [4–12].

The lubricating effect of PTFE is provided by its unique molecular structure, which consists of crystalline slices with a thickness of 20–50 nm [5]. The individual slices can easily slip and transfer as small lumps with an average diameter of 1 μm. It has been well recognised by many researchers that the adhesion between PTFE and metallic counterfaces could be strong enough to develop a stable and continuous third-body transfer film under certain sliding conditions [6–10]. In case of a fibre-reinforced polymer composite sliding against a metallic counterpart, the continuous transfer film can effectively reduce the 'direct contact' of the composite with asperities of the hard metallic counterface. As a result, the subsurface stresses of the composite can be maintained at lower values and thus a lower wear rate is achieved [13]. Graphite also has a layer structure, in which the atoms are arranged in a hexagonal pattern with an interlayer space of 3.35 Å [14]. These hexagonal carbon sheets are held together by weak van der Waals interaction, which may be easily broken under applied stress. In particular, carbon sheeting of graphite is quite stiff, and therefore its transfer film also exhibits

* Corresponding author. Tel.: +86 10 62652669; fax: +86 10 62650450.
E-mail address: zhong.zhang@nanoctr.cn (Z. Zhang).

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stiff behaviour compared to that of PTFE. The purpose of this study is to investigate and compare the effects of the two solid lubricants, i.e., PTFE and graphite on the development of transfer films of epoxy composites under different sliding conditions. In order to elaborate the performance of transfer films developed from two lubricants, the surface morphology, functions and mechanical properties of the transfer films were characterised. The study is expected to improve fundamental understanding in the design of wear-resistant polymer composites.

2. Experimental

Technical details of epoxy nanocomposites, including those of fillers and an epoxy matrix, as well as the composition procedure have been reported previously [1,3]. Four compositions of epoxy nanocomposites were examined here:

(1) [5 vol.% nano-TiO_2 + 15 vol.% SCF],
(2) [5 vol.% nano-TiO_2 + 10 vol.% graphite + 15 vol.% SCF],
(3) [5 vol.% nano-TiO_2 + 10 vol.% PTFE + 15 vol.% SCF], and
(4) [5 vol.% nano-TiO_2 + 5 vol.% graphite + 5 vol.% PTFE + 15 vol.% SCF].

For convenience, these materials are described as composites 'without lubricant', 'with graphite', 'with PTFE' and 'with both PTFE and graphite', respectively.

All wear results were tested using a Wazau pin-on-disc apparatus according to ASTM D3702. Each specimen pin was cut to a size of 4 mm × 4 mm × 12 mm, and a carbon steel disk (German standard 100Cr6) served as counterpart. The results of wear tests have been well summarised previously [1]. After wear tests, the morphology of the transfer films on metallic counterpart surfaces was studied using scanning electron microscopy (SEM) and laser-profilometry. The micro-hardness of these transfer films was measured by a Vickers indenter (angle between side-surfaces was 136°) of a Shimadzu micro-hardness tester to elaborate the mechanical performance of the transfer films. The tests were conducted at room temperature under controlled loading conditions. Table 1 summarizes all the wear tests and each result was an average value of at least three experimental data. Both the frictional coefficient and the contact temperature given in the tables were mean values during the steady state of the wear process.

3. Results and discussion

3.1. Morphology of transfer films

Fig. 1 compares the typical variations of the frictional coefficient against the sliding time for the composite without lubricant and the other two compositions filled with only one kind of lubricant at 1 MPa and 1 m/s. It was observed that both PTFE powder and graphite flakes effectively reduced the duration of the running-in stage and contributed to the continuous transfer films formed on counterface resulting in a lower wear rate. The composite with PTFE achieved the lowest peak value of frictional coefficient and the shortest duration of running-in, which was attributed to a characteristic transfer mechanism of PTFE, the so-called 'lumpy transfer'. In comparison to the transfer film formed by graphite flakes, the transfer of PTFE has the advantage of quicker formation of a stable transfer film due to its larger size and lower binding energy between crystalline slices. However, it was also observed that graphite flakes contributed to a lower stable frictional coefficient (0.38 in. comparison to 0.5 with PTFE) and a lower average wear rate in general (6.4×10^{-7} mm^3/Nm with graphite in comparison

Table 1
Wear results of the composites under various contact pressures and sliding velocities

Composition	*Pv* factors	Contact temperature [°C]	Frictional coefficient	Specific wear rate [10^{-6} mm^3/Nm]
5 vol.% nano-TiO_2 + 15 vol.% SCF (without lubricants)	1 MPa, 1 m/s	46.41	0.43	3.95
5 vol.% nano-TiO_2 + 10 vol.% graphite + 15 vol.% SCF (with graphite)	1 MPa, 1 m/s	25.97	0.38	0.64
	4 MPa, 1 m/s	38.84	0.21	0.82
	8 MPa, 1 m/s	44.12	0.13	1.54
	12 MPa, 1 m/s	43.14	0.09	0.96
	4 MPa, 2 m/s	40.91	0.15	1.54
	4 MPa, 3 m/s	55.77	0.16	2.64
5 vol.% nano-TiO_2 + 10 vol.% PTFE + 15 vol.% SCF (with PTFE)	1 MPa, 1 m/s	29.41	0.50	0.86
	4 MPa, 1 m/s	52.33	0.33	1.12
	8 MPa, 1 m/s	69.12	0.26	1.71
	12 MPa, 1 m/s	74.92	0.18	1.26
	4 MPa, 2 m/s	71.45	0.30	2.64
	4 MPa, 3 m/s	78.57	0.23	2.31
5 vol.% nano-TiO_2 + 5 vol.% graphite + 5 vol.% PTFE + 15 vol.% SCF (with both PTFE and graphite)	1 MPa, 1 m/s	29.74	0.49	0.89
	4 MPa, 1 m/s	50.99	0.33	0.98
	8 MPa, 1 m/s	57.24	0.21	1.22
	12 MPa, 1 m/s	60.65	0.14	0.95
	4 MPa, 2 m/s	54.90	0.21	1.09
	4 MPa, 3 m/s	67.20	0.20	1.40