Impact of the Boron/Epoxy patch on the Reduction of the interaction Effect Inclusion-Cracked Notch

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Abstract. The understanding of the materials fracture requires thorough studies of the phenomena of starting and propagation of the cracks which, in general, occur in the strong stress concentrations zones due to the geometrical and/or metallurgical effects [1]. This also makes it possible to explain the phenomenon of fracture starting and to quantify the SIF with respect to the notch geometry and crack length. In this paper an inclusion-notch interaction effect is modelled using the finite element method. The effect of the inter-distance notch-inclusion and the rigidity ratio of inclusion-matrix are highlighted with regard to the SIF evolution. The SIF evolution of a crack emanating from a notch inside the inclusion as well as the interaction with the inclusion when the notch is outside is studied. The reduction of the SIF due to the interaction crack-inclusion effect by a patch in composite is also determined.

1 Introduction

The maximum stress being reached at the notch roots; place where the first plastic zone will be created [2]. Many materials have important micro-structural heterogeneities such as inclusions, cavities and microscopic cracks … etc. The elastic behaviour of materials is very much affected by the presence of defects which can lead to the weakening of the structure and cause its destruction. In areas with high stress concentrations due to geometric or metallurgical effects, microcracks appear; these microcracks develop and coalescing with each other until they form a macroscopic size crack which can propagate up to the ruin of the structure [2,3].

Many authors [4-7] have studied the presence of inclusions; as well as several studies have focused on the influence of the effect of the notch on the behavior of the material; for this purpose the following authors were cited: Glinka [8], Kujawski [9], Lukas [10], Newman [11], Newman et al. [12], Usami [13] and his [14]. In metals having an inclusion population, the germination of the cavities often takes place starting from these inclusions which generally responds to a normal stress criterion [15,16]. The germination is then the consequence of the localization of the deformation between the cavities resulting from large inclusions. The nature of matrix deformation taking place starting from these inclusions strongly influences the germination process according to the inclusion size and the stress levels.

Studies were carried out on crack emanating from the semicircular notch repaired by a semicircular composite patch in mode I and pure mode II [17–19]. In the same context, the comparison of the results of cracks repaired with an octagonal composite patch was the object of a study by Ouinas et al.[20]. A comparison analysis of the fracture behavior of adhesive bonded lap joints using two notched specimen: circular and semi-circular notches is made by Ouinas [21]. The disbond effect at the crack tip emanating from these notches located in the overlap region was highlighted. It indicates that the variation of K_I^2 versus the disbond has a linear relationship. The authors [22–24] showed the influence of the disbond on the amplification of the stress concentrations factor at the notch root and of the SIF at the crack tip. They concluded that the crack growth rate is dominated by the SIF near the location and size of the preexisting disbonds.

Our prime interest in this paper is the repair or strengthening by bonding a semi-circular composite patch on the region of high stress concentration due to the interaction effect between the notch and inclusion or a crack from the semi-circular notch in interaction with this defect. Two cases are considered: a crack emanating from a notch located inside the inclusion and a crack emanating from a notch located far from the inclusion.

2 Finite element analysis

The interaction effect between an inclusion-notch or inclusion-crack emanating from a notch in a thin plate of height $H = 203.2mm$, width $w = 152.4mm$ and thickness $e_P = 1mm$ has been studied. The plate is subjected to a mono-axial tensile force giving a stress $\sigma = 120MPa$. The mechanical properties of the plate and patch are given in table 1. The adhesive is characterized by its shear modulus G_a and its thickness e_a. Since the plate is thin, therefore a state of plane stress is considered. The patch size is four times the notch radius $\rho_R = 4\rho_{not}$ with $\rho_{not} = 12.7mm$ and the thickness $e_R = 1mm$.

Table 1. Properties of materials.

Property	aluminium	Bron/epoxy
$E_{1c}(GPa)$	72	208.0
$E_{2c}(GPa)$		25.4
ν_{12}	0.33	0.33
$G_{12}(GPa)$		16.6
$G_{13}(GPa)$		16.6
$G_{23}(GPa)$		14.6

Figure 1 shows the geometrical model of the repaired plate in the presence of an inclusion distant d with respect to the crack emanating from the notch. The structure made up of the plate and patch is meshed using the standard eight node quadrilateral elements. This type of elements has been proved to be effective for the elastic linear analysis and with the advantage of well characterizing the singularities.

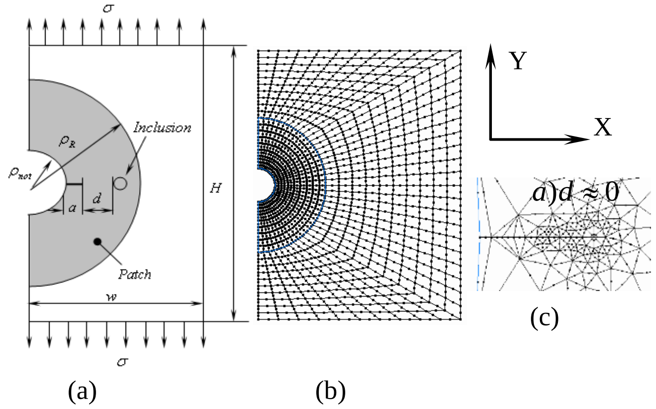

Fig. 1. Finite elements typical mesh : (a) plate, (b) patch and (c) at crack tip.

The finite element analysis is performed using the commercial software Franc2D/L [25]. The stress singularity at the crack tip can be incorporated in the solution by moving the eight nodes to the quarter-point locations [26]. The modified crack closure techniques are used to calculate the SIF. The adhesive layer forces are obtained by integrating the shear stresses in the adhesive. These traction forces being proportional to the displacements, therefore it is possible to express the forces in the adhesive in terms of nodal displacements from which the rigidity matrix of the adhesive element is obtained. The study of the influence of the inclusion and its distance on the variation of the SCF and SIF of a crack emanating from the notch and propagating towards the inclusion is investigated herein. The influence of the patch is also highlighted with regards to the SCF and SIF reductions.

2 Interaction between a semi-circular notch and an inclusion

Metals generally contain a certain number of “hard” particles, called inclusions. These inclusions are of different shapes and sizes. The onset of the ductile fracture of such materials is carried out by de-cohesion of the matrix around the inclusions, or by fragmentation of these, giving therefore formation of micro-cavities. These cavities grow and change form under loading. These inclusions are generally the cradle of the stress concentrations in materials and can therefore be a starting point and propagation of a crack.

The effect due to the presence of inclusion on the behaviour of a notched structure is studied first, and then followed by the investigation of the influence of a composite patch on the reduction of the amplified stresses due to the cumulated interaction of the notch, inclusion and crack.

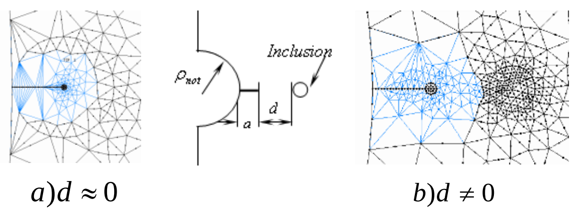

Fig.2. Mesh in the level of inclusion and cracked notch
a) Cracked inclusion at the semicircular notch,
b) Inclusion far from cracked semicircular notch.

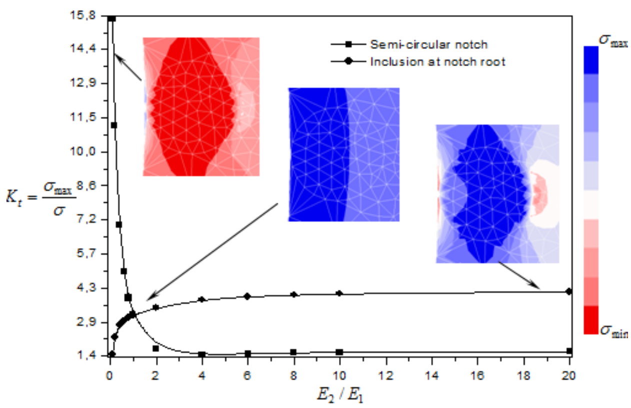

Fig.3. Variation of the SCF on the level of the notch and inclusion vs. rigidities ratio.

In addition, for a better understanding of the phenomenon, the stress distributions in the notch and around the inclusion are considered. In this case the variation of the stress as a function of the notch-inclusion inter-distance and the rigidity ratio inclusion-matrix are studied. The influence of the inter-distance inclusion-notch on the ligament of the plate is also considered. The normal stress distribution around the crack and the inclusion as well as the SIF variation with respect to the crack length and the rigidity ratio inclusion-matrix, are presented. The material properties constituting the plate are: the Young’s modulus E_1 and the Poisson's ratio ν_1.

This plate contains a spherical inclusion having a diameter $d_I = 1mm$ located at a distance d from the notch. This inclusion is characterized by its Young's modulus E_2 and Poisson's ratio ν_2 ($\nu_1 = \nu_2$). Figure 2 represents the geometrical model of the plate studied with two hypothetical preliminary cracks; one inside and the other one outside the inclusion. With the inclusion close or far away from the notch, the zone is meshed using a six node isoparametric triangular elements and particularly at the crack tip where special elements were used.

3.1 Uncracked plate

An adjacent inclusion to the notch is considered, and for a better study of the effect of the mechanical properties of the inclusion, the evolution of the stress at the notch and inclusion roots are represented in Fig.3 as a function of the rigidity ratios matrix/inclusion (E_2/E_1).

When the inclusion is harder than the matrix $(E_2/E_1 > 1)$, the maximum stresses are obtained at the level of the notch and inclusion. This shows that the presence of this type of inclusion weakens the structure and leads to the increase of the risk of a crack onset. This latter can therefore take place either at the notch root or at the inclusion level.

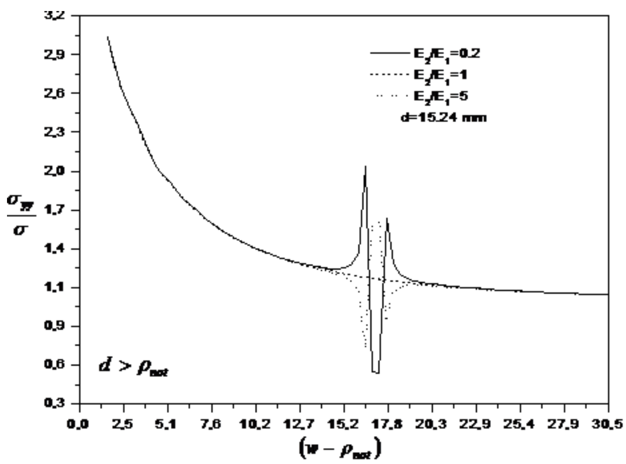

Fig.4. Variation of the normal stress field in the ligament with the presence of inclusion far from the semicircular notch root.

The effect of inclusion is sensitive when it has the same Young modulus as the matrix. The highest stresses are distributed within the notch $(E_2/E_1 = 1)$. When the inclusion presents properties of ductility more important than those of the matrix $(E_2/E_1 < 1)$, the minimum stresses are distributed on both sides of the notch root whereas the maximum stresses are concentrated inside the inclusion. Therefore, an inclusion less hard than the matrix, leads to a more fragile structure and great risk of crack onset.

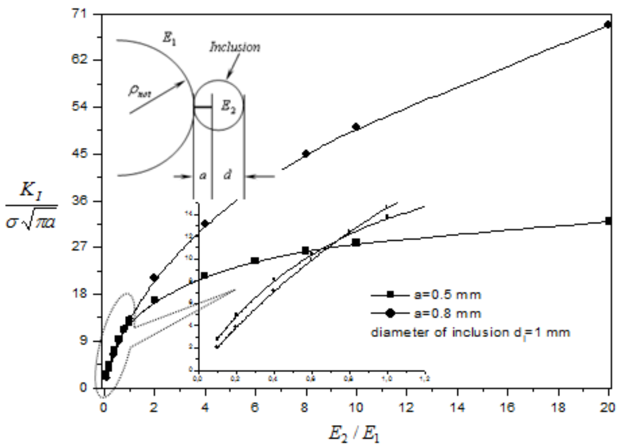

Fig.5. Variation of the SIF vs. E_2/E_1 inclusion/matrix.

The stress at the notch root is noticed to decrease with the increasing ratio (E_2/E_1). This decrease is more pronounced for ratios $(E_2/E_1 \le 2)$ and for values higher than 2, the evolution of the SCF at the notch root becomes insignificant. This can be explained by the fact when the strength properties of the inclusion are much less than those of the matrix, the stress concentrations are at the inclusion level. However, an opposite behaviour takes place at the notch level. The curves cross each other when $(E_2/E_1 = 1)$; the FCC are identical.

In Figure 4, the normal stress variation on the ligament in the presence of an inclusion for a distance $d = 15.24mm$, is plotted. This last shows that, when the distance is higher than the semi-circular notch radius, the maximum stresses are at the notch level for any rigidity ratio value (E_2/E_1). These stresses decrease as we approach the inclusion then increase or decrease at the inclusion/matrix interface compared to the stresses in the matrix depending on the mechanical properties inclusion/matrix. This effect was explained previously.

3.2 Cracked plate

a) Inclusion located at the notch root $(d = 0)$

In this case the crack is in the inclusion and propagating towards the matrix. The variation of the SIF as a function of various ratios (E_2/E_1) is investigated. The curves obtained correspond to the various crack lengths respectively $a = 0.5mm$ and $a = 0.8mm.$. The obtained results are plotted in Figure 5 where it shows that the SIF grows with the increasing rigidity ratios (E_2/E_1). For a given value of (E_2/E_1), an increase in the crack length involves an increase in the SIF, which means that an increase in this ratio leads to a more important energy at the crack tip. The SIF resulting from of a short crack is more important than that of a long crack when the ratios $E_2/E_1 < 1$. For higher ratios; an increase in the crack size causes an increase in the SIF.

To highlight the composite patch effect on the SIF evolution inside the inclusion, the value of the SIF, of both a reinforced and a non reinforced crack, is plotted against the ratio d/a for three different ratios E_2 / E_1.

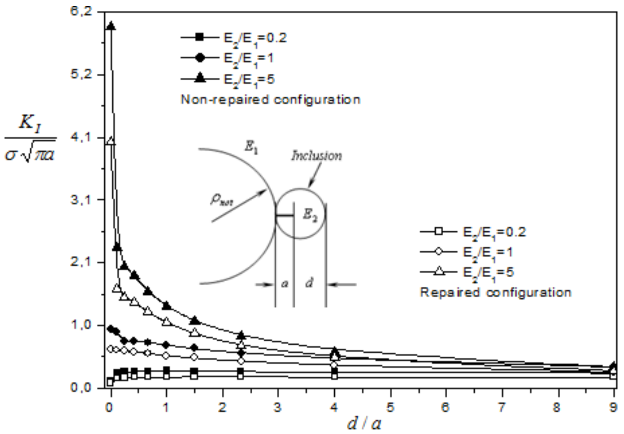

Fig.6. Comparison of the SIF of repaired and unrepaired crack vs. d / a.

It should be noted however that the SIF increases very appreciably with the ratio d / a for a ratio $E_2 / E_1 = 5$, its maximum value is reached at the interface inclusion/matrix. In this case, the crack propagates towards the least hard material (matrix) and its energy weakens as the crack moves away from the interface. For a ratio $E_2 / E_1 = 0.2$, the normalized SIF decrease with the increase d / a ratio. In this case the energy at the crack tip decreases when it approaches the interface. When the matrix and inclusion are both of the same mechanical characteristics $(E_2 / E_1 = 1)$, it is the crack effect which appears and the propagation in the matrix takes place with a constant energy.

It can be noticed as well that the boron/epoxy patch decrease the SIF by approximately 35% for the three cases presented. The reduction of the factor K_I is not very importance due to the cumulative effect the notch and inclusion (Fig.6).

b) Distant inclusion of the notch root (d # 0)

In this case it is supposed that the crack is located in the notch in the matrix and propagates towards the inclusion distant $d = 12mm.$. The behaviour of the normalized SIF against the ratio E_2 / E_1 for two ratios $d / a = 0$ (the crack tip at the interface) and $d / a = 0.2$ (very close to the interface) is investigated. This behaviour is illustrated in Fig. 7. It can be noticed that for $d / a = 0$ the normalized SIF grows suddenly when the E_2 / E_1 ratio decreases. This increase in the SIF is much more pronounced for ratios less than 2 $(E_2 / E_1 \leq 2)$. It is necessary to note however than this phenomenon appears when the crack is very close to the inclusion. The evolution of the SIF with the reduction in the E_2 / E_1 ratio becomes not very sensitive when the inclusion is far from the crack and the interaction effect of inclusion/crack disappears. Since the crack-inclusion interaction when $d = 0$ produces a greater energy at the crack tip, a repair is carried out using a composite patch for different rigidity ratios. The composite patch is found to reduce the normalised SIF in a significant proportion. The maximum SIF corresponds to the ratio $E_2 / E_1 = 0.2$; the composite patch produces a maximum reduction of about 75%.

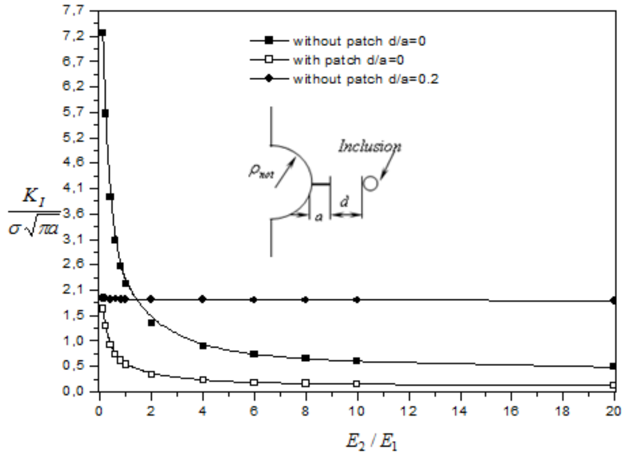

Fig.7. Variation of the SIF vs. E_2 / E_1 for various positions of the crack.

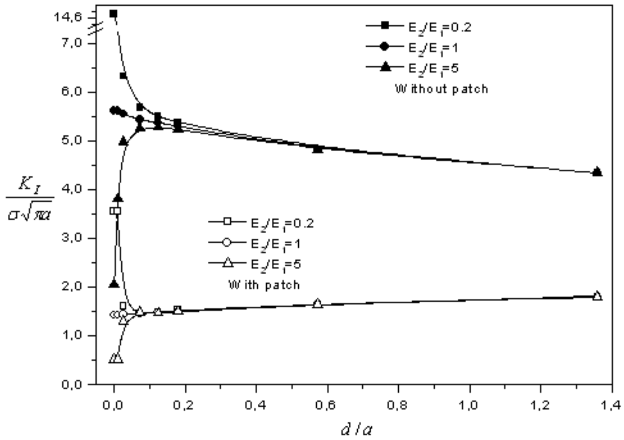

Fig.8. Comparison of the variation of the SIF vs. to the advance of the crack emanating from the notch towards inclusion (repaired and unrepaired).

The effect of the composite patch on the crack propagation towards an inclusion located in the plate ligament for various ratios of matrix/inclusion rigidity is investigated. The influence of the inclusion, matrix properties and the d / a ratio on the behaviour of the normalised SIF is also studied. The results are shown in Fig. 8. It can be noticed that the behaviour of the normalised SIF is strictly the opposite of that presented in Fig. 6. The normalised SIF increases with the d / a ratio for values $E_2 / E_1 = 1$ and $E_2 / E_1 = 0.2$, and decreases when $E_2 / E_1 = 5$. This variation is more important for values $d / a \leq 0.25$. When the d / a ratio tends towards zero, the normalised SIF tends towards a zero value which shows clearly that a harder inclusion can slow down the crack propagation.

It can be noticed that for the three rigidity ratios, the variation of the SIF for a reinforced crack is considerably reduced. This variation becomes important for values $d/a < 0.1$ instead of $d/a \leq 0.25$, therefore the distance of the field of interaction is decreased by 60% in the presence of the composite patch. When the ratio a/d tends towards infinite (i.e. the crack tip is at the interface), the normalised SIF for the three ratio of E_2/E_1 tends towards a value four times less when compared to the unrepaired configuration.

4 Conclusions

This study was undertaken with an aim to study the behaviour of a notched plate under the effect of the presence of a metallurgical defect close to the notch. The strong importance of the crack onset at the notch root is related to the presence of an inclusion in this zone or close to it. During the propagation, the macroscopic crack will coalesce with the cavities created by decohesion at the inclusion level. Since these inclusions are generally harder than the matrix, therefore the following observations could be cited:

-If the crack is in the matrix and propagates towards the inclusion, its energy decreases when the inclusion is harder than the matrix; thus it has tendency, either to stop or change the propagation path. An opposite behaviour occurs when the crack is inside the inclusion, its energy increases when approaching the interface and has the tendency to accelerate.

-The SCF at the semicircular notch root increases exponentially when the inclusion presents properties of ductility more important than the matrix ($E_2/E_1 < 1$). An opposite behaviour occurs at the inclusion level, the SCF of inclusion decreases quadratically. In this case, the maximum SCF at the notch root is obtained for the weakest ratio E_2/E_1, it is of the order of 10 times more important than that of the inclusion.

-When the ratio $d/a = 0$, the interaction crack-inclusion produces a great energy at the crack tip and the maximum reduction of the SIF obtained by the patch corresponding to a ratio $E_2/E_1 = 0.2$ is about 75%.

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