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Technical Report

Foamed-metal-reinforced composites: Tribological behavior of foamed copper filled with epoxy–matrix polymer

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ABSTRACT

To improve the thermal performance and wear resistance of epoxy–matrix polymers, foamed copper materials filled with a curable epoxy matrix have been developed for tribological studies. Graphite flakes were incorporated as friction additive in the epoxy matrix. The tribological properties of foamed-copper-reinforced composites were investigated using a UMT-2 friction and wear tester. The temperature of the frictional area was measured using an infra-red thermal camera, and the effect of metallic skeletons on temperature was calculated by the finite element analysis (FEA). The results show the foamed-copper-reinforced composites are effective in transmitting heat and sharing load along the interconnected metallic skeletons, and therefore possess better thermal conductivity and wear resistance.

1. Introduction

In the field of tribology, polytetrafluoroethylene, polyoxymethylene, polyamide, epoxy resin (EP), and other polymer materials with different tribological characteristics are widely used as solid lubricating materials [1–3]. EP shows good mechanical properties, chemical/corrosion resistance, excellent dimensional stability, and low shrinkage during forming; it is widely used for tribological applications in architecture and automotive, air, and railway transport systems [4]. However, its wear resistance is relatively poor because of the low thermal conductivity of EP; hence, the friction heat accumulated at the interface tends not to dissipate, and the material properties dramatically deteriorate with rising temperatures caused by the heat buildup, which may lead to the failure of the material [5]. It has been reported that EP reinforced with fillers such as graphite, fibers, and metal powders shows good tribological properties [6–11]. The reinforcement phases, especially the metal particles in EP, are usually discrete particles, which lead to discontinuous heat conduction paths. A continuous metallic skeletal structure is expected to help friction heat dissipate more quickly than discrete metal-particle-reinforced composites. Such continuous skeletons could play a double role in improving the polymer strength as well as enhancing heat dissipation.

An open-cell foamed metal has a porous structure with an interconnected 3D metallic network and possesses many special properties, such as low density, specific mechanical performance, high specific surface area, and high conductivity [12]. They have been used for structured templates and supports [13,14], electrodes [15], heat radiators [16,17], muffling devices [18], and so on. Although similar porous structures have been introduced for use in tribological materials [19–21], the tribology literature on foamed-metal-reinforced composites is scarce, probably because the preparation process is still in an early stage [22,23]. Continuing from our previous experiments [24], here we describe foamed copper with an EP matrix polymer. EP was used because uncured EP shows better fluidity and is easier to mold than the powdered polymer and because it is widely used as pouring sealant and binder materials. Therefore, EP was selected as a representative two-component liquid resin. The friction coefficients and wear rates of composites, as well as the temperature field of the sample in the friction process were investigated to better understand the influence of metallic skeletons on composite wear performance.

2. Experimental details

2.1. Materials preparation

Three types of foamed copper (pore density: 10, 20, 40 pores per inch (PPI), porosity: 96%, 93%, 89%, average aperture: 2.68, 1.50, 0.92 mm) were fabricated by electroless copper plating on polyurethane (PU) foam, followed by electro-deposition and removal of non-conductive 3D substrates by burning (Fig. 1a–c). The metallic skeletons were hollow, and the foamed copper samples showed open-celled structures composed of tetrakaidecahedron-like cells with 8 regular-hexagon and 6 square faces (Fig. 1d). The samples were cut into suitable sizes by an ultra-thin diamond blade.

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The matrix material was made from a commercial EP (E51, epoxy equivalent: 185–200 g/eq) cured by a polyamine hardener (618). Graphite flakes with an average particle size of 7 μm (Shanghai Colloid-Chemical Plant) were selected as the traditional filler. Dibutyl phthalate was used as toughener for epoxy resin, and a silane coupling agent was used for the modification of graphite.

The graphite flakes after being modified were kept in an oven at 70 °C for 1 h before the mixing process. EP components were also preheated to 70 °C in order to decrease their viscosity for a thorough wetting of the filler material. After combining the filler with the resin, the mixture was mechanically dispersed under vacuum in order to distribute filler particles uniformly and remove trapped air, which could affect composite compactness significantly. The hardener was then added to the suspension, followed by stirring for about 3 min. Finally, the mixture was poured over the foamed copper in a silicone rubber mold and curing was allowed to proceed (Fig. 2a). To inhibit the precipitation of low-molecular-weight hydrocarbons during curing, the specimen was placed in an atmosphere furnace with nitrogen pressure 0.1 MPa and 70 °C for 3 h. The morphology of the foamed-copper-reinforced composite was shown in Fig. 2b, and the insets through the resulting composite material showed that the foamed copper was effectively encapsulated by the EP–matrix polymer. EP–matrix polymers containing the same fillers in the same amounts but without foamed copper were also made for comparison purposes. All test specimens were machined from the cured composite blocks.

Graphite was incorporated into the composites at 15 wt% which is in accordance with previous studies [25]. Table 1 summarizes all compositions and nomenclature for composites tested in this study. As an example of the naming system applied, a composite consisting of 34 wt% foamed copper (20 PPI), 15 wt% graphite, and epoxy (balancing the remaining content together with toughener and coupling agent) would be given the name EP-Gr-F20.

In our previous studies [24,26], a PTFE–matrix polymer filler sample was molded by the press forming process, and the foamed metal was then crushed to approximately 80% of its initial thickness. Therefore, the sample thickness (i.e., *z*-dimension) cannot be precisely controlled during the preparation of a composite of a foamed metal filled with a PTFE–matrix polymer. However, as can be seen from the preparation process, the fluidity and curing properties of EP, which is a representative liquid resin, enable it to be used as a filler or matrix material to be filled into a foamed metal. Curing of the components eliminates the need to compression-mold the PTFE–matrix polymer, thereby enabling the control of the sample size and simplifying the preparation process.

2.2. Friction and wear testing

Wear tests were conducted using a UMT-2 friction and wear tester (CETR, USA) (Fig. 3a). The composite specimen pin was rotated on a carburizing steel alloy disk in a pin-on-disk configuration, and the trajectory radius in the friction process was 25 mm. The friction and wear tests were selectively conducted at a load of 30–100 N (i.e., 0.3–1.0 MPa). The sliding speed was always 0.26 m/s (i.e., 100 rpm). The initial surface roughness of the disk Ra = 0.2 μm. Because setting a large-scale wearing surface weakens the size scale effects, here the contact interface of the specimens rotating on a disk was 10 mm × 10 mm, while the average apertures of the three types of foamed copper were: 2.68, 1.50, and 0.92 mm. On average, there were approximately 14–100 cells of foamed copper on the wear surface; therefore, the effects of a single cell of foamed copper on the performance of the composites can be meaningfully summarized in those of average size. All tests were conducted for 2 h under dry conditions at room temperature. An electric field was imposed between the specimen and the disk to monitor the tribo-chemical reaction by means of contact resistance (Fig. 3b). The frictional coefficient was recorded and calculated using the ratio between the tangential force and the normal load, and its value was determined by averaging over an entire test. The mass loss of the composite specimen was measured after the wear test in order to calculate the specific wear rate using the following equation:

$$\dot{W}_s = \frac{\Delta m}{\rho F_N L}\ (\mathrm{mm^3/N\ m}) \qquad (1)$$

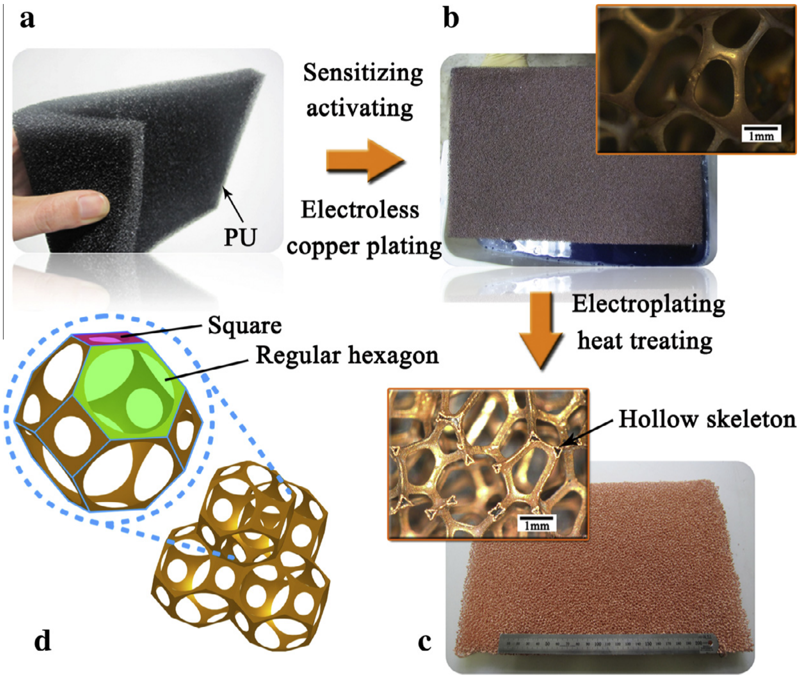

Fig. 1. Preparation and morphology of foamed copper. (a) Polyurethane (PU) foam was used as a template, (b) electrolessly copper-plated PU foam, (c) electroplated and heat-treated foamed copper produced from PU foam; and (d) tetrakaidecahedron-like cells showing 8 regular-hexagon and 6 square faces.