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Study of the Thermomechanical Properties of Bimaterials (Metal/Ceramic)

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Abstract: Bimaterial metal/ceramic assemblies are widely used in applications exposed to severe thermal environments, notably in the aerospace, power electronics and nuclear sectors. Due to the sharp contrast between the mechanical and thermal properties of the two materials (modulus of elasticity, coefficient of thermal expansion), these structures develop complex thermomechanical stress fields, which can initiate or propagate cracks.The present study focuses on the variation in stress intensity factor (SIF) associated with a localized plane crack in the metal part of a metal/ceramic assembly, under one-dimensional thermal loading. The aim is to quantify the influence of the thermomechanical properties of the bimaterial, the position of the crack relative to the interface, and the temperature distribution on the evolution of the SIF. The methodology is based on finite element modeling, with simulations carried out for different thermal loading scenarios (linear gradient, thermal shock), using typical materials such as steel/alumina. The results show that proximity to the interface significantly influences the amplification or attenuation of the SIF, depending on the direction of the thermal gradient and the contrast in properties. When the crack is close to the interface, an asymmetrical redistribution of stresses is observed, which may favor a deviation of the crack towards the interface or the ceramic. Taking these effects into account is essential for predicting the service life of these composite structures.

Keywords: Bimaterial, ABAQUS, Thermomechanical, Stress intensity factor, Metal, Ceramic

Introduction

Numerical modeling of cracked media using the finite element method (FEM) is now an essential tool in fracture mechanics, enabling the precise analysis of crack propagation phenomena in complex structures. The recent rise of numerical simulation techniques has led to significant advances in several engineering fields, particularly in the study of metal/ceramic bimaterials, whose industrial applications have expanded considerably in recent decades.

Numerous studies have contributed to a better understanding of the mechanical behavior and fracture at the interfaces of dissimilar materials. For example, Kim and Suresh (Kim and al. 1994) analyzed normal fracture at bimaterial interfaces, highlighting damage mechanisms dependent on the nature of the mechanical and thermal coupling. Teixeira et al. (Teixeira 1999) focused on residual stresses and cracking in metal/ceramic systems applied to microelectronic devices, while Zhang et al. (Zhang 2008) conducted in-depth finite element analyses on interfacial cracking in metal-ceramic composites. Furthermore, Cai et al. (Cai 2021 & Reddy 2017) studied the mechanical characterization of interfaces in thermocompression assemblies, highlighting the crucial role of material adhesion and compatibility properties. Following this line of research, the present work aims to analyze the evolution of the stress intensity factor (SIF) during crack propagation in a solid-state thermocompression ceramic-metal junction. Previous studies have shown that the intensity and distribution of interfacial stresses in

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such assemblies are highly dependent on the physical, mechanical, and thermal properties of the constituent materials.

The precise determination of these parameters is therefore essential for evaluating the durability, reliability, and serviceability of metal/ceramic bimaterials. Indeed, the performance of these systems under operational conditions depends directly on the level and distribution of interfacial stresses, which determine their resistance to cracking and their long-term behavior.

Method

Presentation of the Model

The model developed for this study is a three-dimensional cracked plate composed of two materials of different natures (metal and ceramic) jointly assembled (Figure 1) with a length L = 20 mm, a height H = 10 mm (H1 = 6 mm for the ceramic and H2 = 4 mm for the metal), and a thickness e = 15 mm. The difference in the coefficient of thermal expansion between the ceramic and the metal leads to a high concentration of residual stresses at the interface. The finite element method numerical simulation software used in our study is ABAQUS.

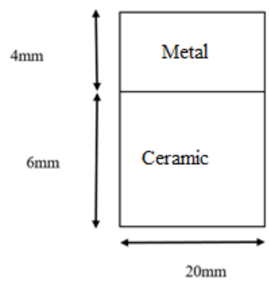

Figure 1. Geometric modeling

We varied the materials constituting our model so as to benefit from the choice of mechanical and physical properties, as well as their production temperature. The mechanical and physical properties of the different materials used are illustrated in Table 1.

Table 1. Mechanical and physical properties of materials

	Young's modulus E(GPa)	Poisson coefficient	Coefficient of thermal expansion α (10^{-6} k)
Alumina	350	0.25	8.5
Zirconia	200	0.28	5.4
AlN	320	0.27	4.2
Copper	100	0.34	16.5
Silver	83	0.37	19
Platinum	168	0.38	9

The meshing of geometry constitutes the longest and most determining part of a numerical model. Figure 2 represents the mesh used for the simulation of the Bimaterial plate containing a central crack. The latter was meshed by quadratic elements of type; the mesh was particularly refined in the vicinity of the crack front for the good precision of the results.

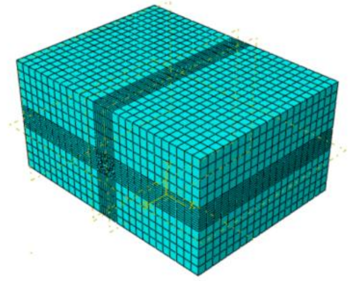

Figure 2. Plate mesh

Results and Discussion

Variation in the Stress Intensity Factor

In this work, we analyze the effect of thermal loading on the behavior of a cracked plate. To this end, the model is subjected to temperature variations below its glass transition temperature (Tg). These temperatures induce thermal stresses in the material according to the following relationship:

$$\sigma_{th} = E.\alpha.\Delta T$$

Where E is the material's modulus of elasticity;
α is the coefficient of thermal expansion;
ΔT is the difference between the reference temperature and the material's temperature.

Our objective is to numerically analyze, using the finite element method, the behavior of cracks under thermal loading in three dimensions. Temperature is a fundamental physical parameter for the fabrication of metal-ceramic assemblies. The study of thermal behavior in bimaterials, specifically copper/Al_2O_3, containing a central crack of size "a" subjected to temperature variations T, is the objective of this work. The behavior of this crack is analyzed in terms of the variation of the stress intensity factor in both opening mode (KI) and shear mode (KII).

The results obtained, presented in Figure 3, illustrate the evolution of the stress intensity factor (SIF) in modes I and II as a function of temperature and crack defect size. It appears that, regardless of the temperature variation ΔT, the SIF in mode I (opening) increases with crack growth, reflecting the direct influence of thermal stresses generated by the heating of the bimaterial. Conversely, the SIF in mode II (shear) decreases with crack propagation, this decrease being more pronounced at relatively low temperatures. Overall, the values for mode II remain significantly lower than those for mode I, indicating that crack propagation occurs primarily in a mixed mode with a dominant opening. This behavior is attributed to the nature of the thermal stresses, which are particularly sensitive to temperatures below the glass transition temperature of the bimaterial.

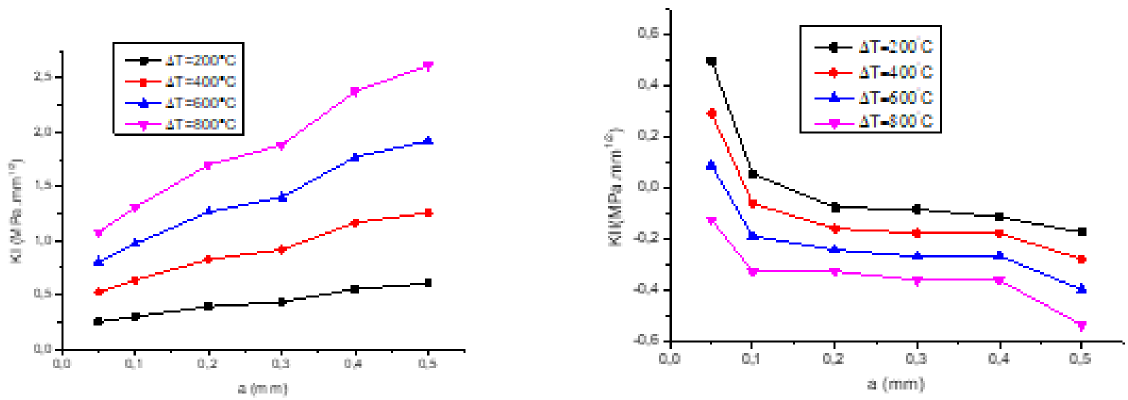

Figure 3. Variation of the stress intensity factor in mode I and II as a function of the crack defect size

We considered it important to study the interaction effect between a crack in one of the two materials forming the structure and its interface. This study deals with the case of a crack in the ceramic parallel to the interface, propagating perpendicularly to it. In our case, we considered a crack of length a = 0.2 mm propagating within the brittle material (alumina). As before, the structure is subjected to thermal stress, and the results of the analysis of this effect are illustrated in Figure 4. These figures show the variation of the stress intensity factor in mode I as a function of the crack-interface distance.

The maximum values of this factor are obtained when the crack-interface distance approaches the mid-height of the ceramic. The stress intensity factor in mode I decreases sharply as the crack moves away from the interface, i.e., for crack-interface distances greater than d = 2.5 mm. Depending on the loading mode, this ratio leads to a strong crack-interface interaction, the level of which increases with the increasing thermal load on the bimaterial.

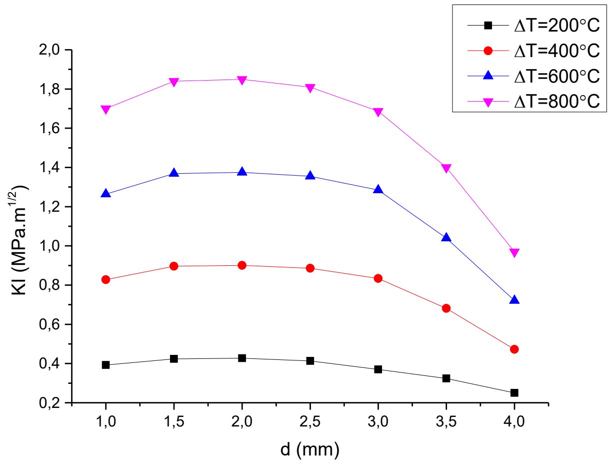

Figure 4. Variation of the stress intensity factor in mode I as a function of the crack-interface distance.

To better illustrate the thermal behavior of the bimaterial during fracture, we studied the case of a central crack for different types of materials (ceramic-metal). The same loading and simulation conditions used previously were retained for this part of the study, with a temperature of 800°C and an interfacial distance d = 1 mm. The model response is analyzed in terms of the variation of the stress intensity factor in the opening mode (KI).

Initially, we analyzed the thermal behavior of a bimaterial for three types of metal/ceramic assemblies: copper/Al_2O_3, copper/ZrO_2, and copper/AlN. The results obtained are illustrated in Figure 5. These figures show the variation of the stress intensity factor in the opening mode as a function of crack propagation for different coefficients of thermal expansion. This parameter increases significantly when the metal is bonded to a ceramic with a very low α coefficient (AlN). High thermal conductivity combined with low thermal expansion makes AlN an excellent material resistant to thermal shock and able to withstand rapid heating and cooling. The KI induced in the Copper/Al_2O_3 bond is greater than that generated in the Copper/ZrO_2 assembly, regardless of the crack defect size.

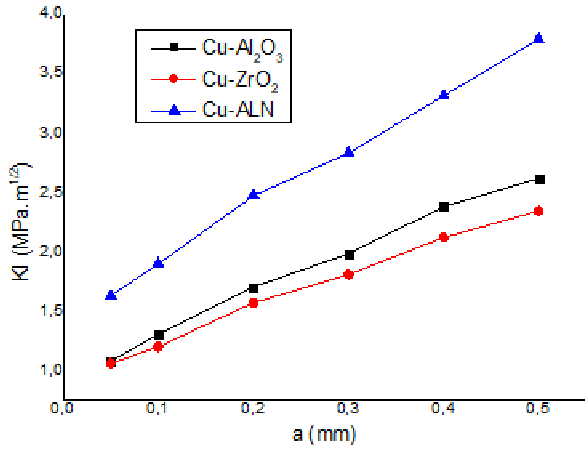

Figure 5. Variation of the stress intensity factor in opening mode as a function of crack progression for different Copper/Ceramic pairs

The results in Figure 6 lead to an analysis of the crack-interface interaction effects when the latter is located on the ceramic. This analysis focuses on three material pairs, characterized by their coefficient of thermal expansion. The figure shows the evolution of the stress intensity factor in mode I as a function of the distance d between the crack and the interface. We observe that the value of KI increases significantly when the crack is close to the interface; this increase is particularly significant for a Cu-AlN pair with a low coefficient of thermal expansion. Moving the crack further from the interface leads to a reduction in the stress intensity factor in mode I. This effect is due to the fact that, far from the interface, the interaction effect disappears completely.

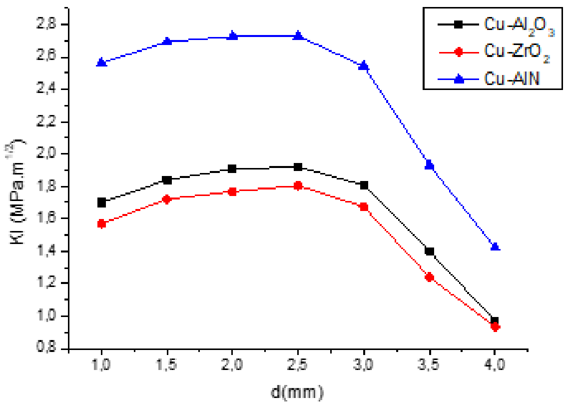

Figure 6. Evolution of the stress intensity factor in mode I as a function of the distance separating the crack and the interface.

Conclusion

Numerical analysis, performed using the finite element method (FEM), of the fracture behavior of a bimaterial subjected to thermal loading leads to the following conclusions:

The stress intensity factor in mode I of a crack propagating perpendicular to the interface is highly dependent on the distance between the crack and the interface. In the immediate vicinity of the interface, the cracking energy increases considerably, reaching values comparable to those of an interfacial crack. Conversely, far from the interface, the interaction effect becomes negligible. Furthermore, the stress intensity factor increases significantly when the metal is bonded to a ceramic with a low coefficient of thermal expansion, such as AlN. The more ceramic (such as alumina) is bonded to a metallic material with a high coefficient of thermal expansion, the higher the stress intensity factor in mode I. However, it remains weak for the silver/Al_2O_3 pair, considered a thermally compatible system. Thus, it can be concluded that, under the effect of thermal stresses, crack propagation occurs primarily in mode I, reflecting a fracture mechanism dominated by crack opening rather than shear.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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