

Numerical analysis of the crack behavior Interface-Fiber: interfacial crack

Abstract

Background: Numerous studies have been conducted on composite materials, concerning development at the microscopic scale. In addition, the elaboration of composites at relatively high temperatures leads to very localized residual stresses in the fiber and the matrix in the neighborhood very close to their interface. These shear stresses put the fiber in compression and the matrix in tension. The objective of this work is to analyze the behavior of cracks initiated in the interface of a unidirectional ceramic fiber-reinforced composite and to study, in three dimensions by the finite element method, the effect of these constraints on the crack behavior appeared in this composite. This behavior is analyzed in terms of stress variation intensity factors in modes I, II and III. The effect of several parameters has been studied.

Keywords: composite, matrix, shear stresses, ceramic, variation intensity factors

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Introduction

The use of composite materials in industrial applications has been increasing for several years, and this in all industries: automotive, aeronautics, space, marine, railway or even sports, medical and nuclear. The performances in terms of mass gain, mechanical properties and manufacturing offer many possibilities of applications, sometimes very complex. Research activities specific to these materials are also very present in laboratories around the world to better understand the behavior of composite structures across many topics of study, with the aim of improving their uses and their adequacy with the industrial application. The joining of ceramics to metals is inherently difficult because of their distinctly different properties. But considerable efforts have devoted to the development of joining technologies during recent past years have led to significant successes.¹ Dissimilar materials had to join together in many technical areas. One example of the ceramic to metal joint is to combine the wear resistance, high temperature strength and thermal or electrical resistance of the ceramic with the ductility of the metal. Due to the difference of the elastic properties and the thermal expansion coefficients of the ceramic and metal the high stresses occur at the intersection of edges and the interface of the joint under mechanical or thermal loading.²

The joining of ceramics to metals is a critically important technology for the effective use of advanced materials.³ Due to differences in thermal and mechanical properties the stresses and strains can develop near a ceramic-metal interface stress concentrations which can result the plastic deformation of metal during both fabrication and under subsequent thermal or mechanical loading (cracking within the ceramic). Tremendous efforts have been made to understand this phenomena⁴⁻⁹ and (for the case of direct bonding without an interior) the effects of material properties and specimen geometry on stress and strain distributions and fracture mechanisms are reasonably well understood. The realization of Silver-Alumina is made in solid state. The mechanical resistance of this assembly depends primarily on the conditions of its elaboration, particularly on the atmosphere of elaboration. The fracture resistance is generally determined according to the nature of the atmosphere of the elaboration of these kinds of junction.¹⁰⁻¹² Silver is a noble metal and by reacting with the alumina do not give an intermediate compound. Assembly of this metal in

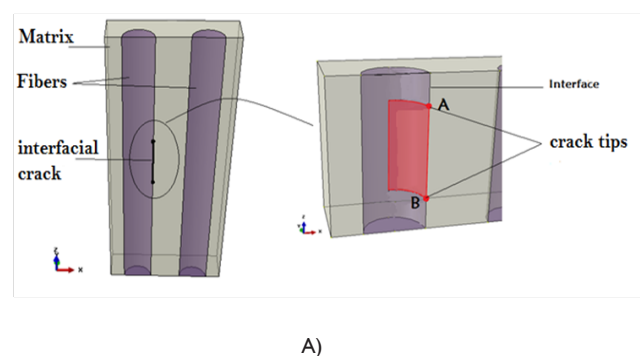
alumina form no-reactive junction. The originality of this part of the work lies in the analysis of the effect of the internal stresses generated in the composite during its elaboration on the mechanical behavior of these materials. We study the effect of these constraints on the behavior of matrix-initiated cracks in two types of Al/Al₂O₃ and Epoxy/C composite materials. In this section we analyze the influence of crack location, size, orientation and propagation.

Method

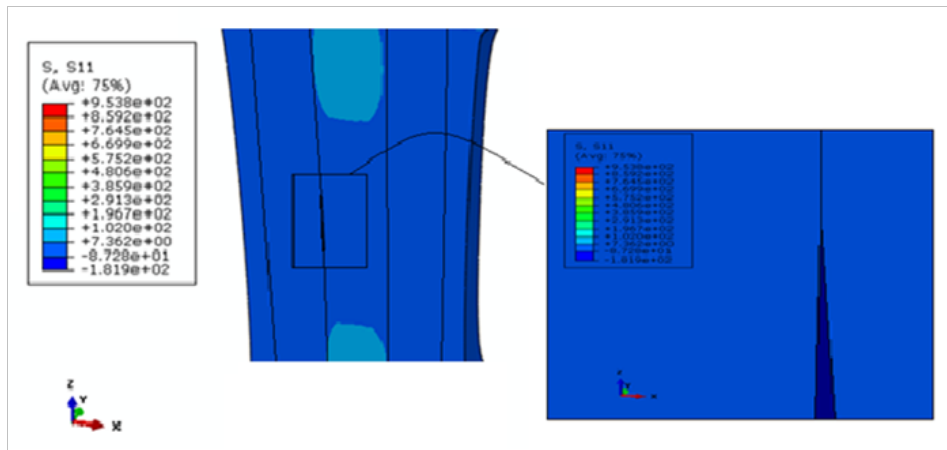
The effect of commissioning constraints on the crack behavior, initiated at the interface of a metal matrix composite (Al/Al₂O₃)¹³ and another organic matrix composite (Ep/C), is studied. The analysis in terms of stress intensity factor variation, of a crack size “a” initiated at the interface Fiber / Matrix as shown in Figure 1A. This cracked structure is subjected to uniaxial compression forces. To do this, opposing forces of uniaxial compression were applied perpendicular to the axis of the “x”. This numerical modelling has been taken using the ABAQUS¹⁴ finite element program

Results

Figure 1B shows the distribution of circumferential stresses by these forces, in the near vicinity of the cracking front. It is observed that these mechanical stresses are important at the tip of the crack. Analyzes show that the increase in crack length and applied load has the effect of increasing the growth of these stresses.



A)



B)

Figure 1 A) The analyzed model, B) stresses distribution. $a=10\mu\text{m}$, compression efforts: $\sigma=150\text{MPa}$.

Discussion

For a better representation of this development, in Figure 2–5, is illustrated the variation of the stress intensity factors in the KI opening mode and in the KII and KIII mixed mode as a function of the size of the interfacial crack. These figures clearly show that there is a defect size greater than 8 microns, beyond which these factors seem insensitive to the advance of the crack. These factors believe then remain almost constant with the advance of the crack. This behavior is all the more accentuated as the cracked structure has a greater fault of cracking. The results given in Figure 4 & 5 clearly indicate that such a cracking defect propagates essentially in mixed mode (modes I). The results obtained in Figure 2 represent the variation of the stress intensity factor in opening mode (mode I) as a function of the stress applied for the two composites ($\text{Al}/\text{Al}_2\text{O}_3$) and (Ep/C). The analysis of this figure

clearly shows that this criterion of rupture is all the more important as the size of the crack is more accentuated. The interfacial crack is all the more unstable as the amplitude of the compressive forces applied is more significant. Our results show that such a crack propagates in pure opening mode. In fact, the values of the stress intensity factor in shear modes (modes II and III) are also marked as shown in Figure 3 & 4. Since the stress applied to the matrix and the fiber exerts to open the crack lips. The kinetics of propagation is proportional to the mechanical stress solicited as well as to the size of the crack. From the results obtained, it is noted that the FIC values for an interfacial crack of the Epoxy/Carbon composite are lower compared to the FIC values of the aluminum matrix composite reinforced with Alumina fibers, due to the properties physical and mechanical different from the two materials. This leads to the propagation of the interfacial crack in the metal matrix composite.

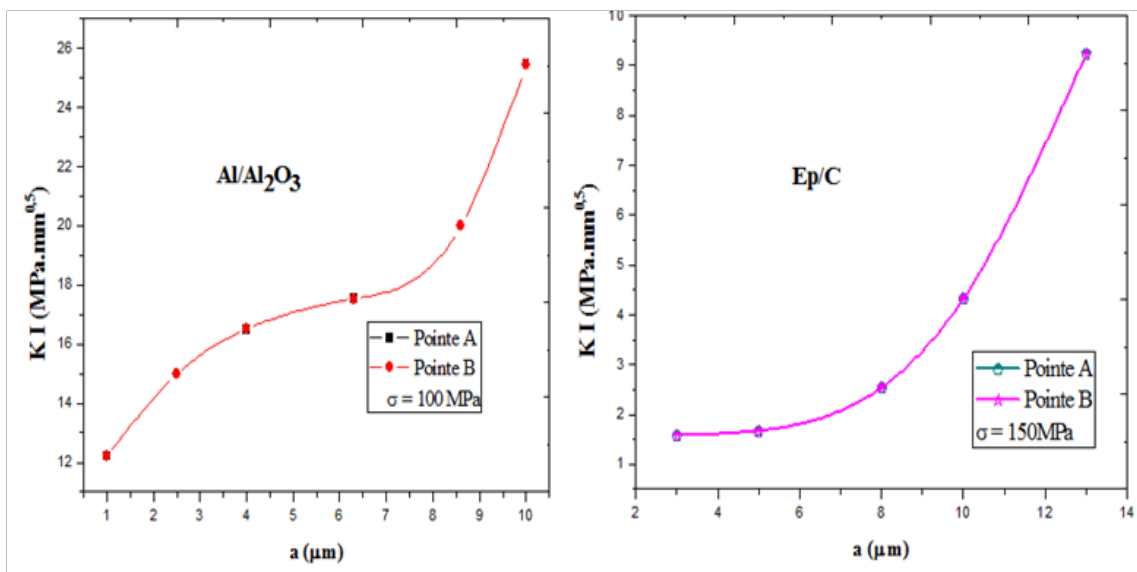


Figure 2 Variation of the stress intensity factor KI as a function of the interfacial crack size and the amplitude of the loading applied.

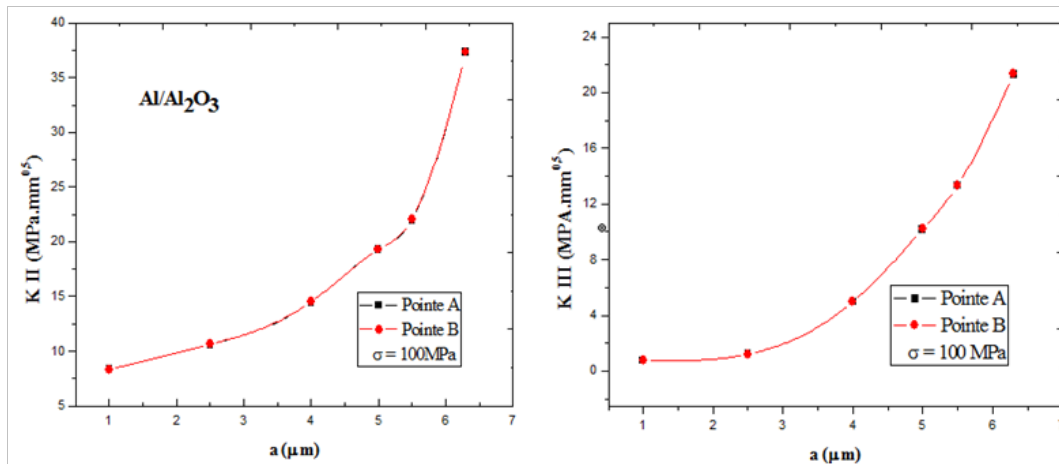


Figure 3 Variation of the stress intensity factor in mode II and III as a function of the interfacial crack size: Al / Al₂O₃.

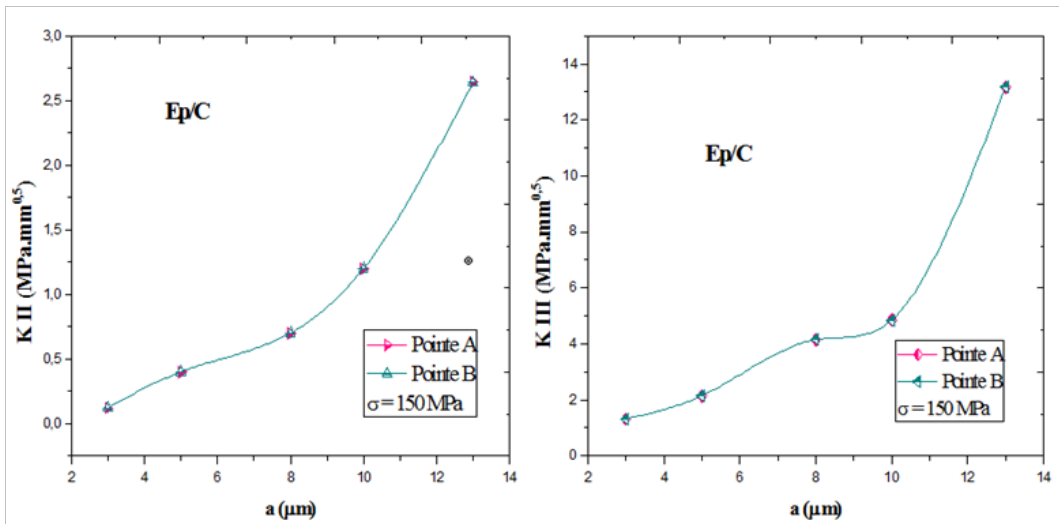


Figure 4 Variation of the stress intensity factor in mode II and III as a function of the interfacial crack size: Ep/C.

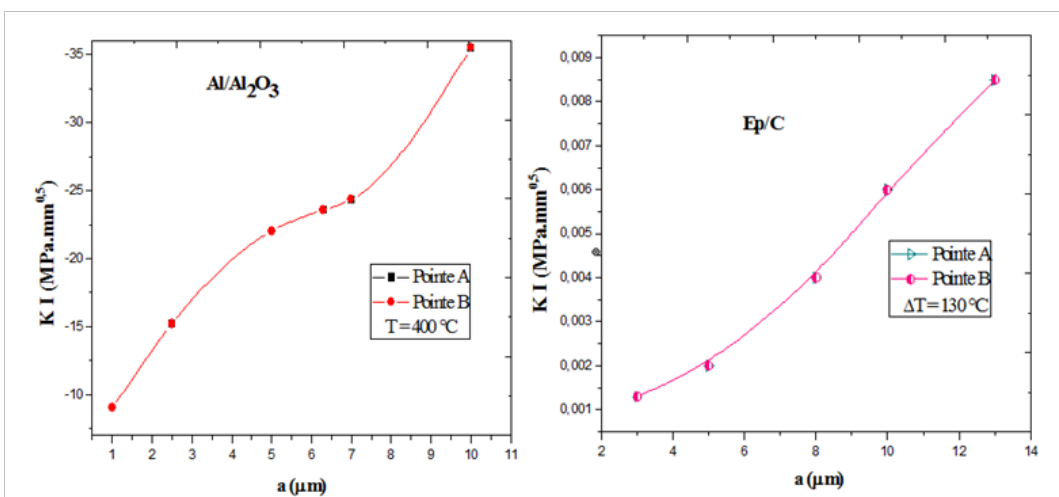


Figure 5 Variation of the FIC according to the size of the crack in mode I.

On the other hand, the effect of the elaboration temperature of metallic and organic matrix composite materials on the behavior of a crack, initiated at the fiber-matrix interface, was studied. The temperature of elaboration of the composites is a fundamental parameter of the mechanical adhesion of the interface; it governs the flow of the aluminum and controls its encrustation on the roughness defects of the alumina.¹⁵ Figure 5 shows the variation of the FIC at the front of this cracking defect in opening mode. This figure shows that the higher this temperature, the more the interfacial crack is more unstable in mode II and III and the absence of the opening mode. The aluminum matrix composite material is subjected to highly localize internal stresses at its interface. The two constituents of the composite (matrix and fiber) are subjected to residual stresses of thermal origin. These constraints are all the more intense as the temperature of implementation is high; the processing temperature is a key physical parameter for the durability of composite materials. It conditions the level and the distribution of residual stresses of thermal origin. Indeed, the stress intensity factor in

shear mode is all the more important that the processing temperature is higher. The effect of this temperature on the behavior of an interfacial crack is illustrated in figure. In Figure 6 is illustrated the influence of the temperature of this assembly on the intensity factor in mode II. Compared to Mode I, the values of this failure criterion are higher, regardless of the temperature. It is the residual stress at the interface, tension in the metal matrix and compression in the ceramic fiber that is responsible for such behavior. Indeed, these constraints, closely related to the temperature difference ΔT , solicit more strongly the shear interface. Which explains the superior propagation in mode II.

In mode III, the values of the stress intensity factor are comparable to those of mode II (Figure 6). This mode of rupture is all the more marked as the size of the crack is more favored. Our results clearly show that a crack initiated at the fiber-matrix interface propagates, under the effect of the internal stresses induced in the fiber and the matrix, in mixed modes (modes II and III). This propagation is all the more unstable as this composite is subjected to high temperatures.

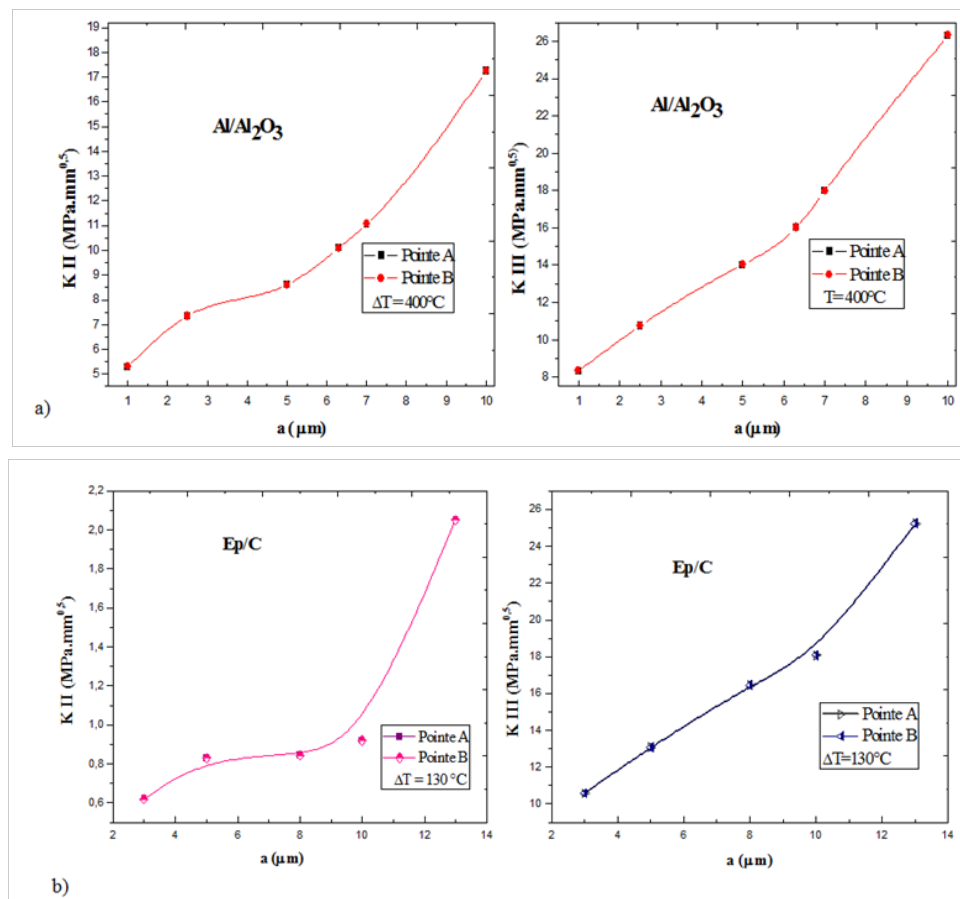


Figure 6 Variation of the FIC according to the size of crack in mixed mode II and III.

On either side, the interfacial cracks of a composite subjected to a thermal loading are initiated during the development process due to the difference in stiffness and the coefficient of thermal expansion between the fiber and the matrix. This difference weakens the adhesion between these two constituents and consequently promotes the initiation of interfacial cracks. The results obtained in this study show that a crack initiated at the interface propagates in mixed modes II and III. This is due to the nature of the states of these

thermal constraints. It can be deduced that it is necessary to optimize the production temperature in order to reduce the residual stresses responsible for the instability of the cracking defect and to ensure good mechanical strength of the interface. In this case, we analyze the combined effect of the two mechanical and thermal loadings, previously studied separately, on the behavior of a crack initiated at the interface between the ceramic and the metal. This type of loading simulates the additional phenomenon of the residual stresses

of thermal origin to the commissioning constraints of materials composed of these two constituents. In other words, a superposition of the two stress intensity factors resulting from the application of the constraints of mechanical origin and thermal origin. The results obtained from this analysis are shown in Figure 7. The latter illustrates the influence of this superposition of mechanical and thermal energies on this rupture criterion in opening mode. It is noted that this type of loading favors the growth of the crack in mode I. It will be noted,

however, that, compared to the individual application of each of these two loadings, their simultaneous application accelerates the kinetics of propagation of this crack. This acceleration is defined in terms of increasing the stress intensity factor. The shear crack growth of his lips, modes II and III, is very insensitive to combined loading (Figure 8). Indeed, the values of the stress intensity factors in these two modes are comparable to those resulting from an individual thermal loading.

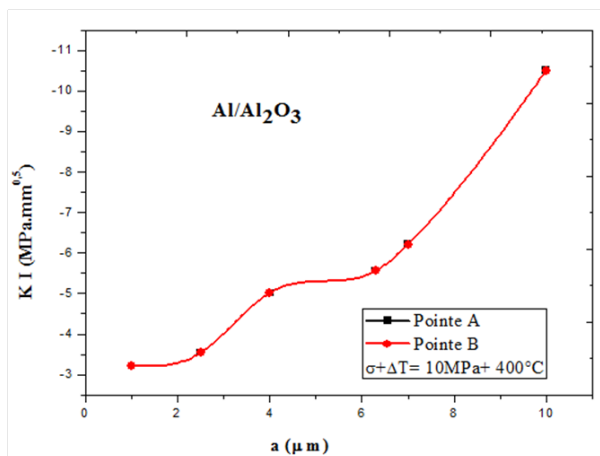


Figure 7 Variation of the FIC according to the size of the crack in mode I.

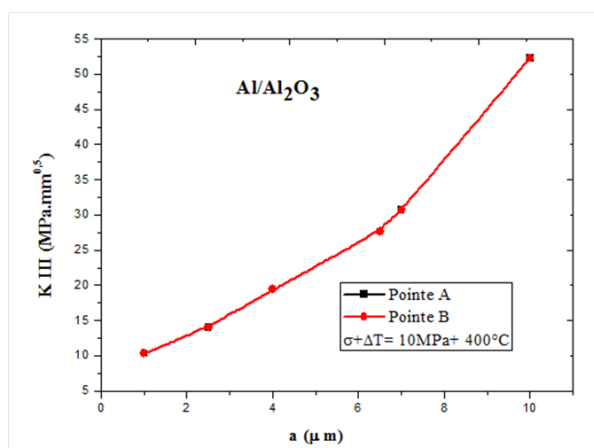
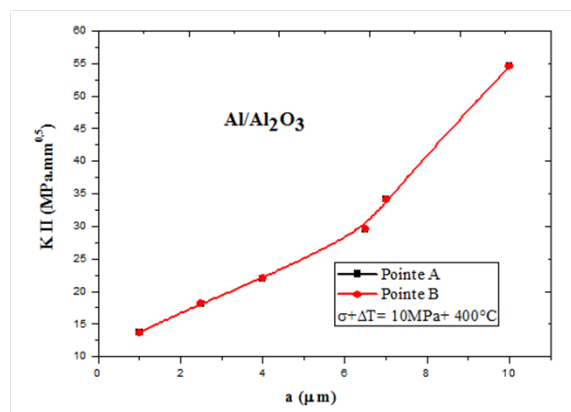


Figure 8 Variation of the FIC according to the size of crack in mixed mode II and III.

Conclusion

The results obtained in this work show that: In the same composite model, a crack occurring at the fiber / matrix interface is unstable in mixed mode and the KII and KIII values are much higher than those of the KI opening mode, for thermal loading. On the other hand, for a mechanical loading (compression), this crack propagates essentially by the opening of its lips.

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None.

Conflicts of interest

Authors declare that there is no conflict of interest.

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