CRACK INTERACTION, COALESCENCE AND MIXED MODE FRACTURE MECHANICS

Y.-Z. Wang1, J. D. Atkinson1, R. Akid2 and R. N. Parkins3
1School of Engineering, Sheffield Hallam University, Sheffield S1 1WB, U.K.
2SIRIUS, The University of Sheffield, Sheffield S1 3JD, U.K.
3Dept. of Mech., Mater. and Manuf. Engng, The University, Newcastle upon Tyne, NE1 7RU, U.K.

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Abstract—Multiple cracks are often observed in engineering structures; and their interaction and coalescence may significantly affect the lifetime of a component or structure. In this paper, the general features associated with crack interaction and coalescence are presented, and the conditions for coalescence in various forms are reviewed. A model has been developed based on the principles of mixed mode fracture mechanics, to provide a rational explanation for the phenomenon of crack interaction and to predict the coalescence conditions. The latter is found to agree reasonably with the experimental observations.

Keywords—Crack interactions; Multiple cracks; Crack coalescence; Mixed-mode behaviour

INTRODUCTION

The multiple cracking problem has received significant attention in recent years, mainly because it presents a very important issue in the prediction of component life. The availability of multiple sites for crack initiation makes it a common feature in many kinds of material failures, including stress corrosion cracking [1–3], fatigue [4–6], corrosion fatigue [7, 8], and thermal fatigue [9]. When such crack colonies are present in a component or structure the failure event is usually preceded by the interaction and coalescence of those cracks. A knowledge of the conditions at which appropriately offset cracks may merge is therefore of importance in assessing structural integrity. This is because once the conditions are satisfied, cracks can be re-characterised as a single larger crack so that the existing methods for fracture analysis can be applied. This knowledge of the crack coalescence condition is, however, very limited, and the methods dealing with such a phenomena are also inconsistent in current engineering codes [10–13]. Furthermore, there is still a lack of rational explanation for the reported observations.

In this paper, the general features associated with crack interaction and coalescence are presented, and the conditions for coalescence in various forms are reviewed. A model is developed based on the principles of mixed mode fracture mechanics, to provide a rational explanation for the phenomenon of crack interaction, and to predict the coalescence conditions. The latter is found to agree reasonably well with the experimental observations.

MORPHOLOGY OF CRACK INTERACTION AND CONDITIONS FOR COALESCENCE

The general features associated with multiple crack development are demonstrated in Figs 1 and 2. In Fig. 1, the final failure of a specimen of Ni–Cr–Mo–V steel fatigued at a low frequency, in a concentrated sodium hydroxide solution, resulted from the coalescence of two large cracks. The latter were formed by the joining of several relatively smaller cracks, as suggested by the
Fig. 1. An example of crack coalescence in Ni–Cr–Mo–V steel cycled at a low frequency in a concentrated sodium hydroxide solution. The large crack has four islands of metal remaining attached, indicating that it resulted from the coalescence of four separate cracks, before coalescing with the large crack at the right.

Fig. 2. Highlights of the process of crack interactions in a specimen of high strength spring steel fatigued at $R = -1$, $F = 30$ Hz in a sodium chloride solution. The number of cycles to failure was 361,960, and the number of cycles at each test interval were (a) $3 \times 10^5$, (b) $3.3 \times 10^5$, (c) $3.5 \times 10^5$ and (d) $3.6 \times 10^5$.

(Pictures taken from acetate replicas.)

islands of metal between the cracks. Figure 2 shows the details of crack interaction process. The micro-graphs shown in Fig. 2 were obtained from acetate film replicas of a corrosion fatigue specimen of a high strength steel exposed to a chloride solution. This clearly indicates that the interaction or coalescence of cracks depends strongly upon their relative location and also the...
crack sizes. Crack A in Fig. 2 initiated relatively far away from the others and its early growth (pictures a, b and c) shows no notable influence from other cracks. This is indicated by the facts that the crack has a straight growth path and the amount of extension from both tips was almost the same. However as the crack length increased crack A began to interact with the crack B, see picture d. The result of this interaction is seen through a change of the propagation directions of the closest crack tips. Also, the extension at the closest tip to B was less than that at the other tip during the test interval between that shown in pictures c and d. That implies that a growth retardation at the interacting tips occurred at some stage during the interaction. The cracks labelled B and C are good examples of crack interaction.

The common features observed for the coalescence of two offset cracks involves a sequence where approaching tips often diverge from their previous paths to some extent and propagate beyond one another before turning towards the opposite crack and joining the latter, as shown partly in Figs 1 and 2. The consequence of this is that a small island of metal is left near the cracks. Cracks B and C in Fig. 2 resulted from the coalescence of 4 and 3 separated cracks, respectively. In later stages, these two larger cracks interacted with one another and with crack A. Also, if a crack is in a position where it is shielded by another crack, such as crack D with respect to crack B and E to C, its further propagation can be retarded or even arrested, as shown in Fig. 2.

Obviously, the frequency of crack coalescence is related to the crack density within the component, that is, the higher the crack density, the greater the chance of two cracks meeting. However, whether crack merging occurs or not will be largely determined by the relative location of the cracks. Information regarding the conditions at which two adjacent cracks may merge is of vital importance for assessing the integrity of a structure which contains multiple cracks. Although no theoretical formula is available for such conditions, various assumptions and empirical expressions have been reported.

The rules set by current engineering codes [10–13] to determine the occurrence of crack coalescence vary from one another and are lacking in consistency. Apparently, the lateral separation of the crack tips is an important parameter in crack interaction, but this has not even been included in some codes [10,11]. Another feature associated with the rules of current codes is that the condition for coalescence is not related to the stress level imposed on the cracked body. This makes them distinctive from the assumptions based on fracture mechanics.

An interaction zone is commonly introduced along the crack tip, and coalescence is assumed to occur when the interaction zones of the approaching tips overlap. Forsyth [14] was among the first to refer the interaction zone to the crack tip plastic zone, so that the size of the interaction zone, in terms of the distance between the interacting crack tips, $h$, can be estimated as follows:

$$ h \propto \frac{\sigma}{\sigma_y} (2a_1 + 2a_2) $$

where $\sigma$ and $\sigma_y$ are the applied and yield stresses of the material, and $2a_1$ and $2a_2$ the crack lengths. This assumption has been adopted in various works [4,6,15].

The interaction zone and coalescence conditions derived by Kitagawa et al. [7] considered the changes in the stress intensity factors by the appearance of a neighbouring crack. When two cracks with a short lateral distance of separation approach, the $K_1$ value of the closest tips may increase significantly. So a series of “equi-interaction regions” can be introduced along the front of a crack tip and so, should another crack tip fall within such a region, the stress intensity factor may increase by a factor $f$. Thus the crack coalescence zone can be defined by one of the equi-interaction regions which has a specific interaction factor, $f_c$, as gained from experiments.

Extensive measurements have been made, by Parkins and co-researchers [2,16,17] and Wang et al. [3,8], of the lateral distance between adjacent crack tips and the lengths of the cracks, in
the context of whether pairs showed evidence of coalescence or otherwise. Despite the different material-environment systems involved and various stress levels applied, it has been shown that merging will almost always occur when the closest tips of adjacent cracks have passed one another. Figure 3 shows some of the results from those measurements for systems involving a Mn–Cr steel in deionised water and a Ni–Cr–Mo–V steel in a sodium hydroxide solution [3]. The lines reasonably separate those cracks that showed evidence of coalescence from those that did not and the slopes of those lines are the same for both systems, despite the involvement of much larger cracks with the Mn–Cr steel. Thus, the maximum value of the lateral separation (h) to achieve coalescence is dependent upon the crack length (2a) according to

\[ h \leq 0.14(2a) \]  

for both systems. Effectively the same expression has been found to hold for systems involving pipeline steels in two different laboratory environments, as well as for service failures [2,16,17], and a high strength spring steel in salt water [8]. Similar results have been reported by Ochi et al. [4] for fatigue in air for mild steel, copper and a 304 stainless steel. Inoue et al. [5] postulated an equation relating the critical offset distance for coalescence to the crack length as well as to the mean grain-size.

The independence of conditions for coalescence from both material and environment implies it must be mechanics related. The stress distribution between the neighbouring cracks is therefore the key to understanding the phenomenon of crack interaction.

**FRACTURE MECHANICS CONSIDERATIONS**

**Stress intensity factors of interacting cracks**

Although no analytic solutions are available for interacting cracks, numerical results have been reported for cracks with various geometric arrangements [18–22]. All the results indicate that, depending on the relative location of the two cracks, the stress intensity factors (SIFs) at the interacting crack tips can be either enhanced, or have no effect, or be reduced due to the effect of
"shielding" by comparison with that of an isolated crack. In addition, the "secondary" modes of SIFs, i.e., Modes II and III, if under Mode I loading, can be induced.

The stress intensity factor solutions for the nearest tip of two equal length offset cracks in an infinite elastic solid subjected to a tensile stress \([18]\) are used for the analysis of crack interaction. The solutions show that the Mode I stress intensity factor, \((K_I)\) increases as the nearest crack tips approach one another, but then declines as the tips pass. In the meantime, the Mode II stress intensity factor \((K_{II})\) becomes significant and the sign changes from positive to negative as the crack tips approach and then pass. The extent of variation in stress intensity factors is however strongly dependent upon the offset distance of the cracks.

Since the secondary stress intensity factor, \(K_{II}\), is introduced when the nearest crack tips closely approach, the crack tips then actually experience a mixed Mode I and II condition during their interaction. Therefore the crack propagation behaviour under a mixed Mode loading condition is most relevant to the phenomena of crack interaction and coalescence.

**Crack propagation under mixed Mode I/II loading**

Crack growth under mixed Mode loading conditions is of practical importance, as many engineering components/structures are actually subjected to very complex loading conditions. Traditional fracture mechanics has concentrated on cracks loaded by tensile stresses, and growing under an opening or Mode I mechanism. However, in recent years, a considerable amount of work has been conducted on the behaviour of cracks loaded by a combination of tensile (Mode I) and shear (Mode II) stresses, and a variety of tests and theories have been developed concerning the threshold condition, propagation direction and growth rate of a crack under such stressing conditions \([23,24]\).

According to the maximum tangential (hoop) stress (MTS) theory \([25]\), the crack advances in a direction (oriented at an angle \(\theta\) to the pre-crack, see the inset on Fig. 4) in which the tensile stress at the crack tip is maximum, therefore assuming a Mode I mechanism of growth. The Griffith theory or the maximum energy release rate (MER) theory \([26,27]\) postulates that combined Mode I and II fracture takes place in an elastic solid along a plane which maximises the energy

![Fig. 4. The crack propagation direction under mixed Mode I and II loading, as predicted by various theories and observed experimentally.](image)
release rate, while in the strain-energy density theory [28] such crack growth is predicted to occur
along the direction which gives the lowest (minimum) strain energy density (MSE). It also has
been proposed that a crack should advance in a direction along which $K_{II} = 0$ [29]. The above
theories were derived from different considerations, but little difference is found among the predic-
tions of these theories for the direction of crack propagation, as shown in Fig. 4 [30] in which
some experimental data is also included. Amongst these theories, the simplest and possibly the
best approach is the maximum tangential stress criterion [23], which was first proposed in 1963
by Erdogan and Sih [25].

Under linear elastic conditions, the near-tip tensile stress component for a crack subjected
remotely to tensile opening and sliding stress intensity factors, $K_I$ and $K_{II}$, respectively, (see the
inset on Fig. 4), can be given by

$$\sigma_\theta = \frac{1}{\sqrt{2\pi r}} \cos \theta \left( K_I \cos^2 \frac{\theta}{2} - \frac{3}{2} K_{II} \sin \theta \right)$$

where $r$ and $\theta$ are the polar co-ordinates centred at the crack tip. This tensile stress approaches
infty as $r$ approaches zero, and so can be represented by a generalised tensile stress intensity
factor, $K_{\theta}$, i.e.,

$$K_{\theta} = \sigma_\theta \sqrt{2\pi r}$$

According to the maximum tangential stress theory, the direction of crack growth under a mixed
$I$ and $II$ loading can be found by calculating the value of $\theta$, i.e. $\theta_0$, that gives the highest value of
$K_{\theta}$, i.e. $K_{\theta_0}$, from the condition $(\partial K_\theta/\partial \theta) = 0$, which gives

$$\frac{K_{II}}{K_I} = \frac{\sin \theta_0}{1 - 3 \cos \theta_0}$$

The threshold condition for crack growth was then proposed by Erdogan and Sih [25] as

$$K_{\theta_0} = K_{IC}$$

where $K_{IC}$ is the Mode I fracture toughness of the material. These expressions imply that the
direction of crack growth under combined Mode I and II loading is only related to the $K_{II}/K_I$
ratio and not the individual values of those stress intensity factors. But whether or not crack
propagation is possible and if so, what growth rate is relevant are dependent upon the value of
$K_{\theta_0}$. This is determined using Eqs (5) and (4), by the actual amplitudes of both the applied $K_I$
and $K_{II}$.

The introduction of a Mode II stress component can have two important, but somewhat
opposing effects on the crack growth:

1. an increase in crack tip plasticity, which can accelerate crack growth, but can also invoke
   plasticity-induced crack closure;
2. crack surface contact and rubbing causing extra crack closure thereby reducing the
   propagation rate.

The results of Shih [31] show that with increasing Mode II components the plastic zone changes
its shape, expands its size and rotates clockwise, centring on its axis near the crack tip. At the
same amplitude of far-field loading, the plastic zone size in Mode II is up to five times bigger than
that in Mode I. For the situation where crack growth is controlled by crack tip plasticity, such as
stage I fatigue crack growth, the increased plasticity associated with the Mode II stress component
may facilitate crack development. However, this increased plasticity is accompanied by a decrease
in the hydrostatic stress and may enhance the crack closure [32]. In addition, the Mode II component introduces shear displacement between the crack surfaces, which may cause crack surface contact, rubbing and even interlocking of the two surfaces, depending upon the roughness of the surfaces. As a result, a shear resistance is introduced between the fracture surfaces; the load is then difficult to transmit to the crack tip, so the driving force at the crack tip decreases. It has been estimated [30] that the shear resistance of pure Mode II can consume 70 to 80% of the crack driving force. It is this crack closure effect that makes Mode II crack propagation difficult under mixed Mode loading.

Also because of these two opposite effects associated with the Mode II component, the results in regard to the threshold and growth rate of a crack subjected to mixed Mode I and II loading were reported as somewhat inconsistent. For example, the experimental results on brittle materials [25,33] and on notched specimens of stainless steel [34] accorded well with the above theoretical criterion (i.e., Eq. (6)), while others [30,35,36] show that the threshold for crack growth was much higher than that predicted by those criterion when the Mode II stress component was introduced. The threshold value for crack growth under pure Mode II loading can be more than twice the value under pure Mode I loading [30,35,36]. It appears that any factor which may influence the crack closure behaviour, such as material microstructure, crack length, method for pre-cracking (notch or pre-fatigue), R ratio, values of the applied $K_I$ and $K_{II}$ and their ratio, can contribute to the crack growth threshold and affect the growth rate of a crack under a mixed mode loading. It is reasonable to assume that if the crack can be fully opened, or closure has not a dominant effect, the introduction of a Mode II component could be expected to enhance the crack growth velocity. Otherwise, in the context of crack closure, the crack growth is likely to be retarded. But, as mentioned above (see Fig. 4), the propagation direction of a crack under mixed Mode I and II loading can be reasonably accurately predicted by the above theories [24,30,33].

THE IMPLICATIONS FOR CRACK INTERACTION AND COALESCENCE

Stress analysis has shown that the appearance of a second crack in the neighbouring region of a crack tip, subjected to remote tensile load, could induce a Mode II stress component. Based on those solutions [18], the changes in the ratio of $K_{II}/K_I$ for the nearest tip of two equal length offset cracks can be obtained, as given in Fig. 5(a), as a function of their relative location in regard to...
to their length. Mixed mode fracture mechanics predicts that a crack will propagate by deviating from its original plane if shear stress is induced, and the positive value of $K_{II}/K_I$ promoting a divergent path with the negative value a convergent one. Figure 5(a) shows that as the crack tips approach, $K_{II}/K_I$ becomes significant (the extent depends upon the offset distance) and the sign changes from positive to negative as the tips approach and then pass. With overlapping the absolute value of $K_{II}/K_I$ reaches a maximum and then decreases until it becomes positive again. Applying Eqs (5) and (4), the crack deviation angle $\theta_0$ from the original crack plane and thus the equivalent Mode I stress intensity factor $K_0$ along the direction of $\theta_0$ can be obtained at each relative location; the latter are given in Fig. 5(b). It is also found that the Mode I component makes a major contribution to the equivalent stress intensity factor, whilst the change of the ratio of $K_{II}/K_I$ follows a similar trend to that of $K_{II}$.

The above indicates that it is the mixed mode stressing condition experienced by the nearest tips of the adjacent cracks that leads to the change of crack growth direction and causes coalescence. The load level will affect the values of $K_I$ and $K_{II}$ for pairs of appropriately distributed cracks, but not the ratios of those quantities and so will not influence the conditions for coalescence. Of course, the load level may influence the crack nucleation rate and the growth velocity. Note also a sharp decline in the equivalent Mode I stress intensity factor $K_0$ and the increase in the value of $K_{II}/K_I$ after the crack tips pass one another. These two effects, as discussed earlier, are likely to enhance crack closure and so reduce the crack driving force, or introduce extra plasticity owing to the large plastic zone size associated with the Mode II stress component. This effect will result in a growth retardation for the nearest crack tips at some stage after overlapping, as was observed with crack A of Fig. 2. In other experiments (e.g. [37]) it has been observed that a pair of cracks might show signs of interaction with their tips moving towards one another but never contacting the opposite crack. Additional plastic deformation was also apparent between neighbouring cracks, as shown in Fig. 6. This plastic deformation was associated with the emergence of slip steps and transgranular cracking. Furthermore, from Figs 5(a) and 4 it can be seen that a value of 0.14 for the constant relating the maximum lateral distance for coalescence $h$ to the crack length $2a$ (Eq. (2)), corresponds approximately to a maximum deviation angle of about 45° from the original growth direction during the interaction and coalescence of two cracks. Equation (2) implies therefore, that any deviation of growth direction less than that angle, as the $h/2a$ ratio increases, will not result in the merging of the two cracks.

Since the ratio of $K_{II}/K_I$ varies with the relative position of the crack tip, a curved crack path will be formed for the interacting tip. A change in crack path during interaction could be further predicted by the principles of mixed mode fracture mechanics, if the stress intensity factors for a curved crack were available. This knowledge is, however, limited, although some solutions for

![Fig. 6. Crack tip effects between linking cracks of a Mn–Cr steel specimen cycled at low frequency in deionised water.](image-url)
kinked cracks have been reported [38]. An attempt is made below of a first order estimation for the path of two offset interacting cracks, with the following simplifications:

1. employing the stress intensity factor solutions for neighbouring cracks whose tips remain parallel [18];
2. assuming cracks propagate following the MTS theory, and
3. ignoring the effect of the stress intensity factor on the growth rate, which means both crack tips extend at the same rate.

These simplifications imply that only aspects of crack growth *kinematics* are considered.

A selection of predictions for crack paths are given in Figs 7 to 9, for different offset heights $h$ in relation to the distance of separation of the crack nucleation sites in the main growth direction ($x$-axis) $2d$. Companions to these figures are the stress intensity factors, $K_I$, $K_{II}$ and $K_{III}$, normalised by the Mode I stress intensity factor for an isolated crack of the same size. This is also assumed to hold for the outer crack tip. The ratio of $K_{II}/K_I$ are also given in these figures as functions of the crack tip position. For the initial geometric arrangements, cracks 1 and 2 originate in the positions of 0 and 10 on the $x$-axis, and are assumed to grow from both tips at the same rate. The stress intensity factors shown in these figures are for crack 1. Cracks grow independently until interaction starts at a certain position which depends on the original positions of the crack nucleation sites. This arrangement also determines whether or not coalescence can be achieved.

For the cases where the lateral separation is relatively small (e.g., $h/2d = 0.1$ in Fig. 7, the insets in Figs 7 and 8 show the detail of crack paths when interaction starts), the approaching tips diverge from their initial growth direction before turning to the opposite crack and then joining the latter, as often observed in experiments and in service. This divergence of a crack tip to avoid another during interaction disappears as the offset height increases (Fig. 8 where $h/2d = 0.5$). After the crack tips overlap, if the tip can not touch the wake of the opposite one before the value of $K_{II}/K_I$ becomes positive, the crack tips will diverge again from one another so that merging will never be possible (Fig. 9). This is found to correlate to a condition where the initial arrangement for crack nucleation sites satisfies $h/2d > 0.85$.

It is also noted that the Mode I stress intensity factors $K_I$ and $K_{III}$ decrease after the crack tips overlap. As the crack extends, the crack length ($2a$) increases so that the ratio $h/2a$ decreases. Comparisons have been made of $h/2a$ at the positions where the crack tip touches the opposite crack when coalescence is permitted, or where the crack has the shortest distance from the other

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**Fig. 7.** Prediction of crack path for the initial arrangement of crack nucleation sites of $h/2d = 0.1$. (a) The predicted crack path; (b) the stress intensity factors for crack 1 as functions of the crack tip locations. (The inset in (a) shows the detail of crack path when interaction starts.)
in the lateral direction if merging is not possible. The value of \( h/2a \) at the above positions increases as the initial offset height \( (h/2d) \) increases, for the situation where crack merging occurs. The maximum ratio of \( h/2a \) for coalescence predicted by this model is 0.21, which is slightly higher than that obtained from experimental measurements (Eq. (2)).

It might be expected that the crack path would curve round even more abruptly to join its neighbour at right angles as crack deviation itself could enhance the Mode II component, so that an even higher value for the above constant would be expected. However, crack growth kinetic considerations raise some different points. Indeed, it has been already illustrated that the Mode I stress intensity factor \( K_{th} \) decreases and becomes less than that for an isolated crack when the tips overlap, while the value for the outer tip could be the same or even greater than that for an isolated crack. The crack closure effect associated with the Mode II component could further reduce the driving force for the propagation of the inner tips during the interaction. The resultant faster extension at the outer tip alters the geometry of the relative crack locations, i.e., it reduces the value of \( h/2a \), and creates a more favourable stress condition for the inner tip to change its growth direction and then to gradually join the opposite crack. Consequently, at the position where the crack tip joins the opposite crack a lower value of \( h/2a \) could be expected than that by only considering the crack growth kinematics, as shown in Figs 7 to 9. This effect will bring the constant in the crack coalescence condition closer to that obtained experimentally.

Although the most common feature associated with crack coalescence involves the development of crack tips overlapping, evidence has been obtained where no apparent overlapping was observed.
Forsyth [14] suggested that cracks could breakthrough when their plastic zones joined and he further postulated the critical offset height for coalescence to be the sum of the plastic zone sizes of the cracks involved (Eq. (1)). Whether or not this situation is involved in the above conditions is likely to depend upon the load level and also the stress status, as the latter influences the plastic zone size. Interestingly, a recent paper [39] produced an analytical result for the constant in Eq. (2) that is in reasonable agreement with the value given by the experimental results (0.14). The approach was also based on consideration of the plastic zone sizes and used dislocations to represent the cracks. Furthermore, the material microstructure may play a role in affecting the crack interaction. In the situation where cracking is predominantly intergranular, merging can happen along a grain boundary if the two approaching cracks share the same grain boundary before their interaction. Figure 10 presents an example of two approaching cracks meeting at a common grain boundary and joining up by mechanical separation of this boundary.

The enhanced plasticity associated with the interacting crack tips and/or the sharp increase in Mode I stresses before the closest tips meet (Fig. 5(b) and Fig. 7(b)) can trigger further crack nucleation between the crack tips, so that crack coalescence could involve the development of those newly formed cracks. This morphology of crack interaction is frequently observed, as has been reported by Parkins and Singh [2] and Wang et al. [3] and is apparent in Fig. 1.

One of the major objectives in the investigation of the criterion for crack coalescence is to re-characterise the crack morphology, so that a new single crack can replace a crack colony. The above analysis, based on mixed mode fracture mechanics, has reasonably explained the empirical relationship of the maximum offset distance for coalescence and the crack size, and well describes the features associated with the propagation of the approaching crack tips. But this analysis has provided little insight into the behaviour of the outer crack tip. The latter is, however, more directly related to the crack re-characterisation, since it is the propagation of the outer tip that represents the behaviour of the new crack. In engineering applications most cracks are three dimensional so the stress/strain fields associated with interacting cracks would be more complicated. The three dimensional elastic-plastic finite element analyses of fatigue crack growth in “thick” centre-cracked plates [40] indicated that crack closure and opening stresses varied through the thickness of the cracked plates. A markedly reduced level of crack closure was found in plane strain than in plane stress; and on the specimen side surface and in the mid-thickness plane, the crack opening stress levels approached the two dimensional solutions for plane stress and plane strain, respectively. It seems very likely that, during interaction and under certain other conditions, cracks may propagate more favourably in the depthwise direction than on the surface, so that crack fronts may make contact in depth with the tips not merged on the surface. This behaviour

Fig. 10. Two cracks coalesce by separating along the common grain boundary in a Mn–Cr steel specimen cycled at a low frequency in deionised water.
of a crack merging at depth without coming into contact at the surface has been observed by Wang [37] and Soboyejo and Knott [41]. In such a situation the crack re-characterisation based on the appearance of the interacting region on the surface may lead to an unsafe result.

While the significance of crack interaction and coalescence in crack growth kinetics has become increasingly recognised, the development of reliable life prediction models capable of handling such a problem remains a major challenge in structural integrity research. Certainly further collection of data concerning the conditions for crack coalescence is needed for different materials and test conditions. Carefully defined experiments, involving not only observation of the behaviour of approaching crack tips in their interaction and coalescence, but also measurements on the growth rates at both inner and outer tips and analysis of the stress/strain fields around them, will further improve understanding of the phenomena.

CONCLUSIONS

(1) The most common feature associated with coalescence of two offset cracks involves crack tip overlapping. The conditions for crack coalescence, obtained experimentally, relate the sizes of cracks and their distances of separation, but are independent of material, stress level or exposure conditions.

(2) It is the mixed mode conditions experienced by the nearest tip of approaching cracks that alters the growth direction and hence causes crack coalescence.

(3) The model, based on mixed mode fracture mechanics, provides a rational explanation for the phenomena of crack interaction and reasonably predicts the coalescence conditions.

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