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A two-parameter approach to assessing notch fracture behaviour in clay/epoxy nanocomposites

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ABSTRACT

Fracture toughness and other mechanical properties of epoxy are known to be affected by the addition of nanoclays. Fracture toughness has been shown by many researchers to depend on the nanocomposite structure with well-dispersed and distributed nanoparticles resulting in improvements in this property by up to 50%. Notch fracture toughness depends on the acuity of the notch as well as on the structure of the nanocomposite. In the present work, a two-parameter fracture criterion based on a critical notch stress intensity factor, $K_{\rho,c}$, and effective T-stress, T_{ef}, was used to study the effect of notch severity and nanoclay addition on the fracture toughness of the epoxy matrix. The results show that the average value of $K_{\rho,c}$ for neat epoxy increased with increasing notch radius while the absolute value of T_{ef} decreased with notch radius. The addition of nanoclay to pristine epoxy reduced the average value of $K_{\rho,c}$ and increased the absolute value of T_{ef}. The critical notch radius was found to be around 1.0 mm and the notch sensitivity was higher for neat epoxy. SEM analysis of the fractured surfaces revealed that the lower $K_{\rho,c}$ for nanocomposites in both mode I and mixed mode fractures was due to early crack initiation at clay clusters or voids at the notch root.

1. Introduction

Extensive research work has been conducted to investigate the effect of nanoclay addition on the properties of different types of polymer matrices [1–14]. In fact, the properties of epoxy-clay nanocomposites are highly dependent on the resultant morphology, which illustrates the degree of clay dispersion into the epoxy matrix [1,3]. An intercalated or exfoliated morphology of epoxy-clay nanocomposites can be obtained depending on the mixing method and the type of epoxy and nanoclay used. Generally, exfoliated structures are reported to possess better properties than intercalated ones since more reinforcement elements are available that carry the applied load in the exfoliated morphology [1,5].

Contradictory results have been reported about the effect of clay addition on epoxy properties. Improvements in mechanical properties such as the modulus of elasticity, tensile strength and fracture toughness due to clay addition have been reported in some studies [1–11], while other researchers found that nanoclay addition had negative or at best no effect on these properties [12,13].

Fracture toughness was seen to increase by up to 50% by Qi et al. [7] for 10 wt% of clay in nanoclay/epoxy composites, while Adam and Alan [8] showed an increase in fracture toughness up to 60% at 3.5 wt% of MMT, but a decrease in fracture toughness after that. Similar behaviour was observed by Yasir et al. [13], who showed that the optimum clay loading was 1.5 wt%. Hussain et al. [16] investigated the effect of the clay concentration on the fracture behaviour of surface-modified MMT/epoxy nanocomposites and found that fracture toughness decreased up to 4 wt% of MMT and increased at 6 wt%, followed by another decrease at 10 wt%.

Improvements in fracture toughness are usually associated with the high degree of exfoliation and the good adhesion of epoxy to clay platelets. On the other hand, Wetzel et al. [19] explained that the presence of nanoparticles in epoxy induces fracture mechanisms such as crack deflection, plastic deformation and crack pinning.

Among the large number of researchers who have addressed the fracture behaviour of nanoclay/polymer composites, Subramaniyan et al. [20] were the only ones to address the combined effects of

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notching and clay on the fracture toughness of the epoxy resin. They reported that, for the case of notched specimens, the neat resin had the highest stress intensity factor at fracture (K_{IF}); the addition of 5% nanoclay reduced the KIF by 30%. Their SEM analysis of the fracture surface revealed that, with the addition of nanoclay, the fracture surface became rougher with considerable tearing. This is usually an indication of higher resistance to crack advance. They concluded that in specimens with a notch, the fracture behaviour was dominated by the stress concentration factor at the notch and not the stress intensity factor at failure.

The above conclusion suggests that it is more correct to use notch fracture mechanics rather classical (crack) fracture mechanics to study notched nanoclay/epoxy composites. It has also been noted that fracture resistance is sensitive to specimen geometry and loading mode through the constraint. The current trend is to use a two-parameter fracture criterion in order to take this effect into account. Eisele et al. [31] pointed out that the fracture toughness K_c or J_c increases with the loss of constraint T stress, A_2 or Q. Nateche et al. [11] and El-azzizi et al. [15] have also pointed out this effect on the notch fracture toughness K_{ρ},c with the critical constraint described by the T_{ef}-parameter.

In this paper, the fracture resistance of epoxy-nanoclay epoxy was determined using notched three-point bend specimens. The critical notch stress intensity factor ($K_{\rho,c}$) and the critical effective T stress ($T_{ef,c}$) as constraint parameters were determined and reported in a Material Failure Master Curve (MFMC),$K_{\rho,c} = f(T_{ef,c})$. SEM was used to study the mechanism of fracture of neat epoxy notched specimens and the nanoclay composites.

2. Background on two-parameter notch fracture resistance

The fracture resistance of a component or a structure exhibiting a notch-like defect can be studied through the concept of notch stress intensity factor using the volumetric method. The volumetric method (VM) [21] is a local fracture criterion which assumes that the fracture process requires a certain cylindrical volume with the effective distance as its diameter. The fracture process volume is the"high stress region" where the necessary fracture energy release rate is stored. The difficulty is in finding the limit of this high stress region. This limit is *apriori* not a material constant, but depends on the loading mode, structure geometry and load level. The size of the fracture process reduced to the effective distance X_{ef} according to the above mentioned assumptions is obtained by examination of the stress distribution. The bi-logarithmic elastic–plastic opening stress σ_{yy} distribution (Fig. 1) along the ligament exhibits three distinct zones. The elastic–plastic stress primarily increases and the nattains a peak value (zone I), then it gradually drops to the elastic–plastic regime (zone II). Zone III represents linear behaviour in the bi-logarithmic diagram. It has been shown by examination of fracture initiation sites that the effective distance corresponds to the beginning of zone III which is, in fact, an inflexion point on this bi-logarithmic stress distribution. A graphical method based on the relative stress gradient $\chi(r)$ associates the effective distance to the minimum of χ. The relative stress gradient is given by:

$$\chi(r) = \frac{1}{\sigma_{yy}(r)} \frac{\partial \sigma_{yy}(r)}{\partial r} \tag{1}$$

where $\chi(r)$ and $\sigma_{yy}(r)$ are the relative stress gradient and maximum principal stress or opening stress, respectively.

The effective stress for fracture σ_{ef} is then considered to be the average value of the stress distribution over the effective distance. However, stresses are multiplied by a weight function $\chi(r)$ in order to take into account the stress gradient due to geometry, the loading mode and the acting distance r. The effective stress can then be obtained from:

$$\sigma_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} \sigma_{yy}(r) \times (1 - r) \times \chi(r))\, dr \tag{2}$$

Therefore, the notch stress intensity factor is defined as a function of effective distance and effective stress:

$$K_{\rho} = \sigma_{ef} \left(2\pi X_{ef} \right)^{\alpha} \tag{3}$$

where K_{ρ}, σ_{ef} and X_{ef} are the notch stress intensity factor, effective stress and effective distance, respectively, and α is the slope of the

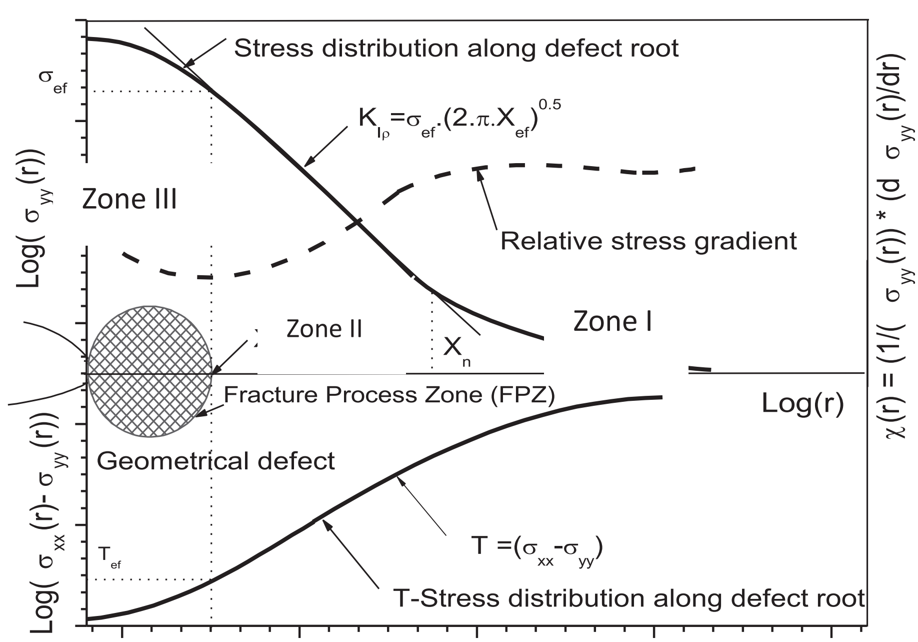

Fig. 1. Determination of the notch stress intensity factor and the effective T-stress at the notch tip (the stress distribution is computed for elastic behaviour).