International Journal of Adhesion & Adhesives 70 (2016) 46–52

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Bonding of ceramics: An analysis of the torsion hourglass specimen

L. Goglio [a,*], M. Ferraris [b]

[a] Department of Mechanical and Aerospace Engineering - DIMEAS, Politecnico di Torino, corso Duca degli Abruzzi 24, Torino 10129, Italy
[b] Department of Applied Science and Technology - DISAT, Politecnico di Torino, corso Duca degli Abruzzi 24, Torino 10129, Italy

ARTICLE INFO

Article history:
Accepted 16 May 2016
Available online 26 May 2016

Keywords:
High temperature adhesives
Ceramics, glass
Finite element stress analysis
Joint design
Torsion test

ABSTRACT

There is a recent and growing interest in joining ceramic parts due to their increased use in several fields such as next-generation nuclear plants, aeronautic engine parts and aerospace components. For high temperature applications, glass-ceramics are used as an "adhesive" for ceramic parts, this generates the need for test methods suitable to assess their bond strength. Unfortunately, the various test procedures currently used lead to different results.

One recent test is based on torsion of hourglass shaped joined ceramics, originated from a modification of the ASTM F734-95 standard, with the aim of obtaining failure under a pure shear state in the bondline subjected to torsion.

However, results obtained from different versions of the hourglass geometry show differences which are still difficult to compare. Moreover, due to the brittle nature of the materials and especially when the adhesive strength is comparable to that of the substrates, the failure is not confined in the bond and propagates also in the substrates. In this case, the results are still of arguable application for design purposes.

The aim of this paper is to give an insight on torsion of hourglass-shaped joined ceramics and on the interpretation of the obtained results, by means of detailed analytical and numerical studies of the stress distribution in the specimen, and taking into account the brittle nature of the materials. The main findings are: i) the stress state in the bondline is not singular; ii) a non-negligible stress concentration arises out of the bondline.

1. Introduction

Ceramics can offer several advantages in terms of strength and hardness, especially under harsh conditions, that exceed the resistance of metals. Low induced radioactivity, thermal stability and resistance to irradiation, in addition to mechanical strength, make SiC-based ceramics suitable for nuclear applications, especially for fusion reactors, and a wide amount of related studies has been presented since long (e.g. [1–5]). Moreover, recently developed aeronautic and aerospace engines use SiC-based composites to improve high temperature resistance in several engine parts [6].

The use of ceramics as a structural material originates the need for suitable joining techniques; being impossible to use welding, several *ad hoc* solutions have been proposed, most of them based on hot pressing techniques [4,5]. To avoid the need for pressure, glass ceramics are used as pressure-less high temperature resistant joining materials for SiC based components [7]. In turn, joining originates the need for a suitable test method to assess the mechanical strength of the joints, and the most significant parameter is deemed to be the shear strength expressed as stress corresponding to the failure load [7,8].

To this aim, several test methods and specimen types were investigated in the last years. The preferred method to measure the strength of bonded ceramics should be the four-point asymmetrical (i.e. antisymmetric) bending test, ASTM C1469 standard [9]. A wide comparison among results obtainable from ASTM C1469 and several other test methods was carried out as an international cooperation ([10–12]). At that stage, to speed up the preparation of the specimens, epoxy adhesive Araldite AV119 (Huntsman Advanced Materials, Basel, Switzerland) was used as a "model" bonding material, suitable to investigate the response of the different specimen types, although the quantitative results were not of interest for high temperature applications.

Lap joint specimens for ceramics of various types (single- or double-lap offset in compression, double-notch in compression [10]) have the common shortcoming of creating in the bond a mix of normal and shear stresses, both non-constant, thus the obtained result is only an apparent shear strength.

Regarding the four-points asymmetrical test ASTM C1469 [9], which should ideally create only shear stress in the bond, several

* Corresponding author. Tel.: +39 011 0906934.
E-mail address: luca.goglio@polito.it (L. Goglio).

http://dx.doi.org/10.1016/j.ijadhadh.2016.05.006
0143-7496/

problems associated with it were pointed out [10], due to: i) the influence of even small misalignments of the specimen and the loading pins; ii) the need for machining notches in the joint if the bonding material strength is in the range 25–50% of the base material strength and the impossibility of applying the method if the bonding material strength exceeds 50% of the base material strength; iii) the difficulty in manufacturing the specimens by cutting from a wider block or preparing them one by one. Moreover, surprisingly, such standard evaluates the shear strength simply as shear force to area ratio, neglecting that the peak stress in the section (parabolic distribution) is 1.5 times higher.

Torsion, causing a state of shear stress in the specimen cross section, is the most promising testing condition. However, in case of square section also normal stress is induced by constrained section warpage in the fixtures; indeed, failures occurred in the SiC, out of the bond [11]. Conversely, torsion of a circular section causes a state of pure shear stress in the specimen, as needed. Unfortunately, results from simple cylindrical specimen exhibited a large scatter, likely due to surface defects; this evidenced the need for creating the bond in a reduced section, designed as the "weakest ring" of the system where failure must occur. Moreover, a straight cylindrical bar requires tight clamping of the ends to apply the torque, which can cause local failure.

Accounting for these issues, the hourglass specimen shown in Fig. 1 was cooperatively proposed by Oak Ridge National Laboratory (USA), Kyoto University (Japan) and Politecnico di Torino (Italy) by modifying the specimen foreseen in the ASTM F734-95 standard [13]. It has the merit to generate a pure shear stress condition in the bond section, while the increased area in the remainder of the specimen makes a failure due to local defects less likely. Moreover, thanks to the square section of the ends, the torque can be applied easily. The size was chosen very small (bonded section diameter 5 or 4 mm) to obtain miniature specimens, easy to be placed in the limited available space when they were exposed to irradiation for nuclear studies [14].

Obviously, the shear stress distribution in a section subjected to torsion is not constant, but can be simply calculated with the well known formula

$$\tau = \frac{T}{J}x \qquad (1)$$

where T is the torque, J is the sectional polar moment of inertia and x is the radial coordinate. Eq. (1) does not account for the notch effect due to the non-straight profile of the specimen, which however can be included multiplying by the relevant stress concentration factor K_t.

This type of geometry was used with encouraging results in several test campaigns, for both AV119-bonded [11,12] and calcia-alumina glass-ceramic (CA)-bonded [15,16] specimens.

In the case of AV119-bonded specimens the adhesive strength, calculated by substituting in Eq. (1) the ultimate value of T, resulted dependent on the size of the specimen [12]. The reason is that such adhesive is to a certain extent ductile; upon loading, once the yield stress is reached in the outer radius, plasticity spreads inwards and the torque can increase, thus the ultimate torque value is attained when the whole section is yielded and depends on section size. Obviously, under such conditions, Eq. (1) is no longer appropriate.

In the case of CA-bonded specimens, it was noticed that in several instances the failure affects the adherends bulk and not only the bond [15]. It was argued if the results obtained under these conditions are comparable to those obtained when the failure affects only the bond.

Trying to address these issues, modified versions of the hourglass specimen geometry were tested, in particular by creating a hollow bonded section (internal diameter 3 mm), obtained either by drilling full half-specimens or by machining half-specimens with ring-shaped section, then bonding them [15,16].

In the case of ductile adhesive, the hollow geometry approximates the ideal situation of a thin ring, in which all the adhesive is at the same distance from the section centre so that the progressive (from outer radius inwards) yielding is avoided.

In the case of brittle glass-ceramic adhesive (CA), it was expected that the hollow geometry could "constrain" the failure to occur only in the bond, without affecting the SiC. The latter fact was checked experimentally in [16] (selected data reported in Table 1 for convenience); it was found that also for the hollow specimens, even more frequently than for the full specimens, the fracture affected the SiC. More specifically, it was observed that the fracture could even start in the SiC, then propagate in the CA. The strength measured from hollow specimens (last two lines in Table 1) was generally lower.

Strength data in Table 1 are simply obtained by applying Eq. (1), thus the stress concentration effect is not accounted for. In a broader view, a more sophisticated assessment of the stress state in the joint specimen would be advisable.

Therefore, a theoretical -analytical and numerical- investigation on the specimen properties can be useful to explain its behaviour. The present paper reports the outcome of a study carried out with this aim. First, the relevant mathematical aspects of the stress state in the specimens are considered; then, the

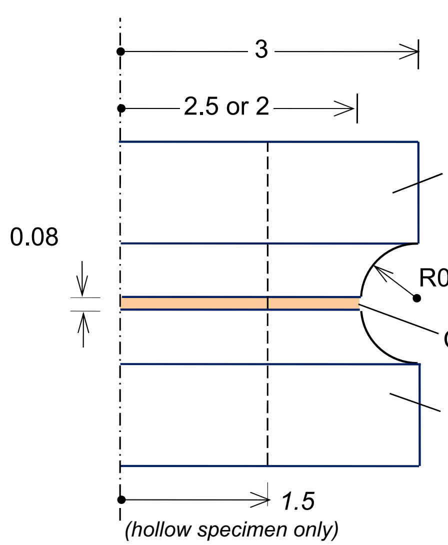

Fig. 1. Schematic of the hourglass specimen.

Table 1.
Shear strength (mean ± standard deviation) obtained from different tests on hourglass specimens by applying Eq. (1); selected values from [16].

Specimen type	No. of specimens tested	Fracture in the CA only		Fracture in the CA and SiC	
		Shear strength (MPa)	No. of specimens	Shear strength (MPa)	No. of specimens
Full $D=5$	12	104 ± 20	5	113 ± 21	7
Full $D=4$	4	103 ± 12	2	124 ± 12	2
Hollow (drilled) $D=5$, $d=3$	10	–	0	78 ± 15	10
Hollow (ring) $D=5$, $d=3$	17	40 ± 6	8	89 ± 21	9

D outside bond diameter, d inside bond diameter (mm).