Viscosity of Unimodal and Bimodal Alumina/Epoxy Mixtures

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Experimental results on characteristics of viscosity η of unimodal and bimodal alumina/epoxy mixtures are shown and discussed based on theoretical consideration. Spherical alumina particles with nominal diameters of $35\mu\text{m}$ and $80\mu\text{m}$, both of which had narrow dispersion of diameter distribution, were used as fine and coarse particles, respectively. η of the unimodal mixture increases remarkably with a volume packing fraction of particle ν_p , and that Brinkman equation can be applied to estimate η from ν_p . On the other hand, η of the bimodal mixture depends not only on ν_p , but also on the ratio of coarse particles to fine ones. For larger ν_p , η of the bimodal mixture becomes smaller than that of the unimodal mixture. It is shown that an approximation procedure of η yields reasonable estimation for smaller ν_p , and underestimation for larger ν_p .

Keywords: functionally graded material, alumina/epoxy mixture, viscosity, bimodal system, unimodal system

1. Introduction

The authors are using a centrifugal method to fabricate functionally graded materials with large size from alumina-particles/epoxy-resin mixtures⁽¹⁾. During the centrifugal process, drag force is one of the major forces experienced by the particles, and hence, it dominates the movement of the particles. It directly depends on the coefficient of viscosity of the mixture, η , and consequently, precise information of η is indispensable for both the fabrication and simulation process⁽¹⁾⁽²⁾.

To evaluate effects of the amount and size of particles involved in the mixture on η , η of unimodal and bimodal alumina/epoxy mixtures were measured under various conditions. Experimental results on the characteristics of η are demonstrated and theoretically discussed.

2. Materials and Experimental Method

Spherical alumina particles with nominal diameters of $35\mu\text{m}$ and $80\mu\text{m}$ were used as fine and coarse particles. Mixtures involving either particle can be regarded as a unimodal system, because this particle had narrow dispersion of diameter distribution⁽³⁾. Meanwhile, the bimodal mixtures involving both particles represent mixtures with suspensions such as a pulverised powder that has a variety of diameters⁽¹⁾⁽³⁾.

For the unimodal mixture, when particles by the volume V_p were mixed with an epoxy resin by the volume V_e , the volume packing fraction of particles is given by $\nu_p = V_p/(V_p + V_e)$. On the other hand, for the bimodal mixture, both the fine and coarse particles by

the volume of V_f and V_c , respectively, were mixed with an epoxy resin. In this case, two kinds of the volume fraction of particles can be defined: one is ratio of all particles to the mixture $\nu_p = (V_f + V_c)/(V_f + V_c + V_e)$, and the other is ratio of the coarse particles to all particles $\nu_{coarse} = V_c/(V_f + V_c)$.

After a given amount of fine and coarse alumina particles was dispersed in an epoxy resin, the alumina/epoxy mixture was de-gassed in a vacuum chamber. Then, η of the mixtures was measured by the viscosity meter when temperature of the mixture became $26 \pm 0.5^\circ\text{C}$.

3. Experimental Results and Discussions

3.1 Viscosity of Unimodal Mixtures ν_p varied from 0 to 45% for both alumina particles.

Fig. 1 shows dependency of η on ν_p . Two symbols of $\bullet$ and $\circ$ in Fig. 1 show experimental values of η obtained for the fine and coarse particles, respectively. Fig. 1 indicates that η increases remarkably with ν_p for both particles. It is also clear that η of the fine particles is slightly larger than that of the coarse ones, and the difference in η becomes notable as ν_p increases.

It is known that η of a unimodal mixture is gener-

Fig. 1. η of unimodal mixtures as a function of ν_p

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ally given as a function of ν_p by the following equation proposed by Brinkman⁽⁴⁾:

$$\eta(\nu_p) = \eta_0 / \left(1 - \frac{\nu_p}{\nu_{max}}\right)^n \quad \dots\dots\dots (1)$$

where η_0 is the coefficient of viscosity of the epoxy resin, ν_{max} is the maximum packing fraction obtainable for the mixtures under consideration, and n is a constant.

Values of ν_{max} and n in Eq. 1 were calculated to fit the measured values shown in Fig. 1. $\nu_{max} = 0.59$ and $n = 2.32$ are obtained for the fine particles, while $\nu_{max} = 0.61$ and $n = 2.28$ are obtained for the coarse particles.

These values of ν_{max} and n along with $\eta_0 = 8.5 \text{ Pa}\cdot\text{s}$ were used to calculate η for various ν_p , and profiles of η thus obtained are plotted by solid and broken lines for the fine and coarse particles, respectively, in Fig. 1. Comparison between the measured and estimated values shown in Fig. 1 demonstrates that the Brinkman equation expressed in Eq. 1 can be applied to estimate η of the unimodal alumina/epoxy mixture from ν_p with reasonable precision.

3.2 Viscosity of Bimodal Mixtures

ν_p varied between 0 to 45%, and ν_{coarse} varied between 0 to 100% for each ν_p . It is noted that the bimodal mixtures with $\nu_{coarse} = 0\%$ and 100% correspond to the unimodal mixtures with the fine and coarse particles only, respectively.

Symbols in Fig. 2 show measured values of η obtained for various ν_p and ν_{coarse} . It is obvious from Fig. 2 that η of the bimodal mixture depends not only on ν_p , but also on ν_{coarse} . η is almost independent of ν_{coarse} for smaller ν_p up to 20%. Meanwhile, for larger ν_p more than 35%, η depends on ν_{coarse} , and η of the bimodal mixture becomes smaller than that of the unimodal mixture (i.e. $\nu_{coarse} = 0\%$ or 100%), and reaches a minimum value at a certain ν_{coarse} of $\nu_{c,min}$ around 60%.

Based on the approximation procedure of η of the bimodal mixture, it can be predicted by using η of the unimodal one, and is given by the following expression⁽⁵⁾.

$$\eta(\nu_p, \nu_{coarse}) = \eta_0 \cdot \frac{\eta_f(\nu_f)}{\eta_0} \cdot \frac{\eta_c(\nu_c)}{\eta_0} \quad \dots\dots\dots (2)$$

Here, $\eta_f(\nu_f)$ and $\eta_c(\nu_c)$ are η of the unimodal mixtures involving the fine and coarse particles, respectively,

and are estimated by using Eq. 1 in advance, where $\nu_f = V_f/(V_e + V_f)$ and $\nu_c = V_c/(V_e + V_f + V_c)$.

Furthermore, $\nu_{c,min}$, at which η becomes the smallest, is estimated by the following expression that includes ν_p and V_e as given values⁽⁵⁾.

$$\nu_{c,min} = V'_e/(V'_f + V'_c) \quad \dots\dots\dots (3)$$

where, $V'_f = \nu'_p V_e/(1 - \nu'_p)$, $V'_c = \nu'_p(V_e + V_f)/(1 - \nu'_p)$, and $\nu'_p = 1 - \sqrt{1 - \nu_p}$.

For the bimodal mixture under consideration, dependency of η on ν_{coarse} were calculated using Eq. 2 for $\nu_p = 5, 20, 35, 45\%$, and the results are plotted by solid lines in Fig. 2. Moreover, $\nu_{c,min} = 51, 53, 55, 57\%$ for $\nu_p = 5, 20, 35, 45\%$, respectively, were obtained by Eq. 3.

It is obvious from Fig. 2 that the approximated results by Eq. 2 quantitatively express dependency of η against ν_{coarse} , and that, in particular, the reduction of η for the bimodal mixtures clearly appears at larger ν_p . The approximation procedure yields reasonable estimation of η for ν_p smaller than 35%, while it underestimates η for ν_p larger than 45%. Meanwhile, $\nu_{c,min}$ is estimated by Eq. 3 with reasonable precision regardless of ν_p .

4. Conclusions

Experimental results on characteristics of η of unimodal and bimodal alumina/epoxy mixtures are shown and discussed based on the theoretical consideration.

η of the unimodal mixture increases remarkably with ν_p , and Brinkman equation can be applied to estimate η from ν_p . On the other hand, η of the bimodal mixture depends not only on ν_p , but also on ν_{coarse} . For larger ν_p , η of the bimodal mixture becomes smaller than of the unimodal mixture, and reaches a minimum value at a certain ν_{coarse} . An approximation procedure proposed by Farris gives reasonable estimation of η for smaller ν_p , while it underestimates η as ν_p increases.

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Symbols: Measured, Solid lines: Estimated

Fig. 2. η of bimodal mixtures as a function of ν_{coarse} for various ν_p