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PLASTIC ZONE FORMATION AND FATIGUE CRACK GROWTH

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INTRODUCTION

Knowledge of the plastic zone at the fatigue crack tip by calculation or experience is one of the best means of investigation to understand the crack mechanism - Rice has demonstrated, the first, by calculation [1] that, a cyclic plastic zone proportional to $(\Delta K/2\sigma y)^2$ should exist at the crack tip.

It has been demonstrated in stainless steels [2] that the presence of this cyclic plastic zone is circumscribed by a monotonous plastic zone whose radius is proportional to $(K/\sigma y)^2$, and G. T. Hahn found identical results in silicon steels [3].

Experimental studies are difficult to realize owing to the small scale in which this phenomenon takes place in a zone difficult to observe. In the present work, we have attempted to throw some light on the formation of the monotonic plastic zone, which is the easiest to be revealed.

We have studied, on one hand, the influence of the ratio R on the radius of the plastic zone, in plane strain, in a stainless steel.

On the other hand, we have measured the plastic zones produced by the application of one or several overloads on the surface of compact aluminum alloy test specimens. This method allows, furthermore, observation of the plastic zone. We have finally related crack retardation, resulting from the application of an overload, to the dimensions measured of the subsequent plastic zone.

Measurement of the plastic zone, in plane strain, is carried out at mid-section of a 20 mm thick test specimen, by use of a microhardness technique described in [2]. In plane stress, the same measurements are made on the surface of 10 mm thick test specimens, by means of a microscope fitted with a dark field.

INFLUENCE OF RATIO R ON THE PLASTIC ZONE

Influence of ratio R = K min/K max on the radius of the monotonic plastic zone has been determined on the mid-section of a compact 316 stainless steel test specimen. Ratios 0.1; 0.25 and 0.6 have been tried.

Experience shows that the effect of K max is mainly on the size of the monotonic plastic zone measured at right angles to the crack direction (Figure 1). It is found that the following relation is confirmed whatever the R ratio:

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$$r_y = 0.06 \frac{K^2 \max}{\sigma y^2}$$

These results can be related to those of A. Pineau, who has found for an INCO 718 steel [4], with the same coefficients, that:

$$r_y = 0.06 \frac{K^2 \max}{\sigma y^2}$$

and to those we found in the past for other stainless steels [2]. The coefficient of proportionality measured is thus smaller than that proposed by Rice (0.15) to the same order of magnitude as that proposed by Irwin [1].

It is interesting to note that the crack propagation rate of 316 steel is not very sensitive to the R ratio and to K max. It thus appears that the mechanism of crack propagation does not depend on the radius of the monotonic plastic zone which is essentially linked to K max. In other words, for a given ΔK, one can observe identical rates and different monotonic plastic zones if the R ratio varies. It seems that the formation of striations is greatly dependent on ΔK and not on K max, since the growth rate is not influenced by the radius of the monotonic plastic zone. According to the assumption proposed by R. M. Pelloux, the spacing of the striations, and the cyclic C.O.D., depend rather on the size of the cyclic plastic zone.

PLASTIC ZONES DUE TO OVERLOADS

When one or several overloads are applied during fatigue cracking of a test specimen, a crack retardation can be noted coupled with the formation of a plastic zone due to temporary overloads. Crack retardation is essentially a phenomenon that concerns the surface of the test specimen and the plastic deformation developed within this surface [5]. Also, it is particularly useful to study the plastic zones due to overloads on the surface of the test specimens where deformations are developed in plane stress. We have chosen, for this study, two aluminum alloys, 2024 T 351 and RR 58 T 651, which well lend themselves to the observation of the plastic zones.

On an electrolytically polished surface, the monotonic plastic zone appears in the shape of two wings forming an angle of 40 to 60° with respect to the crack plane, this angle being smaller for higher overloads. The dimension of the plastic zone in the propagation direction is four to five times smaller than the orthogonal dimension. It is the latter that we have measured.

We have found, roughly, that the radius of the plastic zone under plane stress is given, approximately, by the Irwin equation for 2024, but the measured value is greater than that calculated for RR 58.

For a low stress intensity factor, it can be considered that r_y is constant between one and a hundred consecutive overloads. For high stress intensity factors, the measured r_y appreciably increase between one and ten overloads, but it is constant at fifty and a hundred overloads. It appears that these differences are due to the observation

means which are sensitive to deformation accumulation at each cycle, it being limited by material saturation under given conditions.

Crack retardation is generally related to the size of the plastic zone due to the overload. Wheeler and Willenborg models propose that retardation takes place as long as the plastic zone in the established regime is included in the plastic zone by the overload. We have attempted to confirm these assumptions. The affected crack length a' is always greater than the dimension of the plastic zone r_y in the direction of propagation, but it seems that the minimum rate is reached at the boundary of this zone, as shown by J. Lankford and D. J. Davidson [7].

For 2024, a' is equal to 70 to 100 percent of 2r . For RR 58, a' is roughly 75 percent of r_y, whatever the overload (Figures 2 and 3).

We have observed that frequency has an influence on the retardation process. When the frequency increases from 0.1 to 20 Hz, crack length and the number of affected cycles increases, whereas the dimension of the plastic zone remains unchanged. Under the same conditions, the length of the test produced by the overload decreases.

For a given overload rate, if the number of consecutive overloads is multiplied, the length of the affected crack a' increases in such a manner as to only extend 30 percent of $2r_y$ for higher overloads (Figure 4). It thus seems that a' increases at a lower rate than $2r_y$.

These observations, added to those on the influence of frequency, show that in general there is no simple relation between the diameter of the monotonic plastic zone and crack length where retardation takes place. However, for each configuration, a constant ratio may be found between these dimensions.

CONCLUSIONS

Experimental study of monotonic plastic zones in a stainless steel and in aluminum alloys allows to define the following points:

1) In plane stress, the monotonic plastic zone comprises two wings angled to the crack propagation direction.
2) In plane strain, the radius r_y of the plastic zone is expressed as $(K \max/\sigma y)^2$ whatever the ratio R.
3) There is no simple relation between radius r_y of the monotonic plastic zone and the macroscopic or microscopic crack rate.
4) The crack length, at which a retardation takes place after one or several overloads, is not given simply by the dimension of the plastic zone due to overloads. The number of overloads and frequency of the tests also have an important role.
5) It seems, finally, that these fatigue crack mechanisms cannot be completely defined from only the monotonic plastic zone.

ACKNOWLEDGEMENTS

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REFERENCES

1. RICE, J. R., ASTM STP 415, 1967, 247.
2. BATHIAS. C. and PELLOUX, R. M., Met. Trans, 4, 1973, 1265.
3. HAHN, G. T., HORGLAND, R. G. and ROSENFIELD, A. R., Met. Trans. 3, 1972. 1189.
4. CLAYEL, M., FOURNIER, D. and PINEAU, M., Met. Trans. 6A, 1975, 2305.
5. BATHIAS, C., VANCON, M. and SERTOUR, G., IMC II, 1976, Boston.
6. MILLS, W. J. and HERTZBERG, R. W., Eng. Fract. Mech, 7, 1975, 705.
7. LANKFORD, J. and DEVISON, D. C., J. Eng. Mat. and Techn. Jan. 1976. 17.

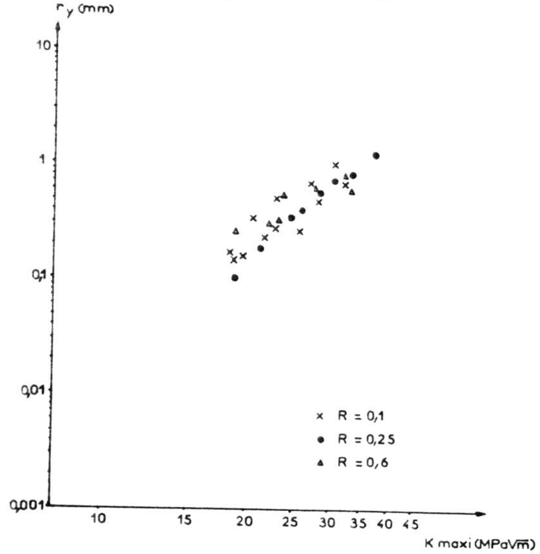

Figure 1 Maximum plastic zone size r_y versus K maxi for different R ratio in 316 stainless steel

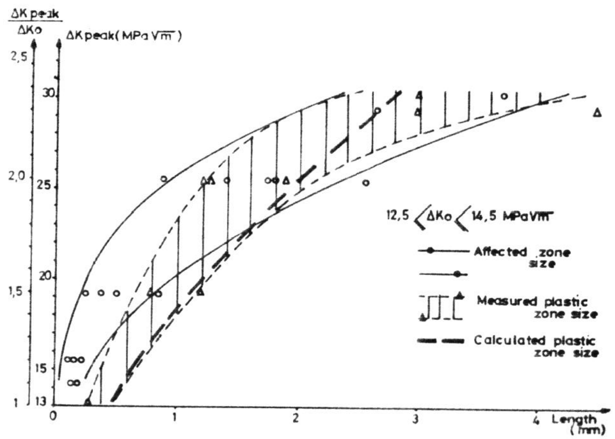

Figure 2 Correlation between affected zone size and plastic zone size in 2024 alloy

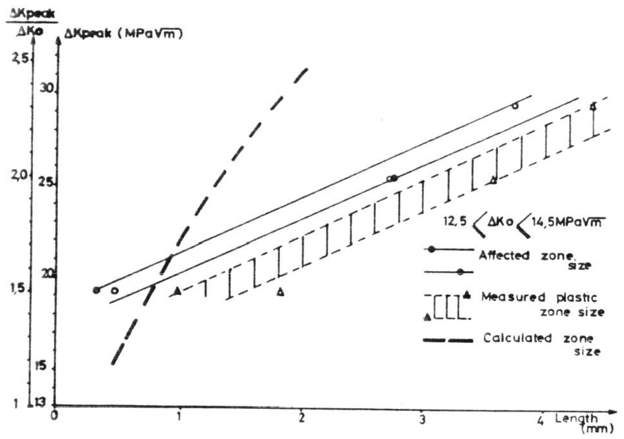

Figure 3 Correlation between affected zone size and plastic zone size in under aged RR 58

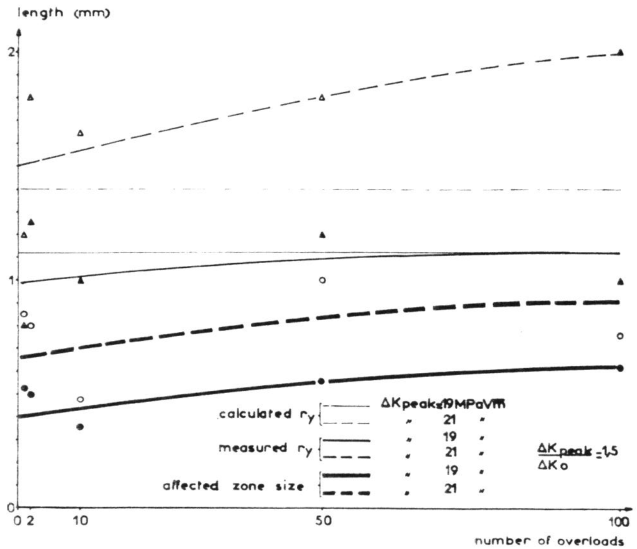

Figure 4 Correlation between affected zone size and plastic zone size for severals overloads in 2024 T351