Computers and Concrete, *Vol. 17, No. 1 (2016) 107-127*
DOI: http://dx.doi.org/10.12989/cac.2016.17.1.107

The effect of micro pore on the characteristics of crack tip plastic zone in concrete

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(Received December 17, 2015, Revised January 12, 2016, Accepted January 12, 2016)

Abstract. Concrete is a heterogeneous material containing many weaknesses such as micro-cracks, pores and grain boundaries. The crack growth mechanism and failure behavior of concrete structures depend on the plastic deformation created by these weaknesses. In this article the non-linear finite element method is used to analyze the effect of presence of micro pore near a crack tip on both of the characteristics of crack tip plastic zone (its shape and size) and crack growth properties (such as crack growth length and crack initiation angle) under pure shear loading. The FE Code Franc2D/L is used to carry out these objectives. The effects of the crack-pore configurations and the spacing between micro pore and pre-excising crack tip on the characteristics of crack tip plastic zone and crack growth properties is highlighted. Based on the obtained results, the relative distance between the crack tip and the micro pore affects in very significant way the shape and the size of the crack tip plastic zone. Furthermore, crack growth length and crack initiation angle are mostly influenced by size and shape of plastic zone ahead of crack tip. Also the effects of pore decrease on the crack tip by variation of pore situation from linear to perpendicular configuration. The critical position for a micro pore is in front of the crack tip.

Keywords: crack; micro pore; crack tip plastic zone; crack growth properties; FEM

1. Introduction

It is well known that concrete is a heterogeneous material containing many natural weaknesses, such as micro cracks, pores and grain boundaries. Under internal or external pressures, these pre-existing defects can induce macro crack, which can in turn change the structure of the concrete (Wang and Kemeny 1994, Haeri 2015a).

Also, Presence of natural weaknesses around the crack tip could change the stress distribution around the crack tip and lead to variations of characteristics of crack tip plastic zone such as plastic zone size and plastic zone shape. Such micro defects affect the fracture toughness and extension or kinking of the macro crack.

A study of the characteristics of crack tip plastic zone (such as plastic zone size and plastic

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http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

zone shape) and crack grow properties (such as crack initiation stress, crack growth length, crack initiation angle and crack growth rate) with presence of crack-pore is important in providing a good understanding of failure behavior of concrete and is helpful to the concrete structural design. Theoretically, linear elastic stress analysis of cracks predicts infinite stresses at the crack tip. In fact, inelastic deformation, such as plasticity in ductile and brittle materials, leads to relaxation of crack tip stresses caused by the yielding phenomenon at the crack tip.

Most concrete materials develop plastic strains when the yield strength is exceeded in the region near a crack tip. Thus, the amount of plastic deformation is restricted by the surrounding material, which remains elastic during loading. The formation of the plastic zone in a homogeneous material depends on the material properties, structural element configuration, and loading conditions. The size of the plastic zone can be estimated when moderate crack tip yielding occurs.

The plastic behavior near the crack tip in engineering materials has been intensively studied using classical plasticity theory based on the Von-Mises yield criterion and the associative flow rules (Rice 1968, Kuang 1997).

The elastic interaction problem between a crack and micro defects in homogeneous solids has been well studied in recent years and a number of analytical solutions have been presented in the literature (Rose 1986, Rubinstein 1986, Horii and Nemat-Nasser 1987, Yang 2011, Yoshihara 2013, Zeng *et al*. 2014, Jiang *et al*. 2014, Haeri 2015b). Many studies have been carried out to determine the plastic behavior near the crack tip (Bian 2004, Botvina 2005, Tong 2007, Antunes 2008, ASTM 2008, Oudad 2009, Kudari 2009, Rans 2009, Kudari 2009, Gao 2010, Huang 2010, Gao 2010, Xin 2010, Caputo 2012, Castro 2013, Sousa 2013, Caputo 2013).

When cracks are analyzed, the behavior of the material ahead of the crack tip is considered isotropic, i.e., plastic deformation occurs identically in all directions and there are no preferred directions for the plastic deformation. In this case, the plastic deformation can be mathematically formulated with the help of classical isotropic plasticity. This situation significantly differs when the crack tip is near a micro-defect; the plastic zone ahead of the crack tip will be affected by the presence of the micro-defects.

The aim of this study is to analyze the effect of presence of micro-crack on the shape/size of the crack tip plastic zone and crack growth properties under pure shear loading using the finite element method for the case of small scale plasticity. This case was selected because a micro-pore cannot affect the plastic zone in large plastic deformation.

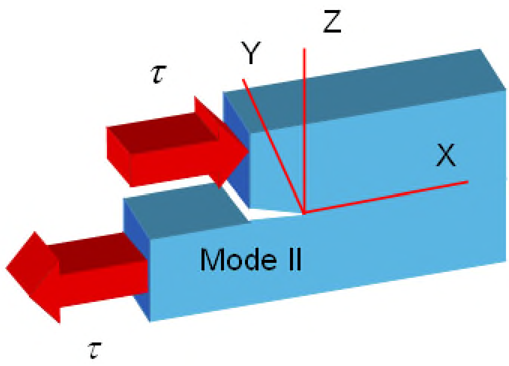


Fig. 1 Sliding mode of fracture

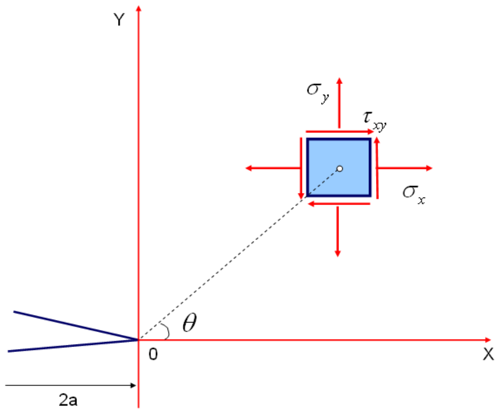


Fig. 2 Stress components at a point near a crack tip in the Cartesian coordinate system

2. The shape of the plastic zone in homogenous materials

Classical fracture mechanics defines sliding mode of fracture from the point of view of surface displacement (Fig. 1).

Fig. 2 shows the state of stresses at a point near a crack tip in the polar coordinate system, where θ=0 denotes the original crack plane and the angle θ varies in the range from -180° to 180°. The anti-clockwise direction is defined as positive for θ. For the stress components, tensile normal stress is defined as positive and shear stress is positive when acting on a plane whose outward normal is in the positive Cartesian direction. According to this sign convention, all stress components shown in Fig. 2 are positive.

For a central crack of length 2a in an infinite plate subjected to a uniform shear stress (τ); the stresses at the crack tip are expressed as (Whittaker 1992)

$$\sigma_x = -\frac{K_{II}}{(2\pi r)^{\frac{1}{2}}}\sin\frac{\theta}{2}\left[2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right] \tag{1}$$

$$\sigma_y = \frac{K_{II}}{(2\pi r)^{\frac{1}{2}}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \tag{2}$$

$$\tau_{xy} = \frac{K_{II}}{(2\pi r)^{\frac{1}{2}}}\cos\frac{\theta}{2}\left[1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \tag{3}$$

$$\sigma_z = \upsilon(\sigma_x+\sigma_y) \tag{4}$$

$$\tau_{xz} = \tau_{yz} = 0 \tag{5}$$

The principal stresses (σ_i…..i = 1,2,3) derived from these stress fields can be calculated from Eq. (6)

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}^2} \tag{6}$$

In plane strain condition (σ_3=0), When principal stresses combined with the standard Von-Mises criteria (Eq. (7)),

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_{yx}^2 \tag{7}$$

Leading to a radius of the plastic zone

$$r_p(\theta) = \frac{K_{II}^2}{\pi\sigma_{yx}^2}\left[6 - \frac{9}{2}\sin^2\theta + \sin^2(\frac{\theta}{2})\right], \qquad K_{II} = \tau\sqrt{2\pi a} \tag{8}$$

The details of these equations have been introduced in (Whittaker 1992, Anderson 1995). In Eq. (8), the coefficient K_{II} is stress intensity factor at the crack tip (its amount depend on the both of the crack length (a) and shear stress (τ)), σ_{yx} is yield stress and $r_p(\theta)$ is radius of crack tip plasticity in each angel of θ. It's to be note that the presence of micro pore near the crack tip can change the coefficient K_{II}, because of stress redistribution as a result of crack-pore interaction, and lead to variation of radius of the plastic zone. Also other conditions like dynamic loading, cyclic loading can control the stress intensity factor and change the plastic zone size.

3. Geometrical and materials models

The model with height "*H*" and width "*W*", *W/H* = 1.0, was subjected under shear loading with amplitudes of 40 MPa (Fig. 3).

This numerical analysis is based on the two dimensional plain strain conditions which are more usual in fracture mechanics literature.

An interface crack with length '*a*' exists at the model. The ratio *a/W* is 1/30. The distance between model boundary and crack tip is 5 times more than crack length. It means that the boundary of model was sufficiently far from the imbedded crack so it has not any effect on the crack tip plastic zone. A circular micro pore with radius *r*=400 μm exist near the crack tip. The distance between the crack tip and the micro pore is *b*. The ratio *b/a* was taken equal to 10%, 15%, 20% and 25% in order to analyze the effect of the distance *b* on the size and the shape of the plastic zone ahead of the crack tip. Three configurations of the position of the micro pore compared to the crack tip are studied (Fig. 3)

(a) Micro pore located at the prolongation of the crack tip.

(b) Micro pore located diagonally below the crack tip. The angel between pore-crack connecting line and crack plane is 45°.

(c) Micro pore shifted perpendicularly below the crack tip.

The elastic properties of the model material are like to mechanical properties of marble. The Young modulus *E*=75.31 GPa, Poisson's ratio (υ)=0.32 and yield stress (σ_{yx})=75 MPa. The uniaxial stress-strain curve of this material is given in Fig. 4.

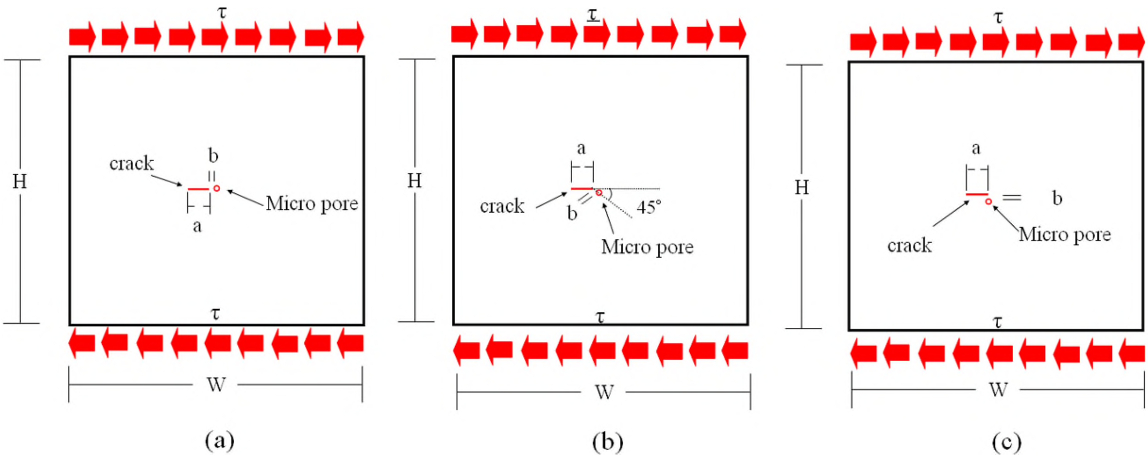


Fig. 3 Geometrical models under pure shear loading, (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip

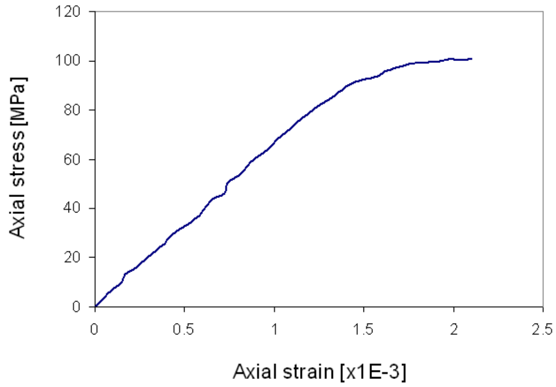


Fig. 4 Uniaxial stress–strain curve of marble

4. Finite element modeling

A two-dimensional finite element code named FRANC2D/L (FRacture ANalysis Code for 2-D Layered structures) is used to do the numerical modeling work. This code was originally developed at Cornell University and modified for multi-layers at Kansas State University (FRANC2D/L 1998), and is based on the theory of linear and nonlinear elastic fracture mechanics (Newman 1992). FRANC2D/L has been developed based on fracture mechanic theory and has a good efficiency to analyze the crack growth properties.

The structure is idealized by quadrilateral four nodes element. Special quarter elements were implemented around the crack tip. Fig. 5 shows typical mesh model of the global structure and near the micro-crack and the micro pore.

The Von-Mises criterion is used to determine whether the stress in the material causes plastic flow. This criterion is chosen because, in addition to the well applicability in fracture mechanic theory, is an ideal criterion for this assumption that concrete segment behaves as a metal material.

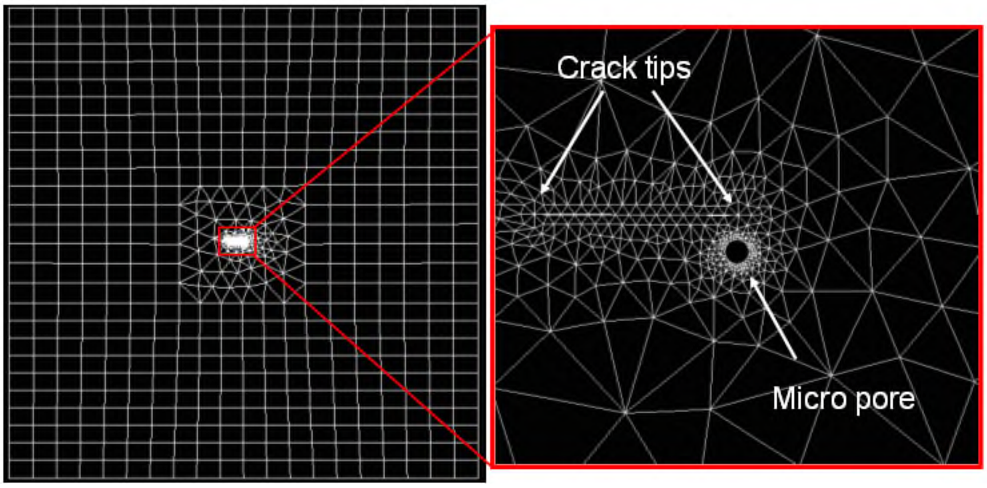


Fig. 5 Typical mesh model; (a) global structure; (b) near the crack tip and the micro pore

In other words, Whereas on of the important source that cause the large differences between mechanical properties of concrete material and metal are grain boundaries, porosity areas and other defects in concrete specimens, therefore in this study it's assumed that there are just one crack and micro pore without any defects (such as grains boundary, dislocation) in concrete segment. In this condition the concrete mechanical behavior is nearly similar to metals behavior what confirm that the von-mises criterion can be applied in this study.

Also, beyond of every thing, this study is a fundamental research that can be used for any problems in concrete, rocks or metals.

Incremental plasticity theory is introduced to model the material non-linearity. The Newton-Raphson iterative method is used as approach for resolving non-linear finite element equations.

5. Analysis and results

The contour of the plastic zone at the crack tip with micro pore is compared to the case of without micro pore. It can be noted in all results presented in this paper that when the effect of micro-crack is non-existent the plastic zone at the crack tip has a regular form which is in accordance with literature (Anderson 1995). In what follows, the effect of the presence of micro-pore near the crack tip on the size and the shape of the plastic zone is analyzed for the three configurations of the positions of the micro-pore shown previously.

5.1 Micro pore located in front of the crack tip

Fig. 6 shows the plastic zone contour ahead of the crack tip without and with the presence of the micro pore. The micro pore was close to the crack tip (b/a=10%). From Fig. 6, it is clear that the plastic zone has a regular shape but different from standard form. It takes the shape of micro pore in its vicinity. Also, the size of plastic zone is bigger than the regular form in all direction. In fact, the crack tip stress intensity increase due to interaction

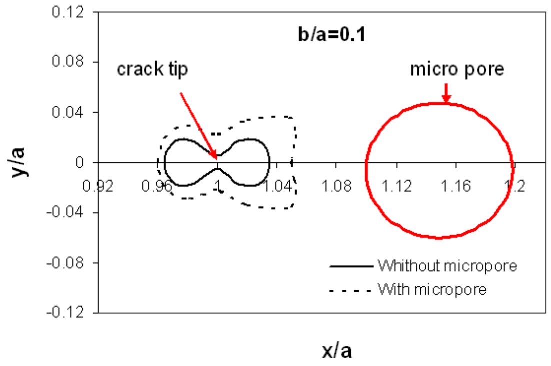


Fig. 6 Contour of plastic zone for configuration "*a*" in Fig. 1 (*b/a*=10%)

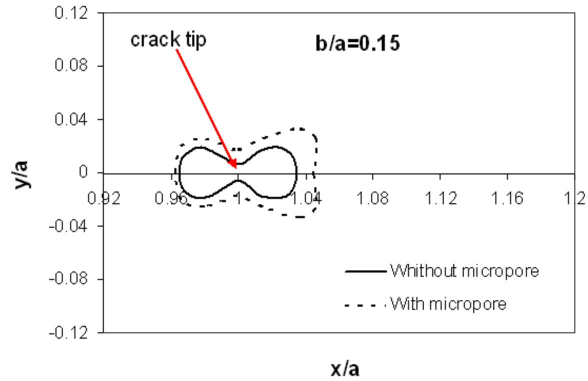


Fig. 7 Contour of plastic zone for configuration "*a*" in Fig. 1 (*b/a*=15%)

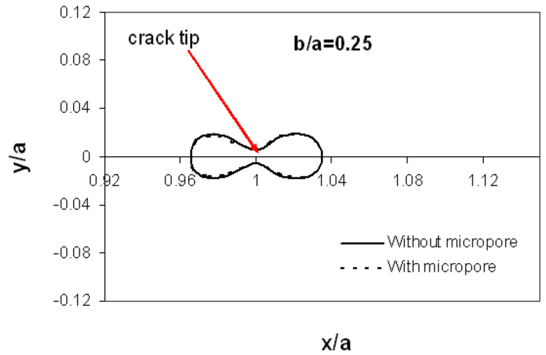


Fig. 8 Contour of plastic zone for configuration "*a*" in Fig. 1 (*b/a*=25%)

between the crack tip and micro pore. According to the plasticity theory, this stress lead to further plastic deformation what explains the fact that the size of the plastic zone is bigger than the regular form.

Fig. 7 presents the contour of the plastic zone for the case of a micro pore located at a relative distance *b/a*=15% from the crack tip.

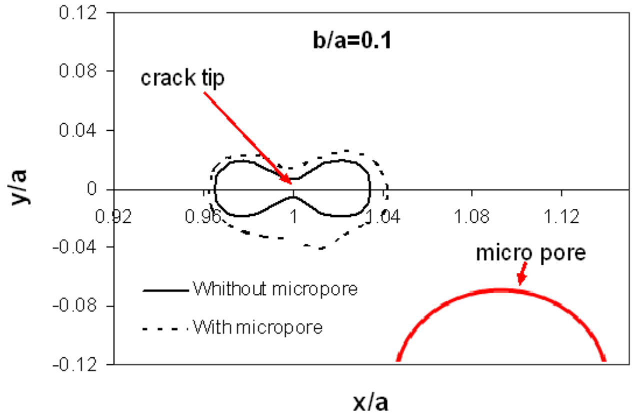


Fig. 9 Contour of plastic zone for configuration “*b*” in Fig. 1 (*b/a*=10%)

In contrast with preceding case, it’s clear that the size of the plastic zone decrease by increasing in the micro pore spacing. In fact the interactions between micro pore and crack tip decrease by pore spacing. This lead to reduction in crack tip stress intensity and finally decreasing in plastic zone size.

It’s to be note that the crack tip stress intensity with presence of pore is bigger than that without micro pore yet what explain the fact that the size of plastic zone is bigger than the regular form.

For the ratio *b/a*= 25%, the effect of the presence of the micro pore disappears completely, and the plastic zone ahead of the crack tip will find its classical l form (Fig. 8).

5.2 Micro pore located diagonally related to the crack tip

Fig. 9 presents the contour of the plastic zone when the micro pore is located at a relative distance *b/a*=10% from the crack tip. It can be seen that the plastic zone has an irregular shape. It shifted diagonally downwards in the presence of the micro pore and takes the shape of the micro pore in the vicinity of pore level. The size of plastic zone at the crack tip was decreased by increasing the micro pore spacing but its amount was bigger than regular form.

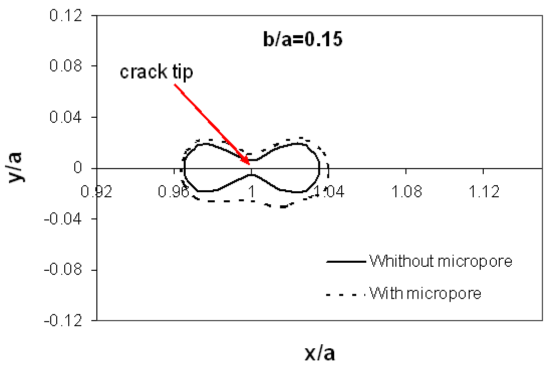


Fig. 10 Contour of plastic zone for configuration “*b*” in Fig. 1 (*b/a*=15%)

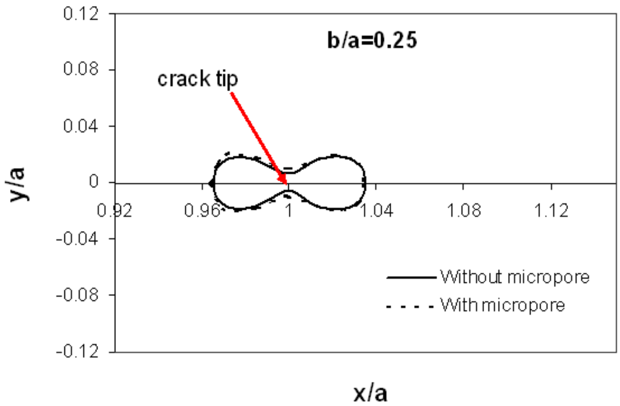


Fig. 11 Contour of plastic zone for configuration “b” in Fig. 1 (*b/a*=25%)

Fig. 10 presents the plastic zone contour ahead of the crack tip for *b/a*=15%. It’s clear that the size of plastic zone ahead of crack tip decrease by increasing in the micro pore spacing but its amount is bigger than regular form yet. Also, the plastic zone has an irregular shape due to presence of pore

For a ratio *b/a*=25% (Fig. 11), the effect of the micro pore on the shape of the plastic zone disappears completely and this zone regains its classical form.

5.3 Micro pore shifted perpendicularly below the crack tip

Fig. 12 presents the contour of the plasticized zone when the micro pore is located at a relative distance *b/a*=10% from the crack tip. It can be seen that the plastic zone shape is nearly equal to standard form but its size is bigger than the regular form. In fact, the movements of micro pore to this new position dose not have any effect on the principal stress directions so that plastic zone shape is nearly similar to standard form. But crack tip stress fields increase because of interaction between the crack tip and micro pore what explain the increasing in the plastic zone size.

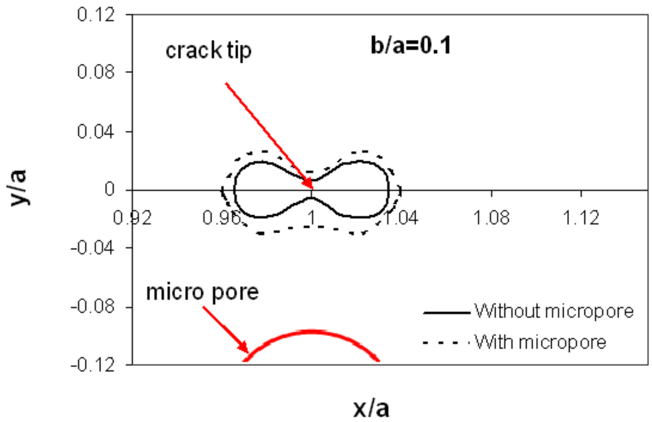


Fig. 12 Contour of plastic zone for configuration “*c*” in Fig. 1 (*b/a*=10%)

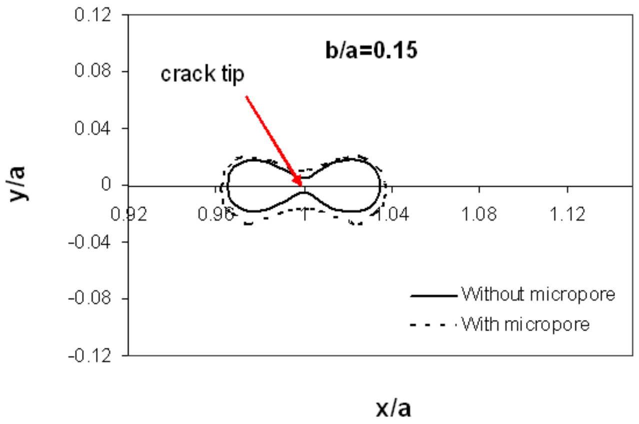


Fig. 13 Contour of plastic zone for configuration III in Fig. 1 (*b/a*=15%).

Fig. 13 presents the contour of the plasticized zone when the micro pore is located at a relative distance *b/a*=15% from the crack tip. It's clear that the size of the plastic zone ahead of crack tip decrease by increasing in the micro pore spacing but its amount is bigger than regular form yet. For a ratio *b/a*=20% (Fig. 14), the effect of the micro pore on the size of the plastic zone disappears completely and this zone regains its classical form.

6. Discussion

The crack tip stress intensity increase due to interaction effect between pore and crack tip what explain the fact that the plastic zone size increase by presence of micro pores near the crack tip. Also plastic zone shape varies with pore situation. Because the pore controls the principal stress direction near the crack tip and affects the plastic zone shape (according to the fracture mechanics approach and plasticity theory). These effects are disappeared by increasing in pore spacing. When micro pore was situated perpendicularly below the crack tip, the pore has less influence on plastic zone size. In this configuration, the effect of micro pore on the size/shape of crack tip

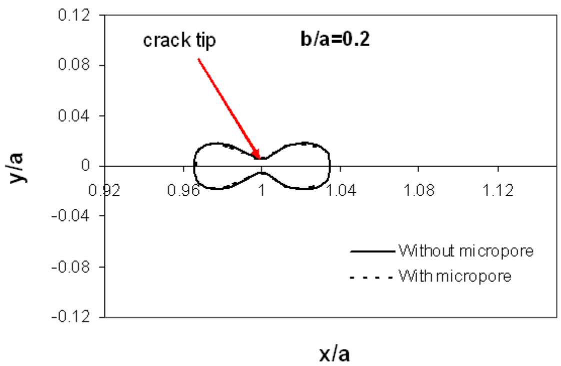


Fig. 14 Contour of plastic zone for configuration III in Fig. 1 (*b/a*=20%)

Table 1 Mechanical properties of model

Mechanical properties	value
Young modulus (GPa)	75.31
Poisson's ratio	0.32
Density (kg/cm^3)	2800
KI (MPa√m)	1
τ (MPa)	65

plastic zone is disappeared completely when *b/a*=>0.2 while in other pore configurations the effect of pore is disappeared completely when *b/a* =>0.25.

Also, when micro pore was in front of the crack tip, the plastic zone was the biggest one. It shows that the crack tip stress intensity in this configuration is bigger than two other cases. It's to be note that the variations of plastic zone size/shape have an important effect on crack growth properties. The following Numerical modeling results reveal this matter.

At the first step, one model having an interface crack with length '*a*', without present of micro pore, has been run under direct shear loading (Fig. 15). The ratio *a/W* was 1/30. One of the most important fracture parameters is the Mode I fracture toughness K_{IC} which been measured by several methods (Zhao *et al*. 1999).

There are different methods for measuring the Mode I fracture toughness, K_{IC} e.g., Semi-Circular Core in Three Point Bedding (SCCTPB), Brazilian Disc (BD), Radial Cracked Ring (RCR), Double Torsion (DT), Chevron Bend (CB), Short Rod (SR), Central Straight Through Crack Brazilian Disk (CSCBD) (Becker 1992, Fowell 1995, Rao 1999, Rao *et al*. 2003, Backers 2004).

Three methods for rock and rock-like and concrete materials have been proposed by the international society for rock mechanics (ISRM) as suggested methods: the CB method, the SR method, the CCNBD method (ISRM 1988).

In this research, Mode I fracture toughness was measured by using cracked chevron notched Brazilian disc (Fowell 1995).

Table 1 shows mechanical properties of model. At the second step, simulations have been done on the models with presence of crack and micro pore. The results of these simulations have been compared with together. It's to be note that the same input data have been applied in all of the simulated models.

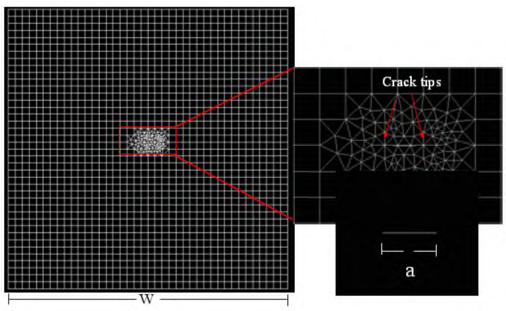
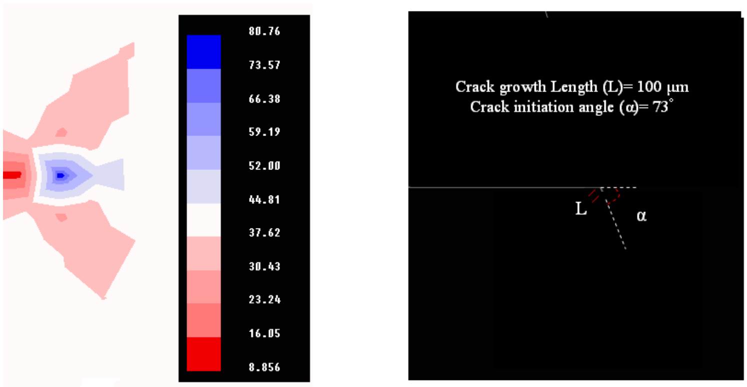
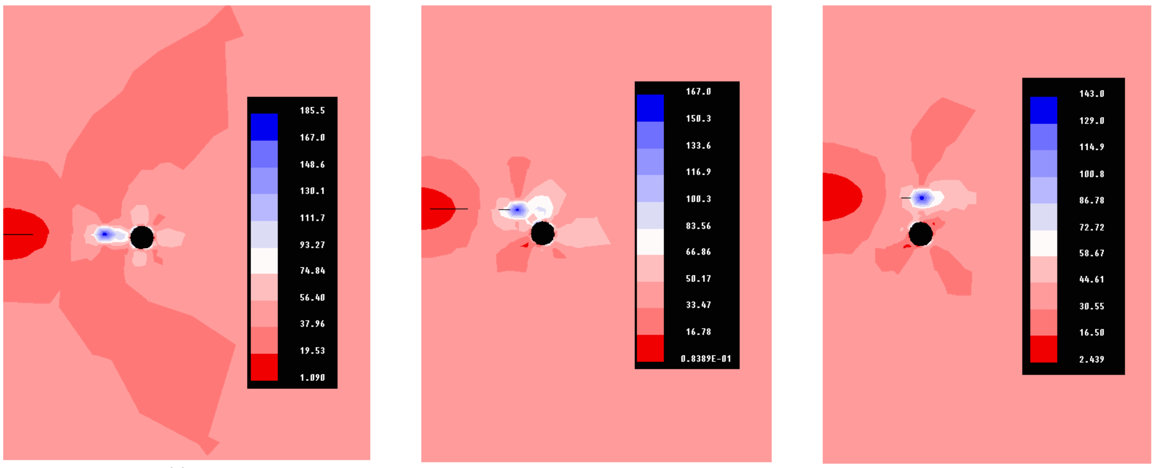


Fig. 15 The model having an interface crack without present of micro pores under pure shear loading



(a) (b)

Fig. 16(a) the contour of Von-Mises stress levels near the crack tip; (b) crack growth properties



(a) (b) (c)

Fig. 17 Contour of Von-Mises stress levels near the crack tip (b/a=10%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip

Fig. 16(a) present the contour of the Von-Mises stress levels near the crack tip without micro pore. As can be seen, the stress intensity at the crack tip has the maximum value of 80.76 MPa. In this condition, the new crack initiate from the crack tip (Fig. 16(b)). The crack growth length was 100 μm and the angle between newborn crack and pre-existing joint was about 73°.

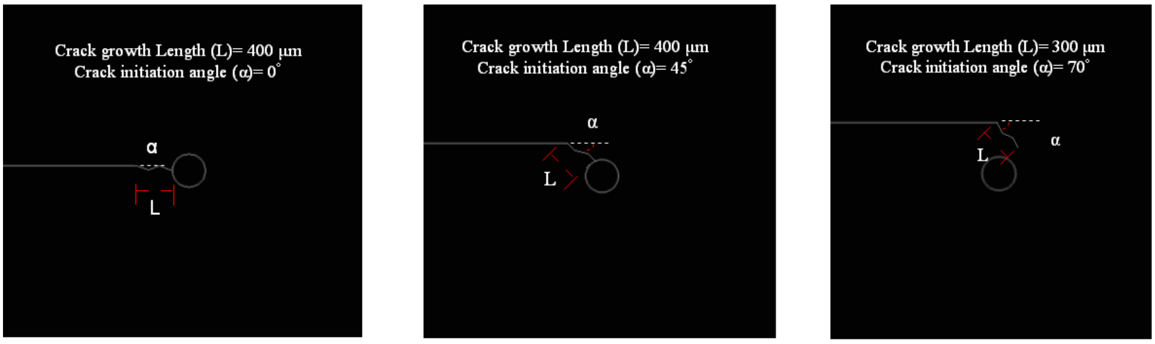
As be said before, some numerical tests are performed on the models consisting pre-existing crack and micro pore. The ratio of *a/w* is 1/30 and micro pore diameter is 400 μm (Fig. 1). Three configurations of the position of the micro pore compared to the crack tip are studied

(a) Micro pore located in front of the crack tip.

(b) Micro pore shifted diagonally below the crack tip. The angel between pore-crack connecting line and crack line is 45°.

(c) Micro pore located perpendicularly below the crack tip.

Four values of the ratio of b/a (see Fig. 1) were chosen equal to 10%, 15%, 20% and 25% in



(a) (b) (c)

Fig. 18 Crack growth properties (*b/a*=10%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip.

order to analyze the effect of pore spacing on the Von-Mises stress levels and crack growth properties.

6.1 The ratio of b/a=10%

Figs. 17(a), 17(b) and 17(c) present the contour of the Von-Mises stress levels near the crack tip for configurations *a*, *b* and *c* in Fig. 1 respectively (*b/a*=10%).

From Fig. 17 and Fig. 16(a), the crack tip stresses were higher than 80.76 MPa due to presence of micro pore and its interaction effects.

The stress concentration at the crack tip is highest for linear pore configurations (185.5 MPa). When micro defect was shifted diagonally to the line of the crack, it decreases at crack tip (185.5 MPa to 167.8 MPa). The stress concentration at the crack tip was less than other cases for perpendicularly micro pores (143 MPa). In fact the interaction effect between pore-crack stresses field decrease by movement of pore below the crack tip.

Figs. 18(a), 18(b) and 18(c), shows the crack growth properties for three pore configurations (*b/a*=10%). When pore exist in front of the crack tip, the new born crack propagates at the prolongation of pre-existing crack till reach the pore surface. The crack growth length is 400 μm and the angle between newborn crack and the pre-existing crack is about 0° (Fig. 18(a)).

When pore shifted diagonally to the line of the crack, the crack growth length is 400 μm and the angle between newborn crack and the pre-existing crack is about 45°. It’s to be note that, however the stress decrease at the crack tip for diagonally micro pore configuration (from 185.5 MPa to 167.8 MPa) but the interaction effect between pore-crack was too high and crack tip stress was enough so that new born crack propagate till reach to the pore level. Also presence of diagonally micro pore changes the principal stress direction so that the crack growth angle increases to 45°.

When pore shifted perpendicularly to the line of the crack (Fig. 18(c)), the crack growth length is 300 μm and the angle between newborn crack and the pre-existing crack is about 70°. In contrast with other configuration, the crack growth length is smallest one. In fact in this configuration, the interaction between pore-crack stresses field is less than other configurations so that it reduce the crack tip stress and crack growth length.

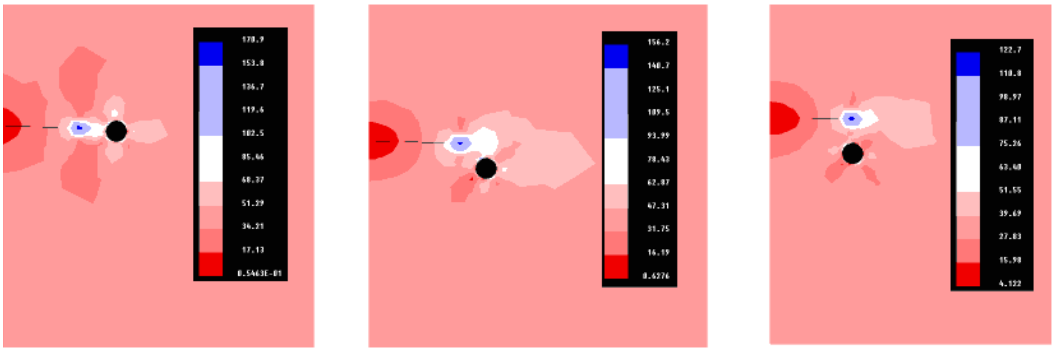
From Fig. 18 and Fig. 16(b) it can be found that presence of micro pore can lead to increasing in the crack growth length and decreasing in crack initiation angle. In fact, presence of micro pore in the vicinity of the crack tip leads to the high interaction between the crack-pore stress fields what causes increasing in the energy at the crack tip and consequently increasing the crack growth length.

Also, presence of micro pore linearly and diagonally at the crack tip change the principal stress direction what explain decreasing of crack initiation angle. It’s to be note that variation of crack initiation angle can change crack propagation path.

From Fig. 18(c) and Fig. 16(b), its worth noting that presence of perpendicularly micro pore has not any effect on the principal stress directions so that crack initiation angle with presence of perpendicularly pore configuration (70° in Fig. 18(c)) is the same as that without of presence of pore (73° in Fig. 16(b)).

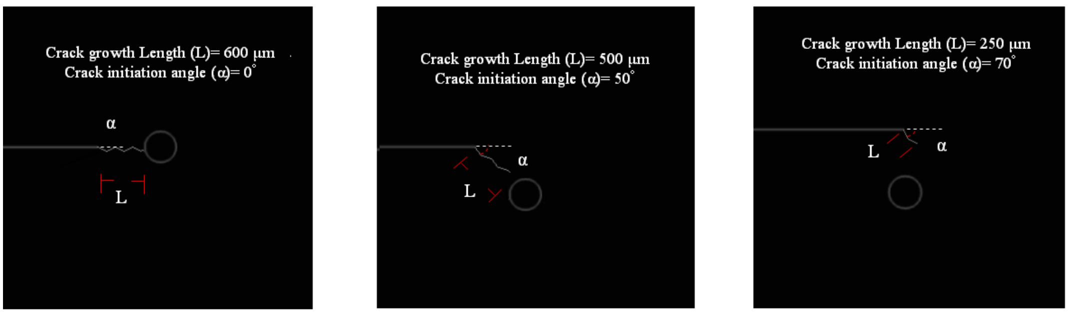
6.2 The ratio of b/a=15%

Figs. 19(a), 19(b) and 19(c) present the contour of the Von-Mises stress levels near the crack tip for configurations *a*, *b* and *c* in Fig. 1 respectively (*b*/*a*=15%). The stress concentration at the crack tip was highest for linear pore configuration (170.9 MPa). It decrease at the crack tip (170.9



(a) (b) (c)

Fig. 19 Contour of Von-Mises stress levels near the crack tip (*b*/*a*=15%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip



(a) (b) (c)

Fig. 20 Crack growth properties (*b*/*a*=15%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip

MPa to 156.2 MPa) when micro defect was shifted diagonally to the line of the crack**.** When micro pore is located perpendicularly to the line of crack the stress concentration at the crack tip is less than other cases (122.7 MPa). From Fig. 19 and Fig. 17, it can be seen that the crack tip stress decrease by increasing in micro pore spacing. Also, from Fig. 19 and Fig. 16(a), the crack tip stress with presence of pore is more that that without presence of pore. It shows that the micro pore has effect on the crack tip stress yet.

Figs. 20(a), 20(b) and 20(c), shows the crack growth properties for three pore configuration (*b/a*=15%).

It's clear that for linear pore configuration the crack propagates parallel to pre existing crack till reach the pore level (the angle between newborn crack and the pre-existing crack is about 0°). The crack growth length is highest (600 μm) because the crack tip stress is highest in this configuration (Fig. 20(a)). Crack initiation grow angle increase (0° to 50°) when micro defect is shifted diagonally to the line of the crack (Fig. 20(b)) and its growth length decrease (600 μm to 500 μm) due to reduction in crack tip stress (see Fig. 19(a) and Fig. 19(b)).

When micro pore is located perpendicularly to the line of crack, the crack growth length is less than other cases (250 μm) and the angle between newborn crack and the pre-existing crack is about 70° (Fig. 20(c)).

It worth nothing that however the crack tip stresses in linear and diagonally pore configurations, (170.9 MPa in Fig. 19(a) and 156.2 MPa in Fig. 19(b)) are less than those in similar preceding configurations (185.5 MPa in Fig. 17(a) and 167.8 MPa in Fig. 7(b)) but the crack growth lengths for *a/b*=15% (600 μm and 500 μm in Figs. 20(a) and 20(b)) are more than those for *b/a*=10% (400 μm in Figs. 18(a) and 18(b)).

In fact for *b/a*=10%, the crack growth was arrested due to connecting with micro pore. When the crack tip reach to pore level, the sharp crack tip change to circular shape and stress is distributed in the pore surface (that is now a partial of crack). This leads to decreasing the energy at the crack tip and arresting the crack. This crack can propagate by further far field shear loading.

But when *b/a*=15%, for two introduced configuration, the crack tip stress is high enough to propagate further than preceding cases.

6.3 The ratio of b/a=20%

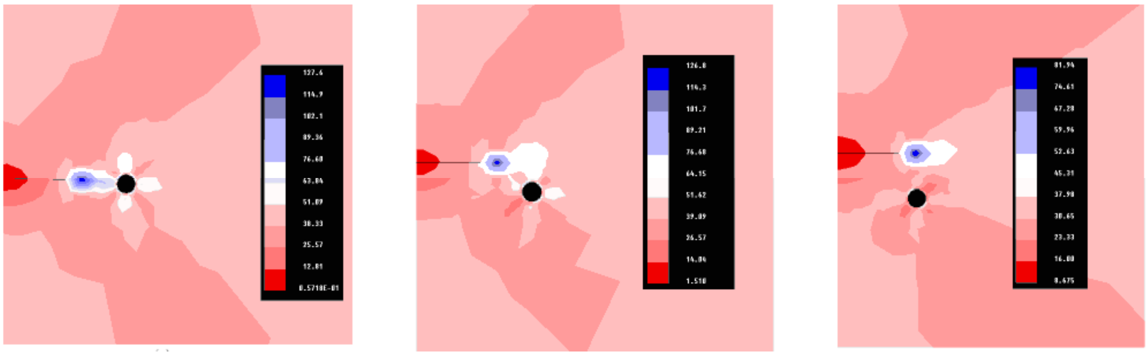
Figs. 21(a), 21(b) and 21(c) present the contour of the Von-Mises stress levels near the crack tip for configurations a, b and c in Fig. 1 respectively (*b/a*=20%). From Fig. 21 and Fig. 19, it can be seen that the crack tip stress decrease by increasing in micro pore spacing.

The crack tip stresses for planar and diagonally pores configurations are nearly equal to each other (127.6 MPa and 126.8 MPa, respectively). It may be related to this fact that the crack tip, in these two configurations, has been situated in the disturbed zones of micro pores but not in the hazard zone (with high interaction effect). Whereas there is not any high interaction between crack tip and micro pore stress fields in disturbed zone therefore the same stresses concentrate at crack tip for planar and diagonally pores configurations.

When a micro pore is located perpendicularly to the line of crack, the stress concentration at the crack tip is less than other cases (81.94 MPa). In this case the pore has not any effect on the crack tip stress so that the crack tip stress is similar to case of without present of micro pore (Fig. 16(a)).

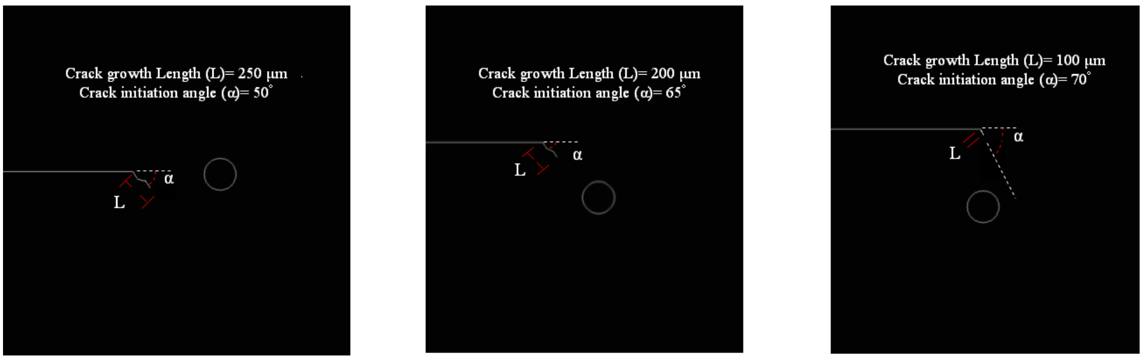
Figs. 22(a), 22(b) and 22(c), shows the crack growth properties for three pore configuration (*b/a*=20%).

When micro pore is sited in front of the crack tip, the crack growth length is 250 μm and the



(a) (b) (c)

Fig. 21 Contour of Von-Mises stress levels near the crack tip (*b/a*=20%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip



(a) (b) (c)

Fig. 22 Crack growth properties (*b/a* =20%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip; (c) Micro pore located below the crack tip.

angle between newborn crack and the pre-existing crack is about 50°.

From Fig. 21(a) and Fig. 19(a), it's clear that when micro pore is far from the crack tip, the crack growth length decrease and crack growth angle increase due to reduction in pore effect.

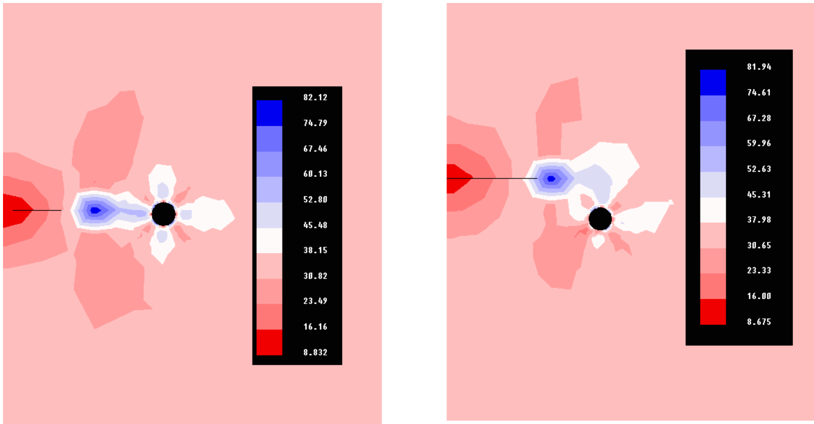
When micro pore was shifted diagonally to the tip of crack, the crack growth length was 200 μm and the angle between newborn crack and the pre-existing crack was about 65°.

Finally for perpendicularly pore configuration, the crack growth length and crack initiation angle is similar to standard form (Fig. 16) what explain the fact that micro pore has not any effect on the crack growth properties in this configuration/situation of micro pore.

6.4 The ratio of b/a=25%

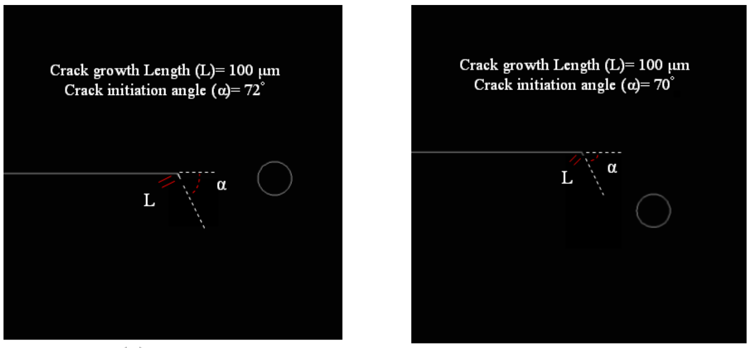
Figs. 23(a), 23(b) present the contour of the Von-Mises stress levels near the crack tip for linear and diagonally pore configurations respectively (*b/a*=25%).

The crack tip stresses for linear and diagonally pore configurations are 82.12 MPa and 81.94 MPa, respectively what's the same as standard value (i.e., 80.76 MPa in Fig. 16(a)). It can be concluded that the effect of micro pore disappears completely in these configurations.



(a) (b)

Fig. 23 Contour of Von-Mises stress levels near the crack tip (*b/a*=25%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip



(a) (b)

Fig. 24 Crack growth properties (*b/a*=25%); (a) Micro pore located at the prolongation of the crack tip; (b) micro pores located diagonally below the crack tip

Also, Figs. 24(a) and 24(b), shows the crack growth properties for two pore configuration (*b/a*=25%). its clear that the crack growth properties (crack growth lengths and crack initiation angles) are similar to standard form (Fig. 16(b)) what explain the fact that micro pore has not any effect on the crack growth properties in these pore configurations.

From above findings, it’s clear that the variation of pore situation from linear to perpendicular configuration lead to decreasing in crack tip stress and crack growth length. In other word, its effect decrease on the crack tip stress. This manner is unchangeable till b/a get the value of 25%.

Also, for linear and diagonal pore configuration, the crack initiation angle increase by pore spacing till get the standard value (73°) but for perpendicular pore configuration the crack initiation angle will be constant by pore spacing and is similar to standard value.

From the above results it can be concluded that the worst position for a micro pore under pure shear loading is when it’s situated in front of the crack tip. Because, the crack tip stress and crack growth length for linear pore configuration have the highest values in contrast with other configuration.

It’s worth nothing that the above findings are in a good accordance with variation of plastic zone size/ shape due to presence of micro pore. In other word, the crack growth length and crack tip plastic zone size has a straight relationship to each other. The more be plastic zone size, the more be crack growth length. It's to be note that this manner depend on the brittle or ductile behavior of crack tip materials. In ductile materials the crack tip stress intensity yield the materials ahead of the crack tip and plastic deformation occurred at the crack tips but in brittle materials the crack tip stress intensity can overcome to fracture toughness of material so that the new crack is initiated from the pre existing crack tip. Therefore, intensifications of crack tip energy in brittle material lead to further crack growth instead of crack tip plastic deformation.

Also there is a fine compatibility between crack initiation angle and plastic zone shape. Variation of plastic zone shape with pore configuration controls the crack initiation angle. As can be seen from Fig. 6 and Fig. 18(a), crack initiate in which direction that there is disturbance in plastic zone shape. In other words, when micro pore is close to crack tip, the crack initiate in which angle that plastic zone take the shape of pore level. Fig. 9 and Fig. 18(b) confirm this manner for diagonally pore configuration too. With increasing in the pore spacing, the plastic zone takes the shape of regular form what explain the crack initiation angle will get the standard value (73°) by increasing the pore spacing.

Whereas perpendicularly pore configuration dose note have any effect on the plastic zone shape, so the crack initiate such a standard form.
it's to be note that the further study is needed to scrutiny the characteristic of crack tip plastic zone and crack growth properties for various cases such as other pore configurations, less values of b/a, and different pore diameters.

In some primary studies, it has been cleared that When *b/a* is less than 10%, the micro pore is circumvented by plastic zone of important size what cause the initiation of second crack at the tip of the micro pore. By propagation of secondary crack the spacing between the secondary crack and pre-existing crack being very small and they are coalesced consequently. This coalescence explains the increases of the crack growth rate of the main crack.

The future results of this pore configuration will be published as soon as possible.

7. Conclusions

In this study the effect of presence of micro pore near a crack tip on the characteristics of crack tip plastic zone (its shape and the size) and crack growth properties, under pure shear loading, has been analyzed. The results show that

• The presence of micro pore in the vicinity of the crack tip increase the plastic zone size and change the plastic zone shape accordance to micro pore spacing and pore configuration respectively.

• When micro pore is close to crack tip (*b/a*=10%) the interaction between pore-crack stress fields is too high. This lead to increasing in both of the crack tip stress intensity and plastic zone size. Also in each pore configuration, the plastic zone takes the shape of pore level in some regions near to micro pore.

• By increasing in pore spacing, the effect of pore presence disappears on the characteristics of crack tip plastic zone so that the plastic zone will take the shape of classical form when the ratio of a/b is about 25%.

• There is a straight relationship between crack tip plastic zone and crack growth length. The more is plastic zone, the more is crack growth length.

• The crack initiation angle is accordance to plastic zone shape so that in each pore configuration the crack initiate in which angle that plastic zone take the shape of pore level. In other words the variation of micro pore configuration will be changed the principal stress directions ahead of crack tip and lead to variation of crack initiation angle.

• The crack growth length decreases by variation of pore situation from linear to perpendicular configuration because of decreasing in crack tip stress. In other word, its effect decrease on the crack tip stress. For linear and diagonal pore configuration, the crack initiation angle increase by pore spacing till get the standard value (73°) but for perpendicular pore configuration the crack initiation angle will be constant by pore spacing and is similar to standard.

• When micro pore is situated in front of the crack tip, it has the most effect on the crack growth properties so that the crack tip stress and crack growth length have the highest value in this configuration. It explains the fact that this position is the worst configuration for micro pore. It's to be note that the crack tip stress and crack growth length have the lowest value for perpendicular pore configuration.

• By increasing in pore spacing, the effect of pore presence disappears on the crack growth properties so that the crack growth length and crack growth angle will be equal to standard value (the values without presence of micro pore) when the ratio of *b/a* is about 25%.

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