THE INFLUENCE OF PRIOR AUSTENITE GRAIN SIZE AND STRESS RATIO ON NEAR THRESHOLD FATIGUE CRACK GROWTH BEHAVIOR IN HIGH STRENGTH STEEL

R. Murakami* and K. Akizono*

*Dept. of Precision Mechanics, Tokushima University,
2-1 Minami-josanjima-cho, Tokushima, Japan.

ABSTRACT

The influence of prior austenite grain size and stress ratio on threshold stress intensity for crack growth, ΔK_{th}, and near threshold fatigue crack growth rate has been studied by means of fracture mechanics and fractography in quenched and tempered Ni-Cr alloy steel where the prior austenite grain size was varied between 21 and 210 μm.

KEYWORDS

Fatigue; crack growth rate; threshold; microstructure; fracture mechanics; fractography.

INTRODUCTION

The fatigue crack growth rate, da/dN, is usually related with the stress intensity range, ΔK, by the following equation (Paris and Erdogan, 1963);

$$da/dN = C\ (\ \Delta K\ )^{m} \qquad (1)$$

where m and C are material constants. At the very low ΔK levels, Eq.(1) does not always hold true, and the threshold stress intensity range for crack growth, ΔK_{th}, is approached (Johnson and Paris, 1968), where the condition of crack growth is described by $\Delta K \geq \Delta K_{th}$. It is known that the value of ΔK_{th} and the near threshold crack growth rates are sensitive to changes in microstructure, mechanical properties and stress ratio (Murakami and co-workers, 1977, 1978; Beevers, 1977). In particular, it has been indicated that the effect of ferrite grain size in low strength steel (Masounave and Bailon, 1976 a, b) was considerably distinct from that of prior austenite grain size in quenched and tempered steel (Carlson and Ritchie, 1977; Ritchie, 1977). However, the difference has not yet been fully explained in the role between the ferrite and the prior austenite grain size. It is also possible that the dependence of ΔK_{th} on grain size is closely related to the monotonic strength such as yield strength, so that the monotonic strength increases usually with decreasing grain size according to well known Hall-Petch equation. When we consider the effect of grain size on ΔK_{th}, it is necessary to divide the roles of grain boundary and monotonic strength. The objects of present paper are to examine the effect of prior austenite grain size on ΔK_{th} and near threshold crack growth rate in high strength steel where the prior austenite grain size was varied considerably without significant changes in monotonic strength, and further to relate it with the effect of stress ratio.

The material used for this investigation was the Ni-Cr alloy steel having the chemical composition shown in TABLE 1. The variation in prior austenite grain size of 21 and 210 µm was obtained by two heat treatment conditions; after austenitising at 1150°C for 3 hrs, furnace cooled to 850°C and heated at 850°C for 0.5 hr, one was oil quenched and tempered at 600°C for 3 hrs, and the other, after austenitising at 850°C for 0.5 hr, was oil quenched and tempered at 600°C for 3 hrs. The prior austenite grain size and mechanical properties were listed in TABLE 2. The mechanical properties of this quenched and tempered steel, as indicated in TABLE 2, have shown that the yield and ultimate strengths were independent of the prior austenite grain size.

TABLE 1 Chemical composition(wt%).

C	Si	Mn	P	S	Ni	Mo	Cr	Cu
0.36	0.25	0.41	0.02	0.006	3.01	0.07	0.77	0.16

TABLE 2 Mechanical properties.

prior austenite grain size µm	$\sigma_{0.2}$ MN/m^2	UTS MN/m^2	H_V (50gf)
21	873	893	227
210	882	900	232

Compact tension specimens 12.5 mm thick were tested. Fatigue crack growth tests were performed on a 10 ton Amsler Vibrophore fatigue machine at room temperature. Tests were conducted under sinusoidal tension at about 40 Hz with three stress ratios, R=0.05, 0.3 and 0.6. Fatigue cracks were initiated from the machined notch at relatively high loads. The loading sequence, following the initiation, involved stepped load reductions at decreasing increment with the sufficient crack growth between steps to extend the crack past the theoretical maximum plain strain plastic zone for the previous load condition. The measurements of crack length were made using a travelling microscope. The threshold, ΔK_{th}, was determined in terms of stress intensity range, ΔK, at which no crack growth could be detected within 10^7 cycles. This corresponds to a threshold defined in terms of a maximum crack growth rate less than 10^{-8} mm/cycle. After the thresholds were approached, the measurements of constant load crack growth rates were conducted over a range of rates between 10^{-6} and 10^{-3} mm/cycle at three stress ratios described above. The stress intensity, K, was calculated using Srawley's equation(Srawley, 1976). Two stage chromium shadowed carbon replicas were obtained from the fatigue fracture surfaces and examined using a transmission electron microscope.

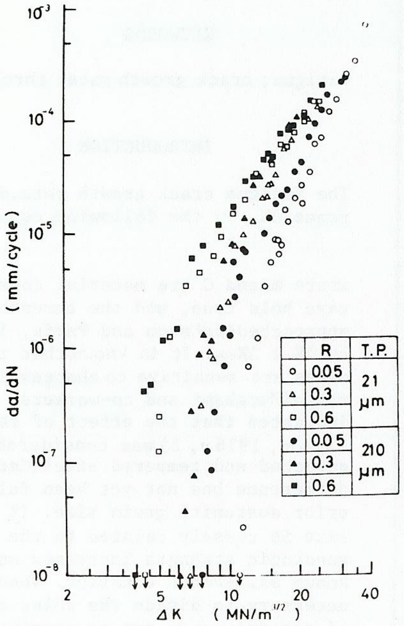

Fig. 1 Relation between the fatigue crack growth rate and the stress intensity range.

RESULTS RELATED TO FRACTURE MECHANICS APPROACH

The crack growth rates, da/dN, for two austenite grain sizes are illustrated in Fig. 1 as a function of ΔK. Prior austenite grain size was varied by a factor of 10 as shown in Table 2. However, at the mid-range of crack growth rates above 5×10^{-6} mm/cycle where the eq.(1) has held true, it is clear that the crack growth rates are very little dependent on prior austenite grain size. At the near threshold crack growth rates below 5×10^{-6} mm/cycle, it is apparent that the Eq.(1) has not held true, and the crack growth rates increase markedly in proportion with grain size for each stress ratio. In other words, the resistance to crack propagation over this threshold rate regime and the ΔK_{th} decrease with increasing grain size at the same stress ratio. But such a grain size dependence for R=0.05 is very marked in comparison with the case of R=0.3 and 0.6. These results have suggested that the process of crack propagation over near threshold rate regime is considerably sensitive to changes in microstructure, involving the prior austenite grain size, in relation to the crack tip opening displacement.

To assess the effect of stress ratio, fatigue tests were performed on the three stress ratios R=0.05, 0.3 and 0.6. At the mid-range of crack growth rates above 5×10^{-6} mm/cycle, it has been found that the crack growth rates increase slightly as the stress ratio increases from R=0.05 to 0.3. However, the marked difference in crack growth rates for stress ratios of 0.3 and 0.6 does not appear. While, at the very low ΔK levels, as the stress ratio increases, the near threshold crack growth rates increase and the ΔK_{th} decreases.

The crack growth rates, da/dN, for two prior austenite grain sizes were illustrated in Fig. 2 as a function of K_{max}. In Fig. 2, it is suggested that the crack growth rates at K_{max} above 15 MN/m$^{3/2}$ do not always depend on K_{max} although the near threshold rates depend markedly on K_{max}. But the dependence of crack growth rate on K_{max} differs slightly between both the prior austenite grain sizes.

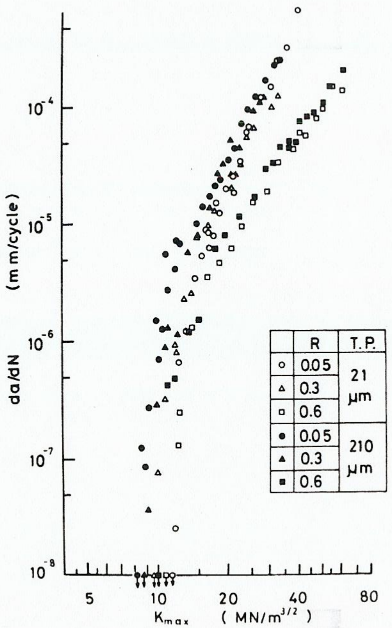

Fig. 2 Relation between the fatigue crack growth rate and the maximum stress intensity.

In TABLE 3, the values of ΔK_{th} and $K_{max,th}$ were presented for each prior austenite grain size and stress ratio, along with the reversed and maximum plane strain plastic zone sizes, R_{yc} and R_y. R_{yc} and R_y were calculated from the following equations(Rice, 1967);

$$R_{yc} = (2/5.6\pi)(\Delta K/2\sigma_{ys})^2 \qquad (2),$$

$$R_y = (2/5.6\pi)(K_{max}/\sigma_{ys})^2 \qquad (3),$$

where σ_{ys} is the monotonic yield strength. As indicated in TABLE 3, the reversed plastic zone sizes at the threshold for each stress ratio always are far less in comparison with the prior austenite grain size. However, the maximum plastic zone sizes for fine grain size are almost equal to the grain size although those sizes for coarse grain size are about one-twentieth of grain size.

TABLE 3 The stress intensity factor and plastic zone size at the threshold.

prior austenite grain size µm	R	ΔK_{th} MN/m$^{3/2}$	R_{yc} µm	$K_{max,th}$ MN/m$^{3/2}$	R_y µm
21	0.05	11.0	4.5	11.6	20
	0.3	6.8	1.7	9.7	14
	0.6	4.5	0.7	11.1	18
210	0.05	7.7	2.1	8.1	9
	0.3	6.1	1.4	8.8	11
	0.6	4.0	0.6	9.9	14

Relations between the ΔK_{th} and the prior austenite grain size were illustrated in Fig. 3 for each stress ratio. It is apparent that the ΔK_{th} for R=0.05 depends markedly on grain size in comparison with the cases of R=0.3 and 0.6. Such a grain size dependence was slightly different from the other results(Kitunai, 1979; Ritchie, 1977) indicated in Fig. 3. This reason can be considered that the yield and ultimate strengths are changed with the prior austenite grain size. In fact, when those have been unchanged with the prior austenite grain size, the ΔK_{th} has the tendency to decrease with increasing grain size(Carlson and Ritchie, 1977). Furthermore, as the stress ratio increases from R=0.05 to 0.6, the values of $K_{max,th}$ for each grain size have scarcely changed although the values of ΔK_{th} decrease.

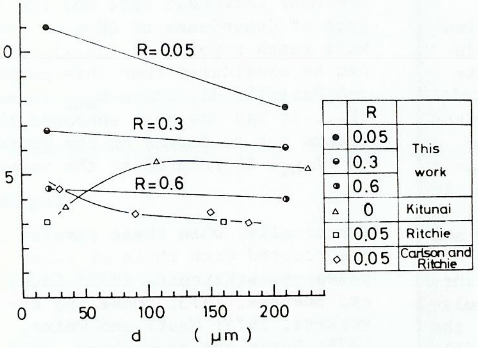

Fig. 3 Relation between the threshold stress intensity,ΔK_{th}, and the prior austenite grain size,d.

FRACTOGRAPHIC APPEARANCE

The fractographic examination showed that the general features of fatigue fracture surfaces have mainly varied with the prior austenite grain size and the ΔK level regardless of the stress ratio. At the very low ΔK levels approaching ΔK_{th}, a typical fractograph in fine grain size material was shown in Fig. 4, where the appearance on either side of a boundary formed by load increasing from ΔK_{th} to some higher ΔK level can be microscopically seen quite flat and microstructurally sensitive. When it was observed at a higher magnification, the definition of striation at the near threshold rate regime, as shown in Fig. 5, was generally very good and existed with the precipitation-like particles having size of 0.2 ∿ 0.5 μm. The typical fractograph in coarse grain size was shown in Fig. 6, where the intergranular facets associated with the stage 2a crack growth which exhibited the slip plane decohesion-like appearance(Murakami and co-workers, 1977; Birkbeck and co-workers, 1971) could be clearly seen regardless of the stress ratio. As the ΔK levels increase above K_{max}=15 MN/m$^{3/2}$, in general, it is found that the whole fracture surface has been dominantly striated as shown in Fig. 7 in spite of the prior austenite grain size and stress ratio.

Fig. 4 Fractograph showing the appearance at the very low ΔK level for the prior austenite grain size of 21 μm($\Delta K = \Delta K_{th}$, R = 0.3).

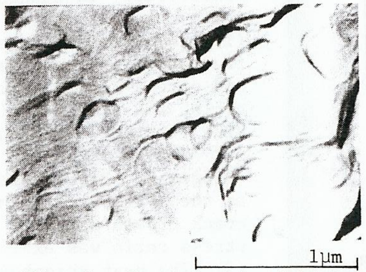

Fig. 5 Fractograph of higher magnification showing the appearance at the very low ΔK level for the prior austenite grain size of 21 μm(ΔK = 7.6 MN/m$^{3/2}$, R = 0.6).

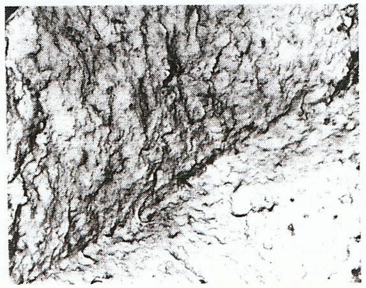

Fig. 6 Fractograph showing the intergranular facet for the prior austenite grain size of 210 μm(ΔK = 11.4 MN/m$^{3/2}$, R = 0.05).

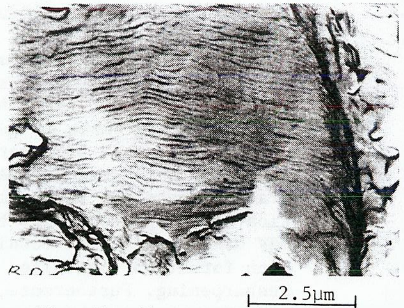

Fig. 7 Fractograph showing the typical striated area(ΔK = 16.3 MN/m$^{3/2}$, R = 0.6).

DISCUSSION

In this paper it has indicated that the transition of microstructurally sensitive-to-insensitive crack growth has been started at about K_{max}=15 MN/m$^{3/2}$ in the same manner as the stress ratio effects. While, the fractographic examination showed that, at the higher ΔK level above K_{max}=15 MN/m$^{3/2}$, the dominant fracture appearance was of the striation regardless of the grain size and the stress ratio, but at the lower ΔK level below K_{max}=15 MN/m$^{3/2}$, the fracture surfaces have differed with each grain size rather than stress ratio. If the fracture appearance is unchanged with the grain size and is of the striation, the crack growth rates are insensitive to changes in microstructure. Similar results have been reported by many researchers(Murakami and co-workers, 1977, 1978; Ritchie, 1977; Bates and Clark, 1969). And further, though the crack growth rates increase slightly as the stress ratio increases from R =0.05 to 0.3, the increase in stress ratio from R=0.3 to 0.6 has almost no changes in crack growth rate. It is possible that such a stress ratio effect is closely related with the striation formation(Kobayashi, Murakami and Nakazawa , 1977).

Elber(1971) has proposed the concept of crack closure and has shown that the effect of stress ratio on crack growth rates is explained by the effective stress intensity,ΔK_{eff}, as follows;

$$\Delta K_{eff} = (0.5 + 0.4R)\Delta K. \qquad (4)$$

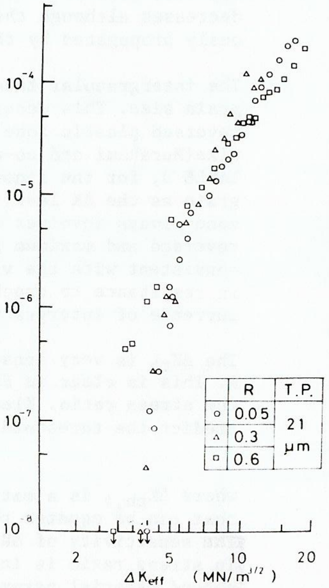

Fig. 8 Relation between the fatigue crack growth rate and the effective stress intensity.

Then, Fig. 8 has illustrated the relation between the crack growth rate and the ΔK_{eff} calculated from Eq.(4) for the prior austenite grain size of 21 μm. The evaluation of crack growth rate in terms of ΔK_{eff} and the comparison with ΔK data(Fig. 1) and K_{max} data(Fig. 2) show that K_{max} becomes more important as the near threshold crack growth rate controlling parameter, but the crack closure is unnecessarily the only controlling factor at the near threshold rate regime. However, for the mid-range of crack growth rate above 5x10^{-6} mm/cycle, it has found that the crack growth rates depend strongly on the ΔK_{eff} regardless the stress ratio. If the dominant fracture appearance is of the striation, the effect of stress ratio on crack growth rate will be explained using the effective stress intensity based on the concept of crack closure. These results are obtained in much the same manner as the case of prior austenite grain size of 210 μm.

Beevers and his co-workers(1973, 1974) have supposed that a two-component mechanism of crack propagation, in which one component is ΔK-dependent and the other K_{max}-dependent, has been operating at the near threshold rate regime. Kobayashi(1977) has also guessed on bases of the facts that are the microstructural fracture facets at this rate regime could be observed that the propagation process was divided into two processes in which one is the intermittence of crack growth and the other continuous crack propagation by striation formation. As indicated in Fig. 5, since the striation-like appearance has been locally observed at the near threshold rate regime, it may be reasonable to consider that the crack has partially propagated by the striation formation controlled in terms of ΔK which is a result of crack tip blunting and resharpening. Furthermore, the occurrence of microstructurally sensitive fracture appearance such as the intergranular facets and the precipitation-like appearance suggests that the crack at the near threshold rate regime will propagate non-uniformly because part of crack has been under the influence of microstructure. Therefore, the whole crack growth rate is not expressed by the linear relation expressed in Eq.(1) and will have been under the remarkable influence of microstructure as the ΔK level decreases although the local crack growth rate, at which part of crack has continuously propagated by the striation formation, will conform to Eq.(1).

The intergranular facets as indicated in Fig. 6 have occurred only in case of coarse grain size. This occurrence of intergranular facets has been shown to occur when the reversed plastic zone size as defined in Eq.(2) is of a similar size to the grain size(Murakami and co-workers, 1977; Birkbeck and co-workers, 1971). As indicated in TABLE 3, for the fine grain size, the reversed plastic zone is restricted within a grain as the ΔK level decreases below ΔK=23.7 MN/$m^{3/2}$ although the maximum plastic zone always involves more than a grain. While, for the coarse grain size, both the reversed and maximum plastic zones always are restricted within a grain. This is consistent with the views proposed earlier. It can be considered that the decrease in resistance to crack propagation with increasing grain size is mainly caused by occurrence of intergranular facets.

The ΔK_{th} is very sensitive to changes in stress ratio, and decreases with increasing R. This is clear in Fig. 9 which has illustrated the relation between the ΔK_{th} and the stress ratio. Klesnil and Lukas(1972) have proposed the empirical relation to predict the threshold behavior as shown in Eq.(5);

$$\Delta K_{th} = (1 - R)^{\gamma} \Delta K_{th,0} \tag{5}$$

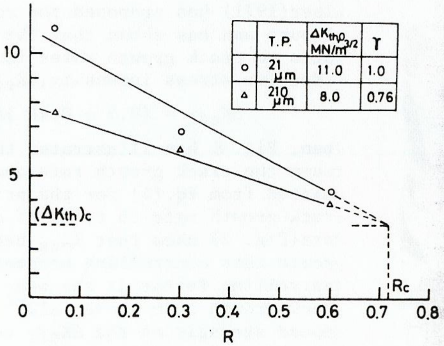

Fig. 9 Relation between the threshold stress intensity, ΔK_{th}, and the stress ratio, R.

where $\Delta K_{th,0}$ is a material parameter that can be equated to ΔK_{th} at R=0. The sensitivity of ΔK_{th} to changes in stress ratio is indicated by a second material parameter, γ. The application of Eq.(5) to available data at three stress ratios shows that, as indicated in Fig. 9, the value of γ is equal to 1 in fine grain size, where the ΔK_{th} is specified by a constant value of K_{max} for a large range of stress ratios and K_{max} appears to controll the crack growth rate, but the value of γ is equal to 0.76 in coarse grain size, at which the ΔK_{th} tends more towards ΔK control than in fine grain size. The degree of sensitivity of the ΔK_{th} to changes in stress ratio appears to vary with the grain size. These results suggest that the prior austenite grain size is an important parameter affecting on the near threshold rate and the ΔK_{th}. Also, as the stress ratio increases, the degree of dependence of ΔK_{th} on grain size decreases and, as inferred from Fig. 9, will reach a point of $(\Delta K_{th})_c$ or R_c where the point is independent of grain size. It can be considered that this point corresponds to the point R_c proposed by Schmidt and Paris(1973), where K_{min} is equal to the stress intensity necessary to open crack, K_{cl}. It has now been supposed that the points $(\Delta K_{th})_c$ and R_c are the material constants not to depend on the grain size. Then, it should be emphasized that the value of $\Delta K_{th,0}$ is related to the value of γ in Eq.(5) as follows;

$$\log \Delta K_{th,0} = A + B\gamma . \tag{6}$$

Practically, when these results are plotted with those of other researchers(Ritchie, 1977; Cooke and Beevers, 1973; Cooke and co-workers, 1975; Mautz and Weiss, 1976; Paris and co-workers, 1972 ; Ohta and Sasaki, 1975), this relation is illustrated in Fig. 10, where the constants in Eq. (6) are $A=\log(\Delta K_{th})_c=0.42$ and $B=-\log(1-R)=0.6$ respectively. The values of $(\Delta K_{th})_c$ and R_c obtained from Fig. 10 are 2.63 MN/$m^{3/2}$ and 0.75 respectively, and agree well with the values indicated by Schmidt and Paris(1973). Then, the increase in the value of γ with decreasing grain size suggests that the value of $\Delta K_{th,0}$ is in inverse proportion to the prior austenite grain size. The present results indicate that the refinement of grain results in improving the resistance to near threshold crack propagation.

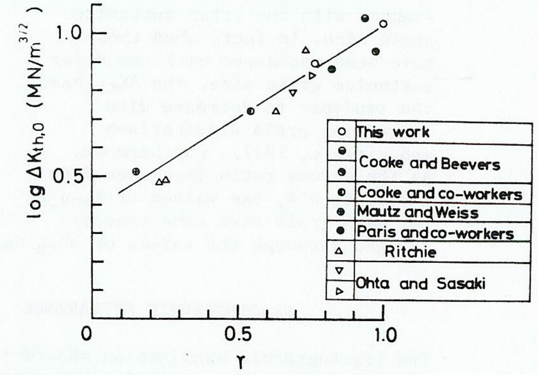

Fig. 10 Relation between the stress intensity, $\Delta K_{th,0}$, and γ in $\Delta K_{th} = (1 - R)^{\gamma} \Delta K_{th,0}$

CONCLUSIONS

The influence of prior austenite grain size and stress ratio on near threshold fatigue crack growth behavior has been studied by means of fracture mechanics and fractography in quenched and tempered Ni-Cr alloy steel where the prior austenite grain size was varied between 21 and 210 μm. The results obtained were as follows.
(1) For the mid-range of crack growth rates above 5×10^{-6} mm/cycle, the dominant fracture appearance was of the striation in spite of the prior austenite grain size and stress ratio. While, for the near threshold crack growth rates below 5×10^{-6} mm/cycle, the striation-like appearance has existed with the microstructurally sensitive fracture appearance such as precipitation-like particle.
(2) The crack growth rates associated with striation formation were insensitive to changes in prior austenite grain size in all stress ratios, and increased slightly as the stress ratio increased from R=0.05 to 0.3. While, the marked difference in crack growth rates in stress ratio of R=0.3 and 0.6 did not appear. The effect of stress ratio was explained by a crack closure phenomenon.
(3) The near threshold crack growth rates in low stress ratio were sensitive to changes in prior austenite grain size. Those in high stress ratio were a little sensitive to changes in grain size. Also, the greatest sensitivity to stress ratio appeared for near threshold crack growth rates in each prior austenite grain size.
(4) The consequence of coarsening of prior austenite grain size was to reduce ΔK_{th} in all stress ratios. The value of ΔK_{th} in both grain sizes decreased with increas-

ing stress ratio. Also, the grain size dependence was observed to decrease with increasing stress ratio.

REFERENCES

Bates, R. C., and W. G. Clark (1969). *Trans. ASM, 62,* 380-389.
Beevers, C. J. (1977). *Met. Sci., 11,* 362-367.
Birkbeck, G., A. E. Inkle, and R. W. J. Wardron (1971). *J. Mater. Sci., 6,* 319-323.
Carlson, M. F., and R. O. Ritchie (1977). *Scripta Met., 11,* 1113-1118.
Cooke, R. J., and C. J. Beevers (1973). *Eng. Fract. Mech., 5,* 1061-1071.
Cooke, R. J., and C. J. Beevers (1974). *Mater. Sci. Eng., 13,* 201-210.
Cooke, R. J., P. E. Irving, G. S. Booth, and C. J. Beevers (1975). *Eng. Fract. Mech., 7,* 69-77.
Elber, W. (1971). *ASTM STP, 486,* 230-242.
Johnson, H. H., and Paris, P. C. (1968). *Eng. Fract. Mech., 1,* 3-45.
Kitunai, Y. (1979). *Reprints of 2nd Fractography Sym.(Soc. Mater. Sci., Japan),* 40-44.
Klesnil, M., and P. Lukas (1972). *Mater. Sci. Eng., 9,* 231.
Kobayashi, H. (1977). *J. Japan Soc. of Mech. Eng., 80,* 492-497.
Kobayashi, H., R. Murakami, and H. Nakazawa (1977). Edited by G. C. Sih and C. L. Chow, *Proc. of Intl. Conf. on Fract. Mech. and Tech.(Hong Kong), 1,* 205-219.
Masounave, J., and J. P. Bailon (1976). *Scripta Met., 10,* 165.
Masounave, J., and J. P. Bailon (1976). *Proc. 2nd Intl. Conf. on Mechanical Behavior of Materials (Boston),* 636-641.
Mautz, J., and V. Weiss (1976). *ASTM STP, 601,* 154-168.
Murakami, R., H. Kobayashi, A. Komine, and H. Nakazawa (1977). *Trans. Japan Soc. Mech. Eng., 42,* 799-809.
Murakami, R., H. Kobayashi, and H. Nakazawa (1978). *Trans. Japan Soc. Mech. Eng., 44,* 1415-1423.
Ohta, T., and E. Sasaki (1975). *Reprints of Japan Soc. Mech. Eng., 750-1,* 123-126.
Paris, P. C., and F. Erdogan (1963). *Trans. ASME, Ser. D, 85,* 528-534.
Paris, P. C., R. J. Bucci, E. T. Wessel, W. G. Clark, and T. R. Mager (1972). *ASTM STP, 513,* 141-176.
Rice, J. R. (1967). *ASTM STP, 415,* 247-309.
Ritchie, R. O. (1977). *Trans. ASME, Ser. H, 99,* 195-204.
Schmidt, F. R., and P. C. Paris (1973). *ASTM STP, 536,* 79-94.
Srawley, J. E. (1976). *Int. J. of Fract., 12,* 475-476.