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Investigation of the Reduction in the Interaction Inclusion-Cracked Notch Effect Using Composite Patches

[1]D. Ouinas, [2]B. Achour , [2]M. Boukendakdji and [2]M. Touahmia

[1]Laboratoire de Modélisation Numérique et Expérimentale des Phénomènes mécaniques
Department of Mechanical Engineering, University Abdelhamid Ibn Badis, Mostaganem 27000-Algeria
[2]Department of Civil Engineering, University of H'ail, Saudi Arabia

Abstract - The understanding of the materials fracture requires a global study of the onset and propagation phenomena of cracks which, in general, occur in the high stress concentrations zones due to the geometrical and/or metallurgical effects [1]. This allows also to explain the phenomenon of fracture onset and to quantify the SIF as a function of the geometry of the notch and the crack length. In this paper, the inclusion-notch interaction effect has been modelled using the finite element method. The effects of the spacing notch-inclusion and the rigidity ratio inclusion-matrix, are highlighted on the evolution of the SIF. The evolution of the SIF of a crack emanating from a notch inside the inclusion and the interaction with this latter is studied. The use of a composite patch to determine the SIF reduction due to the extent interaction crack-inclusion effect is also investigated.

Keywords: Boron/epoxy patch, Stress concentration factor (SCF), Stress intensity factor (SIF), Inclusion-matrix interface, Finite element analysis.

1. INTRODUCTION

The maximum stress is reached at the notch root; place where the first plastic zone is expected to take place [2]. Many materials have important micro-structural heterogeneities such as inclusions, cavities and microscopic cracks...etc.

The elastic behavior of materials is very affected by the presence of defects which can involve the weakening of the structure and cause its destruction.

In areas with high stress concentration due to the geometrical or metallurgical effects, micro-cracks appear; these micro-cracks develop and coalesce to form a macro-crack which propagates until the structure fails [2, 3].

Many authors [4-7] focussed their studies on the presence of inclusions; just as several studies were related to the influence of the notch effect on the materials behavior; in this respect, the following authors are cited; Glinka [8], Kujawski [9], Lukas [10], Newman [11], Newman et al. [12], Usami [13] and Sih [14].

In metals having an inclusion population, the germination of the cavities often takes place starting from these inclusions which in general is the consequence of the normal stress criterion [15, 16]. The germination is therefore the consequence of the localization of the deformation between the cavities resulting from large inclusions. The nature of the matrix deformation taking place starting from inclusions strongly influences the germination process by taking into account the inclusions size and the stress levels.

This paper deals with the repairing or reinforcing using a composite semi-circular patch bonded on the area of high stress concentration due to the interaction between the semi-circular notch and the structure defect (inclusion) where a crack emanating from the notch interacts with the defect. Two cases were considered: a crack emanating from notch located inside the inclusion and a crack emanating from a notch located at a distance from the inclusion.

2. FINITE ELEMENT ANALYSIS

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

Properties	aluminum	boron/époxy
$E_1(GPa)$	72	208.0
$E_2(GPa)$		25.4
ν_{12}	0.33	0.33
$G_{12}(GPa)$		16.6
$G_{13}(GPa)$		16.6
$G_{23}(GPa)$		14.6

Table 1. Properties of matérials.

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 plate and patch is meshed using the quadrilateral standard elements with eight nodes. This type of elements had been proved to be efficient for the elastic linear analysis as well as having the advantage of characterizing the singularities. The singularity at the tip of the crack could be incorporated in the solution by replacing the elements at the tip of the crack by quarter point special elements [17].

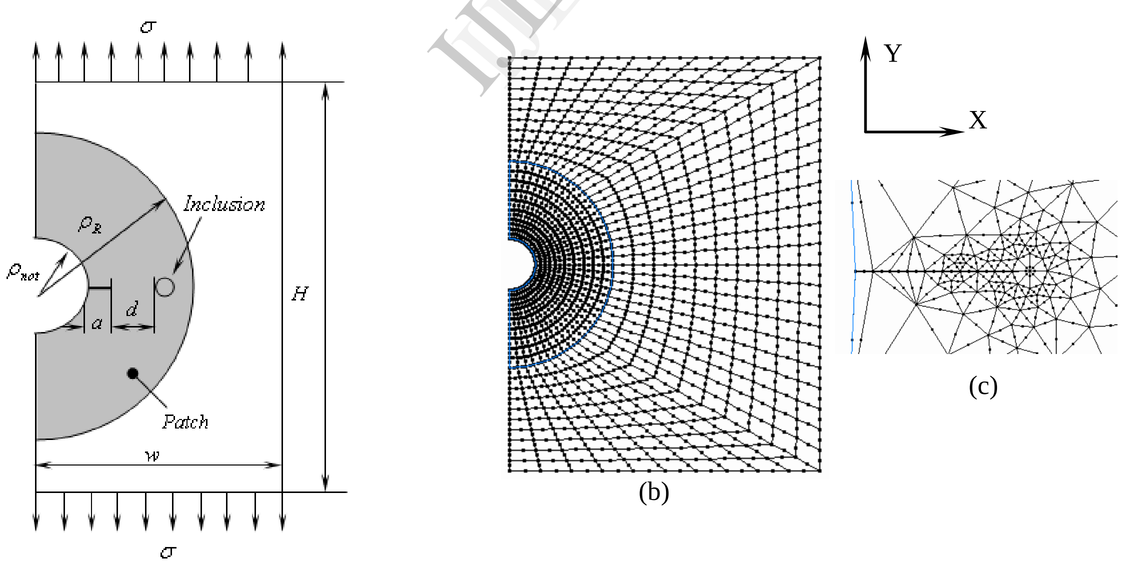


Fig. 1. Typical finite element modelling: plate, patch and crack tip.

The modified crack closure techniques are used to calculate the SIF. The adhesive layer forces are obtained by integrating shear stresses in the adhesive. The traction forces being proportional to displacement, this formulation will make it possible to express the forces in the adhesive in terms of nodal displacement to obtain the rigidity matrix of the adhesive element.

In what follows the influence of 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 studied. The influence of the patch is determined as a consequence of the possible reductions in the SCF and SIF.

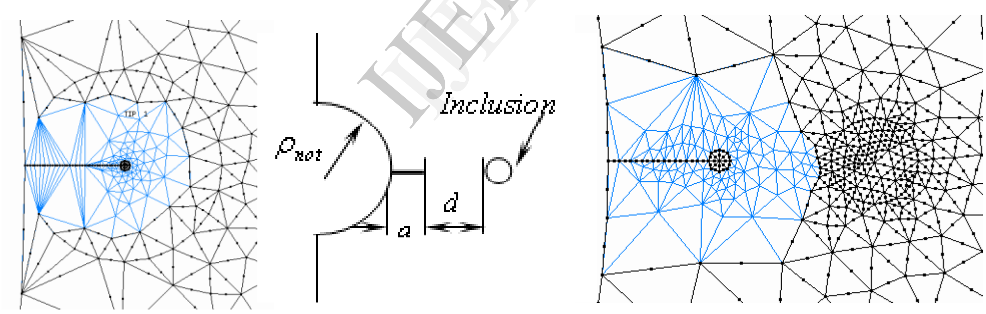
3. INTERACTION BETWEEN A SEMICIRCULAR NOTCH AND THE INCLUSION

The metals generally contain a certain number of particles « hard », called inclusions. These inclusions could be of different shapes and sizes. The onset of the ductile fracture of such materials is carried out by decohesion of the matrix around inclusions leading to the formation of microcavities. These cavities grow and change form due to a subjected loading. The inclusions are generally the origin of the stress concentrations in materials and can be a source of onset and propagation of cracks.

In a first approach, the study of the effect due to the presence of inclusion on the behavior of a notched structure is undertaken. In the second one, the influence of the composite patch on the reduction of the amplified stress due to the cumulated interaction of the notch, inclusion and crack is investigated.

In addition, the study has been extended considering the stress distribution at the notch level and around the inclusion. In this case, the variation of the stress as a function of the notch-inclusion distance and the rigidity ratio inclusion-matrix is studied. The influence of the distance inclusion-notch on the plate ligament is considered. The distance is considered null when the crack is inside the inclusion. The normal stress distribution around the crack and inclusion as well as the variation of the SIF 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 configuration of diameter $d_I = 1mm$ located at a distance d from the notch. This inclusion is characterized by its Young's modulus E_2 and by the Poisson's ratio ν_2 $(\nu_1 = \nu_2)$. The Fig. 2 represents the geometrical model of the plate studied with a preliminary crack inside and away from the inclusion. The plate, notch and inclusion is modelled using triangular isoparametric elements with 6 nodes and special elements at the crack tip.



$a) d \approx 0$ $b) d \neq 0$

Fig.2. Meshing at the inclusion level and cracked notch

a) Inclusion inside a cracked semi circular notch,

b) Inclusion away from the root of a cracked semi circular notch.

3.1. Uncracked plate

Given an inclusion adjacent to the notch with the thickness of the interface tending toward zero, and for a better study of the effect of the mechanical properties of inclusion, the evolution of the stress at the notch root and of inclusion as a function of the ratio of rigidities matrix/inclusion (E_2/E_1) are represented in Fig. 3.

When 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 increase the risk of crack onset. This latter can thus take place either at the notch root or at the inclusion level. Thus, the stresses are more important in the inclusion than inside the notch.

The effect of the inclusion is sensitive when its Young's modulus is the same as the matrix. The highest stresses are distributed around 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 minimal stress are distributed on both sides of the notch root and the maximum stresses are concentrated inside the inclusion. Therefore, an inclusion less hard than the matrix leads to a more weakened structure and great risks of crack onset.

It is noticed that the stress at the notch decreases with the increasing ratio (E_2/E_1). This decrease is very pronounced for ratios $(E_2/E_1\leq 2)$ and for values higher than this number, the evolution of the SCF at the notch level becomes less sensitive. This can be explained by the fact that when the resistance properties of inclusion are much lower than those of the matrix and the stress concentrations are on the level of inclusion. An opposite behavior is noticed on the inclusion level. The curves cross when $(E_2/E_1=1)$ and the SCF is identical.

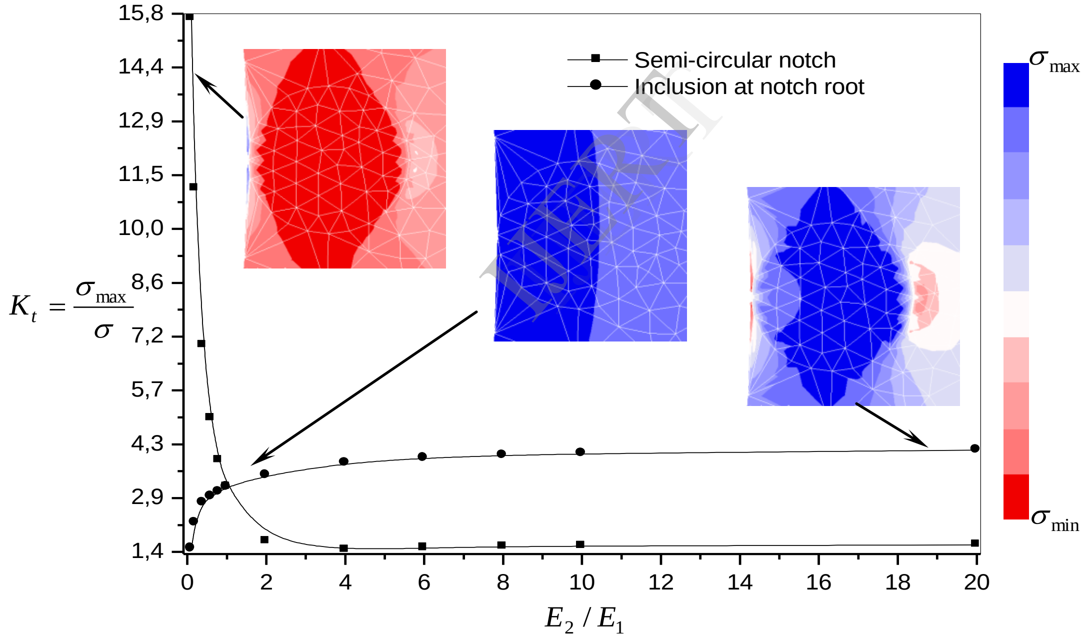


Fig.3. SCF variation at the notch and inclusion level as a function of the rigidity ratios.

In Fig. 4, the variation of the normal stresses on the ligament in the presence of an inclusion for $d=15.24mm$, is plotted. It is noticed that when the distance d is higher than the semicircular notch radius, the maximum stress are at the notch level for any value of the ratio (E_2 / E_1). These stresses decrease gradually towards the inclusion then increase or decrease at the inclusion/matrix interface compared to the stresses in the matrix with respect to the difference of the mechanical properties inclusion/matrix. This effect was explained previously.

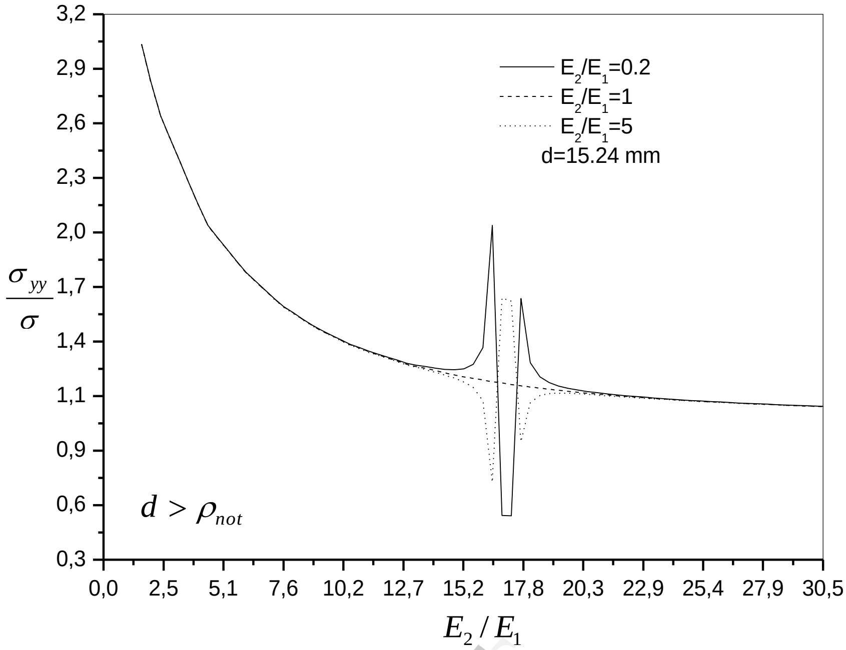


Fig.4. Variation of normal stresses field on the ligament in the presence of an inclusion away from the root of a semi-circular notch.

3.2. Cracked plate

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

In this case the crack is inside inclusion and propagates towards the matrix. The variation of the SIF as a function of various ratios (E_2 / E_1) is studied. The curves obtained correspond to the various crack lengths respectively $a = 0.5mm$ and $a = 0.8mm$. The obtained results are plotted in Fig.5. It is noticed that the SIF grows with the rigidities ratio (E_2 / E_1). For a value of (E_2 / E_1), an increase in the crack length leads to an increase in the SIF. Therefore an increase in this ratio leads to more important energy at the crack tip.

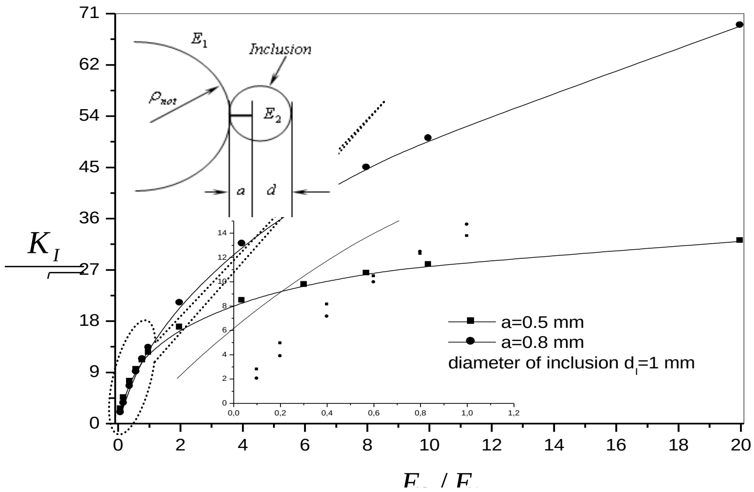


Fig.5. SIF variation as a function of E_2 / E_1 inclusion/matrix.

The SIF of a short crack is more important than that of a long crack when the ratio $E_2 / E_1 < 1$. For higher ratios; the crack size causes the increase in the SIF.

To highlight the effect of the composite patch on the evolution of the SIF inside the inclusion, the SIF of a reinforced and not reinforced crack as a function of ratio d/a for three ratios E_2 / E_1. is plotted.

The distance d decreases as the crack propagates inside the inclusion. It should be noted however that the SIF K_I increases significantly with 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 decreases with the increase of the d/a ratio. In this case, the energy at the crack tip decreases when it approaches the interface. When the matrix and inclusion show the same mechanical properties $(E_2 / E_1 = 1)$, one can consider just one material and it is the crack effect which appears and propagates in the matrix with a constant energy. It can be noticed that the boron/epoxy patch decreases the SIF approximately by 35% for the three cases represented. The reduction of the factor K_I is not very importance in view of the presence of the cumulative effect notch-inclusion (Fig.6).

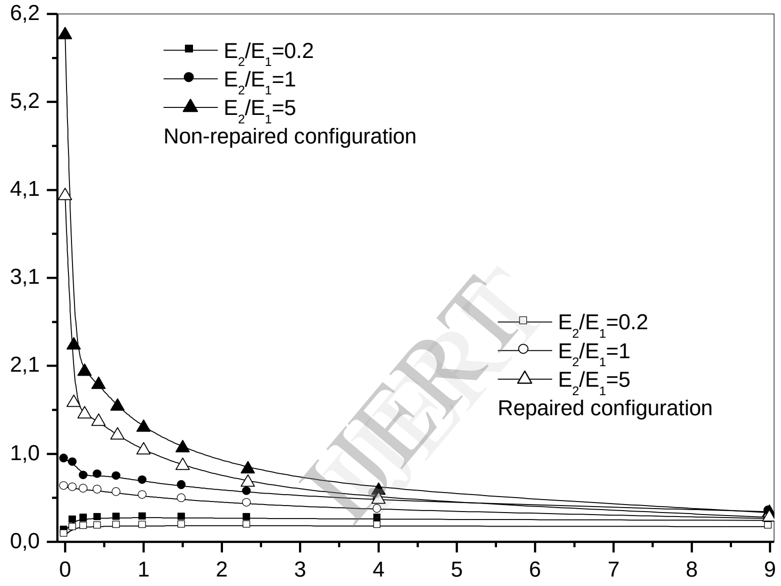


Fig.6. Comparison of the SIF of a repaired and non repaired crack as a function of d/a.

b) Inclusion away from the notch root (d # 0)

In this case the crack is supposed to be located in the notch of the matrix and propagates towards the inclusion distant $d = 12mm$. The behaviour of the normalized SIF as a function of E_2 / E_1 for two ratios $d/a = 0$ and $d/a = 0.2$ ($d/a = 0$, i.e. the crack tip is in the interface and $d/a = 0.2$ at a distance close to the interface), is investigated. This behaviour is illustrated the Fig. 7. It can be noted 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 lower than 2 $(E_2 / E_1 \leq 2)$. It is necessary to note however that 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 inclusion is far away from the crack and the interaction effect of inclusion/crack disappears.

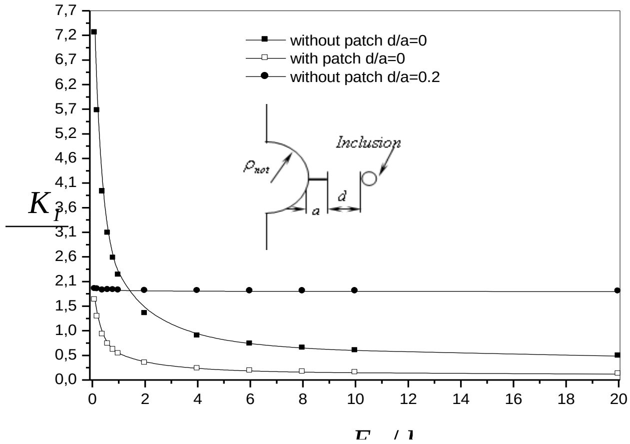


Fig.7. SIF variation as a function of E_2 / E_1 for different

Since the crack-inclusion interaction when $d = 0$ produces a great energy at the crack tip, a repair using composite patches for different rigidity ratios is necessary. It can be noticed that the composite patch reduces the normalised SIF with 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%.

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 behavior of the normalised SIF is also studied. The results are represented in Fig. 8. One can notice an opposite behavior of the normalised SIF than the one represented 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 as well, which shows clearly that a harder inclusion can slow down the crack propagation.

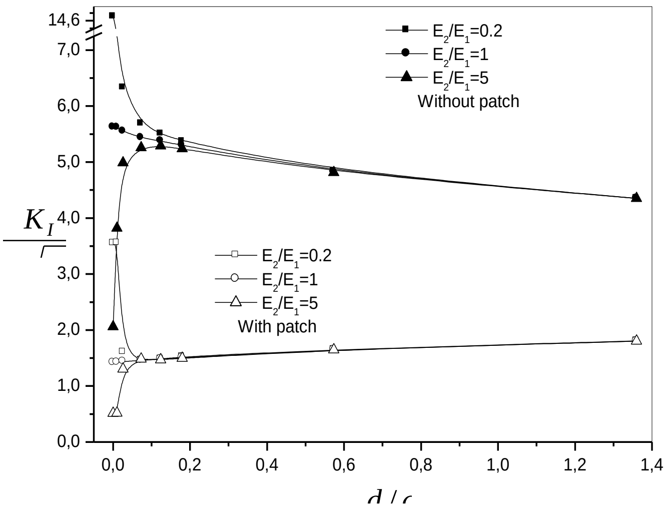


Fig.8. Comparison of the SIF variation as a function of the crack propagation from the notch to the inclusion (repaired and non repaired).

It is noticed that for the three cases of the rigidity ratios, the variation of the SIF 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 from 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 which is four times less compared to the unrepaired configuration.

4. CONCLUSIONS

This study was undertaken with an aim to investigate the behavior of a notched plate under the effect of the presence of a metallurgical defect close to the notch. The high importance of the crack onset at the notch root is related to the presence of an inclusion in this zone or in the close vicinity. Then the created crack due to the interaction effect begins to spread. During the propagation, the macroscopic crack will coalesce with the cavities created by decohesion at the inclusion level. These inclusions being generally harder than the matrix, thus the following observations could be mentioned:

- 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 tends to either stop or change the path of propagation. An opposite behavior occurs when the crack is inside the inclusion, its energy increases and accelerates when approaching the interface.

- 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 inverse behavior occurs at the inclusion level where the SCF 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 interdistance $d/a = 0$, the interaction crack-inclusion produces a great energy at the crack tip, the maximum reduction of the SIF obtained by the patch is about 75% corresponding to a ratio $E_2/E_1 = 0.2$.

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