

# Adaptation of the DCB test for determining fracture toughness of brazed joints in ceramic materials

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We have developed a test, based on a modified applied moment double cantilever beam specimen, to measure the fracture toughness of brazed joints between ceramics and ceramics and metals. Evaluation of samples directly brazed with experimental brazing filler metals showed that the brazed interfaces were generally as tough as the ceramics alone, with toughness increasing proportionally to the toughness of the ceramics. Although the specimen and techniques have so far been used only for direct brazes (no surface pretreatment of the ceramic), we suggest that they would also be valid for joints involving metallization of the ceramics prior to brazing.

## 1. Introduction

Although monolithic ceramic materials have been widely used in the past in non-structural applications such as electrical insulators, crucibles, microwave windows, and pump and valve components for the chemical industry, it has been only in recent times that major efforts have been made to use ceramics in structural applications under severe operating conditions. For example, preheating of the combustion air is a proven way of markedly reducing fuel consumption in a high-temperature furnace.

The mechanical and corrosion property limitations of metal alloys severely restrict the use of metal recuperators to preheat air to about 600°C [1]. However, structural ceramics offer considerable promise for use in high-temperature recuperators for recovering waste heat from hot flue gases at temperatures of 1200°C or higher. Ceramic materials also show considerable promise for use in advanced gas turbine engines. In modern turbine engines, high-temperature superalloys can be used at temperatures up to approximately 1100°C without cooling [2]. However, turbine engines with ceramic components are being developed with turbine inlet temperatures of 1370°C [3]. A number of automotive manufacturers are also working to develop a more efficient diesel engine for cars or trucks that improves efficiency by eliminating the water cooling system, by using structural ceramics to insulate the combustion chamber.

It is becoming more widely recognized that one of the key technologies that will enhance or restrict the use of ceramic materials in high-performance applications (e.g. advanced heat engines or heat exchangers) is the ability to join reliably simple-shape components to form complex assemblies or to join unit lengths of material to form large systems. However, the development of technology for joining ceramics for use at elevated temperatures, high stress

levels, and in contaminated environments has been very limited.

As part of a programme to develop brazing filler metals for such advanced applications, we are studying the mechanical properties of the bond between experimental brazing filler metals and typical structural ceramics. One aspect of this work – the development of a test to measure the fracture toughness of brazed joints containing ceramic materials – is reported in this paper.

## 2. Fracture mechanics approach to adherence in ceramic joining

Adherence in brazed joints is often determined via the stress (or load) required to cause separation, and strength data are useful in both (i) ascertaining a relative ranking of the adherence between systems and (ii) establishing and maintaining quality control during production. However, because the failure stress of brittle systems (the joint and materials on both sides of the interface in this case) is a function of both the maximum flaw size (e.g. an unbonded interfacial area or void in the joint region) and the adherence, a strength test alone cannot be used to determine the fundamental adherence of a system. The values (strengths) obtained by such tests are a function of both the adherence energy and the size of a flaw/defect present in the interface. This flaw size dependence often dominates the strength values obtained for the interface and prevents one from relating strength values to material parameters.

Fracture mechanics can be used to determine the adherence for joined structures in a fashion similar to that used to describe the bulk fracture behaviour in brittle materials. The stress intensity factor  $K$  or strain energy release rate  $G$  can be used to determine the ease of crack propagation either along an interface (adhesive failure) or in an adjacent phase (cohesive

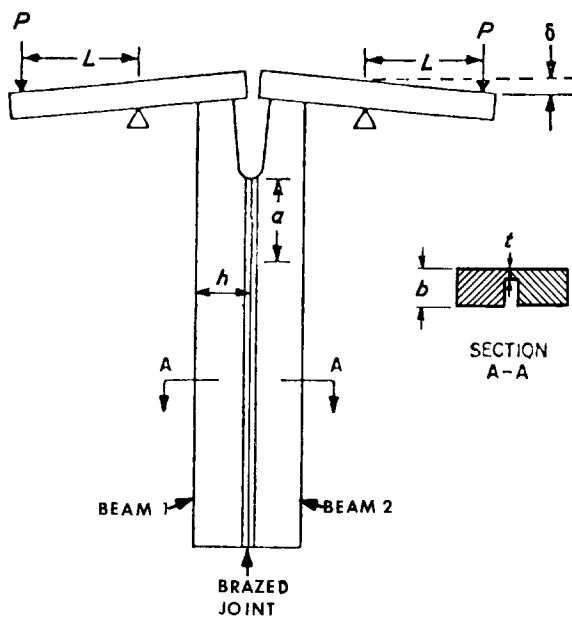


Figure 1 Applied moment double cantilever beam specimen. The loading arms are typically attached by epoxy, making this essentially a room-temperature test.

failure). Adherence can thus be described in terms of the ability of the total joint system to resist fracture, and serves not only as a tool to examine adherence mechanisms, but also as an important design aid. In addition, the critical adherence fracture energies  $\gamma_{ic}^A$  or the critical adherence fracture toughness values  $K_{Ic}^A$  obtained can be related to the values of the bulk materials comprising a joint as well as the stress state at the interface.

The application of fracture mechanics to adherence problems to date has centred on the areas of structural adhesives and composites [4, 5]. In such applications, not only the analysis, but also the measurements of crack tip stress intensity ( $K$ ), can become quite complex even for crack motion along a flat interface between two materials. The reason for this difficulty is that the stresses acting on a crack are not necessarily symmetric and combined loading modes exist (e.g. Mode I, tensile, plus Mode II, shear). However, when the elastic properties  $E$  (Young's modulus) and the Poisson's ratio of the two materials are comparable (in theory they must be identical [6] but in practice, need only approach each other [7]), then the solution is the same as for the crack in a single-phase body. These approximations are valid for the analysis of adherence of many ceramic-to-ceramic and ceramic-to-metal brazements. The result is that one can describe adherence in terms of  $K_I$ , and not combined  $K_I$ - $K_{II}$ , and a much simpler description of crack propagation is obtained.

Experimentally, determination of the adherence of a joint system is simplified by use of the energy balance concept equating the change in the system's strain energy (the strain energy release rate  $G_I$ ) with the total energy for crack propagation ( $2\gamma_i$ ). Because the system can be described in this manner,  $G_I$  is related to  $K_I$  as shown in the equation

$$K_I = \frac{\sigma c^{1/2}}{A} = (G_I E)^{1/2} \quad (1)$$

where  $\sigma$  is the applied tensile stress,  $c$  is the flaw size and  $A$  is a geometric factor. Thus either  $G_I$  or  $K_I$  can be determined experimentally if the other required quantities are known. Several techniques have been developed to determine the adherence of not only adhesives to metal [4, 5], but most recently of ceramics to metals or ceramics to ceramics [8-10]. The technique used here, however, provides a means to obtain  $K_{Ic}$  values in a simpler configuration where crack length measurements are not required to obtain  $K_{Ic}$  values.

Our measurement approach is based on a modification of the applied moment double cantilever beam (DCB) specimen, shown schematically in Fig. 1, which is used to determine either  $K_{Ic}$  or  $\gamma_{ic}$  for bulk ceramics and glasses [11]. The modification accounts for differences in geometry or properties of the materials on either side of the interface, and is applicable as long as the thickness of any material placed at the interface, or any reaction product, has a thickness less than 10% of the width of the beams (as is normally encountered in thick films or brazed joints) [12, 13]. Basically the approach equates the total strain energy release rate with the interfacial energy change in each half of the DCB caused by the creation of new surfaces as the crack propagates (i.e.  $G_{Ic} = 2\gamma_{ic}$ ). (Note that the two halves can thus be different materials or geometries.) In this case

$$G_{Ic} = M^2 \frac{1}{EI} = \frac{M^2}{2} \left( \frac{1}{(EI)_1} + \frac{1}{(EI)_2} \right) \quad (2)$$

where the  $(M/EI)$  terms determine the applied strain energy that is released in each arm during crack propagation. Referring to Fig. 1,  $M$  ( $= \frac{1}{2}PL$ ) is the bending moment supplied by the applied load  $P$  acting through a fulcrum length  $L$  on each half of the DCB specimen,  $E$  is the Young's modulus of either half of the DCB specimen,  $I$  is the moment of inertia, and  $t$  is the thickness of the DCB specimen in the region where the crack propagates. For the purposes of guiding the crack along the region of the interface, the specimen can be reduced in thickness by introducing a groove in that location. The moment of inertia  $I$  is based on the cross-sectional dimensions and the bending axis for each half, so that  $I = bh^3/12$  where  $b$  is the thickness and  $h$  the width of each half of the DCB specimen.

The fracture toughness of both similar and dissimilar material brazements can be determined using a specimen of this type. For the similar material brazement (material in Beam 1 the same as that in Beam 2),  $K_I$  can be determined from Equation 1 with

$$G_I = G_1 + G_2 = 2G_1 \quad (3)$$

since the materials are the same, and

$$G_1 = \frac{1}{2} \left( \frac{P}{2} L \right)^2 \left( \frac{bh^3}{12} \right) \quad (4)$$

For the dissimilar material brazement (material in Beam 1 is *not* the same as in Beam 2), we want  $G_1$  to be equal to  $G_2$  so that the crack will not be deflected towards the beam with the higher strain energy release

rate. We fix  $M$  and  $t$  such that

$$\frac{M_1^2}{t_1} = \frac{M_2^2}{t_2} \quad (5)$$

and then by requiring that  $G_1 = G_2$  can show that

$$b_1 h_1^3 E_1 = b_2 h_2^3 E_2 \quad (6)$$

Thus, by knowing the value of  $E$  in each beam, one can alter the beam dimensions to obtain  $G_1 = G_2$ . This solution is valid when the braze layer has a thickness of less than 10% of the beam width  $h$ , as in Fig. 1, so that the strain energy supplied to drive the crack is supplied by Beams 1 and 2.

Using this experimental approach and analysis, one can determine whether interfacial adherence failure or cohesive failure of the bulk material on either side is the limiting factor in the mechanical behaviour of the joint. For the latter case, the  $K_{Ic}$  value obtained will approach that of the bulk material in a specimen with the same material in the two beams, and that of the less tough material in the case of a dissimilar material joint. Furthermore, when adherence failure occurs at the interface, one can determine how changes in chemical or mechanical bonding or stress state at the interface improve the joint systems.

### 3. Experimental details

#### 3.1. Specimen geometry

The overall dimensions of the typical DCB specimen used to determine the fracture toughness of a bulk ceramic are  $2.5 \text{ mm} \times 9.5 \text{ mm} \times 28.5 \text{ mm}$ . A composite (brazed) specimen of similar materials is made by brazing together two beams each having approximate dimensions of  $2.5 \text{ mm} \times 4.76 \text{ mm} \times 28.5 \text{ mm}$ .

For the case of a dissimilar-material specimen, the thickness  $b$  is held constant and the width of the beam,  $h$ , of the material having lower modulus of elasticity is increased so that the strain energy release rate in each beam will be the same (i.e.  $G_1 = G_2$ ).

For example, if a composite specimen were to contain nodular cast iron and partially stabilized zirconia (PSZ) beams (these materials being of interest for potential use in uncooled diesel engines), and assuming a modulus of elasticity of 205 GPa for the PSZ [14] and 160 GPa for the iron [15], Equation 6 is solved as follows for  $h_{\text{PSZ}} = 4.76 \text{ mm}$ :

$$\frac{E_{\text{iron}}}{E_{\text{PSZ}}} = \frac{160 \text{ GPa}}{205 \text{ GPa}} = \frac{h_{\text{PSZ}}^3}{h_{\text{iron}}^3}$$

or

$$h_{\text{iron}} = \frac{h_{\text{PSZ}}}{0.921} = \frac{4.76 \text{ mm}}{0.921} = 5.17 \text{ mm}$$

so that the cast-iron portion of the specimen would be 5.17 mm wide. For a specimen containing aluminium oxide brazed to the cast iron,

$$\frac{E_{\text{iron}}}{E_{\text{alumina}}} = \frac{160 \text{ GPa}}{350 \text{ GPa}} = \frac{h_{\text{alumina}}^3}{h_{\text{iron}}^3}$$

or

$$h_{\text{iron}} = \frac{h_{\text{alumina}}}{0.771}$$

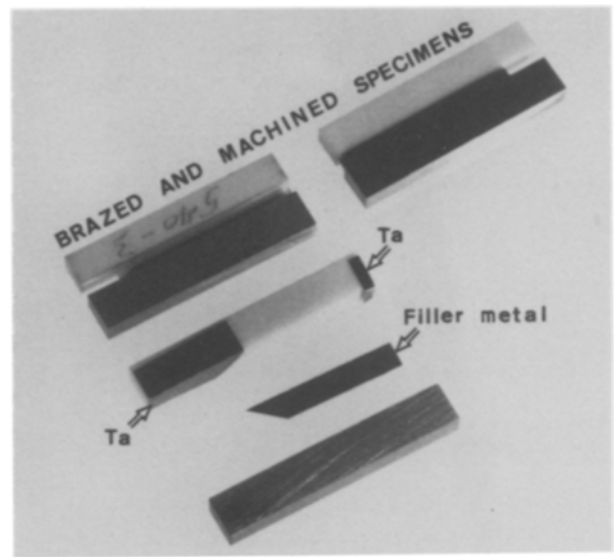


Figure 2 Ceramic and metal bar as prepared for brazing and after brazing, grooving, and notching (upper specimens). The wide tantalum shim and the brazing filler metal are tapered as an aid in precracking the specimen.

so that for a typical specimen (an alumina beam width of 4.76 mm) the width of the cast-iron beam must be 6.17 mm.

#### 3.2. Experimental procedure

The assembly and brazing of the composite DCB specimens are not difficult if a reasonable amount of care is taken. The ceramic or ceramic and metal beams are placed in a ceramic fixture with brazing filler metal foil at the interface. In order to hold the filler metal in place during assembly, a small drop of Nicrobraz cement (Wall Colmonoy Corp., Detroit, Michigan) is applied to one end. To control the final thickness of the brazed joint (a critical variable in any brazement) shims of 0.038 mm thick tantalum sheet are preplaced in the joint (Fig. 2). The wider of the two shims is tapered, as is the filler metal foil, so that an advancing precrack is halted by encountering an increasing width of bonded joint. A slight load across the joint is applied using 0.25 mm thick molybdenum or tungsten sheet springs. Typical composite DCB samples in place in an SiC boat after brazing are shown in Fig. 3.

Our standard procedure for preparing the specimens is as follows. After the samples are brazed, they are ground to remove any exuded filler metal and to remove any misalignment of the surfaces. This operation is done by bonding the specimens to machining blocks using Crystalbond 509 adhesive (Aremco Products, Inc., Ossining, New York) and then machine grinding with a 170 grit diamond-abrasive wheel. After surface grinding, the specimens are grooved and notched to ensure that the crack will propagate through the region of the brazement. These operations are also done using diamond-abrasive wheels (400 grit). Next, the surface of the specimen opposite the groove is hand-lapped with diamond paste (down to  $3 \mu\text{m}$  particle size). A final sharp precrack (flaw) is made in the brazed joint by carefully forcing a wedge-shaped cermet tip into the large notch of the specimen. This operation is conducted under a low-power

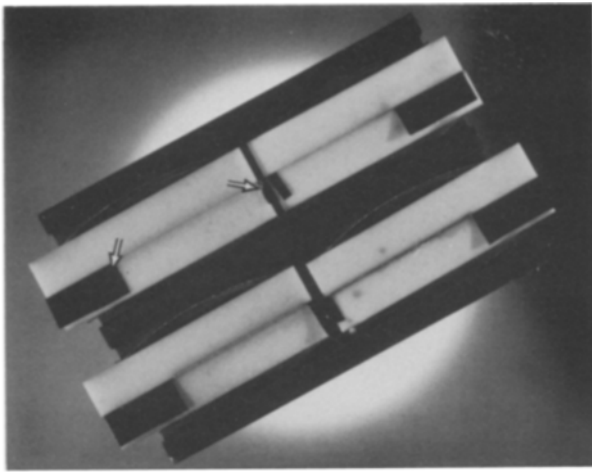


Figure 3 Four composite DCB specimens in SiC boat after brazing cycle. The 0.038 mm thick tantalum shims (arrows) are used to control brazed joint thickness. The wide shims also serve as notches during specimen precracking.

microscope so that the flaw can be observed as it forms. The loading arms are attached using epoxy cement, taking care that the fulcrum lengths  $L$  are equal and that the specimen is perpendicular in two planes to the arms. After the epoxy is cured, the specimens are loaded in a mechanical test machine using the apparatus shown in Fig. 4. The load at failure and the specimen dimensions ( $b$ ,  $h$ , and  $t$ ) are recorded after each test.

Catastrophic crack propagation sometimes occurs during precracking, resulting in the loss of expensive specimens. Therefore, we tested some specimens that

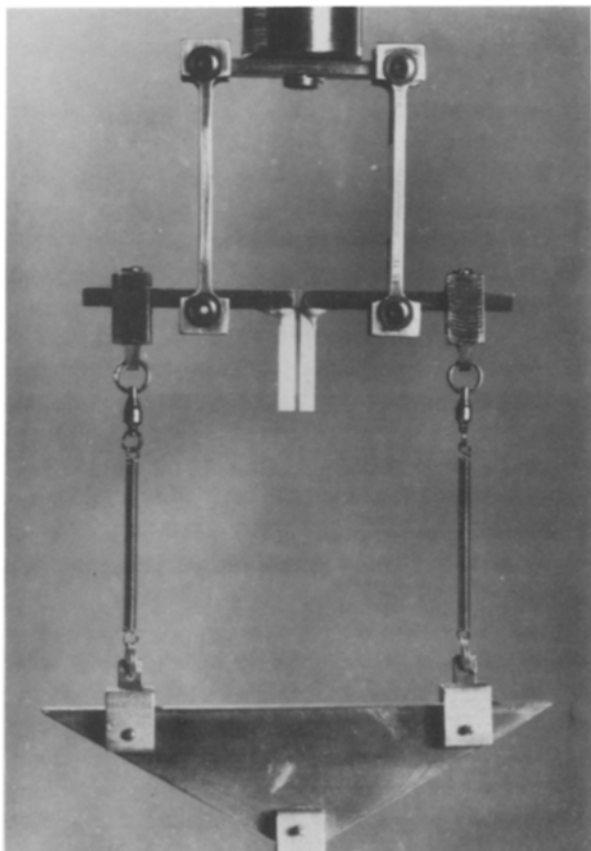


Figure 4 Apparatus for testing DCB specimens in mechanical test machine.

had not been precracked by relying instead on the fine notch generated by the 0.038 mm thick tantalum shim previously described. As will be discussed later, the specimens that were not precracked gave artificially high fracture toughness numbers, so we returned to the precracking operation for the balance of the tests.

### 3.3. Materials

The room-temperature strength and fracture toughness of the ceramic materials included in this work are given in Table I. All of these ceramics are made by pressureless sintering except for the SiC whisker-reinforced alumina composite [16] ( $\text{Al}_2\text{O}_3\text{-SiC}$ ) which was densified by uniaxial hot pressing in a graphite die. These specific materials were chosen because they are prime candidates for many energy conversion or utilization applications, and because they present a broad spectrum in material types and properties.

Ceramic-metal brazements have also been included in our fracture mechanics studies. A major impetus is the attachment of a ceramic piston cap to a metal piston – a joint that is critical to the success of the uncooled diesel engine [17]. A principal piston material being considered is nodular cast-iron (NCI). This material is widely used in many conventional diesel engines (aluminium also being used). In addition to NCI, other materials such as titanium and a TiC cermet are candidate transition materials in advanced joints to accommodate mismatches in coefficients of expansion between a ceramic and metal component.

## 4. Experimental results

### 4.1. Fracture toughness of ceramic-ceramic brazements

The results of the room-temperature tests of the composite DCB specimens of alumina,  $\text{Al}_2\text{O}_3\text{-SiC}$ , and magnesia partially stabilized zirconia joined with experimental brazing filler metals are given in Table II. Note that the critical fracture toughness  $K_{Ic}$  of the brazed samples was generally similar to that of the bulk ceramic. This is an important result because it demonstrates that the brazed joints can be fabricated in such a manner that their toughness is not a limiting factor.

TABLE I Mechanical properties of ceramic materials brazed in this programme

Material designation	Flexural strength (MPa)	Fracture toughness ( $\text{MPa m}^{1/2}$ )*
Coors AD-998 alumina	207	4.6
Degussit AL-23 alumina	156	4.5
Nilcra PSZ (82-94159N)	616	6.0
Nilcra PSZ (85-230MS)	574	14.0
SCW <sup>†</sup>	650	$\geq 8.5$
$\alpha\text{-SiC}^\ddagger$	348	4.0

\* Determined by DCB test.

<sup>†</sup>SiC whisker-reinforced alumina matrix composite under development at Oak Ridge National Laboratory.

<sup>‡</sup>Hexoloy SA, Standard Oil Engineered Materials Co., Niagara Falls, New York.

TABLE II Fracture toughness of ceramic–ceramic brazed DCB specimens

Ceramic material	Brazing filler metal composition (at %)	Brazing temperature (°C)*	Number of specimens	Fracture toughness, $K_{Ic}$ (MPa m <sup>1/2</sup> )	Standard deviation
PSZ (82-94159N)	Cu-27Ag-26Ti	1000	3	6.6	0.55
PSZ (82-94159N)	Cu-46Ag-4Sn-1Ti	800	1	5.2	–
PSZ (85-230MS)	Cu-46Ag-4Sn-1Ti	800	2	7.4	0.07
PSZ (82-94159N)	Cu-44Ag-4Sn-4Ti	800	2	5.0	0.35
PSZ (82-94159N)	Cu-44Ag-4Sn-4Ti	825	2	4.8	0.85
PSZ (85-230MS)	Cu-44Ag-4Sn-4Ti	850	2	12.2	1.06
AL-23	Cu-44Ag-4Sn-4Ti	800	2	6.3	0.85
AL-23	Cu-44Ag-4Sn-4Ti	850	2	6.8	0.35
AD-998	Cu-44Ag-4Sn-4Ti	800	2	5.4	1.13
AD-998	Cu-44Ag-4Sn-4Ti	850	1	6.6	–

\* All specimens brazed for 5 min at temperature, in vacuum of less than 7 mPa ( $5 \times 10^{-5}$  mm Hg).

#### 4.2. Fracture toughness of ceramic–metal brazements

The same procedure is used for fabricating the ceramic–metal fracture toughness specimens as previously described for the ceramic–ceramic brazed specimens. The only difference is that the width of the beam of the material having lower modulus of elasticity is increased, as discussed in Section 3.1. A potential problem area does arise, however, in the case of the ceramic–metal specimens as there is generally a mismatch in the coefficients of thermal expansion of the materials. The results of one such mismatch will be discussed below. When the coefficients of expansion of the ceramic and metal are relatively similar, we have been able to obtain fracture toughness values for these brazements that are comparable to the toughness of the ceramic beam in the specimen, as shown by the data in Table III.

#### 4.3. Fracture toughness of specimens not precracked

The fracture toughness data for a series of specimens that were not precracked prior to testing are given in Table IV. Note that these were all ceramic–ceramic brazements to avoid any influence on the results of residual stresses that might be generated at the interface of a ceramic–metal braze due to mismatch in coefficients of thermal expansion.

#### 5. Discussion

We have experienced difficulty in fabricating ceramic–metal composite DCB specimens due to residual stresses generated by the thermal expansion coefficient mismatch. For example, two of four NCI-to-PSZ brazements made in a vacuum at 800°C were found to have failed by major cracking in the ceramic (Fig. 5) after the surface grinding step. The other two specimens (brazed with the same filler metal but at 825°C) survived the surface grinding operation. However, when they were cemented to a machining block for grooving, we observed that both the ceramic and metal portions of the specimen had been distorted by an apparent mismatch in coefficients of thermal expansion. The magnitude of the deflection in the PSZ ceramic was 0.45 mm, as seen in Fig. 6.

The failures and distortion that occurred in the PSZ-to-NCI specimens were puzzling, as one favourable attribute of PSZ is its purportedly similar value for coefficient of thermal expansion with that of NCI. However, when thermal expansion data were taken for this particular PSZ, we found the existence of a large hysteresis loop as shown in Fig. 7. X-ray diffraction examination revealed that this ceramic did not contain the approximately 40% toughening tetragonal phase that can be obtained in materials of this type, but, in fact, was almost fully monoclinic at room temperature. Apparently some deviation in the processing

TABLE III Fracture toughness of ceramic–metal DCB specimens brazed with experimental filler metals

Specimen No.	Materials	Filler metal composition (at %)	Brazing temperature (°C)*	Fracture toughness (MPa m <sup>1/2</sup> )
530.4	PSZ <sup>†</sup> /NCI <sup>‡</sup>	Cu-46Ag-4Sn-1Ti	800	4.6
533.1	PSZ/Ti <sup>§</sup>	Cu-46Ag-4Sn-1Ti	800	9.9
537.1	PSZ/Ti	Cu-46Ag-4Sn-1Ti	775	5.6
540.1	PSZ/Ti	Cu-46Ag-4Sn-1Ti	775	2.8
540.2	PSZ/Ti	Cu-46Ag-4Sn-1Ti	775	4.2
545.1	SCW <sup>¶</sup> /K-162B <sup>¶</sup>	Cu-46Ag-4Sn-1Ti	800	10.4
545.3	SCW/K162B	Cu-46Ag-4Sn-4Ti	800	9.3

\* All brazes in a vacuum of less than 7 mPa ( $5 \times 10^{-5}$  mm Hg) with hold of 5 min at temperature.

<sup>†</sup>PSZ ceramic 85-230 MS.

<sup>‡</sup>Nodular cast iron.

<sup>§</sup>Chemically pure titanium.

<sup>¶</sup>SCW is a ceramic composite, made by Oak Ridge National Laboratory, consisting of alumina and 20 vol % SiC whiskers.

<sup>¶</sup>K-162B is a TiC cermet made by Kennametal Inc., Raleigh, North Carolina.

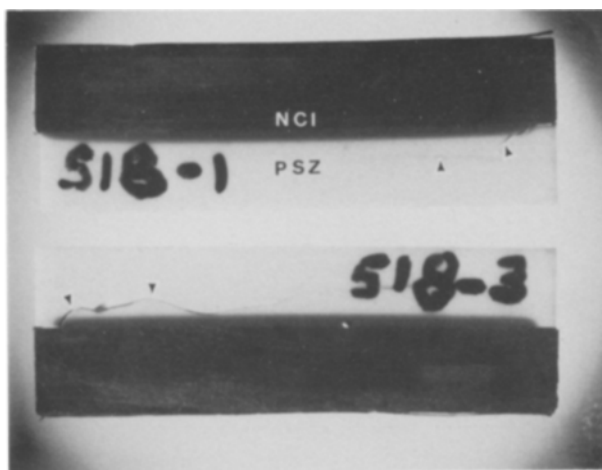


Figure 5 Two ceramic-metal brazed DCB specimens showing cracking in the PSZ (arrows) apparently resulting from mismatch in coefficients of thermal expansion of the NCI and PSZ (82-94159N). The cracks have originated at the notch left by removal of gap-controlling shims.

of this production lot resulted in a ceramic that readily transforms to tetragonal phase on heating and back to monoclinic on cooling; and this latter transformation resulted in failure, or at least major distortion, of our brazed composite specimens.

We repeated the tests with another PSZ ceramic that was identified as 85-230 MS. This ceramic contained about 25% monoclinic phase and a coefficient of thermal expansion of  $10.8 \times 10^{-6} (\text{°C})^{-1}$ . Accordingly, the material did not have the large hysteresis loop in its thermal expansion curve. In these later specimens, the amount of distortion in the PSZ (due to mismatch in expansion with the NCI) averaged 0.11 mm over a length of 28 mm, compared with 0.45 mm for the earlier specimens. The fracture toughness data for composite DCB specimens containing this material and NCI or titanium are also given in Table III.

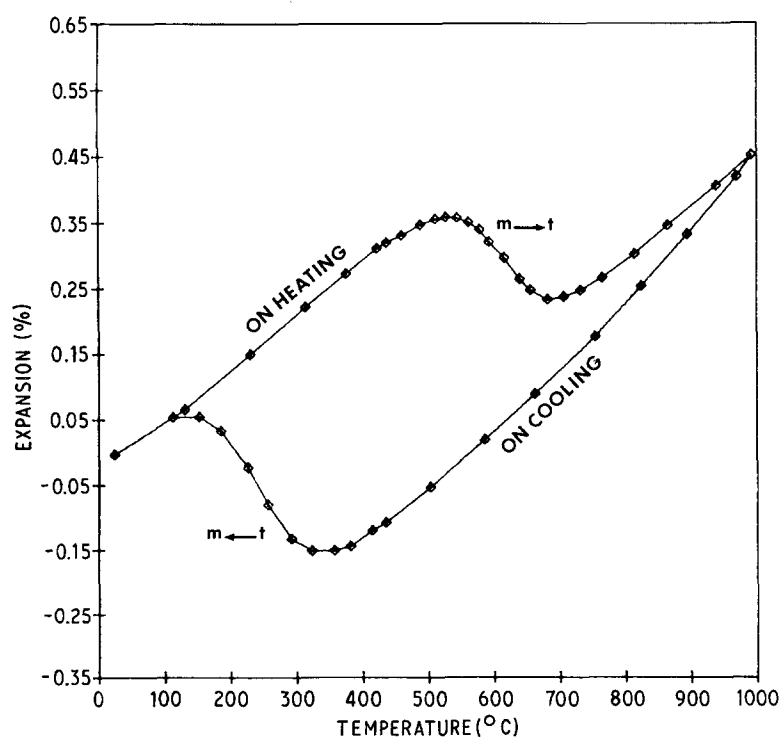


Figure 7 Expansion behaviour of a PSZ material (82-94159N) showing unexpected monoclinic to tetragonal ( $m \rightarrow t$ ) transformation on heating and  $t \rightarrow m$  on cooling. Such transformations (and resulting dimensional changes) resulted in failure or distortion of brazed DCB specimens.

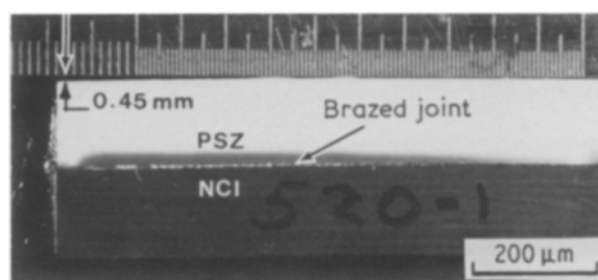


Figure 6 Brazed ceramic-metal DCB specimen showing distortion resulting from anomalous thermal expansion behaviour.

Based on analysis of the data for the unprecracked specimens and low-power optical examination of the fracture surfaces, we concluded that, although the fractures did occur at the interface as intended, these results are not valid. This conclusion was based on the observation that the toughness measured is in all cases higher than that of the respective bulk ceramic. With the DCB configuration, if a brazed joint were significantly tougher than the bulk ceramic, the crack would quickly jump out of the interface into the adjoining ceramic. This apparently did not occur, although admittedly it is difficult to distinguish between the ceramic and non-metallic phases that occur in the brazed joint at the interface between the brazing filler metal and the ceramic. We think that the high  $K_{Ic}$  values are the result of the fact that the crack "pop-in" load is higher than the load (stress) required for propagation of a sharp flaw (precrack). Thus, when under "pop-in" conditions, the calculation yields an anomalously higher toughness value. In addition the toughness values will be influenced by the residual stresses introduced by the transformation of the tetragonal phase to the monoclinic phase on cooling the brazed samples. Studies of these effects are continuing.

## 6. Conclusions

We have demonstrated that a modified applied moment

TABLE IV Fracture toughness of brazed ceramic-ceramic DCB specimens that were not precracked prior to testing\*

Beam material	Filler metal composition (at %)	$K_{Ic}$ (MPa m <sup>1/2</sup> )	Precrack
AD-998		4.6 <sup>†</sup>	Yes
AD-998	Cu-46Ag-4Sn-1Ti	7.2 ± 0.3	No
SiC		4.0	Yes
SiC	Cu-46Ag-4Sn-1Ti	5.6 ± 1.6	No
SiC	Cu-44Ag-4Sn-4Ti	5.7 ± 0.7	No
PSZ82		6.0	Yes
PSZ82	Cu-27Ag-26Ti	6.6 ± 0.6	Yes
PSZ82	Cu-44Ag-4Sn-4Ti	4.9 ± 0.6	Yes
SCW <sup>‡</sup>		8.5	Yes
SCW	Cu-46Ag-4Sn-1Ti	11.8	No

\* All specimens brazed at 800°C for 5 min in vacuum of <0.5 mPa ( $4 \times 10^{-6}$  mm Hg).

<sup>†</sup>Value for toughness of bulk ceramic.

<sup>‡</sup>Al<sub>2</sub>O<sub>3</sub> - 20 vol% SiC whiskers, composite hot-pressed at Oak Ridge National Laboratory.

DCB specimen can be used to determine the fracture toughness of ceramic-ceramic and ceramic-metal brazements. The normal care used in preparing ceramics for all mechanical property tests must be used; but, otherwise, the assembly techniques and fixture used for alignment during brazing are relatively standard practice. One cannot eliminate precracking in such specimens, but this is true in testing either bulk ceramics or brazed joints. In either case one cannot ensure that an atomistically sharp crack will be present unless precracking is used, and thus the  $K_{Ic}$  values can exhibit notch-radius sensitivity.

The DCB technique itself has several advantages over other fracture toughness tests developed for brittle materials. Toughness is determined from the load at failure and some dimensional data, but does not require measurement of the original precrack length. The sample requires very little material and is made up of simple shapes with flat surfaces. The geometry lends itself well to the control of the braze joints dimensions - a critical parameter in the strength of any brazement and an important factor in sample reproducibility. Finally, the DCB specimen can be used at cryogenic temperatures or up to about 200°C (with epoxy attached arms) or modified for compressive loading and tested at elevated temperatures.

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