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Dynamic Interaction of a Propagating Crack with a Hole Boundary

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With 7 Figures

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Summary

The optical method of caustics was used along with high speed photography to study crack propagation and crack-hole interaction in plane PMMA specimens containing a transverse edge crack and a hole lying eccentrically to its axis. The specimens were fractured under different dynamic loads.

Crack-hole interaction is characterized (for a limiting vertical distance of the crack axis from the center of the hole) by a process of attraction — repulsion of the crack towards the hole, interrupted by a momentary crack-arrest at the hole boundary. Increased values of crack propagation velocity and of the stress intensity factor at the tip of the propagating crack are detected during crack-hole interaction.

1. Introduction

The problem of interaction of the stress field at the tip of a propagating crack with stress singularities or stress concentration around definite discontinuities in plane media has become a subject of interest since the early years of scientific investigation of crack problems.

The problem of interaction between collinear cracks was first studied for the static case, [1]—[5]. Interesting results were also revealed in concern with collinear crack interaction or interaction between cracks and boundaries by using the optical method of caustics [6]—[10].

The dynamic problem of crack interaction was studied by Theocaris [11] and Theocaris and Milios [12], by means again of the optical method of caustics. These last investigations revealed interesting results concerning the variation of the stress intensity factors and the crack propagation velocities due to coalescence between the singular stress fields and also showed that interaction results in deviations of the crack paths from their initial axis of propagation.

On the other hand, the study of interaction of a transverse propagating crack with a bimaterial interface [13], [14] or with a longitudinal crack and a hole (with its center on the axis of crack propagation) [15], resulted always in a process of momentary crack arrest. This crack arrest process is constituted of two distinct periods: During the first period, the singular stress field at the crack tip continuously vanishes, although the external load, which caused the singularity, continues to act upon the specimen. The strain and kinetic energy previously deposited at the crack tip is now absorbed by the material near the crack tip. The second period is characterized by the gradual build-up of a new singularity which causes crack reinitiation, this time beyond the "arrester".

In all these cases, the momentary crack-arrest was compulsed, in the means that the material discontinuity did not leave any possibility to the moving crack to avoid interaction. On the other hand, the deviation phenomena connected with dynamic interaction of collinar cracks state the problem of whether a propagating crack has the tendency to avoid or "select" interaction with discontinuities existing in the material. The problem is obviously of interest to practical applications, where external loads can cause coalescence of pre-existing points of stress concentrations in the material, such as microcracks, voids, inclusions etc.

In the present paper the problem of coalescence of a propagating edge crack, initiated under different strain rates, with a hole was investigated, the center of the hole lying always excentrically, at various distances from the axis of the initial edge crack. Both the vertical distance of the crack axis from the center of the hole and the different loading rates were thus considered as parameters influencing the patterns of interaction.

2. The Method of Caustics Applied to Plain Stress Problems

For the study of crack propagation in plane specimens and coalescence of the crack tip singular stress field with the stress concentrations around a hole, it is necessary to determine the variation of the stress intensity factor at the tip of the moving crack and the principal stress concentration around the hole, as well as the crack propagation velocity. For the experimental determination of these parameters the method of optical transmitted caustics was chosen.

According to this method, a convergent of divergent light beam is made to impinge on the vicinity of the concentrations and the transmitted rays are received on a reference plane, parallel to the plane of the specimen. The abrupt variation of stresses in the neighbourhood of the crack tip or the hole boundary results in a reduction of the thickness of these regions due to the Poisson's ratio effect, and to a change of the refractive index of the material. Thus the transmitted rays from the neighbourhood of the crack tip or the hole are concentrated along the caustic.

From the geometric characteristics of the caustic we can calculate with high accuracy, the stress intensity factor at the tip of the crack. Further, we can accurately deduce the position of the extremities of the caustics and thus, derive accurately the instantaneous value of the crack propagation velocity. The stress intensity factor K_I is given by [16], [17], [18]:

$$K_I = C \left(\frac{D_t^{\max}}{\delta_t(c)^{\max}} \right)^{5/2}$$

with

$$C = \frac{1.671}{z_0 d C_t \lambda_M{}^{3/2}}$$

and

$$\lambda_M = \frac{z_i}{z_0 + z_i}$$

where m denotes the magnification ratio of the optical set-up and z_0 the distance between the specimen and the reference screen; z_i is the distance between the reference plane and the focus of the light between, $D_t^{\max}(c)$ the transverse caustic diameter on the reference screen and $\delta_t(c)^{\max}$, a correction factor for the diameter of the caustic which considers its variation due to the dynamic effects and which is expressed by means of the crack propagation velocity c. The values of $\delta_t(c)^{\max}$ are given in monograms included in [18].

For the case of the hole, the method of caustics yields an "optical stress rosette", due again of the reduction of the specimen's thickness at the constrained edges of the hole. From the orientation and the dimension of the "optical stress rosette", we can accurately determine both the orientation of the principal stresses and their absolute difference at the area of the hole, [16], [19].

In order to determine the principal stress directions, the minimum diameters of the caustics are traced and are positioned in two orthogonal directions. Since the minimum diameters are sharply defined by two diametrically positioned cusp points of the caustic curves, the principal directions can be accurately defined.

For the evaluation of the principal stress difference one has only to measure the maximum caustic diameter around the hole. Then the difference between the principal stresses is given by the following relation:

$$\sigma_1 - \sigma_2 = \frac{27 D^4{}_{\max}}{4^7 z_0 R^2 \, dc_t}$$

where $D^{\max}$ is the maximal diameter of the caustic, R the radius of the hole, z_0 the distance between the specimen and the reference screen and c_t the stress optical coefficient for transverse light, while d denotes again the thickness of the specimen.

3. Experimental Arrangement

For our experimental investigation we used a series of 20 PMMA specimens of the same dimensions: $0.3 \times 0.1 \times 0.03$ m^3. All specimens contained an artificial initial edge crack of length $a = 0.025$ m and a hole having a diameter $2R = 0.01$ m, drilled on the specimen's longitudinal axis, but excentrically in regard to the axis of the transverse crack (see Fig. 1).

The vertical distance between the crack axis and the center of the hole, c, was varied, having the value of 0.005 m (that is touching the hole boundary) for the first specimen configuration of six specimens, 0.01 m for the second configuration of six specimens and 0.02 m for the third specimen configuration of again six specimens. Two more specimens were constructed (having a vertical distance $c = 0.005$ m and $c = 0.01$ m respectively) to be used in preliminary tests in order to synchronize the optical part of the experimental arrangement.

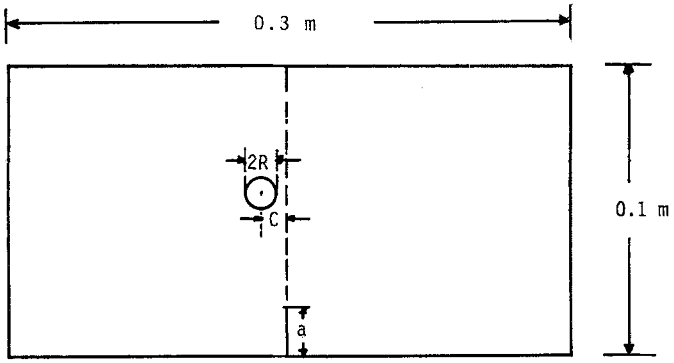

Fig. 1. Geometrical characteristics of the specimens

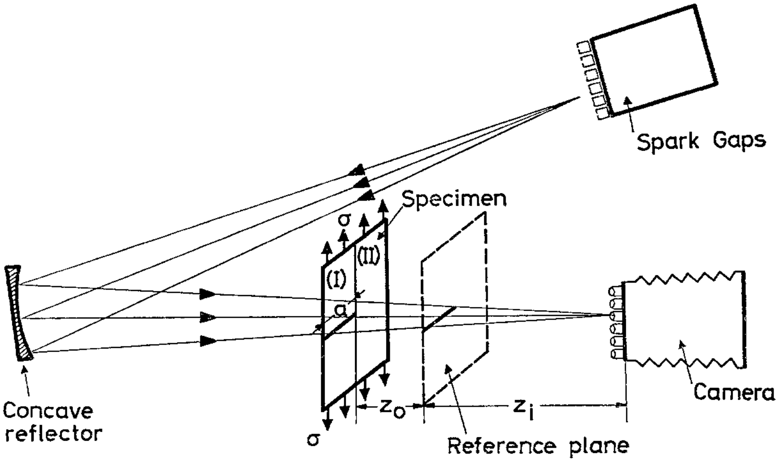

Fig. 2. Optical part of the experimental arrangement

For the study of dynamic crack propagation and interaction a Cranz-Schardin high speed camera was used, disposing 24 sparks with a maximum frequency of 10 frames per second. For the dynamic fracture of the specimens we used a Hydropulse High Speed Testing machine of Carl-Schenk Co. with electronic displacement control, maximum dynamic load of 40 KN and maximum possible strain rate for specimens of 0.30 m length $> e = 80\ \mathrm{s}^{-1}$. The applied dynamic load was recorded by means of a quarz force transducer. The synchronization of the fracture process with the high speed camera was achieved by means of a convenient silver-contact circuit which triggers the sparks with the initiation of crack propagation, eventually with some external delay.

The optical part of the experimental arrangement contains a concave reflector of 0.50 m diameter and a focal distance $f = 7.00$ m. The light beam emitted from each specimen, was focused at the respective lens of the Cranz-Schardin camera, see Fig. 2.

The fracture process of the specimens was undertaken under three different strain rates of $16\ \mathrm{s}^{-1}$, $4\ \mathrm{s}^{-1}$, and $0.4\ \mathrm{s}^{-1}$. Under each strain rate two specimens (for reproducibility reasons) out of each configuration were tested.

4. Results

4.1 Paths of Crack Propagation

A general observation in concern with the trajectory of the propagating crack, is that the hole has the tendency to attract the crack, a result which is thought to be also influenced by the vertical distance of the initial crack axis from the center of the hole and to a much lower extend by the rate of loading.

For the first specimen configuration, that is for the specimens having a vertical distance $c = 0.005$ m (equal to the radius of the hole) and for all three loading rates, the crack reaches the hole, is being momentarily arrested at its boundary, attaining thus a position approximately lying on the holes longitudinal axis. The crack intersects then at this point the hole boundary, is being arrested in the hole, to re-initiate later with a new crack propagation velocity and stress intensity factor at its tip, from a position corresponding to the longitudinal axis of the hole. The above described phenomenon can be seen in Fig. 3. The whole process resembles to the case of a transverse crack coalescing with a hole lying on its axis of propagation, as studied in [15] and needs no further discussion.

For the specimen configuration, where the vertical distance of the initial crack axis from the center of the hole was $c = 0.020$ m (that is twice the diameter of the hole), no practical deviation from the original trajectory of the propagating crack took place. The phenomenon can be thus reduced to the case of crack propagation in a homogenious elastic body. A small attraction effect could be though detected in the case of the lower strain rates of $0.4\ \mathrm{sec}^{-1}$ and $4\ \mathrm{sec}^{-1}$ meaning that as the

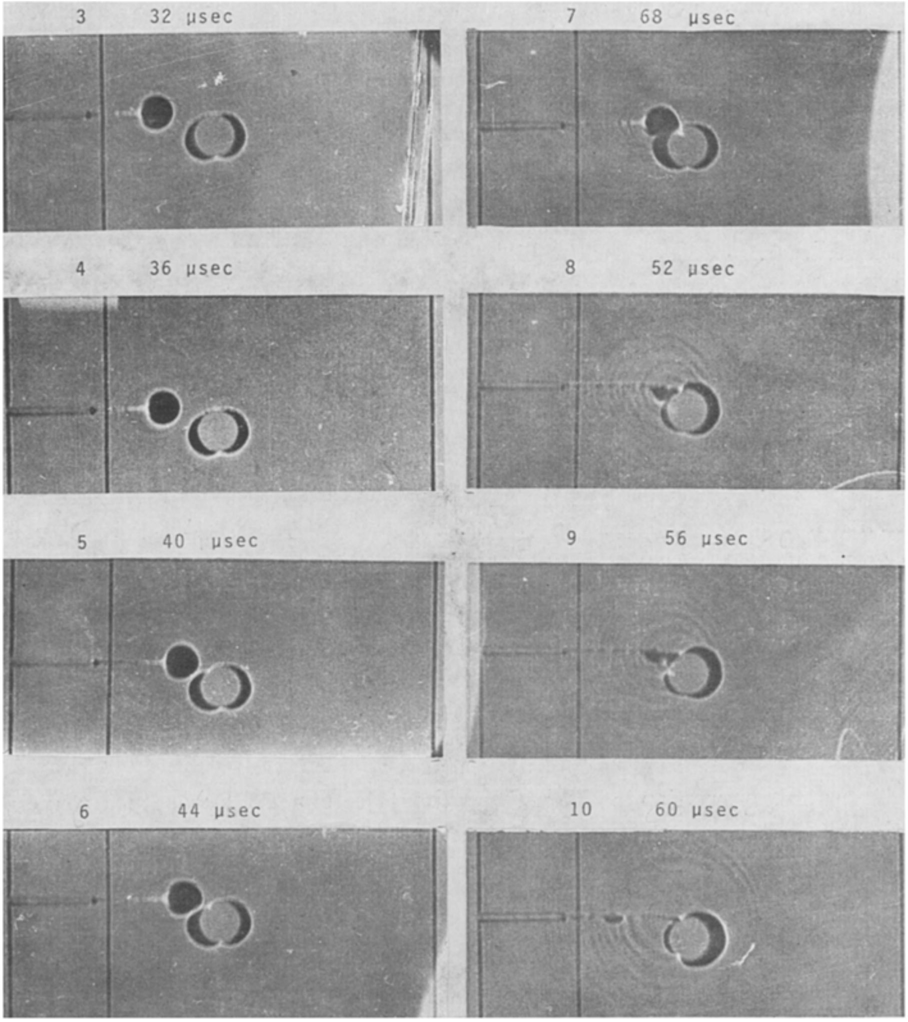

Fig. 3. Series of photographs showing crack-hole interaction for the case of a specimen with $c = 0.005$ m

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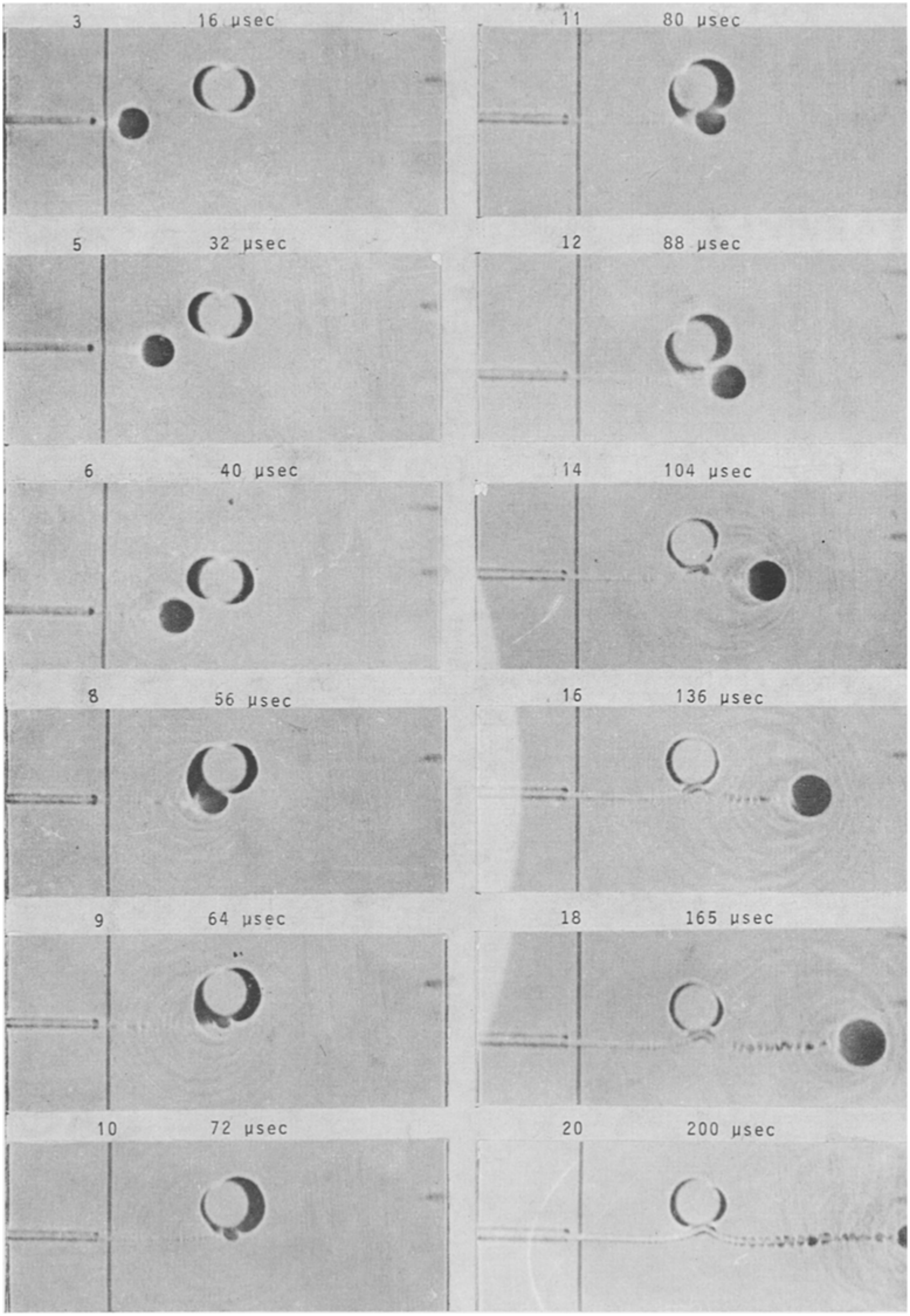
Fig. 4. Series of photographs showing crack-hole interaction for the case of a specimen with $c = 0.010$ m, fractured under a strain rate of $\dot{\varepsilon} = 4\ \mathrm{sec}^{-1}$


3 16 μsec
5 32 μsec
6 40 μsec
8 56 μsec
9 64 μsec
10 72 μsec
11 80 μsec
12 88 μsec
14 104 μsec
16 136 μsec
18 165 μsec
20 200 μsec

crack propagation velocity increases with increasing strain rate, the inertia effects of the crack propagation process are also increasing.

The most interesting phenomena of interaction were revealed in the case of the second specimen configuration, where the vertical distance between the initial crack axis and the hole was $c = 0.010$ m (that is equal the diameter of the hole). In all cases of applied strain rate, the attraction effect of the propagating crack towards the boundary of the hole becomes apparent. (See Fig. 4.) Notice that the crack reaches the hole boundary at its "lowest" point, that is at the point where the maximum principal stress is exerted. When reaching this point, the propagating crack is being momentarily arrested at the hole boundary, without, though, intersecting the hole boundary (that is without entering the hole). It reinitiates in a few microseconds in a direction symmetrically opposite to the attraction trajectory, moving thus now "away" from the hole (that is it is being repulsed from the hole). At a certain distance away from the hole, the crack retains its initial direction, vertically to the applied external load.

It is thus revealed that the phenomenon of coalescence of a moving crack with a hole is characterized, for certain critical vertical distances of the initial

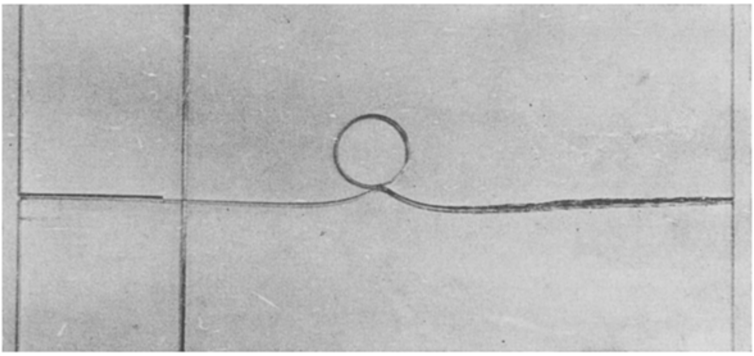


Fig. 5. Photograph showing the path of crack propagation in a specimen with $c = 0.010$ m, fractured under a strain rate of $\dot{e} = 4\ \mathrm{sec}^{-1}$

crack axis from the center of the hole, by a complicated process of attraction towards the hole, momentary arrest at the hole boundary and then repulsion away from the hole. A curved crack trajectory is thus created, which is almost symmetrical in respect to the axis of the hole, as it is shown in Fig. 5, where a photograph of the cracked specimen is presented. The critical distance at which the above mentioned effect of crack interaction with a hole boundary takes place is determined by the strength of interaction between the singular stress field at the crack tip and the stress concentration around the hole. It is thus a result of not only the stress intensity factor at the crack tip, but also of the diameter of the hole which determines, for a given external load, the stress concentration around it.

4.2 Crack Propagation Velocities

Fig. 6 shows the variation of the crack propagation velocity with time for the case of a specimen fractured under a strain rate of 4 $\sec^{-1}$ and having a vertical distance $c = 0.010$ m from the center of the hole, specimen of Fig. 4.

For this case the crack initiates with a velocity of approximately 370 m/sec which is increasing to the value of 460 m/sec as the crack approaches at a distance of nearly 10 mm from the longitudinal axis of the hole. The crack propagation velocity is then constantly decreasing up to the value of $v = 0$ corresponding to frames 9 and 10 of Fig. 4, as the crack is being constantly arrested at the lowest hole boundary. After a crack arrest period which lasts for about 20 μs the crack reinitiates with a considerably higher crack propagation velocity of approximately 570 m/sec, which is though diminised later on, as the crack propagates away

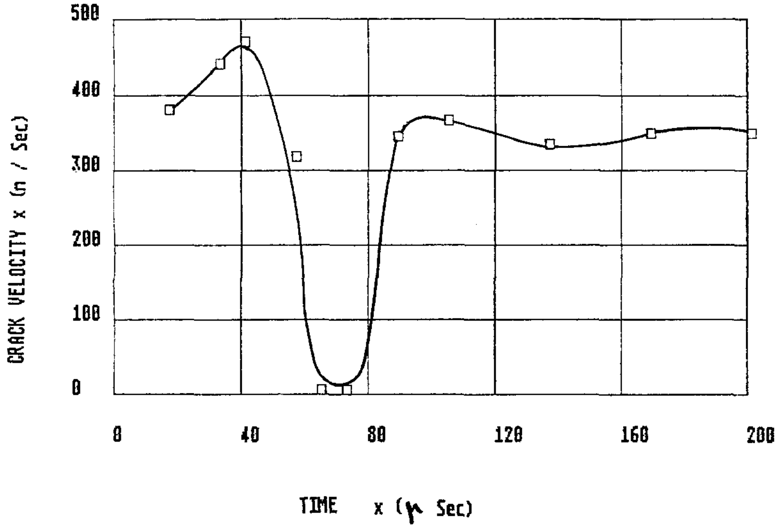


Fig. 6. Variation of crack length with time for the case of a specimen with $c = 0.010$ m and $\dot{\varepsilon} = 4 \sec^{-1}$

from the hole to finally reach a value of about 480 m/sec. A similar variation of the crack propagation velocities was detected for the cases of strain rate values of 0.4 sec^{-1} and 16 sec^{-1} with the difference that the average velocity values were 10% lower in the case of $e = 0.4\,\text{sec}^{-1}$, and 15%—20% higher in the case of $e = 16\,\text{sec}^{-1}$. The crack propagation velocities after crack re-initiation are higher than the crack propagation velocities before crack arrest since now the approximately constant external load is used to initiate a crack with a much greater initial length. This phenomenon was also detected in few other cases of momentary crack arrest, see [13].

4.3 Interaction Process and Stress Intensity Factors

We will now discuss the details of crack-hole interaction for the most interesting case of crack arrest of the hole boundary which is presented in Fig. 4. In the early phases of crack propagation (frames 3, 5, 6 of Fig. 4) a clockwise rotation of the optical stress rosette around the hole can be detected, proving a respective rotation of the principal stresses in the upper part (in respect to the crack axis) of the specimen. This phenomenon is due to the influence of the propagating crack and has been in the past described in detail, [16]. We know therefore the respective counter-clockwise rotation of the principal stresses takes place in the lower semi-plane of the specimen. Notice the intensification of the stress field around the hole as the crack approaches it. Frames 8, 9, 10, 11, show the process of crack-hole coalescence and the phenomenon of crack arrest. In frame 5 the propagating crack has been already arrested at the hole boundary, the singular stress concentration at its tip has been converted into deformation of the hole boundaries, see [15]. In frame 10 the left part of the hole boundary appears released from stresses which are now concentrated at the right boundary. An obvious redistribution of the stress concentrations, accompanied by a counter clockwise rotation of the stress field around the hole in the upper semi-plane takes place in frames 11 and 12, which also involve the process of crack reinitiation. As the crack propagates away from the hole the stress concentration at the hole boundaries diminishes down to a certain level (frame 14) and obtains later on its initial direction, which approximately coincides with the specimens longitudinal axis. Fig. 7 shows the variation with time of the stress intensity factor K_I normalized to its value K_{I0} at the moment of crack initiation. The value of the SIF increases as the crack approaches the hole, diminishes to zero during crack arrest and appears to be increased after crack reinitiation.

The phenomenon of attraction of the moving crack towards the hole boundary at the point of concentration of the principal stress σ_1 can be explained in regard to the direction of the principal stresses in the specific specimen configuration. As the crack propagates the stress field in the upper semi-plane is initially rotated clockwise in respect to the original direction of the applied stress field. Contraversely it is rotated counter-clockwise in the lower semi-plane of the specimen. The

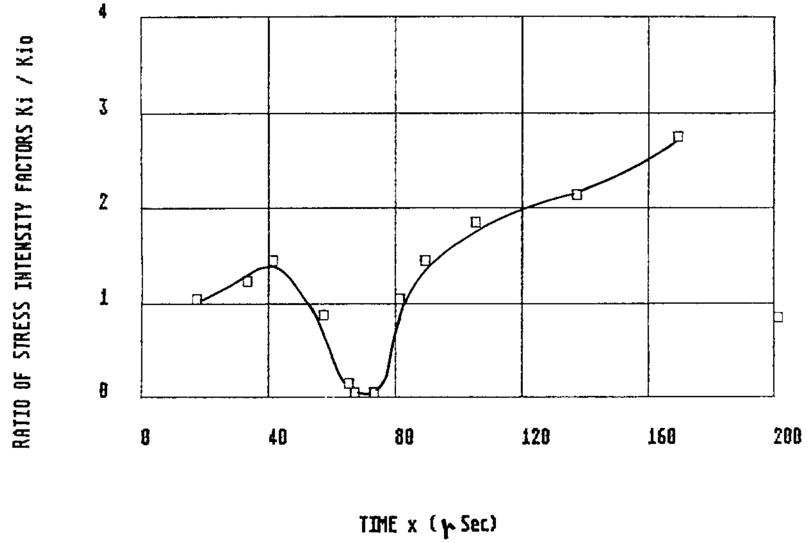


Fig. 7. Variation with time of the normalized values of the stress intensity factor of the tip of a crack propagating in a specimen with $c = 0.010$ m and $\dot{\varepsilon} = 4\ \text{sec}^{-1}$

existence of the hole introduces an asymmetry of the stress distribution in respect to the crack axis in the means that the upper semi-plane contains a stress free area (equal to the extension of the hole). This stress free area deminishes the overall stress in the upper semi plane of the specimen despite the stress concentration around the hole. As the crack approaches the hole it practically reaches an area of asymmetrical stress distribution and it is forced to move away from the semi-plane with the higher stress distribution, that is in a trajectory perpendicular to the direction of the principal stresses of the lower semi-plane. It is thus directed towards the hole boundary. The coalescence with the boundary of the hole results in the crack arrest process. During crack arrest a rotation of the stress field takes place, the principal direction of the stresses at the lower semi-plane rotate clockwise (while the corresponding rotation at the upper semi-plane is as we have already mentioned counter-clockwise). These new directions of the stress fields in the two semi-planes lead to a crack reinitiation away from the hole, in a direction which is again perpendicular to the principal stress of the lower semi-plane. After the crack was moved away from the hole it lies again in a symmetrical stress distribution in respect to the crack axis and its preferential direction is now again the perpendicular to the externally applied load.

Conclusions

The investigation of the process between interaction of a propagating transverse crack and a hole lying eccentrically in respect to the crack's axis showed that for a given hole diameter a strong interaction phenomenon takes place for a certain vertical distance of the crack axis from the center of the hole. The asymmetry of the stress field in the vicinity of the hole results in an "attraction" of the propagating crack towards the hole boundary, a process which ends up with a momentary crack arrest at the hole boundary. Subsequently crack reinitiation this time away from the hole, due to a redistribution of the stress field during crack arrest. The processes of crack deviation, rotation of the singular stress field at the crack tip, crack arrest and crack reinitiation were studied in respect with the variation of the values of the crack propagation velocity and the stress intensity factor of the crack tip.

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