Development of a Test for Determining Fracture Toughness of Brazed Joints in Ceramic Materials

**ABSTRACT.** The characterization and analysis of the adherence in joints between ceramics or a ceramic and a metal are important factors in both the design and reliability of components for structural uses. However, because the failure stress of brittle systems is a function of both the flaw size and the true adherence, a strength test by itself cannot sufficiently describe the quality of a ceramic joint. On the other hand, fracture mechanics can be used to determine adherence in a fashion similar to that used to describe the bulk fracture behavior in brittle materials. We have developed a test, based on a modified applied moment double cantilever beam specimen, that has been successfully used to measure the fracture toughness of joints between ceramics and ceramics and metals. Toughness measurements on samples of ceramics directly brazed with some of our experimental brazing filler metals showed that the brazed interfaces were at least as tough as the ceramics alone. 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 thermal spraying of the ceramics prior to brazing.

**Introduction**

Although monolithic ceramic materials have been widely used in the past in nonstructural 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. The major impetus for most of this interest over the past decade is economics— as fuel costs have increased, so has the need for increased efficiency in a multitude of energy conversion processes.

For example, preheating of the combustion air is a proven way of markedly reducing fuel consumption in a high-temperature furnace. Various fixed-boundary heat exchangers have been used industrially for this purpose. Fuel consumption in a given process can be reduced 40% or more by using recuperation or regeneration to heat air for the burners (compared with use of ambient-temperature air for fuel combustion) with furnace gases in the range of 1300°C (2372°F) and air preheat temperatures above 800°C (1472°F). Recuperators offer significant engineering advantages over refractory regenerators in many industrial processes because they can be interfaced with small to medium size furnaces (they are smaller than refractory regenerators) and their valve and hot ducting requirements are simpler. Metallic alloys have been used predominantly for recuperator construction, but present materials such as austenitic or ferritic stainless steels cannot be used above about 850°C (1562°F). The mechanical and corrosion property limitations of metal alloys severely limit the use of metal recuperators to preheat air above about 600°C (1112°F) (Ref. 1). However, structural ceramics having good thermal conductivity, such as silicon carbide, offer considerable promise for use in high-temperature recuperators for recovering waste heat from hot flue gases at temperatures of 1200°C (2192°F) or higher.

Ceramic materials also show considerable promise for use in advanced gas turbine engines. Efficiency in a turbine engine is directly related to the maximum allowable operating temperature of the materials used in the hot section of the engine. The impetus to increase engine efficiency and performance has led to continuing improvements in material use temperatures. For example, in modern turbine engines, high-temperature superalloys can be used at temperatures up to approximately 1100°C (2012°F) without cooling (Ref. 2). However, turbine engines with ceramic components are being developed with turbine inlet temperatures of 1370°C (2498°F) (Ref. 3). Ceramic materials also offer other advantages in turbine engines, such as higher thrust-to-weight ratios, reduced coolant-air requirements, and a potentially lower cost.

A number of automotive manufacturers are also working to develop a more efficient diesel engine for cars or trucks that is able to eliminate the need for power-robbing cooling requirements, by using structural ceramics in the combustion chamber—cylinder, piston cap and valve plate. In the second generation of the uncooled-diesel engine (sometimes called adiabatic), the use of petroleum materials would be reduced even further by eliminating the oil lubricant through the use of high temperature ceramic bearings.

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 reliably join simple-shape components to form complex assemblies or to join unit lengths of material to form large systems. Although by careful selection of the location or through judicious design a joint in such
applications may not be required to withstand the full intensity of the various service conditions (such as temperature or stress) as the bulk ceramic material itself, it is of course highly desirable that a ceramic-to-ceramic or ceramic-to-metal joint be capable of operation at near-peak conditions. Although ceramic joining technology has been highly developed over the past fifty years or so, most of the effort has been expended in developing materials and techniques for applications that will see service at "low" temperatures and with low structural requirements. The development of technology for joining ceramics for use at elevated temperatures, at high stress levels, and in dirty environments has been very limited.

As part of a program to develop brazing filler metals for such advanced applications, we are studying the mechanical properties of the bonds between experimental brazing filler metals and typical structural ceramics; and 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.

Fracture Mechanics Approach to Adherence in Ceramic Joining

The characterization and analysis of the adherence between dissimilar materials are important factors, from the standpoint of both design and reliability, in such technologies as printed microelectronic circuitry, ceramic-to-metal seals, protective coatings (e.g., ceramic coatings for metal turbines) and non-mechanical joining of components. Adherence is often determined via the stress (or load) required to cause separation. Strength data are useful in both (1) ascertaining a relative ranking of the adherence between systems, and (2) establishing and maintaining quality control during production. However, because the failure stress of brittle systems is a function of both the flaw size (e.g., an unbounded interfacial area or void) and the adherence, a strength test by itself cannot determine the true adherence of a system. Strength test results also do not allow one to relate adherence to material variables in the region of failure—be it at the interface or in the bulk materials on either side of the interface. However, postfailure analysis can be used to augment strength data and to tell whether or not failure occurs at the interface, and the analysis may possibly reveal the defect that caused failure.

This basically raises the issue of how does one select materials to form a joint or interface to achieve the maximum adherence. One approach is to improve the chemical bonding between dissimilar materials, i.e., the material(s) being joined and the adhesive media. Consideration may also be given to minimizing thermal stresses due to thermal expansion mismatches between dissimilar materials. However, the question remains, how does one determine the effect of such approaches on adherence? Measurement of the tensile, flexural or peel strengths of various interfaces are not sufficient by themselves, primarily because they are so strongly dependent on defect or flaw size. Adherence values (strengths) obtained by such tests cannot be related to the similar strengths (which are also flaw size dependent) obtained for the materials on either side of the interface.

On the other hand, fracture mechanics can be used to determine adherence in a fashion similar to that used to describe the bulk fracture behavior 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 failure). Adherence is thus described in terms of the ability of the total system to resist fracture, which serves not only as a tool to examine adherence mechanisms, but also as an important design aid. In addition, the critical adherence fracture toughness values (Kc, Gc) or the critical adherence fracture toughness values (Kc, Gc) 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 of the 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 ν (Poisson's ratio) of the two materials are comparable, in theory they must be identical (Ref. 6); but in practice, they need only approach each other (Ref. 7), and then the solution is the same as for the crack in a single phase body. This is the case 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 Kc, and not combined Kc, and a much simpler description of crack propagation is obtained.

Experimentally, determination of the adherence of a joint system is simplified by the use of the energy balance concept, equating the change in the system's strain energy (the strain energy release rate—Gc) with the total energy for crack propagation (2γc). Because the system can be defined, Gc is related to Kc, i.e.,

$$K_c = \frac{c^{1/2}}{a} = (G_E)^{1/2}$$

(1)

where σ is the applied tensile stress, c is the flaw size and A is a geometric factor. Thus, either Gc or Kc can be determined experimentally. Several techniques have been developed to determine the adherence of not only adhesives to metal (Refs. 4, 5) but also most recently of ceramics to ceramics (Refs. 8–10).

Our approach is based on a modification of the applied moment, double cantilever beam (DCB) specimen, shown schematically in Fig. 1, which was used to determine the critical Kc for bulk ceramics and glasses (Ref. 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, is small (as is normally encountered in thick films or braze joints) (Refs. 12 and 13). Basically, the approach equates the total strain energy release rate with the interfacial energy change in each half of the double cantilever beam caused by the creation of new surfaces as the crack propagates, i.e., Gc = 2γc. (Note that the two halves can thus be different materials or geometries.) In this case,

$$G_c = M^2 = \frac{1}{2E} \frac{M^2}{2(EL_1)} + \frac{1}{2(EL_2)}$$

(2)

where the (M/EL) terms determine the applied strain energy that is released in each arm during crack propagation. Referring to Fig. 1, M = (1/2)L 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
was shown that for an optimally processed thick film, adherence was limited by the fracture toughness of the glass interface improvement the joint systems. Furthermore, when adherence failure is the limiting factor in the mechanical behavior of the joint. For the latter case, the $K_I$ value obtained will approach that of a bulk ceramic. 

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 is the same as that in Beam 2), $K_I$ can be determined from Equation 1 with 

$$G_I = G_1 + G_2 = 2G_1$$

(3)

since the materials are the same, and 

$$G_1 = \frac{1}{2} \left( \frac{P}{E} \right) \left( \frac{b}{2} \right)^2 \left( \frac{L}{12} \right)$$

(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 $t$ so that 

$$\frac{M_1^2}{t_1} = \frac{M_2^2}{t_2}$$

(5)

and then by requiring that $G_1 = G_2$, it can be shown that 

$$b_1 h_1 E_1 = b_2 h_2 E_2$$

(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 brazing layer is thin 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 behavior of the joint. For the latter case, the $K_I$ value obtained will approach that of the bulk material in a similar material joint 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.

For example, in thick film conductors it was shown that for an optimally processed thick film, adherence was limited by the fracture toughness of the glass layer used in these systems to bond the metal conductor to the alumina substrate. Note that this finding is consistent with the fact that the glass has the lowest fracture toughness of the materials in this system. Processing at higher temperatures degraded the adherence by changing the morphology of the glass/metal interface. Similar effects were noted in Si$_3$N$_4$ braze joints (Ref. 12). As shown by earlier results, this approach can also be used when ceramic/metal joints are employed. 

**Specimen Geometry**

The overall dimensions of the typical DCB specimen used to determine the fracture toughness of a bulk ceramic are 2.5 X 9.5 X 28.5 mm (0.10 X 0.37 X 1.12 in.). A composite (brazed) specimen of similar materials is made by brazing together two beams, each having approximate dimensions of 2.5 X 4.76 X 28.5 mm (0.10 X 0.19 X 1.12 in.). 

For the case of a dissimilar material brazing specimen, the thickness ($b$) is held constant and the width of the beam 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., $G_1 = G_2$. If this dimension is not adjusted, during the testing the propagating crack will be deflected towards the beam with higher strain energy release rate.

For example, if a composite specimen were to contain nodular cast iron and partially stabilized zirconia (PSZ) beams (these materials being of interest for an uncooled diesel engine), Equation 6 is solved as follows for $h_{PSZ} = 4.76$ mm: 

$$h_{iron} = \frac{h_{PSZ}}{0.928} = 5.13 \text{ mm}$$

$E_{iron} = 160 \text{ GPa}$ and $E_{PSZ} = 350 \text{ GPa}$, then $h_{PSZ} = 4.76$ mm and $h_{iron} = 5.13$ mm, so that for a "standard" specimen (an alumina beam width of 4.76 mm/0.19 in.) the width of the cast iron beam is 6.17 mm (0.24 in.).

**Experimental Procedure**

The assembly and brazing of the composite DCB specimen is not difficult if a reasonable amount of care is taken. The ceramic or metal beams are placed in a ceramic fixture with a piece of brazing filler metal foil at the interface. Although some specimens were made using filler metals in the form of small pieces cut from an arc melted ingot, in many cases complete flow through the brazed sample was achieved. For a specimen containing alumina oxide brazed to the cast iron, 

$$E_{alumina} = 350 \text{ GPa} \quad h_{alumina} = \frac{h_{PSZ}}{0.928} = 5.13 \text{ mm}$$

$E_{iron} = 160 \text{ GPa}$, and $h_{iron} = 0.771$ mm.

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

**Fig. 3** — Four composite DCB specimens in SiC boat after brazing cycle. The 0.038-mm Ta shims (arrows) are used to control braze joint thickness. The wide shims also serve as notches during specimen precracking.
The 0.038-mm-thick Ta shim previously described. As will be discussed below, the specimens that were not precracked gave artificially high fracture toughness numbers, so the precracking operation was reinstated for the balance of the tests.

Materials

Some of the characteristics of the ceramic materials included in this program are given in Table 1. All of these ceramics are made by pressureless sintering except for our SiC whisker reinforced alumina composite (Ref. 14) (Al₂O₃-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.

For example, SiC is the principal material being tested for high-temperature recuperator applications in waste heat recovery systems because of its excellent thermal conductivity and strength. However, in some recuperator installations, such as those on aluminum remelt and glassmaking furnaces, SiC ceramics are degraded by certain halide species in aluminum melting and alkali oxides in glassmaking. In these applications, alumina or an alumina-matrix composite may prove to be a superior material.

Partially stabilized zirconia ceramics have low thermal conductivity, high toughness (for a ceramic), and relatively high thermal expansion, and are, therefore, the prime candidates for insulating the combustion chamber of the uncooled diesel engine. However, the microstructures of the PSZ's available today are not stable above about 1000°C (1832°F). They are less tough and strong at elevated temperatures (due to the reduced tendency for the tetragonal-to-monoclinic phase transformation that gives them strength and toughness). Therefore, alumina or an alumina matrix composite may emerge as a more viable candidate material. Although there is presently considerable interest in Si₃N₄ ceramics, this material was not included in the study. The impurity and additive levels of Si₃N₄ materials available today vary quite widely, making it difficult to select a representative material.

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 (Ref.

Table 1—Characteristics of Ceramic Materials Brazed in This Program

<table>
<thead>
<tr>
<th>Material Designation</th>
<th>Flexural Strength (MPa)</th>
<th>Average² Surface Roughness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coors AD-99</td>
<td>230</td>
<td>0.74</td>
</tr>
<tr>
<td>Coors AD-998</td>
<td>207</td>
<td>2.65</td>
</tr>
<tr>
<td>Degussit AL-23</td>
<td>156</td>
<td>4.46</td>
</tr>
<tr>
<td>Nilsen PSZ (82-9415SN)</td>
<td>616</td>
<td>0.94</td>
</tr>
<tr>
<td>Nilsen PSZ (83-664AWS)</td>
<td>574</td>
<td>0.94</td>
</tr>
<tr>
<td>Al₂O₃-(SiC)³</td>
<td>650</td>
<td>3.48</td>
</tr>
<tr>
<td>α-SiC⁴</td>
<td>348</td>
<td>0.70</td>
</tr>
</tbody>
</table>

²Determined by profilometer.
³SiC-whisker-reinforced alumina under development at ORNL.
⁴Hexoloy SA, Standard Oil Engineered Materials Co.
The principal piston material being considered to date is nodular cast iron (NCI). This material is widely used in many conventional diesel engines (aluminum is also used). In addition to NCI, other metals (such as Ti and a TiC cermet) that might serve as transition materials to accommodate mismatches in coefficients of expansion between a ceramic cap and metal piston were experimented with.

### Experimental Results

#### Fracture Toughness of Ceramic-Ceramic Brazements

The results of the room temperature tests of the composite DCB specimens of alumina and PSZ joined with some of our experimental brazing filler metals are given in Table 2. Note that the critical fracture toughness, $K_{IC}$, of the brazed samples was generally similar to that of the bulk ceramic.

#### Fracture Toughness of Ceramic-Metal Brazement

The same procedure was used for fabricating the ceramic-metal fracture toughness specimens as was previously described for the ceramic-ceramic brazed specimens. The only difference was that the width of the beam of the material having lower modulus of elasticity was increased as discussed in the section on specimen geometry. A potential problem area did arise, however, in the case of the ceramic-metal specimens, as there was a possible mismatch in 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 close, good fracture toughness values for these brazements were obtained, as shown by the data in Table 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 4. 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.

### Discussion of Results

Difficulty was initially experienced in fabricating the first of the ceramic-metal composite DCB specimens. Two of four NCI-to-PSZ brazements made in vacuum at $800^\circ$C (1472°F) were found to have failed by major cracking in the ceramic (Fig. 6) after the surface grinding step. The other two specimens ( brazed with the same filler metal but at $825^\circ$C/1517°F) survived the surface grinding operation. However, when they were cemented to a machining block for grooving, it was observed that both the ceramic and metal portions of the specimen had been distorted by an apparent mismatch in coefficients of thermal expansion. This effect can be seen in Fig. 7. The magnitude of the deflection in the PSZ ceramic was 0.45 mm (0.017 in.).

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### Table 2—Fracture Toughness of Ceramic-to-Ceramic Brazed DCB Specimens

<table>
<thead>
<tr>
<th>Ceramic Material</th>
<th>Brazing Filler Metal Composition (at-%)</th>
<th>Brazing Temperature (°C)</th>
<th>Number of Specimens</th>
<th>Fracture Toughness, $K_{IC}$ (MPa · m$^{1/2}$)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSZ (82-94159N)</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>3</td>
<td>6.6</td>
<td>0.55</td>
</tr>
<tr>
<td>PSZ (82-94159N)</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>2</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>PSZ (85-230MS)</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>2</td>
<td>7.4</td>
<td>0.07</td>
</tr>
<tr>
<td>PSZ (82-94159N)</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>800</td>
<td>2</td>
<td>5.0</td>
<td>0.35</td>
</tr>
<tr>
<td>PSZ (82-94159N)</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>825</td>
<td>2</td>
<td>4.8</td>
<td>0.85</td>
</tr>
<tr>
<td>PSZ (85-230MS)</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>850</td>
<td>2</td>
<td>12.2</td>
<td>1.06</td>
</tr>
<tr>
<td>AL-23</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>850</td>
<td>2</td>
<td>6.5</td>
<td>0.35</td>
</tr>
<tr>
<td>AD-99B</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>850</td>
<td>2</td>
<td>5.4</td>
<td>1.13</td>
</tr>
<tr>
<td>AD-99B</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>850</td>
<td>1</td>
<td>6.6</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3—Fracture Toughness of Ceramic-Metal DCB Specimens Brazed with Experimental Filler Metals

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Materials</th>
<th>Filler Metal Composition (at-%)</th>
<th>Brazing Temperature (°C)</th>
<th>Fracture Toughness (MPa · m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>530.4</td>
<td>PSZ/NCI</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>4.6</td>
</tr>
<tr>
<td>531.1</td>
<td>PSZ/Al</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>9.9</td>
</tr>
<tr>
<td>537.1</td>
<td>PSZ/Ti</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>5.6</td>
</tr>
<tr>
<td>540.1</td>
<td>PSZ/Al</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>775</td>
<td>2.8</td>
</tr>
<tr>
<td>540.2</td>
<td>PSZ/SiC</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>775</td>
<td>4.2</td>
</tr>
<tr>
<td>545.1</td>
<td>PSZ/SCW</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>10.4</td>
</tr>
<tr>
<td>545.3</td>
<td>PSZ/SCW</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>800</td>
<td>9.3</td>
</tr>
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</table>

### Table 4—Fracture Toughness of Brazed Ceramic-Ceramic DCB Specimens That Were Not Precracked Prior to Testing

<table>
<thead>
<tr>
<th>Beam Material</th>
<th>Filler Metal Composition (at-%)</th>
<th>$K_{IC}$ (MPa · m$^{1/2}$)</th>
<th>Precrack</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD-99B</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>4.3</td>
<td>Yes</td>
</tr>
<tr>
<td>AD-99B</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>7.2 ± 0.3</td>
<td>No</td>
</tr>
<tr>
<td>SiC</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>5.6 ± 1.6</td>
<td>No</td>
</tr>
<tr>
<td>SiC</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>5.7 ± 0.7</td>
<td>No</td>
</tr>
<tr>
<td>PSZ82</td>
<td>Cu-27Ag-26Ti</td>
<td>6.6 ± 0.6</td>
<td>Yes</td>
</tr>
<tr>
<td>PSZ82</td>
<td>Cu-44Ag-45Sn-4Ti</td>
<td>4.9 ± 0.6</td>
<td>Yes</td>
</tr>
<tr>
<td>SCW82</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>8.9 ± 0.6</td>
<td>Yes</td>
</tr>
<tr>
<td>SCW82</td>
<td>Cu-46Ag-45Sn-1Ti</td>
<td>11.8</td>
<td>No</td>
</tr>
</tbody>
</table>
certainly a major value for a ceramic.

The failures and distortion that occurred in the PSZ-to-NCI specimens were somewhat puzzling, as one favorable attribute of PSZ is its purported close match in coefficient of thermal expansion with that of NCI. However, when thermal expansion data were taken for this particular PSZ, the existence of a large hysteresis loop was found, as shown in Fig. 8. X-ray diffraction examination revealed that this ceramic did not contain the approximately 50% toughening tetragonal phase that is typical for other materials of this type, but, in fact, was almost fully monoclinic at room temperature. Apparently, some deviation in processing led to a ceramic that readily transforms to tetragonal 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.

These tests were repeated, but with a more recently manufactured sample of PSZ ceramic, identified as 85-230 MS. This ceramic contains about 25% monoclinic phase and a coefficient of thermal expansion of 10.8 × 10⁻⁶/°C. Accordingly, the material does not have the large hysteresis loop in its thermal expansion curve. In these latest specimens, the amount of distortion in the PSZ (due to mismatch in expansion with the nodular cast iron) averaged 0.11 mm (0.004") over a length of 28 mm (1.1 in.) versus 0.45 mm (0.018") for the earlier specimens. The fracture toughness data for composite DCB specimens containing this material and nodular cast iron or titanium are also given in Table 3.

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 braze 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 nonmetallic phases that occur in the braze joint at the interface between the brazing filler metal and the ceramic. We think that the high $K_I$ values are the result of the fact that a crack “pop-in” load is always higher than the load (stress) required for propagation of a sharp flaw (precrack). Thus, when the artificially high load is used in the calculation, a higher toughness value is given.

Conclusions

We have demonstrated that a modified applied moment, double cantilever beam specimen can be used to determine the fracture toughness of ceramic- and ceramic-metal brazements. The normal care used in preparing ceramics for all mechanical property tests must be used, but, other than that, the assembly techniques and fixture used for alignment during brazing should not pose a problem to others seeking to apply this test. We tried unsuccessfully to eliminate the most difficult aspect of the technique, precracking, but concluded that unprecracked specimens gave artificially high toughness values.

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 single shapes with flat surfaces. The geometry lends itself well to the control of the braze joint thickness—a critical variable in the strength of any brazement and an important factor in sample reproducibility.

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