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Synergistic effect of carbon fibers on the conductive properties of a segregated carbon black/polypropylene composite

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ABSTRACT

Under the assistance of carbon fibers (CFs) with a large aspect ratio, an evident reduction in the percolation threshold of a segregated carbon black (CB)/polypropylene (PP) conductive polymer composite (CPC) has been achieved. The origin of the ultra-low percolation threshold 0.94 vol% is ascribed to the design of a shish–calabash-like conductive network, where the CFs function as bridges between the segregated CB particles and CB particles act as calabashs contributing to the conductive framework. This interesting microstructure causes a synergistic effect on the conductive properties. A model is proposed to evaluate the percolation behavior of the unique CF/CB/PP composite.

1. Introduction

Conductive polymer composites (CPCs) have been applied in many fields, such as sensors, electromagnetic interference shielding, self-regulating heaters, etc. [1–5]. For CPCs, a low percolation threshold (i.e. the conductive filler content at insulator/conductor transition) leads to a good processability, good mechanical properties and a low cost [1,2]. Many efforts have been made to lower the percolation threshold; among them, the design of the segregated conductive structure has been considered as a novel method [1,3]. In our previous work [6], a segregated carbon black (CB)/polypropylene (PP) CPC has been fabricated using PP and CB particles. Compared to the common CB/PP with a percolation threshold 05 vol%, the value of the segregated CB/PP has been reduced to 2.34 vol%. However, this percolation threshold is still high [1,3,7].

Recently, the combination of two or more conductive fillers has been demonstrated as an another effective method to reduce the percolation threshold on the basis of the synergistic effect [8–10]. For example, Wen et al. [9] fabricated CB/PP, multiwalled carbon nanotubes (MWCNTs)/PP and CB/MWCNTs/PP composites by the multistage stretching extrusion. They found that the percolation thresholds were 5.3 vol% and 3.2 vol% for CB/PP and MWCNT/PP, respectively, whereas the value was only 2.6 vol% for the CB/MWCNT/PP composite. Wei et al. [10] found that the percolation threshold of an epoxy resin composite containing graphite nanoplatelets (GNPs) was 1 wt%, while the values were only 0.5 wt% and 0.2 wt% for the composites filled with GNP/CB and GNP/CB/MWCNTs, respectively.

In this article, carbon fiber (CF), which possesses the advantages of a large aspect ratio, excellent mechanical properties, high conductivity, etc. [4], was selected as the secondary filler to bridge the segregated CB conductive network in the CB/PP composite. The synergistic effect of CF and CB on the conductive properties of the CF/CB/PP CPC was investigated.

2. Experimental

The main materials used in this study include electrically conductive CB (VXC-605, Cabot Co. Ltd., USA), PP (T30s, Dushanzi Petroleum Chemical Co., China), and CF with an aspect ratio of ca. 657 (T300-3K, Toray Inc., Japan). The mean length of the CF is ca. 5 mm (Supplementary data). The fabrication processing of CB/PP, CF/PP, and CF/CB/PP composites is shown in Fig. 1. To prepare the composites, PP particles with the diameter of 10–50 μm were first prepared through a dissolving–smashing method developed in our lab [6]. Details about the preparation of the segregated CB/PP are presented in Ref. [6] (Fig. 1a). For the fabrication of CF/CB/PP composite (Fig. 1c), CB and PP particles were first mixed together in a mortar and then the CFs were added. The mixture was subsequently subjected to strong mechanical stirring in ethanol for 1 h and ultrasonication for another 1 h to obtain a well-dispersed filler suspension. After the complete evaporation of ethanol, the mixture was compression-molded into sheets at

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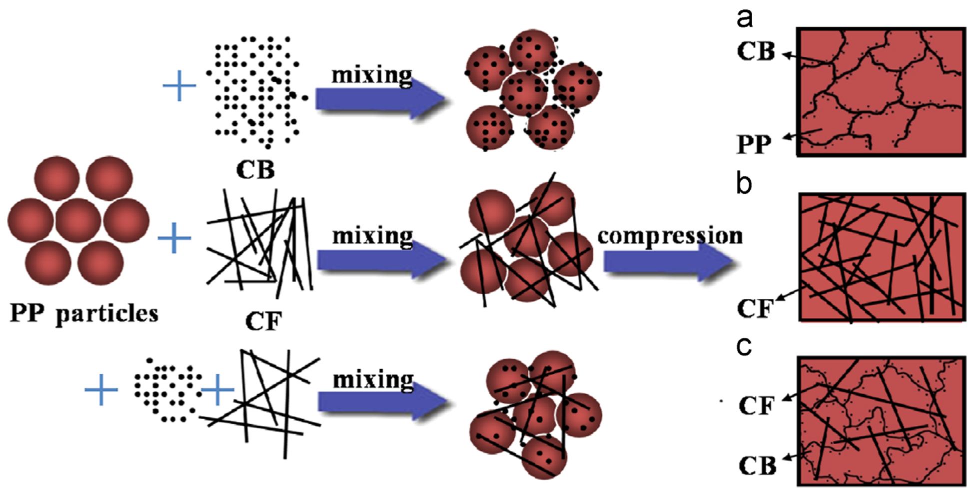

Fig. 1. Schematic for the fabrication of (a) CB/PP, (b) CF/PP and (c) CF/CB/PP composites.

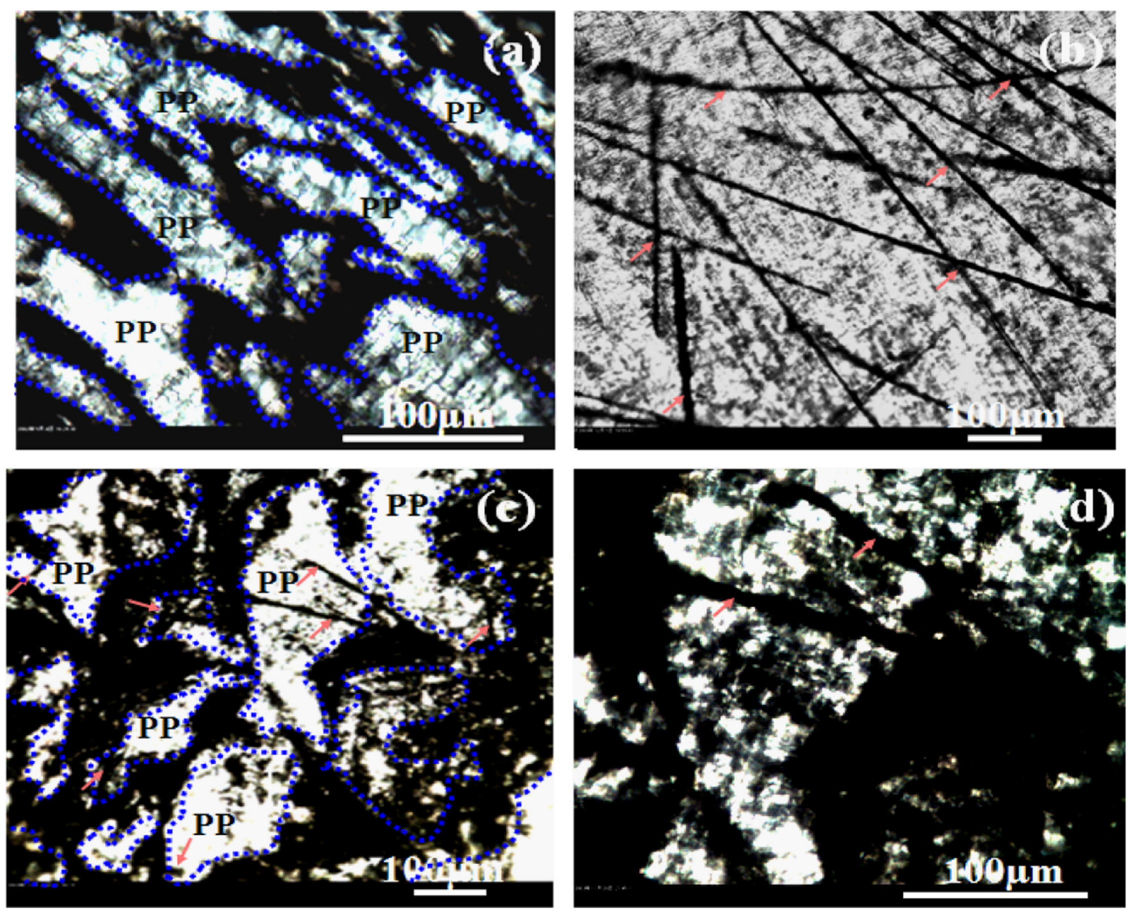

Fig. 2. Optical images of CB/PP (1.38/98.62 by volume) (a), CF/PP (0.31/99.69 by volume) (b) and CF/CB/PP (0.155/0.915/98.93 by volume) (c, d). The red arrows represent the CFs. The black regions indicate the distribution of CB particles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

190 °C under pressure of 15 MPa. The CF content was fixed at 0.155 vol% (it was much lower than the percolation threshold of CF/PP). For comparison, CF/PP was also prepared under the same conditions (Fig. 1b). Four probe method is used to test the resistance of samples when volume resistivity is below $10^6\ \Omega$ cm; a high-resistance meter is applied when the samples have a volume resistivity higher than $10^6\ \Omega$ cm. Dimension of samples for resistivity measurements was $0.6 \times 10 \times 100\ mm^3$. The fractured surfaces of the samples were observed with a scanning electron microscope (SEM, JEOL 7500F, Japan). For optical microscope (OM) observations, the samples were cut into films (10 μm) by a microtome. Mechanical properties of CB/PP, CF/PP and CF/CB/PP were measured using a universal testing machine at a tensile rate of 50 mm/min (Suns UTM2203, China).