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Study on friction and wear behavior of polyphenylene sulfide composites reinforced by short carbon fibers and sub-micro TiO_2 particles

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Abstract

Polyphenylene sulfide (PPS) composites filled with short carbon fibers (SCFs) (up to 15 vol.%) and sub-micro-scale TiO_2 particles (up to 7 vol.%) were prepared by extrusion and subsequently injection-molding. Based on the results of sliding wear tests, the tribological behavior of these materials was investigated using an artificial neural network (ANN) approach. A synergistic effect of the incorporated short carbon fibers and sub-micro TiO_2 particles is reported. The lowest specific wear rate was obtained for the composition of PPS with 15 vol.% SCF and 5 vol.% TiO_2. A more optimal composition of PPS with 15 vol.% SCF and 6 vol.% TiO_2 was estimated according to ANN prediction. The scanning electron microscopy (SEM) observation revealed that this hybrid reinforcement could be interpreted in terms of a positive rolling effect of the particles between the two sliding surfaces, which protected the short carbon fibers from being pulled-out of the PPS matrix.

Keywords: A. Short-fiber composites; A. Particle-reinforced composites; B. Friction/wear; D. Scanning electron microscopy; Artificial neural network

1. Introduction

Polymer composites occupy a considerable market share nowadays as one of the most common engineering materials. They provide a combination of various advantages, such as ease in manufacturing, cost effectiveness and excellent performance, which cannot be attained by metals, ceramics, or polymers alone [1]. In recent years a tremendous interest was raised in scientific and industrial communities to apply polymer composites in sliding components, where their self lubricating properties can be exploited to avoid the need for oil or grease lubrication accompanied with the problems of contamination [2].

The choice of an appropriate matrix is of great importance in the design of wear resistant polymer composites. The required properties of such a tribo-matrix includes high service temperature, good chemical resistance and outstanding cohesive strength [3]. Within this frame, PPS is regarded as a proper tribo-matrix material [4]. Neat PPS, however, is a brittle material with relatively low impact strength [5]. Therefore, various fillers have been incorporated in order to enhance the property profile of PPS. Short carbon fibers (SCFs), which are widely advocated as a decisive reinforcement component, show a remarkable capability to increase the wear resistance of PPS [6]. As for the incorporation of particulate fillers, the problem becomes more sophisticated. Some micro-particles such as Ag_2S, CuS, NiS, SiC and Cr_3C_2 have been reported to improve the wear resistance of PPS, whereas others like PbTe, PbSe, ZnF_2, SnS and Al_2O_3 have been found to

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exercise an adverse influence [7–12]. The concept of adding particles of sub-micro- or nano-scale into polymers is one of the most intriguing subjects in the recent decades. On the one hand, the action of the particle angularity, which is detrimental to the wear resistance, is greatly diminished on those scales. On the other hand, proper particulate nano-fillers contribute positively towards the development of a thin and uniform transfer film and the better adhesion of transfer film to the counterpart during sliding [13,14], which play a crucial role in the enhancement of wear resistance [15]. However, there are few papers that investigated the influence of the hybrid reinforcement of sub-micro/nano-particles and short carbon fibers on the tribological behavior of polymer composites [16–18]. Very recently, Cho and Bahadur [19] reported that a lower wear rate was attained in the case that nano-CuO particles and short carbon/aramid fibers were added into PPS, as compared to that including one of the two fillers alone.

The objective of the present study is to investigate on the tribological behavior of PPS composites filled with short carbon fibers and sub-micro TiO_2 particles. An artificial neural network (ANN) approach, a powerful analytical tool, is introduced to model the functional relationship between the wear properties of PPS composites and the chosen parameters, including material compositions and testing conditions. According to the visualized profiles of the wear properties predicted by the ANNs, an optimal combination of short carbon fibers and sub-micro TiO_2 particles could be obtained to fulfill the hybrid reinforcement, which significantly improves the wear resistance of PPS composites. Moreover, the wear mechanism for the synergistic effect of the two kinds of fillers was also studied based on the scanning electron microscopy (SEM) analysis of the surfaces of sliding bodies.

2. Experimental

Polyphenylene sulfide (Fortron 214 C, Ticona GmbH) was used as a matrix material. Pitch-based short carbon fibers (Kureha M-2007S, Kureha Chemicals GmbH) and TiO_2 (Kronos 2310, Kronos Titan GmbH) were selected as fillers. The total content of the fillers in the matrix was up to 22 vol.%. The average diameter and length of the short carbon fiber were approximately 14.5 μm and 90 μm, respectively. The average size of TiO_2 sub-microparticle is about 300 nm.

The compounding of the fillers with the matrix was achieved via twin screw extruder (ZE25Ax44D, Berstorff). The compounds were further molded into plates ($80 \times 80 \times 4\ mm^3$) using an injection-molding machine (Allrounder, Arburg GmbH). For the purpose of testing, samples were cut into pins with a contact surface of $4 \times 4\ mm^2$. In order to ensure identical flow conditions, only the middle section of the plates were chosen for machining the samples.

Sliding wear tests were completed on a pin-on-disc setup under different pv-conditions at room temperature. The counterpart (steel disc 100Cr6, LS 2542, INA Scheffler KG) was cleaned with acetone prior to test. The surface roughness of the counterpart was measured as average roughness $R_a = 0.19$ μm and peak-to-valley roughness $R_t = 2.20$ μm, respectively, using a Mahr Perthometer (Perthen, Mahr-Perthen). The applied pressure was varied between 1 and 3 MPa, the sliding speed was set as 1 or 3 m/s, and the testing time was fixed at 20 h. For some of the materials, e.g. neat PPS, the test was stopped after 1 h due to the severe wear. In the course of the experiments both the normal and frictional forces were recorded to determine the friction coefficient. The specific wear rate, w_s, was calculated by the following equation:

$$w_s = \frac{\Delta m}{\rho \cdot v \cdot t \cdot F_N} \quad (mm^3/Nm) \tag{1}$$

where Δm is the mass loss, ρ is the density of the material, v is the sliding speed, and t is the duration of test. F_N represents the normal force imposed on the specimen during sliding.

Since the two testing parameters, i.e. the sliding speed v and the applied pressure $p(p = \frac{F_N}{\text{Contact area}})$, are changed independently, a time related depth wear rate, w_t, is introduced to evaluate the wear behavior under various pv-conditions

$$w_t = w_s \cdot p \cdot v = \frac{\Delta h}{t} \quad (mm/s) \tag{2}$$

where Δh represents the height reduction of the specimen after the test.

Finally the morphologies of selected worn pins and wear tracks were examined by SEM (Jeol 6300, Jeol).

3. Artificial neural network analysis

3.1. Principle

The ANN technology is inspired by the biological neural system, and has been used to solve a wide variety of problems in diverse fields (see Refs. [20–22] for the reviews about its application in material science). ANN is ideally suitable for some complex, non-linear and multi-dimensional problems because it is able to imitate the learning capability of human. This means the network can learn directly from the examples without any prior formulae about the nature of the problem, and generalize by itself some knowledge, which could be applied for new cases. A neural network is a system composed of many cross-linked simple processing units, also called neurons. As illustrated in Fig. 1, a neural network is generally defined as three parts connected in series: input layer, hidden layer and output layer [23]. The coarse information is accepted by the input layer, and processed in the hidden layer. Finally the results are exported via the output layer. For convenience, the structure of the neural network is described as the following notation: