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Toughening effects quantification in glass matrix composite reinforced by alumina platelets

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Abstract

A borosilicate glass matrix composite containing alumina platelets was considered to investigate toughening mechanisms and crack tip behavior in dispersion reinforced brittle matrix composites. Fracture toughness was determined by applying the chevron notched specimen technique, and fractographic analysis was employed to reveal the active toughening mechanisms with increasing content of reinforcement. A roughness-induced shielding effect has been quantified to prove the relation between fracture toughness and fracture surface roughness. Theoretical calculations of the fracture toughness enhancement based on a modified crack deflection model developed by Faber and Evans, combined with the influence of the increase in Young's modulus, were found to be in good agreement with experimental data. An effect of residual stresses upon toughening of the investigated composite is discussed.

Keywords: Glass matrix composites; Crack deflection; Fracture surface roughness; Residual stresses

1. Introduction

The very low fracture toughness of glass (~0.6–0.7 MPa $m^{1/2}$) may be improved by introducing in the glass matrix a reinforcing second constituent with high modulus, high strength and/or high ductility in the form of fibers, whiskers, platelets or particulates [1,2]. By optimizing the microstructure of the composites to activate toughening mechanisms the fracture toughness can be substantially increased, e.g. up to a level of about 25 MPa $m^{1/2}$ for composites with unidirectional fibers [3]. The possible synergy of more than one toughening mechanism has been found advantageous in these composites and the better mechanical behavior of the composite over that of the unreinforced glass matrix in term of Young's modulus, flexural strength and fracture toughness has been demonstrated for different systems, both with particle or fiber reinforcement [4,5].

A successful example of ceramic platelet reinforcement of glass is the borosilicate glass/Al_2O_3 platelet composite introduced firstly by Boccaccini et al. [6]. By means of a detailed experimental investigation, the mechanical properties enhancement was ascribed to three concurrent phenomena: the Young's modulus increment resulting from the platelets addition, the presence of a compressive residual stress in the glass matrix, and the crack deflection mechanism [6–8]. There are two additional aspects that have prompted increased interest in this composite system: the glass matrix can be obtained from vitrified waste materials of different origin as investigated among others by Bernardo et al. [9] and Boccaccini et al. [10]; in addition, alumina platelets are a commercial low-cost material commonly employed as abrasive in the polishing industry and are produced in very large amounts. Thus, environmentally friendly and cost-effective materials can be produced in this system, for example for the building industry.

Crack deflection, theoretically described by Faber and Evans [11], was suggested to be one of the mechanisms

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responsible for the toughening effect of the platelets in these composites. The propagation of crack in the glass matrix is altered by a system of residual stresses, caused by the thermo-elastic mismatch between the matrix and the reinforcement and enhanced by the particular aspect ratio of the platelets [6,7]. In fact, examination of the topography of fracture surfaces is usually very enlightening to asses fracture property changes in dependence of particle dispersion in glass matrix composites [8]. Fracture surface microscopic observations are frequently conducted in order to elucidate the toughening mechanisms acting in dispersion-reinforced composites. The direct correlation between the roughness of the fracture surface, as a measure of the degree of crack deflection, and the fracture toughness of dispersion-reinforced ceramic and glass composites has been suggested [8,12–14]. Nevertheless, very limited experimental work has been conducted to quantitatively verify this suggestion and, in fact, some studies have been reported which even negate such a direct correlation [15]. Only the work of Chou and Green [16] on SiC platelet-reinforced alumina composites has attempted to quantitatively correlate fracture surface roughness and fracture toughness due to crack deflection mechanisms.

The present paper deals with system borosilicate glass/alumina platelet composite and aims to analyze the relationship between reinforcement volume fraction and surface roughness with the mechanical properties, especially fracture toughness, both experimentally and theoretically. The crack deflection model of Faber and Evans [11] is thereby extended to capture a synergy between the crack deflection effect and the contribution of residual stresses to toughening. For the first time in the present paper, fracture toughness values of the composites at elevated temperature (500 °C) are also reported.

2. Experimental procedure

The experimental glass matrix composite was fabricated via powder technology and hot-pressing, as described in a previous study [6]. Alumina platelets of a hexagonal shape, with major axes between 5 and 25 μm and axial ratio of 0.2, were used. A commercially available borosilicate glass (DURAN, Shott Glass, Mainz, Germany) was selected for the composite matrix. Specimens containing 0, 5, 10, 15 and 30 vol.% of platelets were fabricated [6] and considered in the present investigation. Relevant properties of the composite constituents are given in Table 1.

As reported elsewhere [7,8,17], the composite microstructure exhibits a dense glass matrix where the platelets are distributed homogenously. The existence of a strong bond between the matrix and the platelets was confirmed by transmission electron microscopy [17]. The thermal expansion mismatch between matrix and reinforcement causes the building of internal residual stresses. The thermal expansion coefficient of the borosilicate glass matrix is much lower than that of the alumina platelets (Table 1), which results in tangential compressive and radial tensile stresses in the matrix upon cooling from the processing temperature [6]. The measurement of these residual stresses was conducted by the fluorescence spectroscopy technique, as reported elsewhere [7].

Table 1
Mechanical properties and thermal expansion coefficient of the composite constituents

	E (GPa)	G (GPa)	ν	α (10^{-6} °C^{-1})
Glass matrix	63	26	0.22	3.3
Al_2O_3 platelets	402	248	0.23	8.9

Fracture toughness values were obtained using the chevron notch technique. Test pieces of a standard cross-section (3×4 mm^2) were cut from disks of diameter 40 mm and thickness 4 mm using a precise diamond saw. A chevron notch with top angle of 90° was machined by using an ultra-thin diamond blade in each specimen. A Zwick/Roell electromechanical testing machine was utilized for the three-point bending test with a span of 20 mm. A crosshead speed of 0.1 mm min^{-1} was used for the loading. Samples were tested at room temperature and at 500 °C. The elevated temperature was selected just below the transformation temperature of the glass matrix ($T_g = 525$ °C [7]). A Maytec high-temperature furnace was used to conduct tests at elevated temperatures. Load–deflection traces were recorded and the fracture toughness was calculated from the maximum load ($F_{\max}$) and the corresponding minimum value of the geometrical compliance function ($Y^*_{\min}$) using the equation [18]:

$$K_{\mathrm{Ic}} = \frac{F_{\max}}{B\sqrt{W}} Y^*_{\min} \tag{1}$$

where B and W are the width and height of the specimen, respectively. The calculation of the geometrical compliance function was based on Bluhm's slice model [19]. The reliability of this technique for determining K_{Ic} in glass and brittle matrix composite materials has been reported elsewhere [20,21].

Scanning electron microscopy (SEM) was used for the fractographic analyses of fracture surfaces of tested chevron notched specimens. Roughness parameters were measured by the optical profilometer MicroProf FRT that utilizes a chromatic aberration of its lens. Different light monochromatic components are focused in different heights from a reference plane and the light scattered from the surface is collected and analyzed by means of a spectrometer. The best-collected light is that focused just on the surface so that the spectral distribution of the light intensity has a maximum at the wavelength of the monochromatic component exactly focused on the surface. The height of the surface irregularities is computed from the wavelength of that maximum. The device works with a vertical resolution of 3 nm and the lateral resolution of about 1 μm. The maximal angle of surface irregularities slopes to the mean plane of the surface must be less than 40°. The three-dimensional reconstruction of surface topology was