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Wear rate and fracture toughness of porous particle-filled phenol composites

Takuya Morimoto [a,*], Tsubasa Suzuki [b], Hiroshi Iizuka [b]

[a] Interdisciplinary Graduate School of Science and Engineering, Shimane University, Nishikawatsu 1060, Matsue, Shimane 690-8504, Japan
[b] Graduate School of Science and Engineering, Yamagata University, Jonan 4–3–16, Yonezawa, Yamagata 992-8510, Japan

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ABSTRACT

We experimentally investigated the effects of filler volume fraction of the phenol composites filled with porous particles on the fracture toughness and the wear rate against a smooth metal surface under multi-pass condition. Porous particles, made from rice husks, of various volume fractions from 0 to 0.5 were added to phenol resin as carbon filler. For the reported results of adhesive wear under multi-pass condition, we correlated the bulk parameters associated with the fracture toughness to the wear rate. We found an empirical power–law relation between the reciprocal of the product of stress and strain at rupture in bending test and the wear rate with various filler volume fractions. We also proposed the modified mixture law of the wear rate by taking account of the area fraction of transfer layer, which can provide a good prediction of the filler volume fraction dependence.

1. Introduction

Generally, polymers exhibit a low coefficient of friction and a moderate wear rate compared with metals and ceramics [1–5]. Since the modulus of elasticity of polymers is one order of magnitude lower than those of metals and ceramics, polymers are often reinforced with particles or fibers to generate stronger and tougher composite materials. In particular, phenol resins are widely used as frictional materials for brake pads and linings of automobiles and trains by reinforcing some fillers. For phenol composites as frictional materials, both high wear resistance and high fracture toughness are very important factors for the reliability.

Rice husk is an agricultural waste produced as by-products during a rice-milling process. One of authors have developed a carbon filler made from rice husk, which holds a porous structure of raw material after carbonization [6]. It can be used as a potential filler for making functional polymer composites which provide some mechanical and electromagnetic functions. In addition, utilization of a large quantity of rice husk produced every year may provide one of solutions to overcome the problem of environmental pollution which has become one of the most important aspect of industry. The addition of fillers to polymer matrix is a fast and cheap method to improve the bulk [7–9] and interfacial [10,11] properties of the base polymer. There are many other approaches to make use of rice husk as a potential filler for polymer composites [12–33].

The wear mechanisms of polymer composites are very complex and they depend on the contact conditions, mechanical properties of the polymer composite and how their parameters lead to the transfer film formation and debris production. The dominant wear mode of polymer composites is adhesive one. However, the types of filler and contact conditions also have the influence and other wear mechanisms such as abrasive one may also be present [34]. Abrasive wear is generally related to the fracture and plasticity of bulk material. For a particle-filled polymer composite the wear behavior is strongly affected on the fracture toughness of bulk material. Thus, the fracture characteristics of the interface and bulk of polymer composites such as wear resistance and fracture toughness are generally designed by controlling the filler volume fraction.

In this paper, we experimentally investigated the effect of filler volume fraction of the phenol composites filled with porous particles on the wear rate and the fracture toughness including the critical stress intensity factor of mode I and the work to rupture. First, the composite materials to be used as specimens were prepared by mixing phenol resin and porous filler, made from rice husk, of various volume fractions from 0 to 0.497. The effect of volume fraction on the fracture toughness of and the wear rate under multi-pass condition were experimentally evaluated. Then,

* Corresponding author.
E-mail address: morimoto@riko.shimane-u.ac.jp (T. Morimoto).

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we correlated the fracture toughness to the wear rate and found that an empirical power–law relation between the reciprocal of the product of stress and strain in bending test and the wear rate of composites with various filler volume fractions. We also quantified the estimation of the wear rate by mixture law approach and proposed the modified mixture law taking account of the area fraction of transfer layer, which can provide in reasonable agreement with the volume fraction dependence of the wear rate for the composites.

2. Materials and methods

2.1. Specimens

Fig. 1 shows the fabrication process of porous particle-filled phenol composites made from rice husks. Phenol resin matrix filled with the porous particles made from rice husk was used as the material for specimens. The porous filler was prepared by pulverizing raw rice husks for three times and then by carbonizing in nitrogen gas atmosphere at 1173 K for 3 h. The median diameter of the particles D_m was 57.6 μm. The distributions for the particle diameters normalized by the median diameters D_m are plotted in Fig. 2. Phenol resin (Air Water Bellpearl Inc., Bellpearl S890) was used as a matrix. The filler was mixed with the phenol resin by controlling the weight ratio, and then it was molded and cured under the appropriate pressures and temperatures in order to prepare the neat phenol resin and 5 different composites in terms of filler volume fraction $\phi = \{0.1,0.2,0.3,0.4,0.5\}$. Finally, post-curing was done at which temperature was linearly increased for 1.5 h and then it was maintained at 443 K for 2 h. After that, it was linearly decreased for 1.5 h. The total process was taken 5 h. The specimens with appropriate size for each experiment were cut out from the plate with the size 100 × 100 × 5 mm^3. Fig. 3 shows optical micrographs of virgin surfaces of the porous particle-filled composites with filler volume fractions $\phi = \{0.1,0.3,0.5\}$. In these figures, we can see the porous structure of the filler remains and phenol resin is embedded in their pores.

2.2. Tensile test

A tensile test at room temperature (296 K) was conducted with a universal testing machine (Shimadzu Co. Ltd., Autograph AG-IS 50 kN). Dimensions of the specimen for tensile test are shown in Fig. 4. The specimens had a dumbbell shape with a gauge length 60 mm, a width 10 mm and a thickness 2 mm. The crosshead speed was 10 mm/min and the average values were obtained from at least five successful determinations.

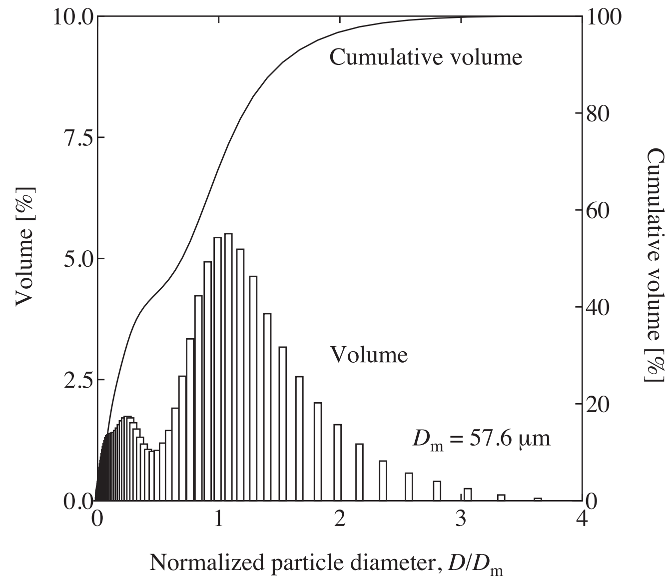

Fig. 2. Diameter distribution of porous particles by pulverizing raw rice husks.

2.3. Bending test

To measure the fracture toughness of mode I at room temperature (296 K) based on ASTM standard D5045-99, a three-point bending test on each pre-cracked specimen was conducted with a universal testing machine (Shimadzu Co. Ltd., Autograph AG-IS 50 kN). Dimensions of the specimen for bending test are shown in Fig. 5. The stress intensity factor K_{IC} can be determined by

$$K_{IC} = \frac{SP_{max}}{BW^{3/2}} \cdot f(\zeta) \tag{1}$$

where

$$f(\zeta) = \frac{6\zeta^{1/2}\left[1.99 - \zeta(1-\zeta)\left(2.15 - 3.93\zeta + 2.7\zeta^2\right)\right]}{(1+2\zeta)(1-\zeta)^{3/2}} \tag{2}$$

and $\zeta = a/W$ for the case of $S/W = 4.0$. P is the maximum load. S, B, W and a are the span length, the thickness, the width and the pre-crack length of the specimen, respectively. The average value was used as the fracture toughness by excluding the maximum and minimum values from 10 experimental results and the standard deviation was also evaluated. Furthermore, the stress, $\sigma_B^{(b)}$, and strain, $\varepsilon_B^{(b)}$, at the rupture point were also identified. These are also

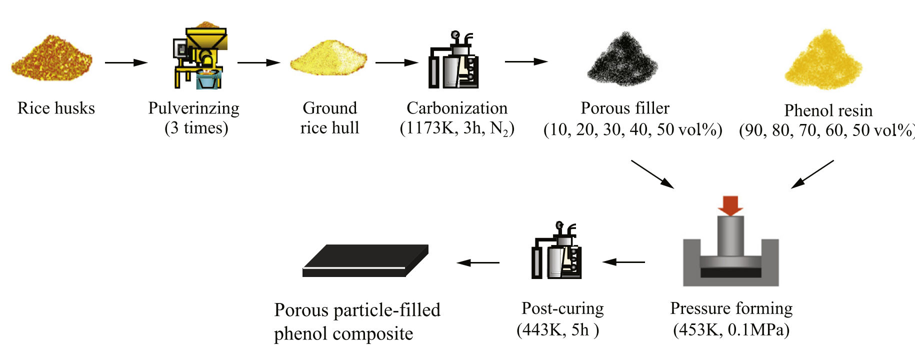

Fig. 1. Schematic illustration of the processing of porous-particle filled phenol composite made from rice husks.