Elastic-Plastic Analysis Of Cracks On Metal/Ceramic Joints

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Abstract. In the present work the finite element method is used to calculate the J integral and the size of plastic zone at the interfacial crack tip of ceramic / metal bi-materials in mode I. The plastic behaviour of the stress–strain curve of the metal is approximated by a Ramberg–Osgood function and the ceramic has a linear elastic behaviour. The effects of the plastic properties of metal and the crack length were highlighted as well as the effect of the metal thickness on the variation of the J integral at the crack tip.

Introduction

Metal/ceramic bimaterials with a mismatch in mechanical properties are frequently encountered in engineering applications. The fracture at or near such interfaces often limits the reliability of these joints. Knowledge of the stress and deformation fields at the crack tip at a metal/ceramic interface is needed in order to develop a fundamental understanding of this fracture process. In many of these situations, cracks initiate at interfaces and advance along or away from the interfaces. The safety of such components inevitably requires a thorough understanding of their behaviour under load. The case of a crack along an interface between brittle and ductile materials has been investigated extensively, both experimentally [1-4] and theoretically [5-12]. The concentration of stresses near the crack tip with applied loading can induce plastic deformation in the nearby ductile section [13]. On one hand, this could lead to increased stress concentration at the crack tip due to the added compliance [14,15], whilst on the other, the energy absorption associated with crack propagation could be increased [12]. It is well established that the mechanical energy release rate for a crack along an interface between two materials is generally higher than for an equivalent crack in a homogeneous material [16]. Tvergaard and Hutchinson [8-10] have studied crack growth along the interface between brittle and ductile materials and showed that the effective toughness, increased with crack extension. The increase resulted from the development of a plastic zone on the ductile side of the interface, and was dependent on yielding behaviour, crack-tip mode mixity and process zone parameters (essentially, crack tip toughness). Consideration of small scale plasticity and shielding models leads to fracture resistance curves with minimum and maximum values differing by more than one order of magnitude.
In the present work the finite element method is used to calculate the J integral and the size of plastic zone at the interfacial crack tip of ceramic / metal bi-materials in mode I. The plastic behaviour of the stress–strain curve of the metal is approximated by a Ramberg–Osgood function and the ceramic has a linear elastic behaviour. The effects of the plastic properties of metal and the crack length were highlighted as well as the effect of the metal thickness on the variation of the J integral at the crack tip.

Results and analysis

Fig. 1 illustrates geometrical model of interface crack in pure mode I. The bimaterials consist of two materials: alumina and metal, characterized by their mechanical properties respectively E_1 = 345 GPa , ν_1 = 0,3 and E_2 = 72 GPa, ν_2 = 0,3. The ceramic has a linear elastic behaviour and the metal has an elastic plastic behaviour. The plastic behaviour of the stress–strain curve of the metal is approximated by a Ramberg-Osgood function. The geometrical characteristics of the plate are the length H and the width w such as w=H. One consider edge interface cracks of length a. The plate is subjected to a tension load uniformly distributed with σ_0= 70 MPa. Eight noded isoparametric elements are used to mesh the bi-material plate. Fig. 2 shows typical mesh model of the plate. The plane stress conditions were supposed. Calculations were carried out by the finite element ABAQUS code [17].

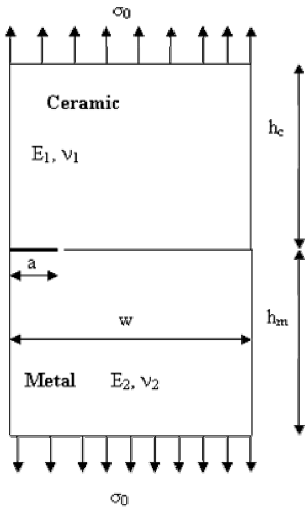

Figure 1: Geometrical model of plate.

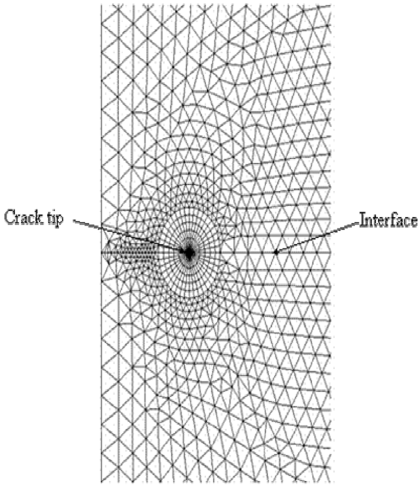

Figure 2: Mesh model of plate.

Effect of the metal yield stress

The aim of this study is to analyze the effect of the yield stress of the metal on the J integral variation and the extent of the plastic zone at the interface crack tip. Fig. 3, illustrates the stress–strain curve of metal for various yield stresses (n=6). The effect of the yield stress of metal is shown on the Fig. 4. This one represents the variation of the J parameter according to the normalised crack length. One can observe according to Fig. 4 on the one hand that, the effect of the yield stress of metal appears until a normalised crack length a/w>0,25. For low crack length, the J parameter is almost constant; this can be due to the low intensities of stresses and strains fields at the crack tip. In addition, the J integral decreases when the yield stress of metal increases; this phenomenon is more significant when the (a/w) ratio increases. Indeed, one note a significant difference between the values of the J integral it is about 65 % when the yield stress decreases for 350 MPa to 200 MPa. Our results show clearly that the value of the J integral depends on the nature of material. Indeed, the most ductile material led to a high value of the J integral. This increase characterizes the size of the plastic zone. The value of this integral decrease with the increase of the properties of resistance. Generally, the strain energy characterizing the size of the plastic zone, is more significant in a ductile material than in a brittle material.

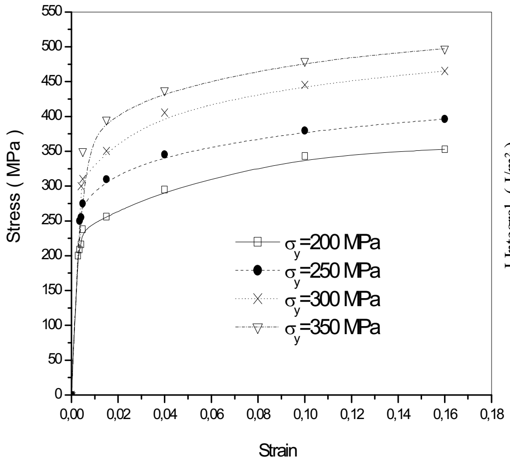

Figure 3: Stress–strain curve.

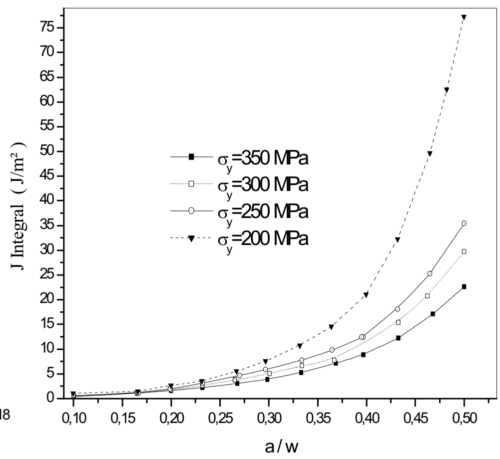

Figure 4: Variation of J integral vs a/w for various values of yield stress.

Fig. 5 illustrates the size of the plastic zone according to the nature of the materials (yield stress). The extents of the plasticized zones were given using the Von Mises criterion in plane stress for normalised crack length a/w = 0,33. It is noted that the metal whose properties of ductility are high presents the most significant size of the plastic zone. At crack tip of a ductile material the fields of strain are considerable involving more significant plastic zone. In this case, the mechanical energy at the crack tip is absorbed by material in the form of dislocations. The increase of this energy is significant leads to an increase of density of the dislocations leading to more significant plastic zone. The size of the plastic zone depends not only on the nature of metal related to ceramics, but also of the intensity of the mechanical energy at the crack tip.

If we compare the sizes of the plastic zone at the crack tip of various yield stress of metal we observe, for example, that the radius of the plasticized zone of the metal whose yield stress is σ_y = 200 MPa is worth four times the radius of the plastic zone of the metal of which yield stress σ_y = 350MPa.

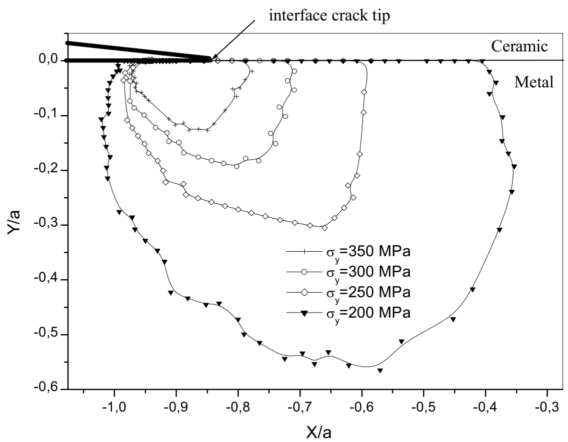

Figure 5: Size of plastic zone at interface crack tip for various values of yield stress.

Effect of hardening exponent

Fig. 6, illustrates the variation of the J integral according to the a/w ratio for various values of the hardening exponent n. It can be see that the most significant values of the J integral are obtained for high crack lengths and high value of hardening exponent. Indeed, an increase in the hardening exponent of material involves an increase in J integral in this case, the properties of ductility of metal increase, involving an increase in the values of J integral. The hardening exponent characteristic of the plastic strain of a material is directly related to the value of the J parameter.
It is noted however that, the effect of the hardening exponent appears only for high crack lengths. Indeed, for the low sizes of crack (a/w<0,3) we observe that the values of the J integral are almost equal whatever the hardening exponent. To show the effect of the hardening exponent on the variations of the strain field and the size of the plastic zone we represent on Fig. 7, the variation of the Von Mises equivalent stress for a/w = 0,33. It can be see that the equivalent stress is strongly related to the hardening exponent. Indeed, the highest values of the equivalent stress are obtained for the low values of n. In this case, the properties of resistance of metal increase, involving an increase in the equivalent stress. The increase in the hardening exponent of material involves an increase in the properties of ductility of metal. This led to the stress relaxation at a crack tip; this relaxation of stress generates a significant plasticization which slows down the propagation of crack. This shows clearly that a material with elastic plastic behaviour stores energy in the form of plastic strain. A great quantity of energy at the crack tip contained in a ductile material is absorbed in the form of plastic strain by metal. If we compare the values of the σ_{eq} / σ_y for n=6 and n = 12 we can note a variation of about 10%.

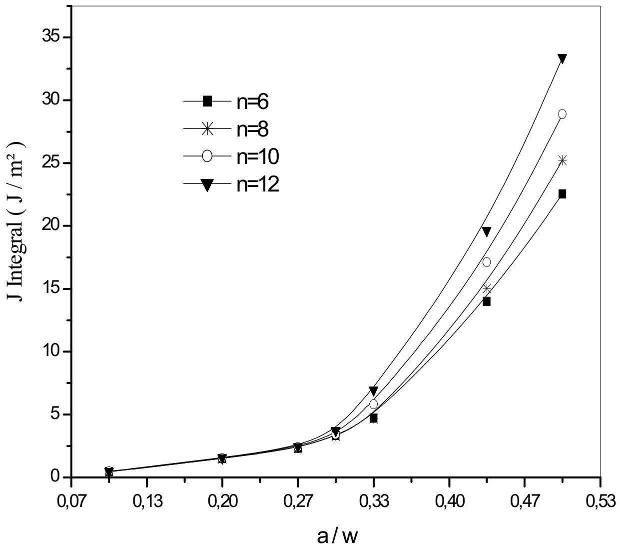

Figure 6: Variation of J integral vs a/w for various values of the hardening exponent.

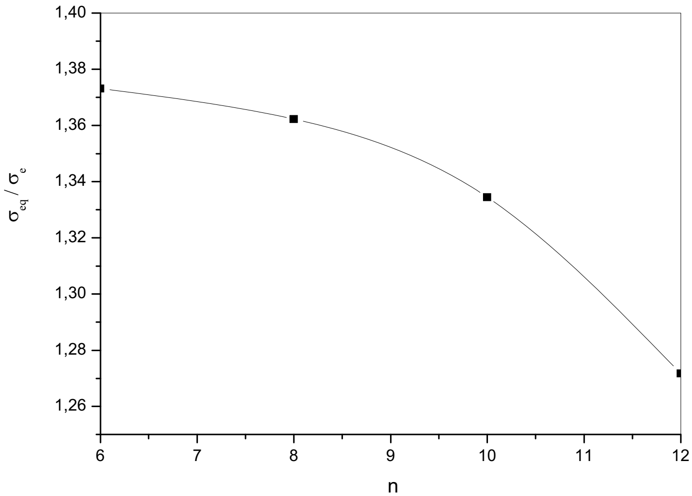

Figure 7 : Variation of equivalent stress vs hardening exponent.

The effect of the hardening exponent on plasticization at the crack tip is shown on the Fig. 8. The latter illustrates the extent of the plastic zone for three hardening exponent n = 6,12 and 18. We notice that the radius of the two plastic zones at crack tip thus depend on the hardening exponent and on the strain energy stored in metal. Indeed, the variation noted between the plastic zones increase with the hardening exponent. This variation does not exceed the 10% for n=6 and n=12. When the hardening exponent increases from 6 to 18, the variation noticed between the plastic zones is about 50%.

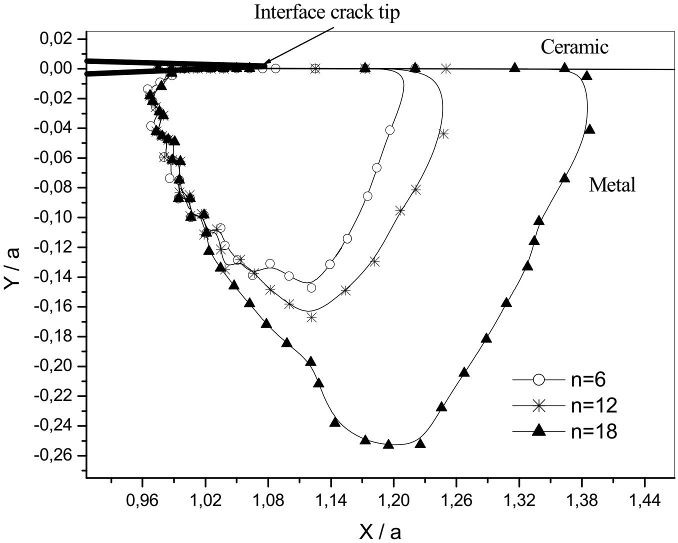

Figure 8 : Size of plastic zone for various values of the hardening exponent.

Effect of bimaterial thickness

Fig. 9, shows the variations of the J integral according to the normalised crack length for various ratios h_C / hm. It is shown that for low crack lengths whatever are the ratios hc/hm , the values of the J integral are almost constant. The effect the thicknesses of the couple ceramic/metal on the variation of the J parameter appears when a/w > 0,14; we observe that the J integral increase quickly when the metal thickness decreases (hc/hm=3). The reduction of ceramics thickness (hc/hm=1/3) involves a reduction in the J integral. The variation noted between the value of the J parameter for hc/hm=3 and hc/hm=1/3 increase with the crack length; it reaches 50% for a/w=0,28. The reduction of the metal or ceramics thickness leads to the increase in the strain energy involving an increase in the J integral. When the thickness of metal is close to that of ceramics, It is noted that the variation of the J integral is almost constant. This effect is more significant for low crack lengths.
The results of Fig. 9, show that the reduction of the metal thickness compared to ceramics leads to the increase in the J parameter and consequently to the increase of the size of the plastic zone at the crack tip as indicated in Fig. 10. This one illustrates the plastic zone size for the ratios hc/hm = 1,3 and 6 and for a/w=0,3. The extent of the plastic zone at the crack tip strongly depends on the ratio thicknesses of two materials of the couple ceramic/metal. Indeed, the radius of the plastic zone for hc/hm=6 ratio is worth almost triple of that of the ratio hc/hm=1. This increase in the plastic zone can be due to the significant plastic strain caused by the reduction of the metal thickness. This phenomenon is confirmed by other authors [18,19].

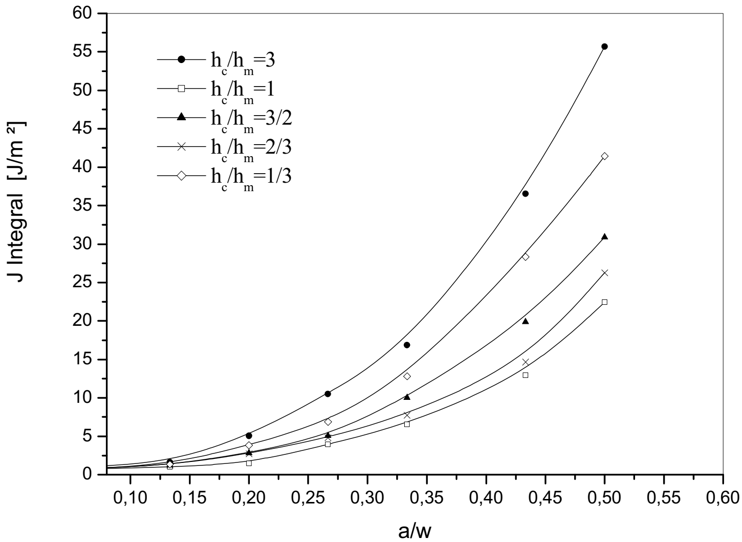

Figure 9: Variation of J integral vs a/w for various ratios h_C / hm.

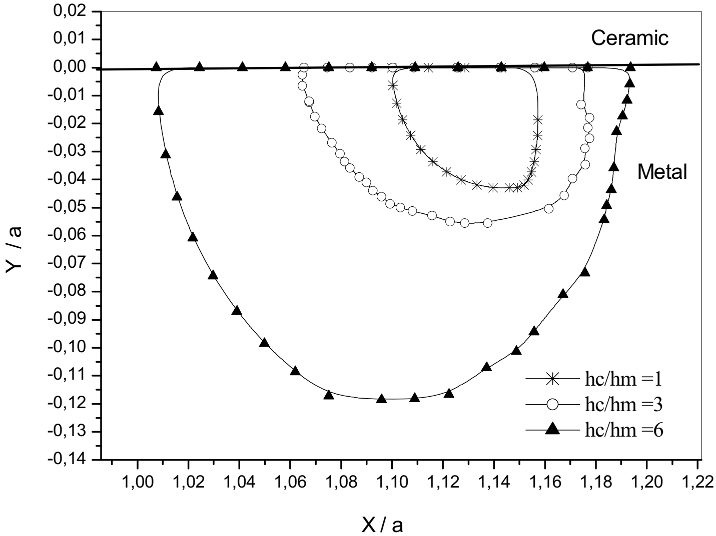

Figure 10 : Variation of J integral vs a/w for various ratios h_C / hm.

Conclusion

In this study the J integral has been used to analyze the fracture behaviour of ceramic/ metal bi-materials. The obtained results allow us to deduce the following conclusions:

- The values of the J integral depend on the crack size and on the nature of metal, there is a critical size of the crack beyond of which there is risk of brutal propagation of the crack which can lead to a brutal fracture of the junction. A variation of the yield stress in the Ramberg–Osgood function influenced strongly the results. The J integral value decreases as the mechanical properties increase.
- The hardening exponent characteristic of the plastic strain of materials is directly related to the J integral value and the plastic zone extent of. The increase in the hardening exponent of material involves an increase in the properties of ductility of metal.
- The thickness of metal join to ceramics plays a very significant role in the mechanical resistance of the bimaterial. The reduction of the metal or ceramics thickness leads to the increase in the strain energy involving an increase in the J integral and the size of the plastic zone.

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