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Fatigue Crack/Residual Stress Field Interactions and Their Implications for Damage-Tolerant Design

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Residual stress fields are now widely accepted to have significant influence on fatigue crack growth. Tensile stresses have detrimental effects on fatigue lives, whereas compressive residual stresses can be beneficial. Control of fatigue lives via residual stress is now established in many industrial applications, using techniques such as shot peening or cold expansion. However, knowledge of the processes that occur when a fatigue crack grows through a pre-existing stress field is far from complete. Although the residual stress field will clearly have an effect on crack growth, the crack will equally have an effect on the residual stress field. The determination of this effect is not trivial, and direct measurement may be the designer's best safeguard. This article outlines the complementary effects that a growing fatigue crack and a residual stress field have on each other. Two types of residual stress field are considered: mechanically induced and thermally induced. The results are discussed in terms of the implications that residual stress interactions have for damage-tolerant-based design.

Keywords crack growth, damage tolerance, fatigue, neutron diffraction, residual stress, weight functions

1. Introduction

Residual stresses exist in many manufactured components as a consequence of the thermal or mechanical processing applied during production. Local plastic deformation of a material will produce a residual stress variation, as will rapid cooling from elevated temperatures, where material yield strength is usually significantly lower than at room temperature.

To the engineer, residual and applied stresses are completely separate entities. Applied loads and the stresses they cause are usually well understood, but the comparatively "unseen" residual stress state can often be extremely problematic. Although residual and applied stresses are manifested in identical physical mechanisms on an atomic scale, the engineer is more concerned with the failure of a component at an apparently safe load.

Furthermore, in the context of fatigue, it is a cyclic *applied*, not residual, stress that will drive fatigue crack growth (in the absence of thermal cycling effects). As shown later in this article, fatigue crack growth can cause a change in the residual stress field while the applied loading remains unchanged (though the local stresses due to the applied loads will also change). Therefore, several reasons exist as to why applied and residual stresses are commonly treated as separate mechanisms affecting material behavior.

Extensive literature covers many different types of residual stress fields and the effects that such stresses have on fatigue (for example, Ref 1-14). The residual stresses that are discussed are generally those which are termed type I or *macrostresses*, which vary over relatively large distances, equivalent to many times the grain size in the material.

First, it must be noted that residual stresses are well established as a mechanism by which fatigue resistance can be altered. The proceedings of the *Third International Conference on Shot Peening* (Ref 15) contain many references on the beneficial effects that a compressive stress on the surface layer of a material can have in improving the fatigue strength of the material. While agreeing with this conclusion, Elber (Ref 16) notes that, if a crack becomes sufficiently long that it passes through the compressive layer into the tensile stress field (that must exist below the compressive layer in order for stress equilibrium to be maintained), then the crack growth rate will increase relative to that which would occur in the material if no residual stress were present. This is exemplified by the cracking of thermally toughened glass, where a sheet will fragment entirely following the initiation of a small crack into the tensile stressed region at the center of the plate. Similarly, Wilks et al. (Ref 17) have postulated that a crack grown through a compressive residual stress field will "balloon" when it reaches the tensile subsurface region, that is, the crack appears short on the surface where the compressive residual stress field exists, but continues to grow at an accelerated rate in the subsurface tensile region.

These effects are not universally applicable, however. Underwood et al. (Ref 2) have shown that fatigue crack growth is not necessarily dominated by the residual stress field at the crack tip. Cracks grown through a measured compressive residual stress field were seen to exhibit the expected retardation in growth rate, but no corresponding increase was observed when the crack reached a region of material that contained a tensile residual stress. This was attributed to a relaxation and redistribution of the stress field due to the passage of the crack. Therefore, once the crack has begun to grow through the thickness of a test sample, it is not necessarily applicable to perform an analysis based on the residual stress field that was present prior to crack growth, and indeed this can lead to nonconservative life prediction if redistribution is not taken into account

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(Ref 18). For stress-controlled fatigue tests performed on smooth specimens, relaxation of both the long-range macrostresses and the small-scale *microstresses* (stresses that vary on the scale of the grain size or particle spacing in a material, and which can arise from differences in thermal expansion between phases, for example) has been observed (Ref 19). Consequently, some change in residual stress would be expected in long-cracked samples, due to relaxation of the stress in the immediate vicinity of the crack. Longer cracks can also be affected by closure (point contacts across the crack faces while an opening load is still being applied, reducing the overall stress-intensity range experienced at the crack tip) in the crack wake (Ref 20-22), perhaps to a greater extent than the near-tip stresses.

Although it is clear that residual stress is a factor that affects fatigue behavior, it is not trivial to predict quantitatively how a given residual stress field will enhance or degrade the fatigue performance of a component. Modeling methods such as weight function methods rely on use of the initial residual stress field for prediction of the changes in effective stress intensity as the crack advances. This does not account for the changes that crack growth and the associated local plasticity will have on the stress field. Also, the weight function approach considers only the stresses behind the crack tip when evaluating the stress intensity due to the residual stress field, although Beghini et al. (Ref 13) have shown nonetheless that this is a useful approach for analyzing residual stress effects. The process is highly interactive, and is discussed in the next sections of this article.

When a residual stress field is present, a growing fatigue crack is likely to exhibit a different growth rate from a crack growing in stress-free material. This has obvious implications for lifing of components where a damage-tolerant approach is adopted, assuming a known fatigue crack growth rate and load cycle characteristics. A tensile, accelerating stress field can lead to an overestimate of the component life, whereas a compressive residual stress could provide a nonconservative life.

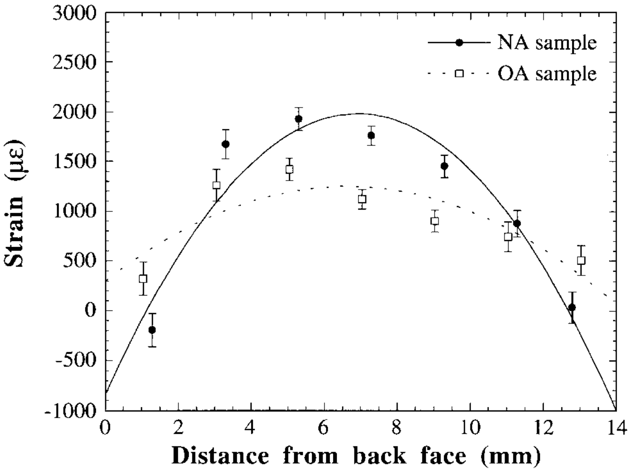


Fig. 1 Residual strain variation in the Al matrix of two metal-matrix composite samples. One was cut from a plate that had been water quenched from 505 °C and naturally aged (NA); the other was given an overaging (OA) heat treatment at 180 °C for 48 h, which has partially relieved the residual strains (Ref 14)

Although this article does not claim to provide answers to this dilemma, the authors attempt to illustrate the effects that residual stresses have via some fairly simple examples. It will also be shown how stress fields can be redistributed by a growing fatigue crack.

2. Measurement of Residual Stress Fields

2.1 Experimental Techniques

Many methods exist to determine residual strain or stress, ranging from destructive to nondestructive and from experimentally simple to complex. For a review of these methods and techniques, see Ref 23.

Techniques used to obtain the results presented in this article were neutron diffraction and Sachs boring. Neutron diffraction is a nondestructive technique that uses the high penetration of neutrons into materials to probe deep (several centimeters) beneath a surface, with the strain being determined from shifts in the position of Bragg diffraction peaks (Ref 24-29).

Sachs boring is a destructive method that involves removing of material from either the inner or outer diameter of a cylindrically symmetric object and monitoring the changes in strain on the other diameter, that is, outer or inner, respectively. From this change the pre-existing residual stress field can be calculated (Ref 30-33).

2.2 Experimental Measurements

In this section, results are presented for two examples that illustrate the interaction between residual stress and fatigue crack growth. The first example deals with the growth of a fatigue crack into a quench stress field, illustrating the effect that crack growth has on stress variation. The second covers the stress field around a cold expanded fastener hole and the effect that this has on fatigue behavior.

Quench Stress Field. Quench stress fields have been fairly well documented using neutron diffraction stress measurements. Measurements have been made in monolithic aluminum alloys (Ref 34) and metal-matrix composite materials (Ref 14, 35-37). As expected, the results show that the in-plane stress varies parabolically from compression at the sample surfaces to tension in the center. This is in agreement with predictions from finite-element-based modeling techniques (Ref 38, 39).

Metal-matrix composites (MMCs) are particularly interesting for the study of residual stress, as the difference in properties between the metal matrix and ceramic reinforcement produces a thermal mismatch stress. The matrix possesses a net tensile stress, and the reinforcement possesses a net compressive stress (Ref 40-45). The results for each phase do not, therefore, exhibit stress equilibrium, but are displaced relative to zero stress (or strain).

This is shown in Fig. 1 (Ref 14), which illustrates the strain variation in a MMC bar that was cut from a quenched plate; the plate was solution heat treated at 505 °C for 2 h, followed by a cold water quench. For comparison, Fig. 1 also shows the reduction in the strain variation that can be achieved by overaging a sample, following a quench, at 180 °C for 48 h. All measurements presented for MMCs in this article were performed on a material that was produced by a powder metallurgy route and which consisted of a 2124 Al matrix reinforced with 20 wt% SiC particles. The particles had a nominal diameter of 3 μm.

Such a strain variation is easily converted to stress, which is generally more useful in design, provided that sufficient measurements have been obtained. The strain distributions along the three principle axes are required, if these can be inferred from the symmetry of the specimen and the known loading conditions; otherwise, six independent directions are needed.

Stress Field around a Cold Expanded Hole. Cold expansion of fastener holes is now being widely applied in the aerospace industry (Ref 46) to improve the fatigue lives of airframe components. The technique essentially consists of pulling an oversized mandrel through a hole to induce a compressive hoop stress at the hole, caused by plastic flow during deformation.

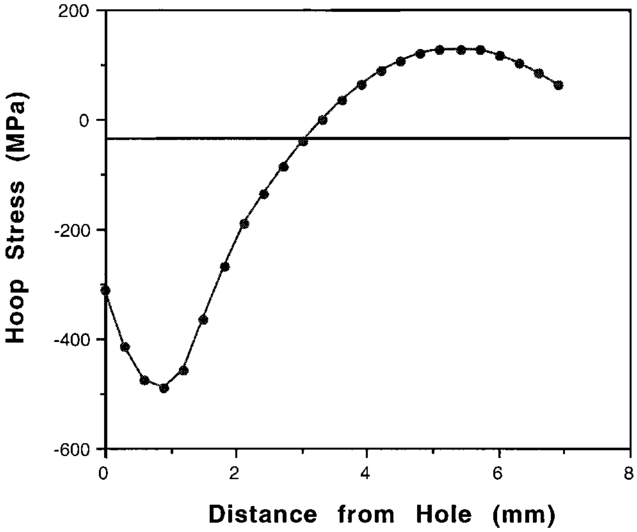


Fig. 2 Residual hoop stress distribution at an unreamed 4% expanded hole. The hole was expanded using the Fatigue Technology Incorporated (FTI) split sleeve process.

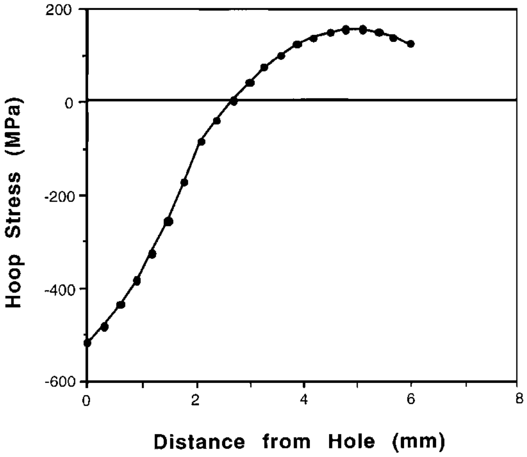


Fig. 3 Residual hoop stress distribution at the center of a reamed 4% expanded hole. The hole was expanded using the Fatigue Technology Incorporated (FTI) split sleeve process.

The most widely used process for hole expansion is that developed by Fatigue Technology Incorporated (FTI) of Seattle, USA (Ref 46). This process uses a lubricated split sleeve between the mandrel and the internal surface of the hole, which prevents direct contact between the mandrel and hole and thereby minimizes material flow in the through-thickness direction. Using this method, a maximum practical single pass expansion of 6% can be attained, although the optimum fatigue benefit has been suggested to occur at slightly lower expansion, around 4%, depending on the application and local geometry (Ref 47).

The Sachs boring method was used to measure the residual stress distribution around a 4% FTI expanded hole (Ref 48). The hole was located centrally in a 300 × 40 × 5mm plate of 7050-T76 aluminum. The effects of reaming the hole, where some material is removed from the inner surface following expansion, was also studied. Reaming is widely used after expansion to bring the hole to correct tolerance before joining.

Figure 2 shows measurements of the residual hoop stress distribution through the thickness of the plate. The distribution is as expected, with the stress field varying from compression at the surface to tension in the far-field. The maximum compressive stress is found ~1 mm below the surface.

The effect of subsequently reaming this hole is shown in Fig. 3. Clearly, reaming the hole has moved the maximum compressive stress to lie at the surface of the hole. This is advantageous in terms of improving the fatigue life of the joint, because the compressive residual stress in the material at the hole edge has been increased.

Having described two specific residual stress fields—those in a quenched plate and those near a cold expanded hole—consideration now turns to how and why such residual stress distributions may be changed in service.

3. Experimental Measurements of Redistributed Residual Stress Fields

Loading a specimen can cause a change in residual stress via two possible mechanisms—by causing plasticity near a stress raiser or by the passage of a crack. These two effects can act simultaneously. Once a crack has passed through a region of residually stressed material, it is clear that there will be some relaxation of the pre-existing residual stress. It is not clear, however, as to what degree this will occur. The plastic zone around the crack will be local compared to the scale of the body in which the crack is growing, but there will clearly be a change in residual stress in the vicinity of the crack path, which has implications for modeling crack growth. For example, once the residual stress field has changed from its initial condition, use of the weight function technique is no longer applicable. To use such a method correctly, the stress field, or a good approximation of it, must be known at each stage of crack growth.

This section examines the effects of crack growth on the stress field in a material for the cases described in the previous section.

3.1 *Quench Stress Field*

The composite bar containing the quench strain field shown in Fig. 1 was fatigued to produce a long crack through ~0.6 of the bar thickness (Ref 14). The strain variation in the Al matrix of the bar following this test is shown in Fig. 4. Similar measurements have been obtained from overaged samples. The stresses obtained from the matrix of such a sample are shown in Fig. 5. The stress can be calculated from the measured strains if the three principal strains are measured, which was the case here.

Clearly, the passage of the crack has had a significant effect on the form of the stress distribution, relative to that shown in Fig. 1 (the strain variation shown closely follows the form of the stress variation in such quenched samples, Ref 49). This can probably be explained by a combination of relaxation, and subsequent redistribution, of the stress behind the crack tip. Behind the crack tip, there has been significant relaxation of the stress field, whereas ahead of the crack there is a tensile stress that tends toward compression as the back face of the sample is approached.

This significant change in stress highlights the difficulty of using techniques such as weight function modeling. Although the stress in the far field, several millimeters from the crack line, is likely to be unchanged relative to the uncracked condition (Ref 50), the stress along the crack line is markedly different. Weight function modeling derives its results by considering tractions on the crack flanks, and therefore the stress along the crack line will be of prime importance.

The use of the weight function method to predict the effect of a residual stress field on crack growth is described in more detail in Section 4, along with discussion of its potential usefulness as a practical design tool.

3.2 *Cold Expanded Hole Stress Field*

Similarly, fatigue loading affects the pre-existing residual stress field around a cold expanded and reamed hole (Ref 48). When used in-service, the fluctuating loads experienced by a fastened joint will act in such a way that the residual stress state may be altered, either by the creation of plastic deformation or the initiation and growth of cracks. If this is the case, calculations of the fatigue behavior that use the initial stress field may not be valid.

Results are shown in Fig. 6 for specimens containing 4% FTI expanded holes that were fatigued for 50,000 cycles at various levels of cyclic stress, using a stress ratio of 0.1 and maximum applied stresses between 145.5 and 165.5 MPa. The initial stress field in each case was the same as that shown in Fig. 3. The stress concentration factor for the tested geometry was 3.2 and the yield strength of the Al 7050 material tested was 543 MPa; theoretically, all tests were ostensibly elastic with no gross plasticity at the hole (Ref 51).

The general trend exhibited by the results is that a higher applied load provides a larger change in the residual stress field, almost certainly due to plastic deformation and/or crack initiation near the hole edge. Below 150 MPa, no change is apparent in the residual stress field, but at higher stresses the stress distribution is altered. The stress at the surface of the hole is reduced, the maximum compressive stress moves to greater depths, and the overall maximum compressive stress is reduced.

At 150 MPa, there is a change in the residual stress field, even though this is the "fatigue limit" for this sample geometry, at and below which the sample did not fail during constant-amplitude fatigue loading. It was also found that the observed residual stress relaxation is dependent on the number of cycles applied, in addition to the magnitude of the stress. Figure 7 shows results for a hole that was fatigued at 150 MPa (the fatigue limit) for varying numbers of cycles between 10,000 and 6.5×10^6.

After 10,000 cycles, the stress changed very little from its initial state. However, as the number of applied cycles increased, it can be discerned that the stress at the hole edge be-

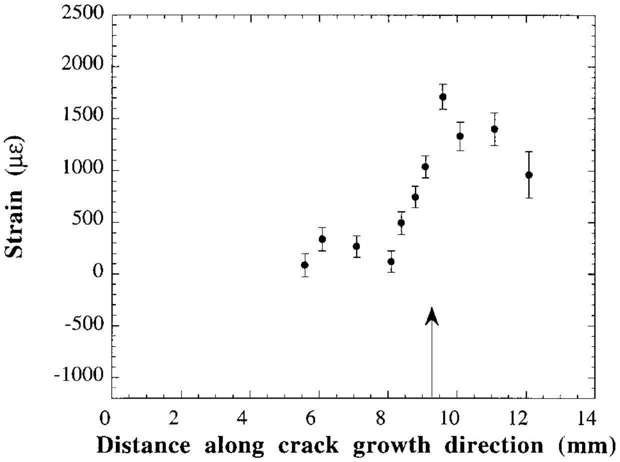


Fig. 4 Longitudinal strain variation in the matrix of an unloaded, fatigue cracked composite bar, as a function of position along the crack growth direction. The arrow indicates the position of the crack tip. The bar was cut from plate that had been water quenched from 505 °C. The edges of the plate from which the sample was machined were at 0 and 14 mm.

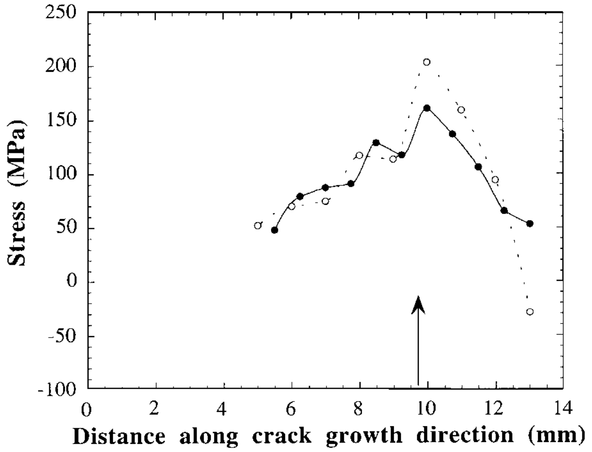


Fig. 5 Longitudinal (crack-opening) matrix stresses in an overaged (180 °C for 48 h) composite specimen as a function of position along the crack growth direction, with (dotted line) and without (continuous line) an applied bending load. The arrow indicates the position of the crack tip. The edges of the plate from which the sample was machined were at 0 and 14 mm.

gins to relax to zero, and there is a corresponding reduction in the maximum value of the compressive stress. The movement of the point of maximum compressive stress does not appear to be as great in this case as for the higher applied stresses in Fig. 6. It may be, therefore, that the mechanism for relaxation of the stress field is slightly different in the two cases and may be more dependent on crack growth at the higher applied stresses. This will be examined in Section 5, where fatigue crack growth data are presented for this system.

4. Weight Function Modeling of the Effects of Residual Stress on Fatigue Crack Growth

Knowing the residual stress that is present in a material, it would be extremely valuable to be able to predict what effect the stresses will have on a growing crack. On a microscopic scale, it may be simply stated that a compressive residual stress will retard a crack and a tensile stress will accelerate it, but it is not trivial to describe the effect of a long-range macrostress variation on the progression of a crack. As an example, consider the quench stress field that was introduced earlier.

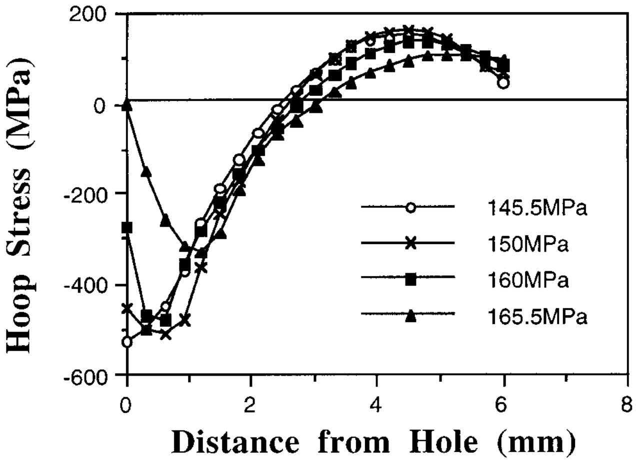


Fig. 6 Relaxation of the residual hoop stress at a reamed 4% FTI expanded hole for different levels of applied stress. 50,000 load cycles were applied.

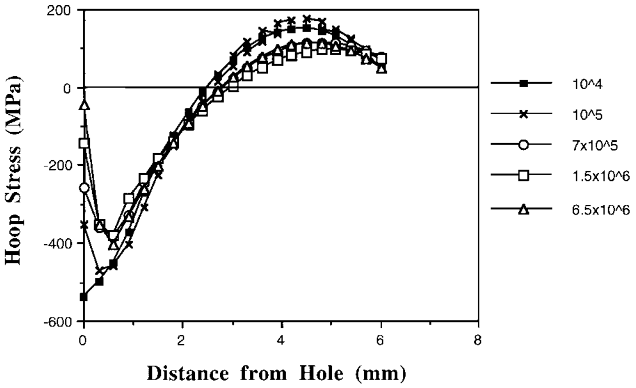


Fig. 7 Relaxation of the residual hoop stress at a reamed 4% FTI expanded hole, using an applied stress of 150 MPa

For a crack in a particular specimen geometry under known applied loads, many solutions for the value of K at the crack tip have been derived, and the solutions may be used in structural design or for the determination of the applied ΔK in fatigue testing such as that performed during this study. Solutions for different geometries have been tabulated by, among others, Rooke and Cartwright (Ref 52) and Tada et al. (Ref 53). Even though many solutions are available, derived by various means and levels of complexity, the results are often not applicable to new problems with complex structures and loading conditions (Ref 54).

The weight function concept is a versatile way by which stress-intensity factors may be derived without excessive computation yet with good accuracy (Ref 54). The concept was first outlined by Bueckner (Ref 55), who showed that the stress-intensity factor at a crack tip due to applied loading can be derived by integrating these loads, multiplied by a "weight function," over the crack length:

$$K = \sqrt{W} \int_0^a \sigma(x)\, m(a,x)\, dx \qquad \text{(Eq 1)}$$

where K is the crack tip stress intensity, $m(a, x)$ is the weight function of the cracked body, which is related to the crack length a and the coordinate x along the crack growth direction, and W is a characteristic length, the width of the specimen through which the crack is growing, for example. This equation was also derived subsequently by Rice (Ref 56) from a different theoretical base.

The weight function itself can be derived by such methods as differentiating a known elastic displacement solution with respect to crack length (Ref 54, 56), by use of Westergaard stress functions (Ref 57), which were also used previously for determination of stress-intensity factors (Ref 58), and by finite-element methods (Ref 54, 57). Other techniques are also available, see Tada et al. (Ref 53) and Wu and Carlsson (Ref 54).

Tada and Paris (Ref 59) have shown that it is valid to obtain values of crack-tip stress intensity, arising from a residual stress distribution, by superposition of the residual stress field onto the crack geometry in a weld. More recently, Beghini et al. (Ref 7, 13) have demonstrated the applicability of weight functions to a similar residual stress-based example as that used for the composite samples described here, using compact tension specimens with weld-induced residual stresses. Kang et al. (Ref 8) used the same method for welded single edge-notched bend (SENB) specimens, which is the same sample geometry used in this project.

Tada et al. (Ref 53) indicate that, for the determination of stress intensities arising from residual stress fields, it is simply necessary to integrate the Green's function of K_I for the crack geometry being studied, the Green's function being the K_I solution for a pair of concentrated splitting forces on the crack surfaces. Parker (Ref 60) notes that the stress intensity so derived can be used in a fatigue analysis, because both applied and residual stress intensities are derived using linear elastic concepts, and hence can be directly superposed. Parker also indicates that redistribution of the residual stress field during crack growth does not invalidate the superposition principle. Although this is strictly true, it will cause a variance in the calculated results from the actual problem, because the model neither assumes nor calculates any redistribution of the residual stress field, as noted elsewhere (Ref 2, 3, 18).

The application of the weight function technique to a known geometry is reasonably straightforward. Once the initial loading conditions (or residual stress field) are known, the crack-tip stress intensity is calculated from Eq 1, often using simply a series expansion.

Figure 8 shows the result of applying a weight function analysis to the problem of a parabolically varying residual stress field, similar to that shown in Fig. 1, with a compressive surface stress of 250 MPa. The effect of the residual stress field, assuming no redistribution, clearly varies depending on the depth of the crack.

It is doubtful as to whether this method is useful as a design tool, except on a qualitative basis. Although the near-surface values may accurately describe the effect of the residual stress field in retarding (or accelerating) a crack, values for longer cracks must be treated with care. In many practical situations, it will therefore be necessary to perform direct measurement of crack growth to identify the effects of the residual stress field.

5. Effects of a Residual Stress Field on Fatigue Crack Growth

Returning to the current two main examples, this section considers how the growth of a fatigue crack is affected by the presence of a long-range residual stress field. This is as important as the effect of the crack in redistributing the stress field, if one is to be able to make predictions of the benefit (or otherwise) of a residual stress field on the fatigue life of a component.

5.1 Quench Stress Field

The mechanism by which a residual stress field influences fatigue crack growth is not simple to identify. A widely used measurement of the driving force for fatigue crack growth is the level of crack closure. Crack closure is a well-documented phenomenon in which the faces of the crack come into contact above zero load. An excellent summary of this phenomenon can be found in Suresh (Ref 22). It is caused by mechanisms such as plastic stretching of the crack wake (Ref 61-63) coupled with roughness of the fatigue surfaces (Ref 64-66). It prevents the fatigue crack from experiencing the full range of applied stress intensity by restricting the displacement range at the crack tip.

If a compressive residual stress field is present, this can influence the level of crack closure by exerting a clamping force on the crack faces, which then increases the stress intensity required to open the crack. This can be measured as higher "closure," where the closure point is taken to be the transition from closed to open, as measured from the compliance of the sample. The compliance is measured by recording the load and a displacement, such as the crack-opening displacement.

Closure curves rarely show a simple transition from "open" to "closed" cracks, and it is found that there are three possible definitions of the "closure" load in a material (Ref 14). These definitions are illustrated in Fig. 10.

For an ideal crack, which opens and closes at a distinct load, these three parameters would be coincident. For a real crack, it is not obvious what information is being supplied by each measurement (Ref 14). Once $K_{cl,up}$ is reached, the stress field

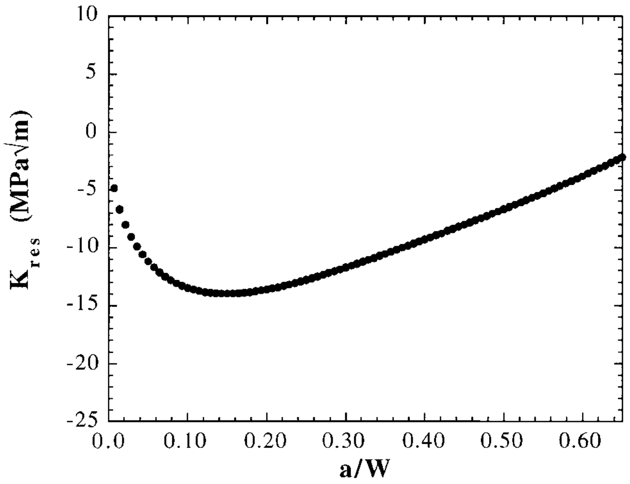


Fig. 8 K_{res} for a parabolic residual stress field, with a surface stress of 250 MPa (Ref 70)

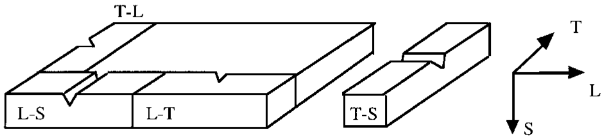


Fig. 9 Axis conventions for samples cut from rolled plate

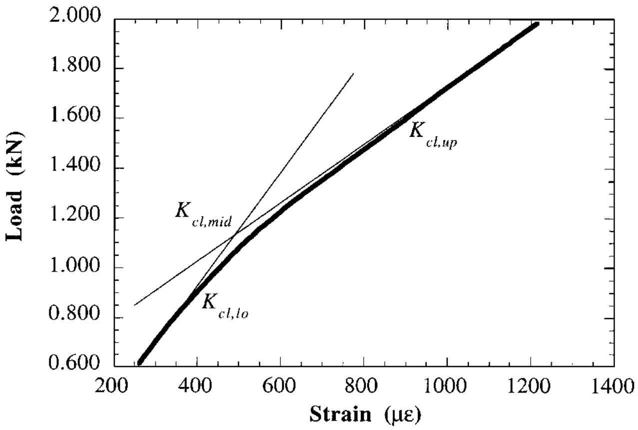
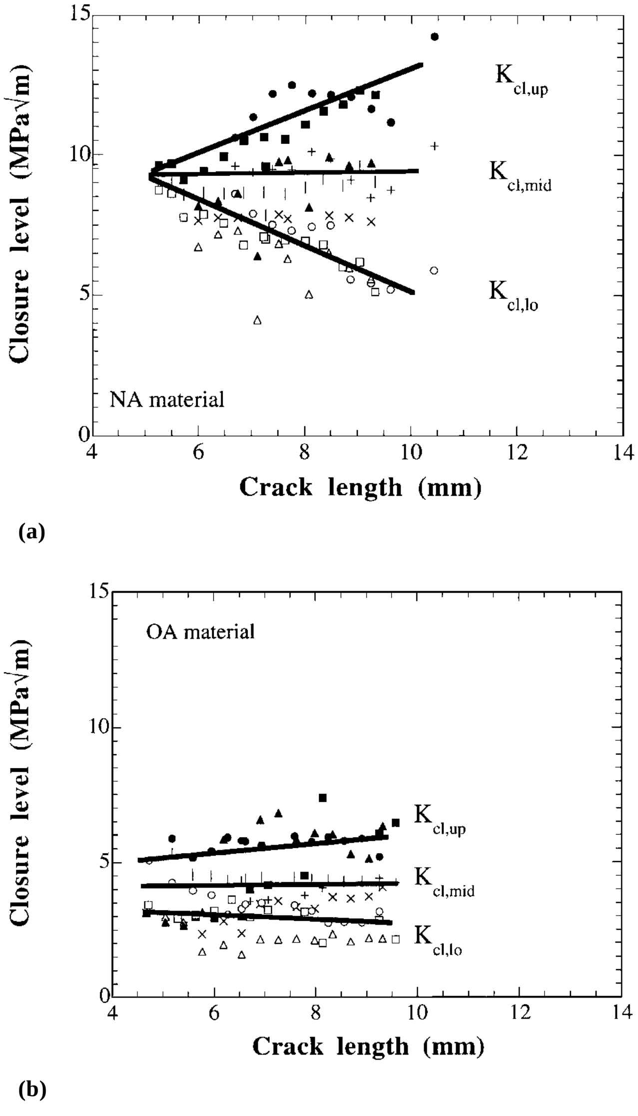


Fig. 10 Load-displacement trace indicating the three possible definitions of the load at which closure occurs. The strain readings are the compressive strains measured on the back of a sample loaded in four-point bending, and the load readings are the applied compressive bending loads

may no longer be of the $1/\sqrt{r}$ variation consistent with the linear elastic fracture mechanics (LEFM) definition of stress intensity (Ref 67); so this point may also not provide a realistic representation of the closure stress intensity which reduces the applied ΔK. It is nonetheless instructive to compare results obtained from residually stressed and stress-relieved samples.

The stress field that was described in Section 2 was used as the basis for a study of the effects of a stress field on fatigue crack growth (Ref 14, 68). The results measured for the three closure parameters for naturally-aged (residually stressed) and overaged (stress-relieved) composite samples are shown in Fig. 11.



(a)

(b)

Fig. 11 (a) Closure levels in the naturally aged composite, measured using $K_{\mathrm{cl,up}}$ (filled symbols), $K_{\mathrm{cl,lo}}$ (open symbols), and $K_{\mathrm{cl,mid}}$ (line symbols). Data from a series of tests are presented (Ref 14). (b) Closure levels in the overaged composite, measured using $K_{\mathrm{cl,up}}$ (filled symbols), $K_{\mathrm{cl,lo}}$ (open symbols), and $K_{\mathrm{cl,mid}}$ (line symbols). Data from a series of tests are presented (Ref 14).

As shown in these figures, there is a significant change in the evolution of closure between the two materials. The naturally aged (NA) material, in which high levels of residual stress are expected to be present, exhibits uniformly higher levels of closure, regardless of the point used to draw the conclusion, than does the overaged (OA) material. Additionally, the NA material exhibits a change in the values of $K_{\mathrm{cl,up}}$ and $K_{\mathrm{cl,lo}}$ as the crack grows through the residual stress field. The fact that no such variation is observed in the OA material strongly indicates that the residual stress field affects the opening behavior of the crack, and this may help to explain the reasons for the impact of the residual stress field on crack growth rates.

Modeled results presented by Choi and Song (Ref 69) also support the conclusion that there is an increase between $K_{\mathrm{cl,up}}$ and $K_{\mathrm{cl,lo}}$ as the crack grows, and that the crack opening behavior is affected when a residual stress field is present.

To summarize, although it is possible to measure crack closure and attempt to relate this to the effect of the residual stress field, the effect of the stress field on crack opening may make such measurements extremely difficult to interpret. It is therefore advisable to look for beneficial effects of residual stress via crack initiation or growth rate retardation, rather than using closure as a measure.

5.2 Stress Field around a Cold Expanded Hole

The beneficial effects of a compressive residual stress field on fatigue life has been applied widely in engineering practice. Although for many years the assumed mechanism of fatigue life improvement was taken to be a suppression of crack initiation, it is now clear that effects on fatigue crack growth rate can be at least as important.

To illustrate this, the fatigue crack propagation behavior from a hole in a 7050-T76 plate was investigated both with and without the presence of a residual stress field from cold expansion (Ref 48). The results are summarized in Fig. 12. It is clear that expansion of the hole has had highly beneficial effects on the fatigue resistance of the material. Both time to initiation

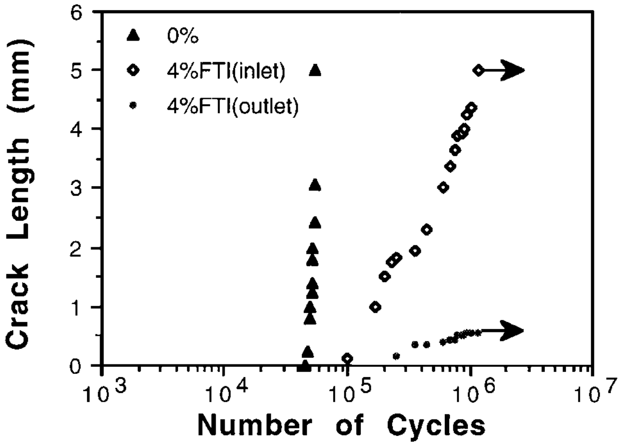


Fig. 12 Crack growth inside an unexpanded hole and at the inlet and outlet surfaces of a 4% FTI expanded hole. "Inlet" and "outlet" refer to the direction in which the expansion mandrel was passed through the hole.

and the crack growth rate are retarded by the compressive residual stress field at the hole.

For the unexpanded hole, failure of the sample occurs very rapidly after initiation of the crack, within ~10^4 cycles of initiation. The expanded hole exhibits significantly improved fatigue resistance. Although cracks were observed to initiate at both sides of the hole, they arrested after ~10^6 cycles (10^3 cycles after initiation), and the sample did not fail at the stress that was applied (150 MPa). Therefore, even though cracks are initiated by the stress concentration at the hole edge, the fact that they grow into a compressive residual stress field and are arrested essentially makes them "safe" as long as these compressive residual stresses do not further relax due to plasticity or temperature effects.

This result now facilitates the incorporation of modeling and residual stress measurements presented earlier. The applied stress of 150 MPa corresponds to the stress limit below which the samples did not fail during fatigue (i.e., they survived over 10^7 applied loading cycles). Crack growth is occurring, even though the cracks do not cause failure of the samples. However, fatigue cracks are present in samples fatigued at this load, therefore explaining the relaxation of residual stress for the samples fatigued at 150 MPa; the relaxation is due to the passage of the fatigue crack. A conclusion can therefore be made that, during fatigue loading in the absence of large-scale plasticity, crack growth is the major cause of stress relaxation.

6. Conclusions

The intention of this review has been to highlight points for discussion in the area of the effects of residual stress on fatigue crack growth. A residual stress field will clearly have some effect on a growing fatigue crack. A compressive residual stress field will retard crack growth, whereas a tensile stress field will accelerate it.

Knowledge of the stress field does not automatically lead to knowledge of its effects on fatigue, however. Modeling techniques such as weight functions will provide an indication of the expected contribution of the residual stress field to the crack-tip stress intensity, but the approach has limited validity, because of the change in the residual stress field in the sample once a crack begins to grow. Weight functions should therefore be regarded as providing an "upper bound" to the effects of the residual stress field.

When considering a given component, crack growth rates are often the best indicator of the effect of a residual stress field. Although crack closure monitoring can reflect the effects of a residual stress field on the growing crack, the results are not helpful in terms of life prediction because of the possible complexities of the crack opening behavior.

Consequently, although residual stress fields can be used advantageously, the best quantification of the benefit comes from direct measurement. The possibility of a beneficial effect can be investigated via modeling, with subsequent validation by experiment. Ideally, comparison among samples with and without the residual stress field should be made. Improvement in fatigue durability can then be quantified directly, which allows the benefits of the residual stress field to be used alongside the assurance of accurate lifing.

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