Fracture of metal/ceramic interfaces

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Abstract

The present paper examines metal/ceramic interfaces. Energy release rates are calculated with the finite element method for different elastic–plastic material laws of the metal. The local strain field of the metal is measured during a four-point bending test with an optical method and compared with results from the simulations. The aim of the work is to understand the influence of interface strength and material properties on the energy release rate. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Metal/ceramic interfaces; Cohesive surface model; Finite element method; Energy release rate; Optical displacement measurement

1. Introduction

Metal/ceramic joints become more and more important in modern technology, because they combine the properties of metals like ductility and high electrical and thermal conductivity and the properties of ceramics like high hardness, corrosion resistance and capacity of resistance to wear. Dealing with metal/ceramic joints, one important point of interest is the energy release rate, which occurs during interface fracture, because the interface is often the weakest part of such combined materials. Of special interest is the influence of interface strength, material properties and specimen geometry on the energy release rate [1,2]. This is one point which is examined in the present paper. Additionally, the energy release rate is separated into an elastic and a plastic part. This is done by using the finite element method under a macroscopic point of view. This means that effects like pores, impurities or segregations are not taken into account. In order to compare the simulations with experimental results the chosen model geometry is, like in the experiment, a four-point bending specimen (Fig. 1). The hardmetal cylinders of the testing machine are modelled, too. Typical specimen dimensions are \((1.6 \times 3.8 \times 32) \text{ mm}^3\). Most of the presented results are obtained with two-dimensional simulations. The ceramic is treated as purely elastic, whereas the metal is described by an elastic–plastic constitutive equation with the Mises theory. Both materials are modelled as isotropic. All finite element simulations are performed with the commercial code ABAQUS [3].

2. Energy concept

The energy release rate during fracture is given by the following relation [4,5]:
where $dA$ is an infinitesimal crack growth increment, $W_D$ the dissipated energy, $W_S$ the external energy due to surface forces and $U_E$ is the internal energy of the specimen, i.e. the elastic energy. If we assume additionally that the external energy does not depend on the crack length, we obtain

$$\tilde{G}_C = \frac{d}{dA} (W_D + W_S - U_E).$$

This relation is illustrated in Fig. 2. Two force–displacement curves of specimens with a difference in crack surface of $dA$ are shown. From the area between the curves we can obtain the energy release rate $\tilde{G}_C$. Furthermore it is possible to separate the total energy release rate into an elastic part $G^e_C$ and a plastic part $G^p_C$. Both, the simulations and the experiments are done under the boundary condition of a constant displacement velocity of the upper hardmetal cylinders of the testing machine as sketched in Fig. 1.

3. Experimental methods

The metal/ceramic joints are fabricated by diffusion bonding in a high vacuum machine. The chosen materials are niobium and alumina. Typical bonding times are 3 h with a bonding pressure of 10 MPa and a bonding temperature of 1400°C. The heating-up rate is $\approx 7.8$ K/min and the rate of cooling is $\approx 11.8$ K/min. The advantage of the combination alumina/niobium is the lack of residual stresses due to approximately the same thermal expansion coefficients. The specimens are tested in a four-point bending machine under a constant displacement velocity of 6 $\mu$m/min. During testing, the local strain at the specimen surface is determined by an optical measurement method [6,7]. The method is two-dimensional and, therefore, can only be detected in plane deformations. The surface of the specimen must show a stochastic pattern to apply the method. This is generated by a covering coating of TiO$_2$ and finely divided black laquer. A picture of a prepared specimen is shown in Fig. 3. To obtain the local strain, two pictures are taken by a CCD-camera, a reference picture of the undeformed state and another picture of a deformed state during the four-point bending test. It is possible to determine the local displacements from the change of the pattern from the first to the second picture. The local strain can be calculated from the deformations. In addition to the four-point bending test, compression tests with pure niobium were made to obtain the plastic behaviour of niobium. The obtained stress–strain curve is shown in Fig. 6. The elastic material data (Table 1) were taken from the literature [8].

4. Modelling

The interface crack is modelled with the cohesive surface model [9]. In this model the crack path
is prescribed and lies, in the present case, exactly in the interface. Crack initiation and crack growth are simulated by a stress criterion. Therefore, debonding occurs when the normal tension transmitted through the interface reaches a critical value $T_{\text{crit}}$, which can be determined from experiments by inverse modelling. We examine only mode I fracture. The energy release rate occurring during fracture is calculated and separated in elastic and plastic parts as described in the following. The total energy for the specimen with a crack of length $a_k$ is

$$E_{a_k} = \int_0^t \int_V \sigma_{ij} \varepsilon_{ij}^{\text{el}} + \int_0^t \int_V \sigma_{ij} \varepsilon_{ij}^{\text{pl}}$$

$$= E_{a_k}^{\text{el}} + E_{a_k}^{\text{pl}},$$

where $E_{a_k}^{\text{el}}$ denotes the elastic energy and $E_{a_k}^{\text{pl}}$ the plastic energy of the specimen with volume $V$ and $\varepsilon_{ij}^{\text{el/pl}}$ is the elastic, respectively, plastic strain rate.

From two calculations with a difference in crack length $da = a_k - a_l$ we obtain the two parts of the energy release rate as follows:

$$G_C^{\text{el}} = \frac{E_{a_l}^{\text{el}} - E_{a_k}^{\text{el}}}{da},$$

$$G_C^{\text{pl}} = \frac{E_{a_l}^{\text{pl}} - E_{a_k}^{\text{pl}}}{da}.$$  \hspace{1cm} (4)

5. Results

5.1. Force–deflection curves

The force–deflection curves of four-point bending tests are an important interface between simulation and experiment. In order to compare numerical and experimental results, these curves play an important role and thus the influence of different parameters like specimen geometry, Young’s moduli and deformation state on these curves was studied in initial simulations only for the elastic region. This is shown in Fig. 4. All these parameters show a strong influence on the force–deflection curves. Therefore, all values have to be determined exactly. To decide, whether plain stress or plain strain simulations are more suitable a three-dimensional simulation was made for comparison. The result was that the force–deflection

![Fig. 3. Specimen surface, prepared with TiO$_2$ and black lacquer for the optical measurement method.](image)

![Fig. 4. Initial studies with elastic materials. $E_c$ and $E_m$ are the Young’s moduli of the ceramic and of the metal, respectively (pd means plain strain, ps plain stress).](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$\nu$</th>
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<tbody>
<tr>
<td>Alumina</td>
<td>390</td>
<td>0.27</td>
</tr>
<tr>
<td>Niobium</td>
<td>104.9</td>
<td>0.397</td>
</tr>
</tbody>
</table>

Table 1

Elastic properties
curves of this simulation and one of the plain stress simulations matched very well (Fig. 5). Therefore, all further simulations were done with plain stress formulation. This is also advantageous for the comparison of calculated strains and measured strains at the specimen surface because this is dominated by plain stress conditions, too.

5.2. Energy release rates

Next, the four-point bending specimen was modelled with an elastic–plastic material law for niobium (Fig. 6). One study was done with a constitutive equation fitted to the compression tests (model 1) and for comparison another simulation with the material law model 2, which is characterized by a lower yield limit. In Fig. 7 the force–deflection curves for both simulations are shown. In addition an experimental curve is depicted, which is nonlinear at the beginning due to pull-in faults. The reason for the discrepancy in the plastic regime may be caused by a different material law for niobium in the tensile regime. The fracture occurred at the interface and was brittle. In the simulation, the interface strength can be varied in a wide regime by varying the critical normal tension $T_{\text{crit}}$. Under the same external loading, e.g. the same displacement of the upper hardmetal cylinders of the bending machine, the normal tension at the interface depends strongly on the material law. This is shown in Fig. 8. The approximate position of the formerly introduced

Fig. 5. Comparison between two- and three-dimensional calculations: The plain stress curve matches exactly the curve obtained by a three-dimensional simulation. The curve for the plain strain simulation is steeper.

Fig. 6. Stress–strain curve from the compression test and constitutive equations (model 1 and model 2), used in the simulations.

Fig. 7. Comparison between experimental and calculated force–deflection curves from four-point bending tests.

Fig. 8. Influence of the external load on the critical normal tension. The circle marks the experiment from Fig. 7.
experiment is marked by the circle. In addition, the curve for a purely elastic material law of the metal layer is shown. For all three cases the energy release rate was calculated, and separated into elastic and plastic parts. Fig. 9 shows the dependence of the total and the elastic energy release rates on the crack criterion, the critical normal tension $T_{n}^{\text{crit}}$. The difference between total and elastic parts is given by the plastic part. For the purely elastically simulated niobium the plastic energy release rate is zero and, therefore, the total energy release rate is equal to the elastic energy release rate. As can be seen the influence of a lower yield limit in the constitutive equation of the niobium consists in two facts. First, the region of dominance of the plastic energy release rate, e.g. the divergence of the elastic from the total energy release rate, begins at smaller $T_{n}^{\text{crit}}$, second, the divergence is stronger. It should be noted here, that the maximum of the normal tension appears at the notch and at the edge of the specimen, respectively, at the edge of the specimen. The circle marks the experiment. Fig. 10 shows the dependence of the plastic energy release rate on the elastic energy release rate for the two elastic–plastic models. The curve for model 2 with a lower yield limit shows a steeper and faster increasing gradient than the curve for model 1.

5.3. Local strain field

In the following, the calculated and measured local strain field at the specimen surface will be compared (Fig. 11). Shown is the niobium part of the four-point bending specimen just before fracture occurs. As can be seen, the qualitative matching is quite good for the strain components $\epsilon_{xx}$ and $\epsilon_{yy}$. The slight asymmetry in the experimental strain field may be due to artificial strains from a tipping of the specimen out of the focal

Fig. 9. Elastic ($G_{C}^{el}$) and total energy release rates ($G_{C}^{tot}$) for varying $T_{n}^{\text{crit}}$. The circle marks the experiment from Fig. 7.

Fig. 10. Plastic versus elastic energy release rate for the two different models (model 1 and model 2).

Fig. 11. Comparison between calculated (left) and measured (right) local strain field at the surface of the niobium part of a four-point bending specimen. The scales are the same for the simulation and the experiment.
plane of the camera. This problem can occur with the two-dimensional optical method. For further studies we plan to use a three-dimensional optical method to avoid such problems.

6. Conclusions

The presented results showed, that it is possible to calculate elastic and plastic energy release rates for interface fracture in metal/ceramic joints. Further, a strong influence of the yield stress on the normal tension at the interface was shown. To obtain a functional correlation between the interface strength, the material properties and the ratio of elastic to plastic energy release rate more studies must follow. It is planned to use the Ramberg–Osgood law [10] to model the metal layer, because this allows a systematic variation of the material parameters. Finally, the comparison between calculated and measured strains at the specimen surface showed a good qualitative matching.

Acknowledgements

The presented work is funded by the Deutsche Forschungsgemeinschaft within the Graduiertenkolleg “Internal Interfaces in Crystalline Materials”, which is gratefully acknowledged.

References