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NUMERICAL ANALYSIS OF INTERFACIAL DEBONDING OF METAL/CERAMIC BIMATERIAL USING FEM

The bimaterials applied in various fields of industry consist mainly of ceramics and metal. Their damage is mainly due to the presence of residual stresses generated during their manufacture. The damaged area is closely related to the high production temperature. The aim of this study is to analyze the effect of these factors on the behavior of an interfacial and sub-interfacial crack in the volume of alumina material. This behavior is studied in terms of variation of the stress intensity factor (SIF) in Modes I, II and III. A study by means of the finite element method (FEM) was carried out. This work demonstrates that the risk of sudden propagation of these cracks is all the more probable when the bimaterial is produced at high temperatures. The elastoplastic behavior of the metal considerably minimizes this risk by plasticizing the metal, which allows strong relaxation of the residual stresses.

Keywords: stresses, crack, interface, bimaterial, FEM

Nomenclature

FEM	finite element method
E	Young's modulus
w	width of bimaterial model [mm]
l	length of bimaterial model [mm]
t	model thickness [mm]
a	crack size [mm]
d	distance between two cracks
Z	axial coordinates of the model
ε_m	elastic deformation of the metal
ε_c	elastic deformation of the ceramic
α_m	thermal expansion coefficients of the metallic material
α_c	thermal expansion coefficients of the ceramic material
T_0	initial temperature
T	temperature
σ_R	residual stresses
ν_m	Poisson's ratio of the metal
K_I K_{II} K_{III}	mode I, II, III linear elastic stress intensity factor, [MPa·m$^{0.5}$]
Kc	material fracture toughness [MPa·m$^{0.5}$]
σ_0	applied uniform stress
Y	geometric factor

INTRODUCTION

Bimaterials – of the ceramic-metal type – are generally produced at relatively high temperatures. This temperature is chosen according to the material whose melting point is the lowest. Cooling from this temperature to ambient temperature induces internal stresses in the close vicinity of the interface of the two constituents of the bimaterial. Many studies on the cracking behavior and damage of bimaterials have been conducted. A technique for characterizing interface damage in bimaterials was studied in [1, 2] to characterize the damage in bi material fiber optic assemblies. In [3] an another author studied the effect of residual thermal stresses in composite materials. Study [4] reveals that during the composite development process, residual stresses of thermal origin arise. A micromechanical model was presented in [5] and another model by the finite element method allowing a crack to be obtained in pure opening mode ($K_I > 0$) which was proposed in [6]. Papers [7, 8] presented a composite material model to study the effects of interfacial crack propagation and damage on the elastic/plastic behavior of a metal matrix of a SiC/Ti type composite. A study was conducted in [9] on the effect of the size of the crack in a bi-material. Using finite element analysis of the crack point along a bimaterial interface [10], a theory was introduced to calculate the growth rate of fatigue cracks. A study was performed in [11] on the effects of the fiber volume fraction on the thermal expansion behavior of a composite. In [12], solutions were given regarding fracture mechanics in terms of singularities at the crack front, as well as singular stresses at points such as corners, interfacial joints and edges. Then in [13], an approach was used to model a crack; it was shown that by knowing its dimensions, the fracture energy can be obtained. The originality of this work leads to the analysis of the damage and behavior of cracks initiated in a bimaterial. To do so, this analysis was carried out on the size of the defect, its location, its interaction with the interface and the temperature. The behavior of the cracks was analyzed with respect to the variation in the stress intensity factor (SIF) in Modes I, II and III using the finite element method (simulation software Abaqus 6.14), for an Al/Al_2O_3 bimaterial.

FINITE ELEMENT MODELING

Representation of numerical model

The Abaqus calculation code version 6.14 [14] was used to simulate the interfacial debonding and residual stresses effect behavior in a bimaterial model. The numerical model developed for this study is a three-dimensional structure containing two materials with diametrically opposed properties (aluminum and alumina) produced at an elevated temperature. The temperature was chosen according to the lowest melting point (Fig. 1). This bimaterial was subjected to thermal loading with: width (w = 3 mm), length (2h = 4 mm) and thickness (t = 1 mm). The studied model contains a central crack initiated in the interface.

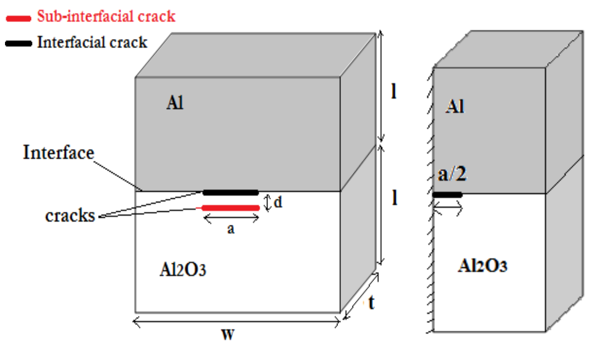

Fig. 1. Analyzed cracked model

The applied boundary conditions are:

$$U_Z = 0$$

The chosen boundary conditions of symmetry were fixed (Fig. 2). The type of mesh used was quadratic elements C3D20RHc (20-nodes elements (Fig. 3)) with 20273 elements in the model in total. For the reliability of the results, the adopted mesh size was sufficiently refined, particularly at the cracking edges and at the interface. This is a digressive mesh along the (Y axis), with symmetry along the Z axis.

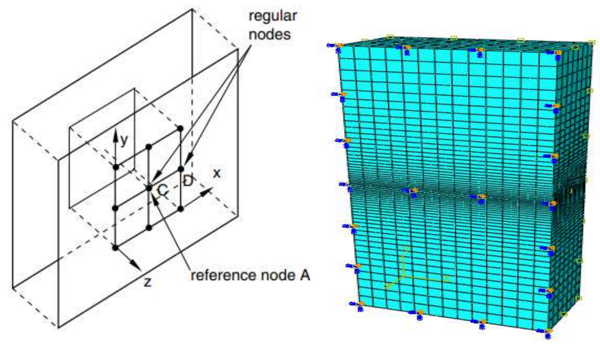

Fig. 2. Boundary conditions in model

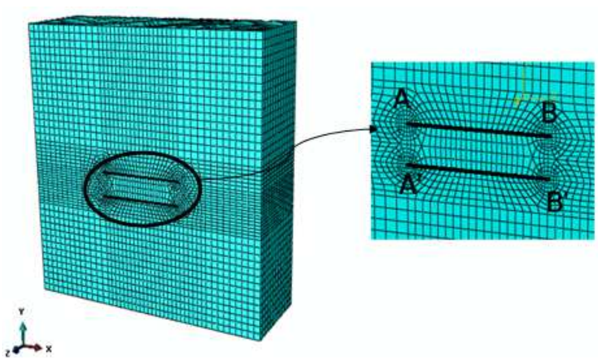

Fig. 3. Model mesh

TABLE 1. **Mechanical properties of used materials [15]**

Materials	Material behavior	E [GPa]	Poisson's ratio ν	α [°C-1]
Al_2O_3	Elastic	345	0.27	8.8E-006
Al	Elastic	67.5	0.33	23.5 E-006

Ceramic-metal type bimaterials are generally produced at relatively high temperatures. In fact, when cooling at ambient temperature, residual stresses appear at the interface due to the difference in the coefficients of thermal expansion of the two materials. Many studies have revealed that the intensity of the residual stresses depends on the nature of the two components of the bimaterials bonded together. Owing to the production temperature of the bimaterial, the metallic material shrinks much more than the ceramic material, the result of the shear stress at the bimaterial interface due to the equalization of the elastic deformations:

$$\varepsilon_m = \alpha_m (T_0 - T) \quad (1)$$

and

$$\varepsilon_c = \alpha_c (T_0 - T) \quad (2)$$

These residual stresses depend on the difference between the coefficients of thermal expansion of the two materials, and the production temperature, the modulus of elasticity and the Poisson's ratio of the bimaterial:

$$\sigma_R = \frac{(\alpha_m - \alpha_f)(T - T_\circ)}{\frac{1+\nu_m}{2E_m} + \frac{1-2\nu_c}{E_c}} \quad (3)$$

In addition to the mechanical constraints, these stresses can be responsible for damage of the composite materials (bimaterial type). Their analysis is of great importance for the durability, reliability and performance of these materials produced by thermo-compression. To do this, three-dimensional numerical analysis using the finite element method was carried out.

Calculation of stress intensity factor

The stress intensity factor (SIF) K_I is the only significant parameter, which makes it possible to know the state of stress and strain at any crack tip. Irwin [16] shows that at the level of the stress field in the vicinity of the point of the crack rupture occurs when K_I reaches critical value K_{Ic}. This is a characteristic of the material called "tenacity"; this factor is expressed in Mode I in the form:

$$K_I = Y\sigma_0\sqrt{\pi a} \quad (4)$$

Irwin's formula ensures that:

$$J = \frac{K_I^2 + K_{II}^2}{E'} + \frac{K_{III}^2}{2\mu} \quad (5)$$

CASE OF INTERFACIAL CRACK

Effect of production temperature

By studying the literature, it was noted that a few works deal with the propagation of cracks on the level of the interface. An analysis of the production temperature of the bimaterials was carried out on the behavior of the interfacial crack. The results presented in Figure 4 show the variation in SIF in Failure Mode I as a function of temperature. The temperature at which the bimaterial is produced is a main parameter for the mechanical adhesion of the interface. It determines the level of the residual stresses according to relation (3).

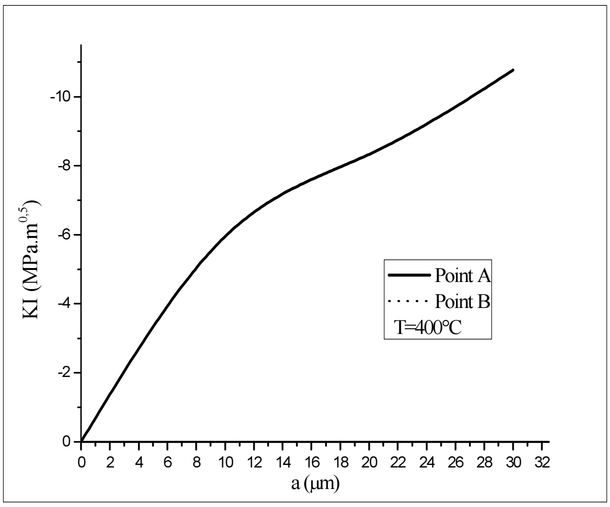

Fig. 4. Variation in SIF according to crack size (Mode I)

Figure 5 reveals the effect of temperature on the behavior of the crack. This figure shows that the crack essentially propagates in mixed Modes II and III. The predominant failure mode is Mode III. The crack, initiated at the alumina-aluminum interface, is all the more unstable as the bimaterial is produced at high temperatures. The difference between these two failure criteria is all the greater as the crack propagates along the interface. It is the internal metal tension and ceramic compression stresses that are responsible for these modes of propagation. In Modes II and III, when the temperature is high, it gives a higher SIF (Fig. 5) and the values of the factors resulting in the two crack fronts are the same (Point A and B). The following figure shows that the residual stresses favor the instability of the crack in Modes II and III.

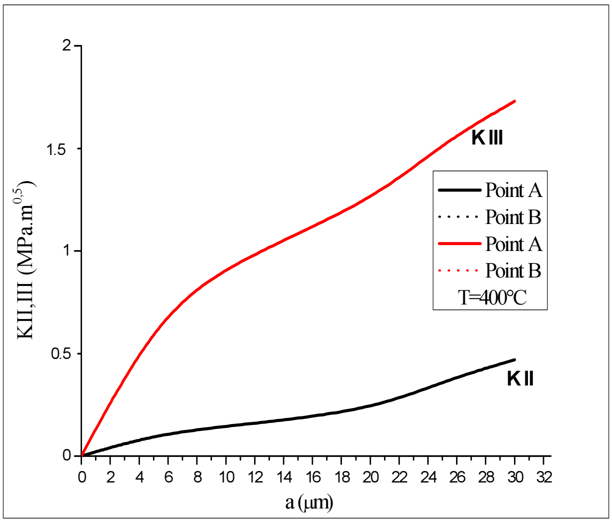

Fig. 5. Variation in SIF according to size of crack in Modes II and III

Case of sub-interfacial crack

Effect of temperature

The distance d between the two cracks (interfacial and sub-interfacial) was defined in (Fig. 1). In this part of the study, an analysis was made on the behavior of the crack defined above (crack red color in Fig. 1). The variation in SIF in Mode I by varying the distance between the two cracks (interfacial and sub-interfacial) is given in Figure 6. As indicated previously, the production temperature is a parameter determining the mechanical strength of the interface. Figure 1 clearly shows that such a crack propagates mainly in pure opening mode (Mode I), its effect on the behavior of a crack, initiated in parallel alumina and located near the interface. Cracks initiated in bimaterials produced at high temperatures are very unstable as they propagate suddenly, causing a dangerous rupture of the bond. In fact, the values of SIF in Mode I are higher than the alumina cracking resistance. For crack sizes equal to 10 µm, the critical stress intensity factor K_{Ic} (4 MPa√m) of this material is widely exceeded. It is therefore important to optimize the production temperature to reduce residual stresses, a source of crack initiation and ensure a good mechanical bond at the bimaterial interface.

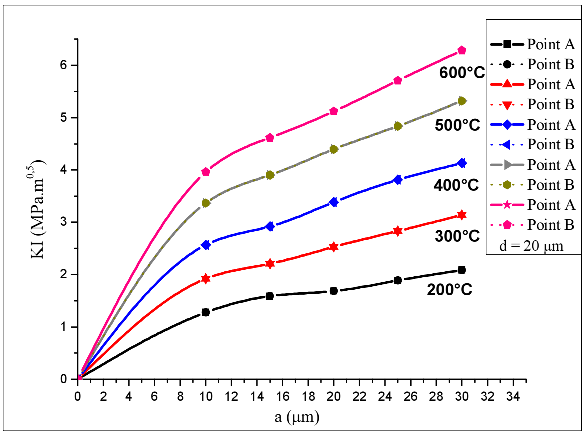

Fig. 6. Variation in SIF as function of production temperature in Mode I

Interface effect

The depth of the damaged zone of the alumina corresponds here to the extent of the residual stresses in the ceramic. To highlight this part of the study, a crack initiated parallel to the interface is progressively moved away from the interface. Figure 7 shows the variation in SIF in Mode I as a function of distance from the interface. The distance effect determines when the crack is located near the interface. This crack behavior is defined in terms of values that are too high for this stress intensity factor K_I. From the graph, the values (K_I) tend to cancel out when the crack is initiated sufficiently (at 1.8 mm) from the interface. This distance therefore corresponds to the distribution of the residual stresses. The extent of this distribution is lower when the bimaterial is produced at low temperatures.

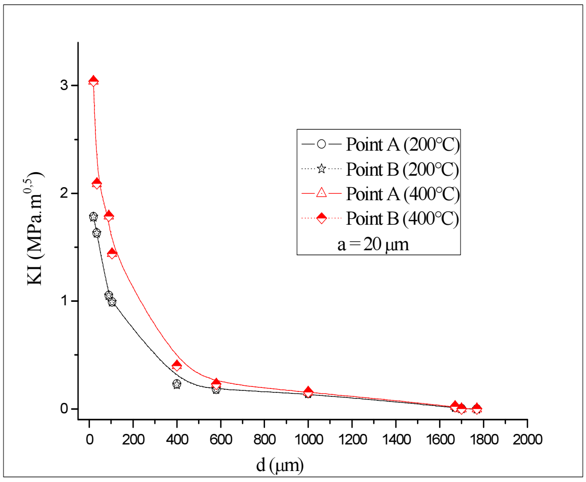

Fig. 7. Variation in SIF in Mode I from interface

Effect of metal behavior

The plastic behavior of aluminum allows strong relaxation of residual stresses as shown in Figure 8, which is explained by the low Mode I SIF values obtained. It is the plastification of the metal that is responsible for such behavior. The relaxation of these stresses is twofold: by plastic deformation of the metal during production of the bimaterial and by the formation of plastically deformed zones in the vicinity of the cracking front. Figure 8 shows that the effect of residual stresses promotes the risk of crack initiation in interfacial and sub-interfacial cracks. This risk is defined here by the kinetics of crack propagation as a function of the variation in the stress intensity factors in Mode I. A rate of 5.9% less for stress intensity factor K_I for the case of an elastoplastic metal gives good results for minimizing the stresses (Table 2). This behavior and the results are in good agreement with those from other works, among which are the authors of [17-19], who studied the effect of the residual thermal stresses on the damage of composite materials and the influence of the mechanical and thermal properties of the two materials (ceramic and metal) on the origin of residual thermal stresses by the finite element method.

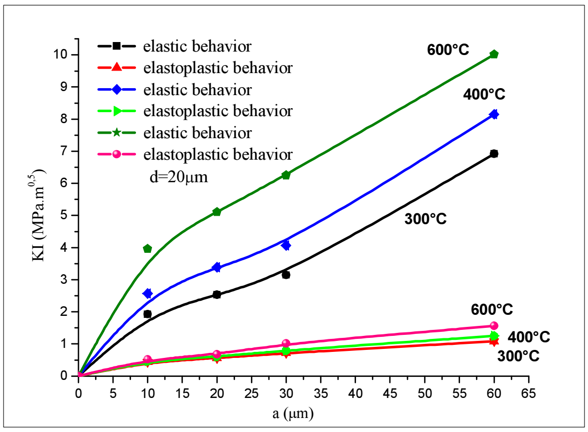

Fig. 8. Variation in SIF in Mode I (elastic and elastoplastic metal behaviors)

TABLE 2. **Comparison of K_I values at 400°C**

a [mm]	K_I [MPa·m$^{0.5}$]			
	interfacial crack	sub-interfacial crack (elastic behavior)	sub-interfacial crack (elasto-plastic behavior)	$\Delta KI/KI\%$
20	–8.23	3.45	0.5	5.9

CONCLUSIONS

The results obtained in this study show and indicate that:

- A crack initiated at the interface propagates in mixed Modes II and III.
- The residual stresses cause the instability of the cracks initiated in the ceramic and the probability of rupture by an increase in SIF.
- The tenacity of the ceramic is widely exceeded ($K_I > K_{Ic}$) for materials produced at high temperatures.

- The area of damage is closely related to the production temperature of the bimaterial.
- Elastoplastic behavior considerably delays the propagation of Mode I cracks by plasticizing the metal.
- The FEM analysis makes it possible to delimit the boundaries that depend on the fracture parameters of the metal and the ceramic. Thus, a low value of interfacial toughness is a necessary condition to avoid interfacial debonding.

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