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Effect of alumina dispersions on the thermal conductivity/diffusivity and thermal stress resistance of a borosilicate glass

Hot-pressed glass–crystal mixtures are used as model materials for studies of the properties of brittle matrix composites. Properties such as elastic behaviour [1–3], strength [2, 4] and fracture toughness [3, 4] have been studied extensively for glass matrices with an alumina-dispersed phase. However, such composites in their own right are also candidate materials for engineering applications involving thermal stress. This note presents data for the thermal conductivity and thermal diffusivity of glass–alumina mixtures, which permits an assessment of the effect of the crystalline phase on thermal stress resistance.

The specific glass–alumina specimens in this study were prepared in a programme addressing the fracture toughness [3] of a borosilicate glass with alumina dispersions. The glass consisted of 70 mol% SiO_2 plus B_2O_3 and Na_2O in a molar ratio of 0.67. The alumina dispersions were spherical with a diameter of 25 ± 7 μm. Details for the specimen preparation and microstructure were presented earlier [3]. This particular glass–alumina system was selected because of the close match between the coefficients of thermal expansion of the two phases, in order to minimize or eliminate the formation of micro-cracks due to internal stresses; such cracks could have a significant effect on the thermal conductivity [5].

The thermal diffusivity of the composites was measured over the temperature range from room temperature to about 600° C by the laser-flash diffusivity technique [6] using equipment described in detail elsewhere [7], with the transient temperatures of the specimens during the test being monitored by *IR*-detectors. The thermal conductivity was calculated from the thermal diffusivity using values for the density of the alumina and the glass of 3.987 and 2.454 g cm^{-3}, respectively, and literature data for the specific heat of alumina [8] and a borosilicate glass of composition similar to the glass of the present study [9].

Fig. 1 shows the experimental data for the thermal diffusivity as a function of temperature for a number of compositions for which the volume fractions were determined from the composite densities after hot-pressing [3]. For some of these compositions, Fig. 2 shows the calculated values of thermal conductivity. The

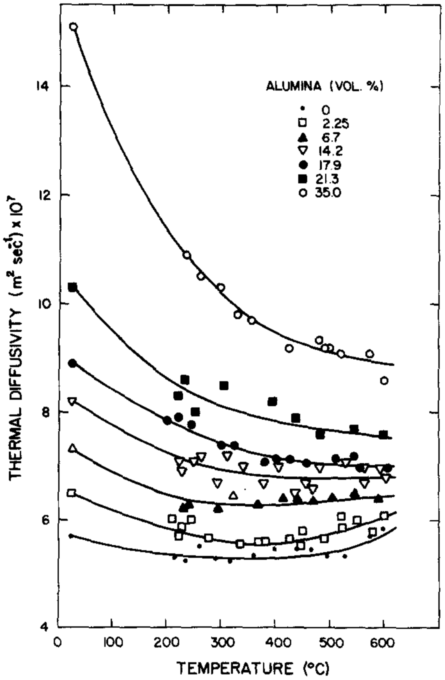

Figure 1 Effect of temperature and composition on thermal diffusivity of glass–alumina composite.

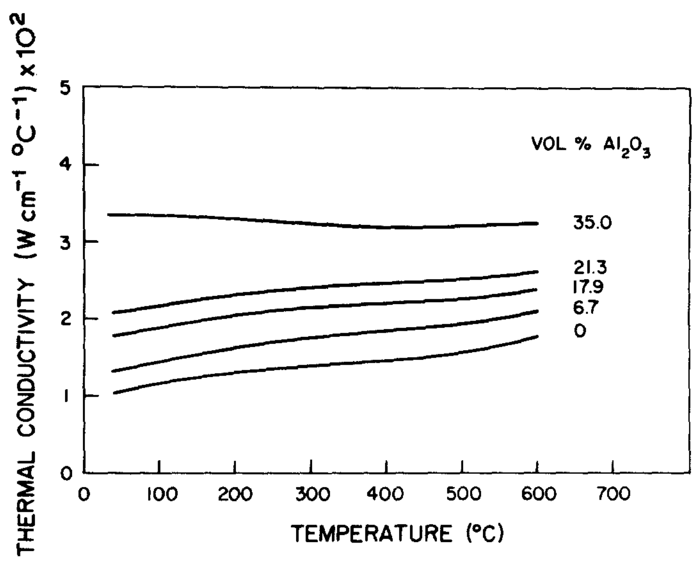

Figure 2 Calculated thermal conductivity of glass–alumina composites.

relative effect of temperature and composites can be explained on the basis of the general heat conduction processes in dielectric materials. Owing to the relative differences in elastic properties and degree of crystallinity, the thermal conductivity and diffusivity of the glass is expected to exhibit much lower values and a lower temperature dependence that the corresponding values for the alumina. For these reasons, addition of alumina particles to the glassy plane is expected to increase the magnitude of the thermal diffusivity with a corresponding increase in its temperature dependence, in agreement with observations. The positive temperature dependence of the thermal diffusivity of the glass at the higher temperatures is probably attributable to a contribution of internal radiation to the heat transfer process.

The values of the thermal conductivity show a much lower relative temperature dependence than the thermal diffusivity, because the positive temperature dependence of the specific heat compensates for the negative temperature dependence of the thermal diffusivity. It may be noted that at the highest volume fraction the variation in thermal conductivity with volume content alumina lies above the values calculated by the Rayleigh–Maxwell theory [10, 11], which is appropriate only for dilute concentrations of spherical inclusions.

An assessment of the anticipated effect of the alumina phase on thermal stress resistance can be made on the basis of its influence on thermal stress resistance parameters. As a measure of the resistance of a brittle material to the initiation of thermal fracture, two well-known [12] parameters are: $R = S_t(1-\nu)/\alpha E$ and $R' = S_t(1-\nu)K/\alpha E$, in which S_t is the tensile strength, ν is Poisson's ratio, α is the coefficient of thermal expansion, E is Young's modulus and K is the thermal conductivity. The resistance to crack propagation and corresponding loss in load-bearing ability after thermal fracture initiation described is given by the parameters [13], $R_{st} = (G/\alpha^2 E)^{1/2}$ and $R'_{st} = (GK^2/\alpha^2 E)^{1/2}$ for stable crack propagation and $R'''' = GE/S_t^2$ for unstable catastrophic crack propagation. In these latter parameters G is the fracture energy, related to the critical stress intensity factor, $K_{IC} = (2GE)^{1/2}$. Fig. 3 shows the relative variation of these parameters with volume fraction alumina as calculated from the thermal conductivity and mechanical [3] property and strength [14] data for these materials. The location of the curves for the parameters R_{st}, R'_{st} and R'''' must be considered only approximate in view of the lack of sufficient data points to plot the curves accurately. Nevertheless, sufficient data were available to indicate that these parameters vary significantly with alumina content.

As judged by the variation of the parameters R and R', the addition of the alumina phase has only a minor influence on the thermal conditions required to initiate fracture. In fact, the variation in R indicates that the alumina phase actually decreases thermal stress resistance. The parameter R' increases primarily because the increase in K

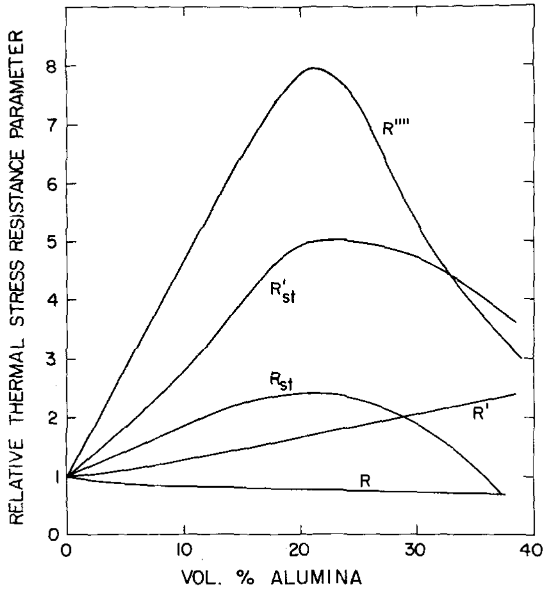

Figure 3 Relative thermal stress resistance parameters of glass–alumina composites.

exceeds the increase in E. As indicated by experimental data, the values of R and R' could be increased by increasing the composite strength by decreasing the alumina particle size.

The major increases in the parameters R_{st} and R'_{st} and especially R'''', indicate that the alumina crystalline phase has a large effect on the nature of crack propagation following thermal fracture. Specifically, under conditions of both stable and unstable fracture the extent of crack propagation should be reduced appreciably accompanied by a major increase in the retention of load-bearing ability or any other property affected by cracks. The general shape of the curves in Fig. 3 for R_{st}, R'_{st} and R'''' indicates that optimum resistance to thermal crack propagation can be obtained at approximately 20 vol % alumina.

These results suggest that by incorporating a high conductivity crystalline phase in the glassy material, the resistance to the initiation and the catastrophic nature of thermal fracture of a glass can be improved significantly. Well-controlled thermal stress experiments to confirm this conclusion should be of interest.

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