Inorganic whiskers reinforced bismaleimide composites
Part II  The tribological behavior of BMI/potassium titanate composites

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The whisker-reinforced polymer composites have good friction and wear properties and widely used in many fields. Potassium titanate (K$_2$Ti$_6$O$_{13}$) whiskers have good properties, lower prices and show good foreground in whisker-reinforced polymer matrix composites. The surface properties of the whisker are vital for the performance of the reinforced composites. In this paper, the friction and wear properties of potassium titanate whiskers reinforced bismaleimide composites and the surfaces of whiskers treated by coupling agents were studied. Two coupling agents, a silane compound (KH550) and a titanate (NDZ311) were selected to treat the surface of K$_2$Ti$_6$O$_{13}$ whiskers, respectively. Three whisker-reinforced BMI composites, K$_2$Ti$_6$O$_{13}$/BMI, K$_2$Ti$_6$O$_{13}$(KH550)/BMI and K$_2$Ti$_6$O$_{13}$(NDZ311)/BMI, were prepared and their tribological behaviors were investigated. Results show that the wear-resistance of the matrix improved by the incorporation of whiskers into the matrix, while the improvement efficiency is depended on the nature of the surface of whiskers and whisker content. The composite containing KH550 treated whiskers has the best wear-resistance, and that containing untreated whiskers has the poorest wear-resistance among the three composites. Experiment results were explained from the point of the interfacial adhesion between the matrix and whiskers as well as the surface morphologies of worn surface and wear particles of the matrix and composites.

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1. Introduction

Nowadays, there are an increasing number of applications in which friction and wear are critical issues [1]. Polymer composites containing different fillers and/or reinforcements are frequently used for these purposes [2–5]. And it is now widely recognized that friction and wear properties of some polymers may be significantly improved by filling them with inorganic compounds.

For designing the composites of wear-resistant polymer composites, the matrix should possess a high temperature resistance and have a high cohesive strength [1]. Epoxy, polyester and phenolic resins have been used as the matrix to prepare friction and wear materials for many years. However, in order to further increase wear-resistance, the matrix with high thermal resistance is needed. Bismaleimide (BMI) is one of most important high performance thermosets that have been widely used in many related industries where high performance properties are required [7–9]. Well, pure BMI is brittle and has poor processing characteristics, so many modified BMI systems have been developed. A system made up of 4,4'-bismaleimidodiphenyl methane (BDM) and o, o'-diallyl bisphenol A (DBA), BDM/DBA, has been proved to be a good matrix for advanced composites [10, 11], therefore, the system was chosen as the base matrix in this paper.

Recently, inorganic whiskers reinforced polymer composites have attracted considerable attention of many investigators because whiskers exhibit high stiffness and strength, and they are nearly free from internal flaws owing to their small diameter, hence the yield strength of whiskers tends to approach the maximum

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Theoretical value expected from the theory of elasticity [12–15]. Potassium titanate (K2Ti6O13) whiskers have been an ingredient of great interest during past decades due to its thermal stability and good compatibility with binder resins. The K2Ti6O13 whiskers consist of fine ceramic poly-crystalline whiskers and have tunneling structures with relatively high modulus and strength. These whiskers are white acicular in appearance and have the chemical formula of K2O·6TiO2, and their diameter and length are 0.8–1.2 µm and 30–50 µm in average, respectively. The SEM micrograph of K2Ti6O13 whiskers is showed in Fig. 1. Furthermore, K2Ti6O13 whiskers have outstanding friction and wear properties as well as self-lubrication [16]. One of most important features is that K2Ti6O13 whiskers are the only whiskers that have achieved breakthrough in commercial use [17].

The surface treatments of whisker are important for the properties of the whisker-reinforced polymer composites. Two coupling agents, a silane compound (KH550) and a titanate (NDZ311) were selected to treat the surface of K2Ti6O13 whiskers in this paper, and one whisker-reinforced BMI composite and two treated whisker-reinforced BMI composites were prepared and the tribological behaviors of these composites were investigated.

2. Experimental

2.1. Materials

4,4′-bismaleimidodiphenyl methane (BDM) (mp156–158°C) is provided by Northwestern Chemical Engineering Institute (China), o,o′-diallyl bisphenol A (DBA) is purchased from Sichuan Jiangyou Chemical Factory (China), K2Ti6O13 whiskers were kindly supplied by Qihai Haixing Science and Technology Development Ltd. (China). A silane compound KH550 and titanate (NDZ311) were bought from Nanjing Shuguang Chemical Factory (China), and the chemical formulae of these two coupling agents are showed in Fig. 2. Acetone was bought from Xi’an Chemical Factory (China). All the materials involved in this work are of industrial grades and used as received without any further purification.

2.2. Surface treatment of whiskers

K2Ti6O13 whiskers were dried at 105–110°C, then added into appreciated quantities of acetone solution of KH550 or NDZ311 with thoroughly stirring to form homogenous whisker solution. After that evaporated the solvent at room temperature for 8 h, subsequently dried at 80–90°C for 2 h, the resultant whiskers were coded as K2Ti6O13 (KH550) or K2Ti6O13 (NDZ311), respectively.

2.3. Preparation of neat BMI resin (the matrix)

100 g BDM and 80 g DBA were placed in a flask equipped with a mechanical stirrer and thermometer. The mixture was heated to 110–130°C for 20 min, and then was degassed in a vacuum oven at 120°C for 15 min. After that, the mixture was cast into the glass mould for curing and postcuring per following procedures:

Curing: 145°C/2 h + 160°C/2 h + 180°C/2 h + 200°C/2 h
Postcuring: 220°C/8 h.

2.4. Preparation of BMI/ K2Ti6O13 composites

100 g BDM and 80 g DBA were placed in a flask equipped with a mechanical stirrer and thermometer. The mixture was heated to 110–130°C for 20 min, then pre-weighted K2Ti6O13 whiskers were added into the mixture with thoroughly stirring. Thereafter the mixture was degassed in a vacuum oven at 120°C for 15 min and cast into the glass mould for curing and postcuring per the procedures described above. The obtained composite was coded as BMI/K2Ti6O13. The SEM micrograph of the composite is showed in Fig. 3, from which we can see the distribution of the whisker in the matrix instead of the whisker agglomerate together. Other two kinds composites were prepared by similar method described above except the employed whiskers were K2Ti6O13 (KH550) or K2Ti6O13 (NDZ311), respectively, then the resultant composites were