BRIDGING TOUGHENING OF EPOXY RESINS BY DISPERSSED THERMOPLASTICS

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ABSTRACT: The particulate toughening behaviour of epoxy resins modified by ductile thermoplastics is elucidated here by various bridging models. The experimental data for three different epoxy/PSF systems are presented to illustrate the trend of the toughening characteristics. The conventional continuous bridging model is shown to have underestimated the effect of the particulate toughening. A joint application of the discrete bridging model and the multiple bridging model, however, shows promising results for modified epoxy systems such as AG80/DDS/PSF and E51/DDS/PSF. These models also provide quantitative descriptions for the crack pinning phenomenon previously observed by Fu and Sun [1] in AG80/DDS/PSF.

KEYWORDS: bridging model, toughening, crack pinning.

I. INTRODUCTION

The significance of particulate toughening in brittle thermosetting matrix was observed using epoxy resin modified by soft dispersions of carboxyl terminated nitrile rubber (CTBN) [2], the presence of these dispersed rubber-balls enhances the fracture energy of the material system by a factor of 10 to 30. Different mechanics models, such as the rubber-ball stretching model of Kunz-Douglas et al. [3] and the cavitation/localized shear band model of Kinlock et al. [4], have been proposed to explain the toughening mechanisms caused by soft second-phase particles. The aim of the present paper, however, is directed to another toughening mechanism induced by the precipitation of relatively stiff and ductile thermoplastics within the brittle epoxy matrix. The mechanical behaviour of epoxy resins modified by dispersed PSF particles was recently reported by Fu and Sun [1]. In contrast to the soft particles (such as CTBN) and the hard and brittle particles (such as glass balls), PSF is ductile and has stiffness comparable to the epoxy resin matrix. Crack pinning was observed directly in one of the systems examined by them, which is conjectured to be responsible for the toughening behaviour of this system [1]. It is the intention of this paper to develop a quantitative mechanics model to characterize this toughening and crack pinning phenomenon. One appropriate model particularly suitable for ductile and moderately stiff particle dispersion is the bridging model developed in the research on the other material systems, especially in structural ceramics. We will first describe the experimentation and the testing data for three different epoxy systems. Continuous, discrete and multiple bridging models will be introduced in turn to correlate the test data. The last two models, which incorporate both bridging and crack pinning, can describe the toughening behaviour of AG80/DDS/PSF without using any adjustable constants.

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II. EXPERIMENT

The tested materials are the thermoplastic (PSF in particular) modified epoxy resins. Two types of epoxy resin employed are AG80 (a Chinese trade brand) and E51, with two different curing agents DDS and Piperidine (abbreviated as Pip in the sequel). Three epoxy resin matrices are prepared for testing. The single phase mechanical properties of them (as well as PSF) are listed in Table 1, where the test data of PSF are taken from bulk specimens. The fracture toughness of various material systems in Table 1 and throughout this paper is measured according to ASTM E-399-83. The dimensions of the three point bending specimen are 5 × 10 × 55 mm. The morphology of those material systems indicates an island-type microstructure of dispersed PSF particles if the weight content of PSF per epoxy matrix is less than 15%. The SEM fractography of these material samples shows typical flat brittle fracture surfaces cutting through continuous epoxy resin matrices. Crack deflection and microcracks are hardly seen. We can conclude that the toughening effect is due to various plastic phenomena (such as volume dilatation, craze, void formation, microcracks and localized shear bands) have no significant influence. On the other hand, the mechanical behaviour of the particulate PSF phase which is encountered during crack growth process must certainly play an important role in the toughening mechanism. The stress-strain curve of the single-phase PSF bulk specimen is tested, and the tensile testing result is plotted in Fig. 1. This curve can be simulated accurately by the following elastic idealized plastic-failure curve

\[
\sigma = \begin{cases} 
E\varepsilon & 0 \leq \varepsilon \leq \varepsilon_s \\
\sigma_s & \varepsilon_s < \varepsilon \leq \varepsilon_f \\
0 & \varepsilon > \varepsilon_f
\end{cases}
\]  

(1)

Some characteristic values in the above constitutive law are

\[
\sigma_s = 70 \text{ MPa} \quad \varepsilon_s = 2.8\% \quad \varepsilon_f = 100\%
\]  

(2)

Here we use the upper value of \(\varepsilon_f\) given in Table 1 because the spherical shape of the particles retards the occurrence of necking. In contrast to the conventional dispersion hardening mechanism, here PSF represents a ductile weak phase, its Young’s modulus is somewhat less than of the epoxy matrices. The dispersed particles of this type is unable to enforce geometrical or kinematical constraints on the cracking process within the brittle epoxy matrices. On the other hand, the ductile PSF particles can provide certain bridging forces (far exceeding the one available from the CTBN particles) which are sufficient to constrain the matrix cracking. Consequently, PSF par-