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Investigating tensile behaviour of toughened epoxy paste adhesives using circumferentially notched cylindrical bulk specimens

K.B. Katnam*, A.J. Comer, W.F. Stanley, M. Buggy, T.M. Young

Irish Centre for Composites Research (IComp), Materials and Surface Science Institute (MSSI), University of Limerick, Limerick, Ireland

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ABSTRACT

Toughened epoxy adhesives are frequently used to bond metals and polymer-matrix composite materials in many structural applications. The mechanical properties of adhesives are often characterised by testing either bulk adhesive specimens or bonded joints (*i.e. in-situ* form). In this paper, cylindrical bulk specimens with circumferential notches were manufactured and tested to investigate the tensile behaviour of an epoxy paste adhesive toughened with hollow glass microspheres. Bulk specimens were manufactured from the paste adhesive using injection moulding. Tensile tests were conducted for strain-rate and stress triaxiality effects by varying displacement rates and notch radii, respectively. Fracture surfaces were examined using optical and scanning electron microscopy to identify failure mechanisms. The results obtained from the toughened paste adhesive indicate that strain-rate and stress triaxiality influence its tensile fracture behaviour.

1. Introduction

Epoxy adhesives are often used in structural applications for bonding primary and secondary structural components. For example, in the aeronautical industry [1], the main use of structural adhesives is in bonding internal structural elements (*e.g.* stringers) to skins in fuselages, wings, ailerons, *etc*. The strength of adhesively bonded joints primarily depends on the mechanical properties of adherend, adhesive and adherend–adhesive interface [2,3].

To characterise the mechanical properties of adhesives, experimental tests are performed on either bulk adhesive specimens or bonded joints (*i.e. in-situ* form). To compare the mechanical properties of the bulk material form with the in-situ material form, research studies [4–8] have been conducted and found that the mechanical behaviour of the two forms are similar. On the contrary, it has also been observed that the variation in adhesive bondline thickness influences the strength of bonded joints, which is often related to the *in-situ* material behaviour (*i.e.* with constrained process zones [9,10] and triaxial stress states [11,12]). It is not yet fully understood whether the mechanical properties of adhesives can accurately be determined by testing either bulk specimens or bonded joints. In addition, second-phase particles, *e.g.* glass microspheres [13–16], are often used to toughen epoxy adhesives—making it more difficult to accurately determine the mechanical properties of toughened adhesives.

It is often seen that the mechanical behaviour of epoxy adhesives, being polymers, are sensitive to strain rates [17–19] and triaxial stress states [20–23]. Moreover, to model and accurately predict the mechanical behaviour of adhesively bonded joints [24], experimental characterisation of bulk adhesive for different strain-rates and triaxial stress states is important. In this regard, a two-part toughened paste adhesive was considered for the current study to investigate the tensile fracture behaviour for different strain rates and tri-axial stress states. The objectives of the study were to: (a) develop a novel manufacturing process and a test setup to cure and test cylindrical bulk specimens from paste adhesives, (b) investigate the tensile fracture behaviour of a toughened epoxy adhesive as a function of strain-rate and stress triaxiality and (c) examine the failure mechanisms involved.

Cylindrical bulk specimens were manufactured by injecting uncured paste adhesive into a two-part mould—this approach can, in general, be used to manufacture bulk specimens from paste adhesives. Tensile tests were performed on circumferentially notched cylindrical specimens [25–27] for different notch radii and displacement rates. Furthermore, fracture surfaces were examined using optical and scanning electron microscopy to identify failure mechanisms. The results obtained from the toughened paste adhesive indicate that strain-rate and stress triaxiality influence its tensile fracture behaviour, which may consequently influence the fracture behaviour of bonded joints.

2. Materials and manufacturing

2.1. Two-part epoxy adhesive

A two-part toughened epoxy paste adhesive—a research grade structural adhesive for aerospace applications—was used to

* Corresponding author. Tel.: +353 61202253; fax: +353 61202944.
E-mail address: Kali-Babu.Katnam@ul.ie (K.B. Katnam).

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manufacture bulk specimens. Hollow glass microspheres of different sizes are added in the adhesive to improve its toughness by the manufacturer. The adhesive was supplied by the manufacturer in a dual cartridge form. For the current study, a dispenser-mix technique was employed to manufacture bulk adhesive specimens. The dispenser was loaded with a dual cartridge and a static mixer, and compressed air was pumped into the system to get a uniform adhesive paste from the nozzle of the static mixer.

2.2. Adhesive injection and curing

To manufacture cylindrical bulk adhesive specimens, a two-part mould was designed with stepped cylindrical grooves—the top and bottom moulds are shown in Fig. 1a. The mould was designed to manufacture five specimens at a time. The dimensions of each stepped cylindrical groove were chosen to cure cylindrical specimens with 40 mm in length and 5 mm in radius (see Fig. 1b). Moreover, hollow aluminium cylinders (30 mm length, 10 mm external radius and 5 mm internal radius) with internal threads were used in the manufacture process (see Fig. 1c). A release agent was applied to the stepped cylindrical grooves to prevent adhesion. The two hollow cylinders were located in each stepped cylindrical groove and the top and bottom moulds were closed. The adhesive was then injected into each groove from one end, as shown in Fig. 2, to minimise air entrapment and void formation. Furthermore, the nozzle of the static mixer was cut to increase the adhesive bead size to match the diameter of the cylindrical specimens to avoid rheological issues (*e.g.* tensile fracture of the uncured adhesive). The adhesive was cured at 80 °C for 4 h in an oven (Binder ED23).

2.3. Bulk specimens

To produce circumferentially notched specimens, the cured specimens were notched using a lathe machine [28]. Notch tip radius was varied and four different specimens were manufactured (see Fig. 3). The dimensional details (in mm) of the bulk specimens are shown in Fig. 4. The notch geometry was varied to induce failure at different triaxial stress states. The V-notch was introduced with a radius of approximately 0.02 mm and a V-angle of 60°. In all the specimens, the radius of the cylindrical specimens at the notched region was reduced to 3 mm from 5 mm (see Fig. 4).

3. Numerical modelling

To calculate the stress concentration factors and the stress triaxiality values in the manufactured bulk specimens, axisymmetric finite element models were used and quasi-static stress analyses were performed for different notch geometries using axisymmetric elements (CAX4R, 4 node bilinear elements with

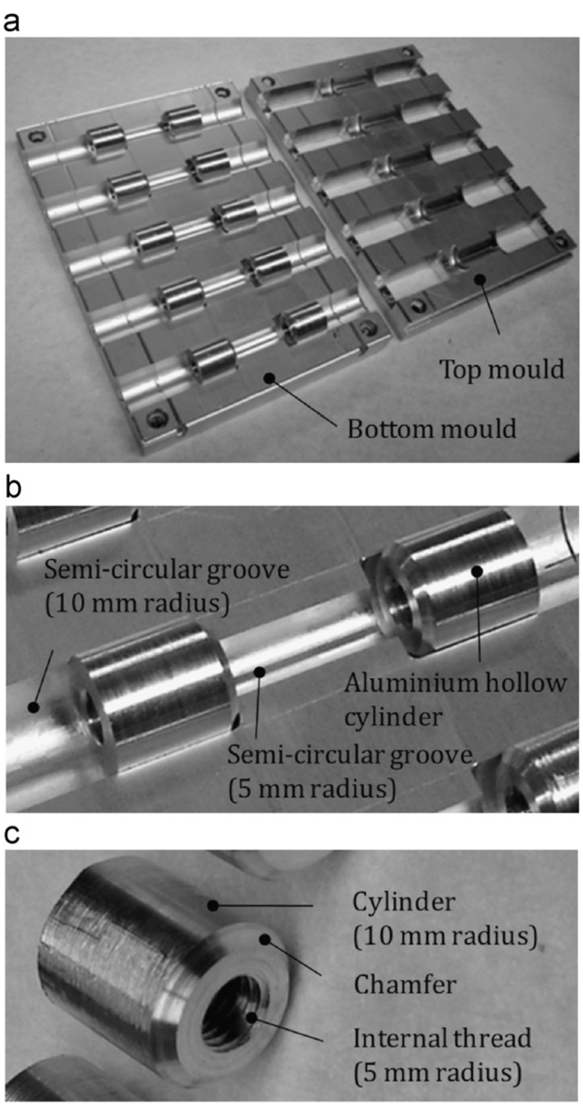

Fig. 1. Manufacturing tools: (a) top and bottom aluminium moulds, (b) stepped semi-circular grooves to accommodate aluminium hollow cylinders and (c) aluminium hollow cylinder with internal thread.

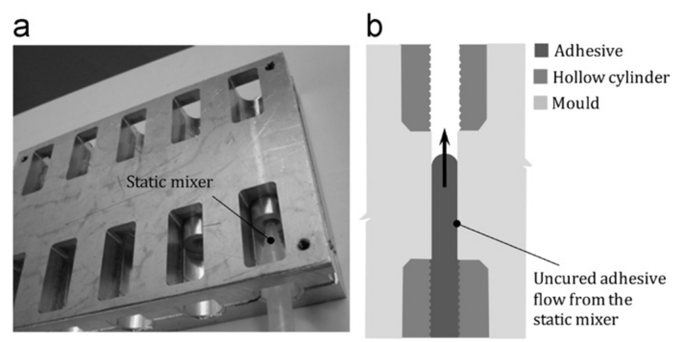

Fig. 2. Curing bulk specimens: (a) adhesive injection using a static mixer and (b) a schematic showing uncured adhesive flow.

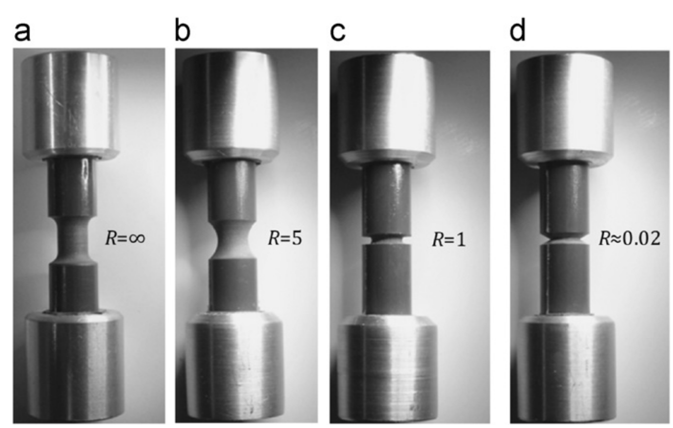

Fig. 3. Circumferentially notched cylindrical specimens with different notch tip geometries ($R=\infty$, R=5 mm, $R=1$ mm and $R\approx0.02$ mm).