NEAR THRESHOLD FATIGUE CRACK GROWTH IN STEELS - AN ANALYSIS BASED ON CRACK TIP PLASTIC DEFORMATION

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ABSTRACT

A number of researchers have suggested that a fatigue crack may grow by a plastic deformation process at a crack tip. Neumann has made direct observation of the shear slip-off process at the crack tip in a single copper crystal. Plastic shear deformation is concentrated in two sets of intersecting slip bands. The neighboring slip bands are separated by "non deforming" slabs. These slabs move away from a crack tip, one at a time, like the teeth of a zipper during the unzipping process. Kuo and Liu have modeled the unzipping process using the finite element method. The calculated crack growth rate agrees well with the measured growth rate in the structure insensitive crack growth region.

The analysis of the crack tip plastic deformation process is extended to the near threshold region by taking the cyclic creep and stress relaxation processes into consideration. The inter-relation of the crack tip deformation, the crack growth transition point, the threshold, and the crack growth rate in the near threshold region was analyzed. Based on grain boundary as a barrier to plastic deformation, a fatigue crack growth equation was derived. The crack growth rate is related to cyclic yield strength, Young's modulus, ΔK_{th}, and a metallurgical structural parameter, the mean free path for dislocation movement. The derived crack growth equation fit the data of a number of steels, in the near threshold region as well as in the structure insensitive region, if the crack growth in a steel is caused by plastic deformation process.

INTRODUCTION

Linear elastic fracture mechanics has been used to correlate fatigue crack growth data. In the intermediate ΔK region, da/dN is insensitive to microstructures, while in the near threshold region, da/dN is microstructure sensitive. In recent years, the microstructural effects on fatigue crack growth have been studied, but a comprehensive quantitative theory is

still lacking.

A fatigue crack in a ductile material may grow by a plastic deformation process. Orowan has suggested that a crack may grow by an alternate shear slip process on two sets of intersecting conjugate slip planes at a crack tip [1]. The crack tip slip process has been suggested by a number of researchers [2,3,4,5] and it has been modified or renamed as crack tip blunting [2] and shear decohesion [5]. Neumann [6] has made the direct observation of the alternate slip-off process in copper single crystals under cyclic load.

Plastic shear deformation is concentrated in two sets of intersecting slip bands. The neighboring slip bands are separated by "non deforming" slabs. Upon loading, these slabs move away from a crack tip, one at a time, like the teeth of a zipper during the unzipping process. The unzipping fatigue crack growth was modeled by Kuo and Liu [7] using the finite element method. Their calculation agrees well with the data in the intermediate ΔK region [7,8]. But it differs considerably from the measured crack growth data in the near threshold region.

Below the intermediate ΔK structure insensitive region, the rate of fatigue crack growth decreases with ΔK. Below a transition point ΔK_t, da/dN decreases much more rapidly until a crack seems to stop propagating at the threshold ΔK_{th}. Liu and Liu [9] have shown that $\Delta K_{th} \simeq 0.7\ \Delta K_t$ for more than fifty sets of fatigue crack growth data. More recently, they have developed a semiempirical fatigue crack growth relation for steels [10]. The crack growth equation agrees with the data of a number of steels if the growth process is caused by crack tip plastic deformation.

Fatigue crack growth caused by "cleavage" fracture, which often occurs in high-strength steels, and crack growth in aggressive environments will accelerate the overall crack growth rate and cause the discrepancy between the measured rate and the rate calculated based on the deformation crack growth process.

This paper will review and synthesize the recent analyses of the near threshold fatigue crack growth by Liu and Liu [9,10].

THE RELATION BETWEEN ΔK_t AND ΔK_{th}

Based on the unzipping model of fatigue crack growth, Kuo and Liu [7] calculated the crack growth rate,

$$da/dN = 0.018\ \Delta K^2/E\sigma_{Y(c)} \qquad (1)$$

where $\sigma_{Y(c)}$ and E are cyclic yield stress and Young's modulus respectively. The calculated crack growth rates agree well with the measured growth rates and striation spacings in the intermediate ΔK region, where the crack growth is insensitive to microstructures [7,8].

The solid curves in Fig. 1 are the crack growth data of five steels

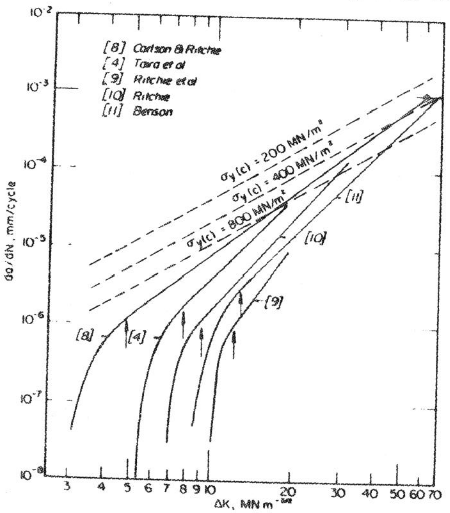


FIG. 1 Fatigue crack growth curves of steels. Ref. [9]

in the structure sensitive crack growth region. The dashed lines, for three typical cyclic tensile yield strenghts of 200, 400, and 800 MN/m^2, represent the calculated growth rates according to the unzipping model. As discussed earlier the unzipping model does agree with the crack growth data in the microstructure insensitive region. Immediately below the microstructure insensitive region, ΔK in the range of 20 to 40 MNm$^{-3/2}$, the data start to deviate from the calculated rates. The measured growth rates lie along a straight line of much steeper slope. Below a transition point, $\Delta K = \Delta K_t$ and $da/dN = \ell_t$, da/dN decreases much more rapidly. The transition points are indicated by the arrows in Fig. 1. When ΔK decreases to the threshold ΔK_{th}, a crack seems to stop propagating.

If we use the macro cyclic tensile yield strength to calculate crack growth rates, Eqn. (1) is applicable only when the plastic zone size r_p is several times larger than the grain size. For plane strain crack tip plastic zone, we have

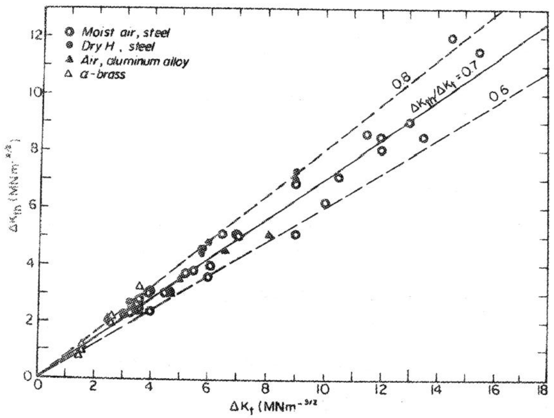


FIG. 2

The relationship between ΔK_t and ΔK_{th}. Ref. [9]

$$r_p = \Delta K^2/6(2\sigma_{Y(c)})^2 \qquad (2)$$

We assume r_p to be five times the grain size. With a typical grain size of 40 μm and a value of 800 MN/m^2 for the cyclic yield stress range, i.e., $(2\sigma_{Y(c)})$, the calculated value of ΔK, is nearly 30 MNm$^{-3/2}$. When ΔK is in the vicinity of this value, the measured growth rate starts to deviate from the calculated rate. This certainly agrees with the data in Fig. 1.

Liu and Liu [9] have examined fifty sets of crack growth data in the literature and have determined the values of ΔK_t and ΔK_{th}. The results are plotted in Fig. 2. The empirical relation is

$$\Delta K_{th} = 0.7\ \Delta K_t \qquad (3)$$

In the near threshold region, da/dN is sensitive to microstructure. It is reasonable to expect that a number of different crack growth mechanisms are operational in the region. The specific mechanism operational in a given material depends on the microstructure of the material. Lal and Weiss [11] and subsequently Weertman [12] have proposed a maximum fracture stress theory for ΔK_{th}. Liu and Liu [9] have proposed that the minimum slip step size and the cyclic creep and stress relaxation causes the transition point and ΔK_{th}. Liu and Liu [10] have also proposed a model of grain boundary barrier for ΔK_t and ΔK_{th}. A model of crack closure could be applicable to thin specimens, and a model of brittle fracture along grain boundary might be applicable to the crack growth in aggressive chemical environments. This paper will review and synthesize the models of minimum slip step size and grain boundary barrier for structure sensitive fatigue crack growth in the near threshold region.

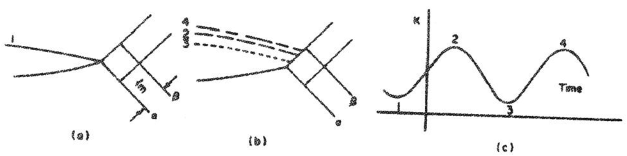


FIG. 3 Cyclic creep movement of crack front. Ref. [9]

According to the unzipping model, the non deforming slab must have a minimum finite size ℓ_m. The value of ℓ_m must vary from one material to another. The absolute minimum of ℓ_m is one atomic spacing. When crack growth rate is less than ℓ_m, the crack front "retreats" during the unloading half cycle. This retreating process may account for the drastic decrease in da/dN when ΔK is below ΔK_t. At ΔK_t, $da/dN = \ell_m$.

Figures 3a and 3b show the back-and-forth movement of the crack front under a cyclic load when da/dN is less than ℓ_m. The numbered locations of the crack front correspond to the numbered positions of the loading cycles in Fig. 3c. As the cyclic load continues, the crack front creeps forward to the intersecting conjugate slip plane β. As the creep deformation takes place, the mean stress relaxes. When the crack front reaches β, the unzipping process shifts to the conjugate slip plane. If the crack front still cannot reach the conjugate slip band, when the maximum cyclic creep shear slip is realized and when the mean stress is fully relaxed to zero, the crack stops propagating. The corresponding ΔK is ΔK_{th}.

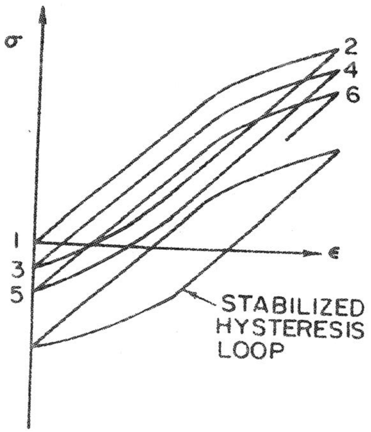


FIG. 4 Stress relaxation.

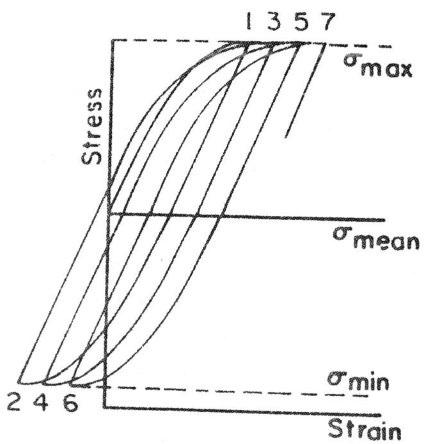


FIG. 5 Cyclic creep caused by positive mean stress.

Cyclic creep and stress relaxation take place when a positive mean stress exists. Figure 4 shows the stress relaxation when the imposed strain range $\Delta\varepsilon$ is fixed. The σ_{max} decreases, cycle by cycle, until the mean stress relaxes to zero. A stablized hysteresis loop is shown with $\sigma_{mean} = 0$. The σ_{max} of the stablized hysteresis loop is reduced to $\Delta\sigma/2$. Without stress relaxation, $\sigma_{max} \approx \Delta\sigma$.

Figure 5 shows the cyclic creep when $\Delta\sigma$ is fixed and σ_{mean} is positive. The cyclic creep strain is positive and increases in every cycle. At a crack tip, the cyclic plastic deformation combines both of these processes.

In the region immediately above ΔK_t, the straight lines of the crack growth data in Fig. 1 can be written as

$$da/dN = A(\Delta K^2/2E\sigma_{Y(c)})^m \tag{4}$$

where $2\sigma_{Y(c)}$ is the cyclic yield stress range and where m and A are empirical constants. A material must experience the total yield stress range before plastic deformation takes place. At the transition point, according to the unzipping model with a finite ℓ_m,

$$da/dN = \ell_t = \ell_m = A(\Delta K_t^2/2E\sigma_{Y(c)})^m \tag{5}$$

At ΔK_{th}, the cyclic creep crack increment is equal to ℓ_m. It is the difference between the crack increment when the mean stress of the crack tip field is fully relaxed and the crack increment without relaxation. If the crack tip increment under a monotonic load follows the same relation as that given by Eqn. (4), the monotonic crack increment without stress relaxation is

$$\Delta a_m = A(K_{max}^2/E\sigma_Y)^m \tag{6}$$

When the mean stress is fully relaxed and the effective yield stress is reduced to $\sigma_Y/2$, the total crack increment by the shear deformation is

$$\Delta a_t = A[K_{max}^2/E(\sigma_Y/2)]^m \tag{7}$$

The cyclic creep shear slip is the difference between these two quantities. With the approximation of $\sigma_Y \approx \sigma_{Y(c)}$, $\Delta K \approx K_{max}$, and $m \approx 1$, the cyclic creep crack increment by the shear mode is

$$\Delta a_c = A[\Delta K^2/E\sigma_{Y(c)}] \tag{8}$$

At ΔK_{th}, Δa_c is equal to ℓ_m.

$$\Delta a_c = \ell_m = A[\Delta K_{th}^2/E\sigma_{Y(c)}] \tag{9}$$

Combining Eqns. (5) and (9), and assuming m = 1, we have

$$\Delta K_{th} = 0.7\ \Delta K_t \ .$$

This is the solid line in Fig. 2.

This unzipping model of the transition point and the threshold is related to the size of the minimum slip step, ℓ_m. The value of ℓ_m depends on the microstructures and the stacking fault energy of the crystal. If the stacking fault energy is low, the partial dislocations will not be able to cross-slip, and ℓ_m will be large. If dislocations can easily cross-slip, then the effective ℓ_m is much reduced. ℓ_m must also be related to other microstructure features. When the value of ℓ_m is very small because of cross-slip, as is possible in the case of ferritic steels, the rapid decrease in da/dN below ΔK_t could be caused by other microstructural mechanisms before the effect of the minimum slip step size is realized.

It is well known that grain boundaries serve as dislocation barriers and impede plastic deformation. The effects of grain boundary on crack tip deformation and fatigue crack growth were studied by Taira et al. [14], Eylon and Bania [15] and Masounave and Bailon [16]. Yoder et al. [13] suggested that at ΔK_t, the size of the crack tip cyclic plastic zone is equal to grain size, G.S., or the mean free path for dislocation movement, $\bar{\ell}$. A fatigue crack propagates by a cyclic plastic deformation process. When the cyclic plastic zone is equal to grain size and the cyclic plastic zone runs against a grain boundary, the deformation process is impeded and the crack growth rate is greatly reduced. Therefore, we have, at ΔK_t

$$r_{p(c)} = \Delta K_t^2/2\pi(2\sigma_{Y(c)})^2 = \text{G.S.} \tag{10}$$

If a fatigue crack grows by a deformation mechanism, the crack tip plastic zone has to be able to overcome the grain boundary resistance of a steel. When the crack tip plastic zone fails to penetrate the grain boundary barrier, a crack will stop propagating. Therefore, at the threshold,

$$r_p = K_{max,th}^2/2\pi\sigma_Y^2 \approx \Delta K_{th}^2/2\pi\sigma_Y^2 = \text{G.S.} \tag{11}$$

A relation between ΔK_t and ΔK_{th} can be obtained by combining these two equations

$$\Delta K_{th} = (\sigma_Y/2\sigma_{Y(c)})\Delta K_t \tag{12}$$

For a given material, the ratio $\sigma_Y/\sigma_{Y(c)}$ is a constant, but the value of the ratio varies from material to material. If the ratio is 1.4, Eqns. (12) and (1) are the same.

We have presented two models of crack growth threshold. The finite thickness of the non-deforming slab of the unzipping model is more likely to be applicable to fcc crystals with low stacking fault energies, while the grain boundary barrier model is likely to be applicable to bcc crystals with "strong" grain boundaries such as iron and steel. The bcc crystals cross-slip easily, and the value of ℓ_m could be very small. The transition point would take place at very low ΔK. The grain boundary effect is realized long before the effects of the finite slip step size.

The driving force for the cyclic creep to reach the minimum slip step size, ℓ_m, and the driving force to overcome the grain boundary resistance is $(\Delta K-\Delta K_{th})^2$. According to these two models, fatigue crack growth rate must be related to the cyclic creep rate or to the rate of overcoming the grain boundary resistance. Therefore, da/dN must be related to this geometry.

THE NEAR THRESHOLD FATIGUE CRACK GROWTH BEHAVIOR OF STEELS

The straight lines of the fatigue crack growth data in the region immediately above the transition point, ΔK_t in Fig. 1 can be described by the equation

$$da/dN = A[\Delta K^2/2E\sigma_{Y(c)}]^m \tag{13}$$

as discussed earlier. At the transition point, $\Delta K = \Delta K_t$ and $da/dN = \ell_t$

$$da/dN = \ell_t = A[\Delta K_t^2/2E\sigma_{Y(c)}]^m \tag{14}$$

The analysis by Yoder et al. [13] together with the earlier works by Taira et al. [14], Eylon and Bania [15] and Masounave and Bailon [16] have shown rather convincingly that the transition point, ΔK_t in steels is caused by the grain boundary acting as a barrier to plastic deformation. The quantity ΔK^2 in Eqn. (13) can be considered as the potential that drives for crack tip plastic deformation. At ΔK_{th}, the effective driving force becomes zero and the crack comes to a halt. Therefore, it is reasonable to consider the effective driving force to overcome the grain boundary resistance to plastic deformation as proportional to $(\Delta K-\Delta K_{th})^2$. Fatigue crack growth is directly related to crack tip plastic deformation, therefore crack growth rate must be related to the quantity $(\Delta K-\Delta K_{th})^2$. Taking the first approximation, Eqn. (13) can be modified to the form

$$da/dN = B[(\Delta K - \Delta K_{th})^2/E\sigma_{Y(c)}]^m \qquad (15)$$

At the transition point, Eqn. (15) becomes

$$da/dN = \ell_t = B[(\Delta K_t - \Delta K_{th})^2/E\sigma_{Y(c)}]^m \qquad (16)$$

ΔK_t and ΔK_{th} are linearly related according to Eqn. (3). Therefore $(\Delta K_t-\Delta K_{th})^2$ can be written as $\eta\Delta K_{th}^2$. Hence Eqn. (16) becomes

$$da/dN = \ell_t = B'[\Delta K_{th}^2/E\sigma_{Y(c)}]^m \qquad (17)$$

Dividing Eqn. (15) by Eqn. (17), one obtains

$$\frac{da}{dN} = C\ell_t[\frac{\Delta K}{\Delta K_{th}} - 1]^{2m} \qquad (18)$$

If we modify the equation slightly to fit the data, we obtain

$$\frac{da}{dN} = C\ell_t[\frac{\Delta K}{\Delta K_{th}} - \beta]^{2m} \qquad (19)$$

where β is an adjustable parameter for empirical fit.

Figure 6 shows the data for 300M steel tempered at four temperatures (100°C, 300°C, 470°C, and 650°C) and tested at values of R (0.05

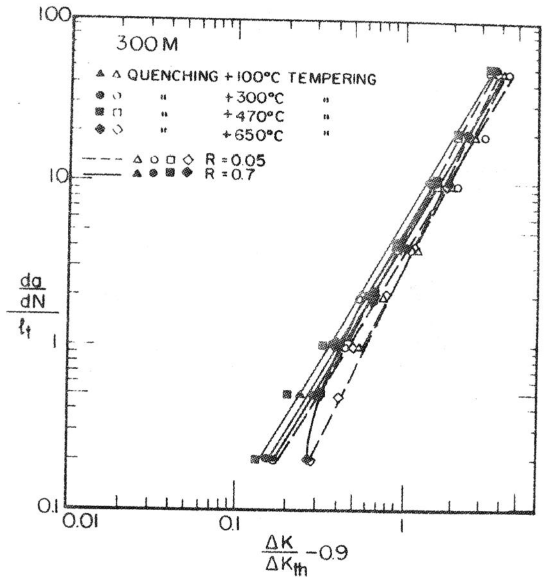


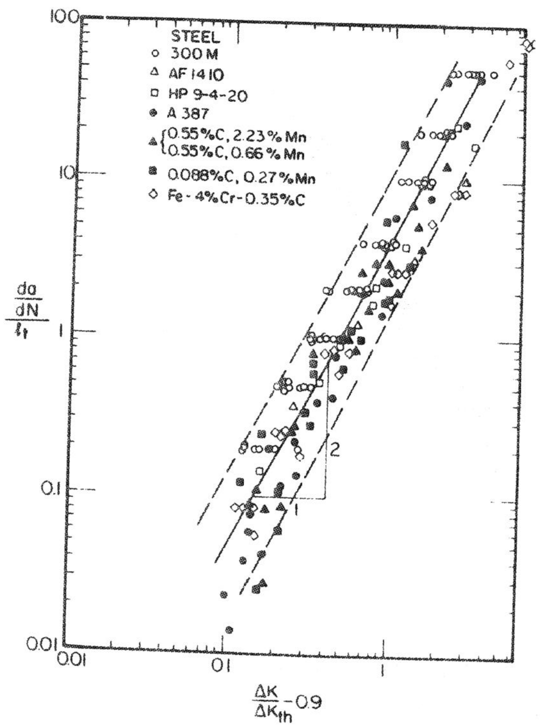
FIG. 6 Fatigue crack growth data of 300M steel. Ref. [10]

and 0.7). A single value of $\beta = 0.9$ fits all of the data. Figure 7 shows the plot of nine different steels with a total of thirty-four combinations of steels, heat treatments, and R values. In Fig. 7 one symbol is used for all the data of the same steel. For example, all eight sets of the crack growth data for the 300M steel are represented by the same symbol, open circle. In general, the data for the high yield-strength steels tested at high R ratios lie in the top half of the scatter band, and the data of the low- and medium-strength steels tested at the low R ratios lie in the lower half of the scatter band.

Figure 8 shows the similar plot of the twelve steels reported and analyzed by Yoder et al. [13]. The dashed lines indicate the scatter band of the data in Fig. 7. The data fit well with $\beta = 0.9$ and m nearly equal to one. The empirical equation that fits the broad band of the data in Figs. 7 and 8 is

$$da/dN = 3.0\ \ell_t[\Delta K/\Delta K_{th} - 0.9]^2 \qquad (20)$$

The value of the proportional constant C in (19) depends on the value of



○ Ritchie; Metal Science, 8/9 (1977)

△□ Ritchie; Chang, Paton; Fatigue of Eng. Mat. & Structures 1 (1979)

● Ritchie, Suresh, Moss, J. of Eng. Mat. & Tech. 102 (1980)

▲ Cooke, Beevers; Mat. Sci. & Eng. 13 (1974)

■ Druce, Beevers, Walker; Eng. Fracture Mech. 11 (1979)

◇ Carlson, Ritchie; Scripta M. 11 (1977)

FIG. 7 Fatigue crack growth data of steels. Ref. [10]

the R ratio and the tensile yield stress with an average value of three for the broad data band. Equation (19) can be used to fit the empirical data by adjusting the proportional constant C and, if necessary, the values of β and m.

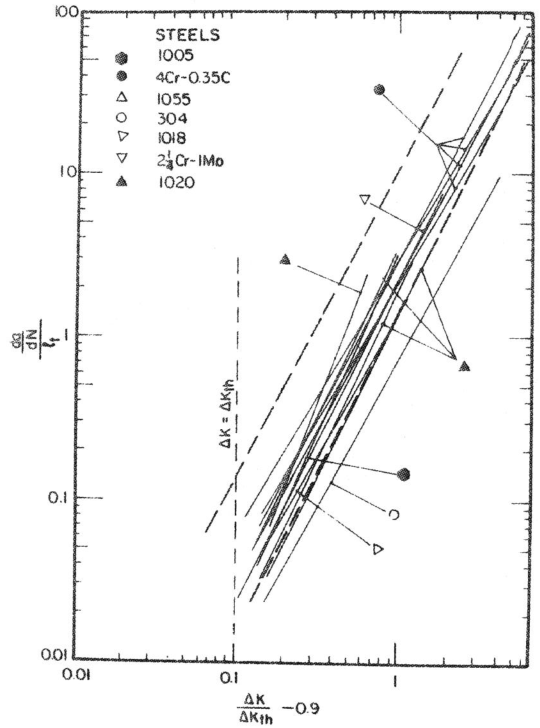
Yoder et al. [13] have shown that the transition point ΔK_t is

$$\Delta K_t = 5.5\ \sigma_Y \sqrt{\bar{\ell}} \qquad (21)*$$

where σ_Y is the tensile yield strength and $\bar{\ell}$ is the mean free path for dislocation movement, for most of the steels it is grain size. Therefore Eqn. (16) can be written as

$$da/dN = \ell_t = B\ (\Delta K_t - \Delta K_{th})^2/E\sigma_{Y(c)} = D\Delta K_t^2/E\sigma_{Y(c)} \qquad (22)$$

*Equation (21) differs less than 10% from Equation (10).



⬢ Benson; Metal Sci. 13 (1979)

● Carlson, Ritchie; Scripta M. 11 (1977)

△ Cooke, Beevers; Mat. Sci. & Eng. 13 (1974)

○ James, Schwenk; Met. Trans. 2 (1971)

▽ Suzuki, McEvily; Met. Trans. 10A (1979)

▽ Ritchie, Suresh, Moss; J. of Eng. Mat. & Tech. 102 (1980)

▲ Taira, Tanaka, Hoshina; Fatigue Mechanisms ASTM STP 675 (1979)

FIG. 8 Fatigue crack growth data of steels. Ref. [10]

The quantities $(\Delta K_t - \Delta K_{th})^2$ and ΔK_t^2 are linearly related. By substituting Eqn. (21) into (22), and assuming $\sigma_Y \approx \sigma_{Y(c)}$, one obtains

$$\ell_t = D'(\sigma_{Y(c)}/E)\bar{\ell} \qquad (23)$$

Thus ℓ_t and $\bar{\ell}$, are related so that Eqn. (19) becomes

$$\frac{da}{dN} = C'\bar{\ell}\ \frac{\sigma_{Y(c)}}{E}\ \left(\frac{\Delta K}{\Delta K_{th}} - 0.9\right)^2 \qquad (24)$$

The quantity ΔK_{th} can be eliminated by using the linear relation between ΔK_{th} and ΔK_t and the relation between ΔK_t and $\bar{\ell}$. Thus Eqn. (24) relates fatigue crack growth rate directly to the microstructural parameter $\bar{\ell}$ and the deformation properties $\sigma_{Y(c)}$ and E. If fatigue crack growth is caused by crack tip plastic deformation, one would expect such a relation to exist.

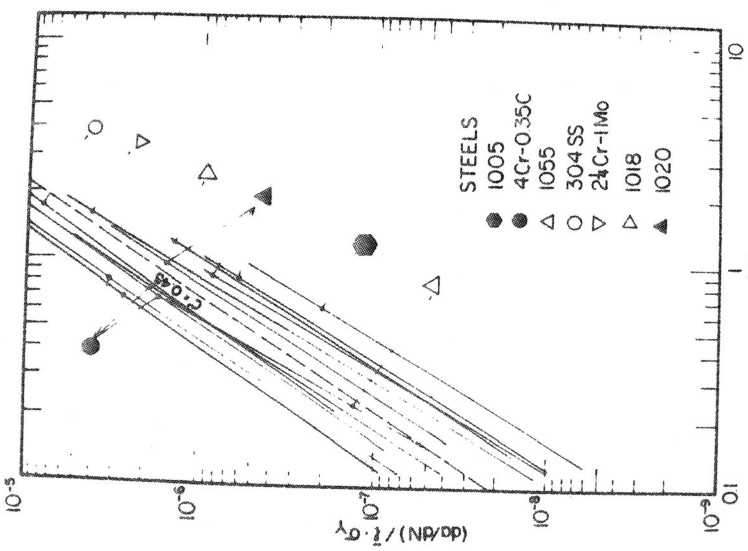


FIG. 9 Fatigue crack growth in Steels. Ref. [10]

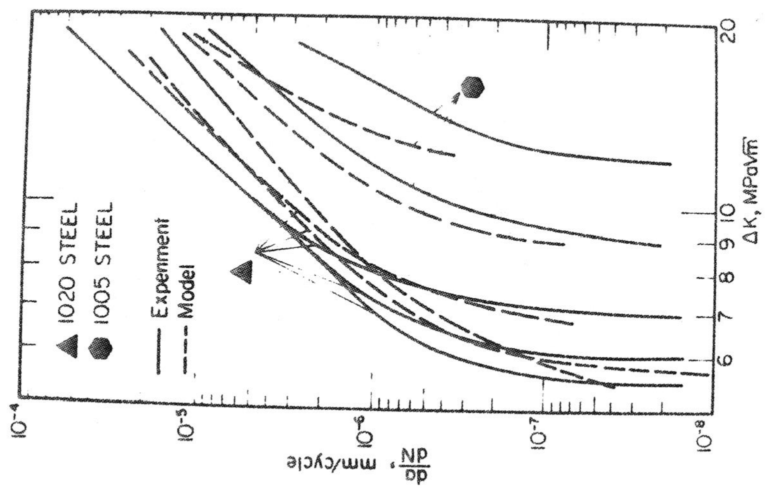


FIG. 10 Fatigue crack growth in steels. Ref. [10]

When a crack tip plastic zone is smaller than the grain size, the value of $\sigma_{Y(c)}$ in Eqn. (24) is no longer a constant. When a plastic zone is away from the grain boundary, the value of $\sigma_{Y(c)}$ should be that of a single crystal. When the plastic zone spans two neighboring grains, the value of $\sigma_{Y(c)}$ is determined by the interaction of the slip systems of these two grains. When we use $\sigma_{Y(c)}$ as a constant, we are essentially averaging over a number of grains across the crack front as well as averaging over the grains within the crack increment during each crack growth measurement. The necessary adjustment from the macro-tensile yield strength to the local yield strength needed to make such a calculation can be absorbed into the constant C'.

Yoder et al. [13] analyzed the transition point ΔK_t and $\bar{\ell}$ of 15 steels. The values of $\bar{\ell}$, ΔK_{th}, and σ_Y of these steels are shown in Table I*. These values are used to plot the data in Fig. 9.

TABLE I Ref. [13]

Steel	Symbol	$\bar{\ell}$ (μm)	σ_Y (MPa)	ΔK_{th} (Measured MPa√m)
1005	⬢	24.0	411	8.8
		70.0	368	11.7
4Cr-0.35C	●	0.83	1324	4.4
		0.47	1324	3.4
		0.41	1303	3.3
		0.38	1324	3.0
1055	△	27.0	399	12.0
304	○	76.0	715**	16.0
2¼Cr-1Mo	▽	36.0	290	9.0
1018	▷	36.0	293	7.8
1020	▲	78.0	366	5.3
		20.5	275	5.7
		55.0	194	6.8

*The data of 1007 steel is not sufficient for analysis.

**Cyclic yield stress.

Because of the lack of the data of cyclic yield strength, the monotonic tensile yield strengths are used except for 304 stainless steel, where the cyclic yield strength is used. The dashed line is the average line with a slope of 2. The proportional constant C' of Eqn. (24) for the dashed line is 0.45.

The measured and the calculated crack growth rates of these steels are shown in Figs. 10 to 12. The value of 0.45 for C' is used in Eqn. (24) for the calculations. Figure 10 shows the data for 1020 and 1005 steels. The agreement between the measured and the calculated crack growth rates in 1020 steel is better than in other steels we analyzed. There is a large difference in monotonic and cyclic yield strengths of 304 stainless steel 255/715 MPa. For such a large difference, the transient deformation behavior from monotonic to cyclic yield strength must play an important role in the cyclic plastic deformation and the growth of a fatigue crack. This transient behavior may cause the large difference in crack growth rates of the 304 stainless steel shown in Fig. 11. The measured and the calculated crack growth rates in 2-1/2 Cr-1Mo steel agree very well. The measured and the calculated crack growth rates agree fairly well for 1018 steel, but a large difference exists for 1055 steel (see Fig. 11). The difference could be caused by the low monotonic yield strength (399 MPa) used for the growth rate calculation. A higher value for cyclic yield strength will increase the calculated rate and will improve the correlation.

Figure 12 shows the data for 4Cr-0.35C steels. The tensile yield strengths of these steels are approximately 1300 MPa and their values of $\bar{\ell}$ vary from 0.38 to 0.83 μm. In high yield-strength steels, a fatigue crack often grows by a combination of fracture and deformation processes. The fracture process will certainly increase the growth rate, and the measured crack growth rate will be much faster than the calculated rate based on the deformation mode of fatigue crack growth, as shown in Fig. 12.

Equation (24) is derived for the deformation mode of crack growth. It will not be valid if fracture is a dominant factor in crack growth as is possible in the high-strength 4Cr-0.35C steels. If the data for the 4Cr-0.35C steels are excluded, the average value of C' is 0.3. Above the transition point, $\Delta K >> \Delta K_{th}$, the second term in Eqn. (24) can be neglected. With the relations $\bar{\ell} = \Delta K_t^2/5.5^2\sigma_{Y(c)}{}^2$, $(\Delta K_t/\Delta K_{th})^2 = 2$, and C' = 0.3, Eqn. (24) becomes Eqn. (1). Therefore, Eqn. (24) can be used to correlate with the data in the intermediate ΔK region as well as in the near

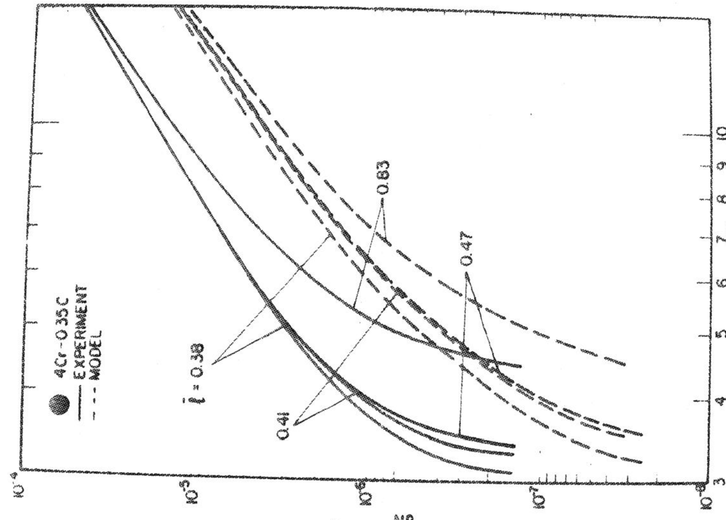


FIG. 12 Measured and calculted fatigue crack growth in steels. Ref. [10]

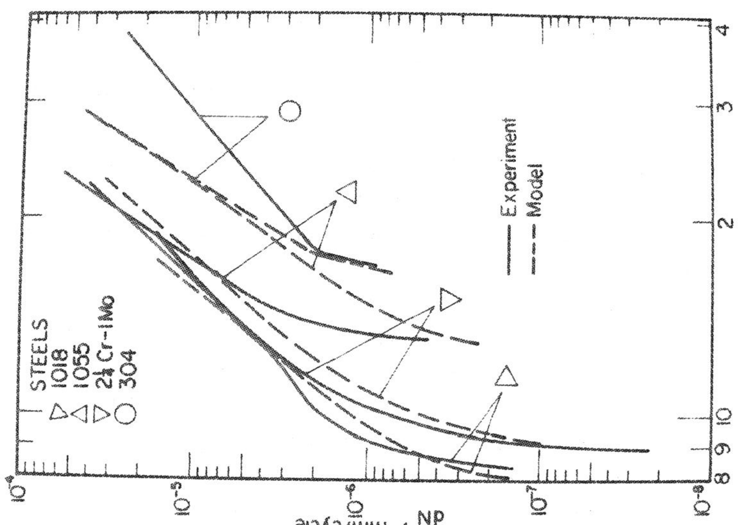


FIG. 11 Measured and calculated fatigue crack growth in steels. Ref. [10]

threshold region.

The fatigue crack growth model is semiempirical. However, the construction of the model is based on the physical process of crack growth. If constructed correctly, it will serve as a quantitative predictive model, and the calculated crack growth rate can serve as a reference to be compared with the measured rate in assessing the effects of brittle fractures and aggressive environments.

DISCUSSION

This is our first attempt to relate fatigue crack growth to microstructures. The deformation and fracture characteristics of a material are related to a number of microstructural features. $\bar{\ell}$ is only one of them. The effects of all of the other features are neglected. A more detailed study will improve the data correlation.

In making the calculations of the crack growth rate, we used the monotonic yield strengths of the steels. According to the derivation of the crack growth equation based on the unzipping model, cyclic yield strength should be used. It is expected that the cyclic yield strengths of these steels will improve the data correlation.

The proposed crack growth model in the near threshold region is derived from the grain boundary resistance to cyclic plastic deformation. Little is known about these material behaviors under cyclic load. Additional research in this area could verify, disprove, or improve the model.

The threshold as well as the rapid decrease in da/dN near ΔK_{th} are often attributed to crack closure. A similar relation between ΔK_{th} and ΔK_t can be derived if one considers the relaxation of the residual compressive stress in the crack tip plastic zone and the gradual diminishing of the crack closure.

A fatigue crack may grow by a deformation process, a fracture process, or a combination of these two. Equation (24) was derived from a deformation mode of fatigue crack growth. For a high yield-strength and brittle steel such as the 4Cr-0.35C steel in Fig. 12, the fracture process is likely to play an impotant role in its crack growth, and the fracture process will accelerate its overall crack growth rate, so that the measured crack growth curves in Fig. 12 are displaced to the upper left of the

calculated curves. Aggressive chemical environments will promote brittle fractures along grain boundaries and will also accelerate fatigue crack growth. The quantitative effects of brittle fractures and chemical environments remain to be investigated.

In the near threshold region, a crack front is more likely a curve in a three-dimensional space. Bifurcation often takes place. Therefore, the local stress intensity factor varies from point to point along the crack front. The effects of the local variation of K on the overall crack growth behavior need to be analyzed.

In most of the above research areas we need to study both the mechanics and materials behavior. A thorough understanding of the physical processes of deformation and fracture is necessary for accurate and correct mechanical modeling. Yet a qualitative and descriptive study on the physical processes of deformation and fracture will not be able to offer the quantitative results needed for design, failure prevention and life prediction. Clearly the mechanical and metallurgical studies have to go hand in hand. Perhaps this new area of multi-disciplinary research effort can be called metallurgical mechanics.

SUMMARY

1. A fatigue crack may grow by the plastic deformation process at a crack tip.
2. A mechanical model of fatigue crack growth is constructed, based on the crack tip plastic deformation process-the unzipping process. The unzipping crack growth calculation agrees well with the measured crack growth rate in the structure insensitive region.
3. Two models for crack growth threshold are proposed. One model is based on the finite slip step size of the unzipping process. It is suggested that the proposed threshold model might be applicable to fcc crystals of low stacking fault energy.
4. A second model is proposed based on grain boundary acting as the barrier to plastic deformation. It is suggested that this model is applicable to bcc crystals with a strong grain boundary to resist plastic deformation.
5. A semiempirical theory for fatigue crack growth is constructed, based on crack tip cyclic deformation characteristics. The theory relates crack growth rate to a microstructural parameter, mean free path for dislocation movement. The theory agrees well with the measure growth rates of a number of steels.

6. Where the fracture process plays an important role in fatigue crack growth - for example, crack growth in high-strength steels and in aggressive chemical environments, the measured crack growth rate is faster than that predicted by the theory based on crack tip deformation.

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REFERENCES

[1] Orowan, E., Fracture and Strength of Solids, Rep. Prog. Phys. 12 (1949) 185-232.
[2] Laird, C., in Fatigue Crack Propagation, ASTM STP 415 (1967) 131-180.
[3] Neumann, V. P., Zhurnal Metallkde 58 (1967) 78-789.
[4] Tomkins, B., Philosophical Magazine 18, No. 155 (1968)1041-1066.
[5] Pelloux, R. M. N., Transactions of the American Society of Metals 62 (1969) 281-285.
[6] Neumann, V. P., New Experiments Concerning the Slip Processes at Propagation Fatigue Cracks - I, II, Acta Met 22 (1974) 1155.
[7] Kuo, A. S. and Liu, H. W., An Analysis of Unzipping Model for Fatigue Crack Growth, Scripta Met. 10 (1976) 723.
[8] Liu, H. W. and Kobayashi, H., Stretch Zone Width and Striation Spacing - The Comparison of Theories and Experiments, Scripta Met. 16 May 1980.
[9] Liu, H. W. and Liu, Dai, Near Threshold Fatigue Crack Growth Behavior, Scripta Met., May 1982.
[10] Liu, H. W. and Liu, Dai, A Quantitative Analysis on Structure Sensitive Fatigue Crack Growth in Steels - Based on Crack Tip Plastic Deformation (To be published).
[11] Lal, D. N. and Weiss, V., An Analysis of Non-Propagating Fatigue Cracks, Met. Trans. A, 6A (1975) 1623.
[12] Weertman, Fatigue Crack Growth in Ductile Metals, Mechanics of Fatigue, Ed. T. Mura, ASME, AMD-47 (1981).
[13] Yoder, G. R., Cooley, L. A., and Crooker, T. W., A Critical Analysis of Grain-Size and Yield-Strength Dependence of Near-Threshold Fatigue Crack Growth in Steels, Naval Research Laboratory, NRL Memorandum Report 4576, July 1981.
[14] Taira, S., Tanaka, K., and Hoshina, M., in Fatigue Mechanisms, ASTM STP 675, J. Fong, Ed., ASTM, Phil. Pa. (1979) 135-162.
[15] Eylon, D. and Bania, P. J., Met. Trans. A., 9A (1978) 1273-79.
[16] Masounave, J. and Bailon, J. P., Scripta Met. 10 (1976) 165-170.