IN SITU MID-WIDTH AND NEAR-SURFACE MEASUREMENTS OF THE RETARDATION OF THE PROPAGATION OF A CRACK AFTER AN OVERLOAD

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By using our so-called MU3F method and apparatus which is based on the diffraction of ultrasonic waves by crack tips, we were able to measure the local crack closure length and to discriminate the behavior of a crack in the plane strain and plane stress regions during fatigue, which allows to investigate the retardation phenomenon due to overload. We have determined the crack closure profile under loading in a A533B CT specimen. We applied 125%, 150% and 200% overloads. After a 1mm crack propagation past overload, we measured an increase of crack opening load and of closure length. After the overload, at mid-section, the crack propagation was immediately slowed down. On the contrary, near the surface, the propagation was not affected for approximately 0.3 mm of growth before being slowed down.

INTRODUCTION

A great deal of scientific investigation has been devoted to the fatigue crack growth retardation resulting from the application of overloads. This important phenomenon could be explained by the following concepts : crack tip closure, residual stress around crack tip and crack tip blunting. These three explanations for crack closure phenomenon are principally based on the optical observations of the crack tip behavior on surface, which is limited to the plane stress region even though in a great part of the cases the fatigue crack growth is subject to the plane strain condition. The different stress condition is likely to induce dissimilar behavior of crack growth. We have applied a ultrasonic technique to investigate the crack tip behavior affected by overloading. The technique called "MU3F" was developed by D. De Vadder and D. Bouami (1) and an improved experimental apparatus was presented by Park et al.(2, 3, 4). It consists in measuring the diffracted ultrasonic wave by the fatigue crack tip. Echodynamics (echo amplitude vs. probe translation) provide crack tip location, and the amplitude informations about blunting. In order to verify its effectiveness the crack opening loads obtained with this technique were compared with those determined by conventional CMOD method.

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EXPERIMENTAL CONDITION

A conventional CT25 specimen of A533 Gr. B which has a yield stress equal to 460MPa was used to investigate the retardation phenomenon due to an overload cycle. Crack propagation was carried out at constant ΔK : K_{max} = 25MPa$\sqrt{m}$, R=0.1. A ramp cycle of 0.1Hz was applied manually for overloading. 10 Hz was used during crack propagation and 0.1Hz for P-δ recording by CMOD technique and 0.025Hz for P-δ-Ultrasonic diffraction amplitude. The number of acquisitions was about 300 to 400 and sampling of the diffracted ultrasonic beam was carried out every 0.02mm for static loading and 0.05mm for cyclic loading by moving the transducer in the direction of crack growth.

Crack length was measured at the mid-section of specimens by using MU3F technique and at the surface by optical observations. Note that the fatigue crack growth could be measured by MU3F without interruption of cycling contrary to optical measurement. Following four kinds of recording were performed after every 1mm of propagation : P-δ by CMOD, echodynamic at the mid-section of the specimen and along the crack front under increasing load, and P-δ-Ultrasonic amplitude.

EXPERIMENTAL RESULTS

125%, 150%, and 200% overloads were applied. We payed attention to make clear four points : crack front affected by the overload, blunting effect at the mid-section of the specimen, crack propagation after overloading, and comparison between the results of CMOD and those of MU3F.

On the shape of the crack front affected by the overload cycle

Let us examine, first of all, the aspect of echodynamics before and after overloading. Before application of a 200% overload we recorded echodynamics along the crack front under increasing load step by step (Fig. 1).

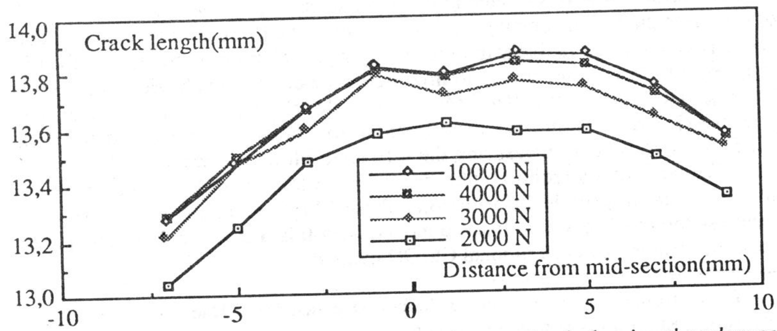

Fig. 1 Crack tip profile before application of an overload, showing the advance of the crack profile, i.e. the diminution of the closure, with increasing load.

As shown in Fig.1, before overloading we could observe an advance of crack profile as a function of the load due to crack opening, however after overloading the crack profiles remained unchanged even with increasing the load (Fig. 2).

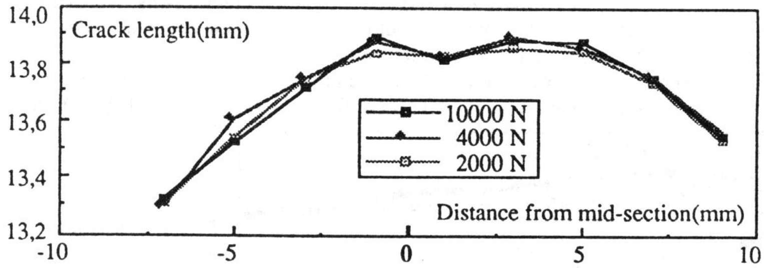

Fig. 2 Crack tip profile after 200% overloading, which demonstrates the absence of crack closure.

We could also observe an absence of crack front advance under increasing load after overloading in the three load cases, this means no crack closure. Overloading gave rise to suppression of crack closure. In case of 125% overloading crack closure was not detected even before overloading because the crack already opened at the minimum cyclic load 1200N. Our measurements of crack profiles cover about 70% of the specimen thickness, thus the suppression of crack closure is related to the part governed by plane strain. These results confirm those of Ray et al (5), obtained with a transparent material, polycarbonate. They observed suppression of closure on about 60% of the specimen thickness just after overloading.

On the blunting of the crack tip at the mid-section of specimens by overloading

During application of an overload we made the following data acquisitions : load, crack mouth opening, and ultrasonic amplitude diffracted by the crack tip with the transducer fixed where the beam axis crosses through the crack tip. The last one allows to consider the crack tip behaviour during fatigue cycling. Fig. 3 demonstrates the variation of the ultrasonic amplitude as a function of the load, which was obtained in a stainless steel specimen in case of constant amplitude fatigue cycling. During normal fatigue cycling the ultrasonic response of the crack tip is reversible, as long as the crack growth is negligible as compared to the ultrasonic wave length.

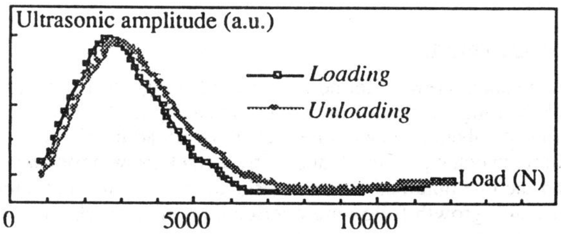

Fig. 3 Ultrasonic amplitude as a function of load during fatigue cycling for 316L stainless steel specimen

However in case of an overload the ultrasonic response is completely different from this one. Fig. 4 shows the ultrasonic amplitude as a function of the load in case of a 200% overload. In this figure the ultrasonic amplitude increases very rapidly to a maximum and decreases slowly to a stage at which the crack opens. An extra load blunts the crack tip in such a way that the ultrasonic amplitude decreases. The plastic deformation of the crack tip leads to an irreversible movement of the crack tip which remains opened even after unloading. Thus the ultrasonic response during unloading is no longer the same than on loading. This confirms the observation of Ray et al(5).

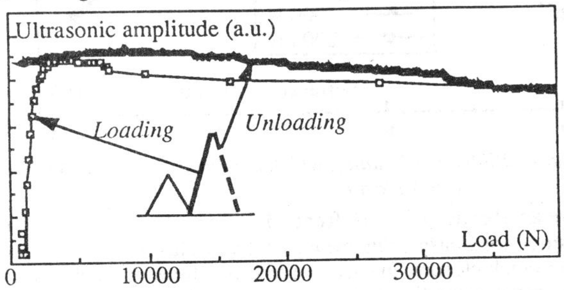

Fig. 4 Ultrasonic amplitude as a function of load during a 200% overload cycle for A533B specimen.

What happens if a crack is under sucessive cyclic overloading? In order to answer this question we took the data for the same parameters during the second overload cycle. Fig. 5 shows the result in case of successives 150% overloads. In the previous figure we have seen that when the first overload cycle was applied the ultrasonic response was no longer reversible, however in second overload cycle this irreversibility disappears, i.e. the crack tip movement with respect to ultrasonic wave becomes symetric. The interpretation is that the effect of the first overload on the crack tip is much more important than the effect of second overload.

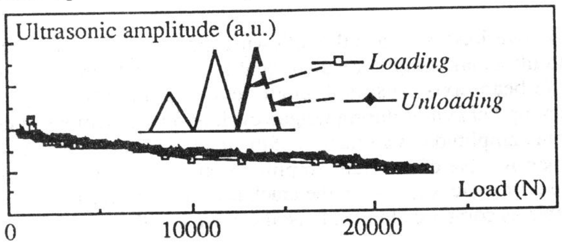

Fig. 5 Variation of the ultrasonic amplitude as a function of load during the second of two 150% overload cycles for A533B specimen.

On the crack growth following an overload

After a 200% overload the crack grew under normal cyclic loading for 1 mm, and the echodynamics were taken along the crack front under increasing load. This crack front is superimposed on the one obtained just before a 200% overload in Fig. 6.

At the same load (5000N) the crack profile advance after a crack growth following an overload is greater than the one obtained before overloading. It means a greater crack closure length after crack growth following overloading,. The crack closure length is as long at the mid-section as near the surface of the specimen.

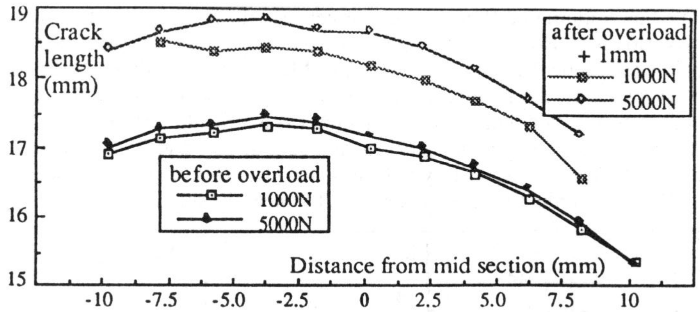

Fig.6 : Crack profile change before overloading and after a 1mm crack growth following 200% overloading

If we compare the crack closure lengths obtained at the mid-section of the specimen in these two cases, we deduce that the crack closure measured after crack growth following an overload increases from 0.2mm to 0.55mm and that the crack opening load goes up from 2800N to 3800N(Fig.7), which confirms the results obtained by numerous researchers (6,7).

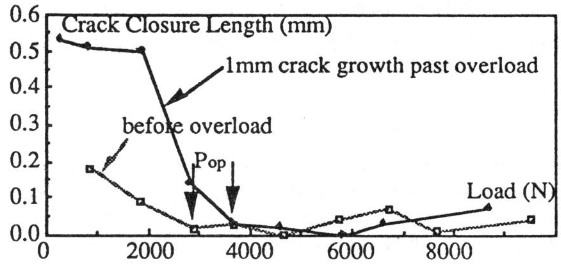

Fig. 7 Crack closure length at the mid-section of specimen measured before overloading and after 1mm crack growth following overloading

<u>Comparison between the results of CMOD and those of ultrasonic measurements</u>

The measurement of CMOD was also carried out at every step to compare its results with those of MU3F. The results of P-δ' were treated numerically in three cases : before and during a 150% overload, after a 1mm crack growth following overloading. The crack opening load P_{op} decreases after overloading from 5500N to 2800N and increases again up to 3600N after crack growth. It has same trend than the results of MU3F except for the level of crack opening loads. Considering the crack profile change of the previous results, we have P_{op} = 4000N before overload, 1500N just after overload, and 4000N after crack growth.

The results obtained by the two methods (CMOD and MU3F) for the three overload cases (125%, 150% and 200%) were compared in Fig. 8, in which we can see that in two cases, 125% and 200%, K_{op} drops to a large extend and after crack propagation it increases up to or above its original value. In case of an 150% overload, the results of MU3F display the same tendency. However the K_{op} measured by CMOD before overloading is believed to be too high as compared with the other results.

Note that important differences appear between the results of the two methods just after overloading. Results of CMOD show that K_{op}, just after overloading, are not negligible (about 6MPa$\sqrt{m}$) while those of MU3F are only about 2MPa$\sqrt{m}$. After crack propagation the results of both methods become similar in the three cases. According to the calculation of Chermahini (8) overloading results in a decreasing crack opening load P_{op} about 20% for the central part and 25% near the surface, whereas the experiments of Ray (5) show that the crack closure disappears for the internal part and reduction of P_{op} of about 20% near the surface.

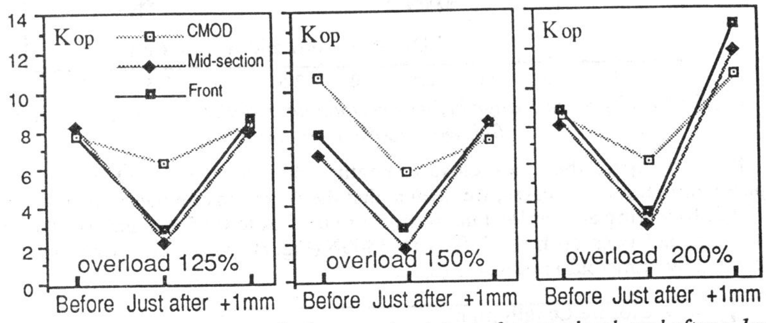

Fig. 8 : Comparison of Kop : before overload, just after overload, and after a 1mm propagation past overload

DISCUSSION

The measurement of the crack length at the mid-section of the specimen allows to examine the crack tip response affected by overloading. The measurement of crack growth at the mid-section of specimens could be carried out every several hundreds of cycles at a 20Hz fatigue frequency , which corresponds to a crack growth less than 10μm in case of da/dN=10^{-8}m/cycle. But at the surface the optical measurement obliged us to interrupt fatigue cycling at every 0.3~0.4mm of crack growth. That is the reason why in the following Figures we could not gather enough surface data points as compared with those obtained at the mid-section of specimen. In Fig.9 to12 crack lengths are measured from the application of the overload, at the surface and at the mid-section. As shown in figures 9 and 10, the crack growth behaviors after overloading are not similar in the plane stress and the plane strain regions. At the surface the crack tends to grow continuously longer about for 0.3~0.4mm after overloading with a little faster velocity whereas in the plane strain region its speed drops immediately. These differences are enhanced as we represent the growth rates as a function of crack length in Figures 11 and 12.

After overloading the crack growth rate is accelerated at first at the surface whereas it drops immediately to a minimum value at the mid-section of the specimen. This is in a good agreement with the results obtained by Robin (6), McEvily (9), and Fleck (10), whereas the results of Ray (5) tend to show a different behavior ; immediate acceleration and deceleration at the mid-section and immediate deceleration at the surface. This is probably due to the different characteristics of materials.

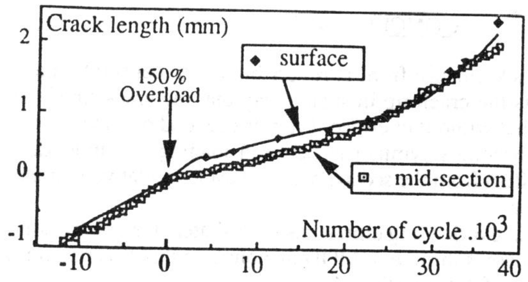

Fig. 9 Crack length as a function of the number of cycles (150% overload)

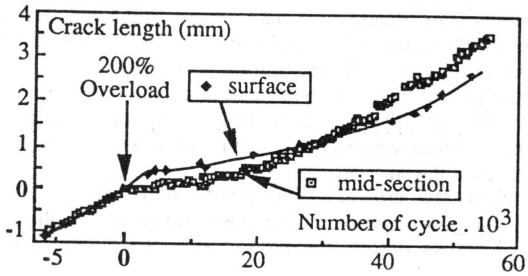

Fig. 10 Crack length as a function of the number of cycles (200% overload)

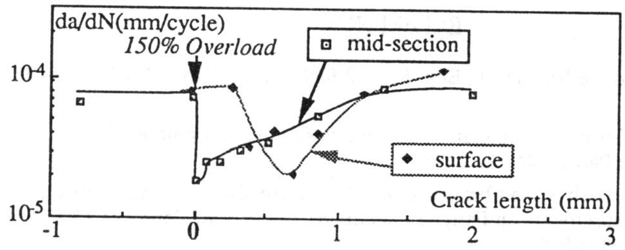

Fig. 11 Crack growth rate (150% overload)

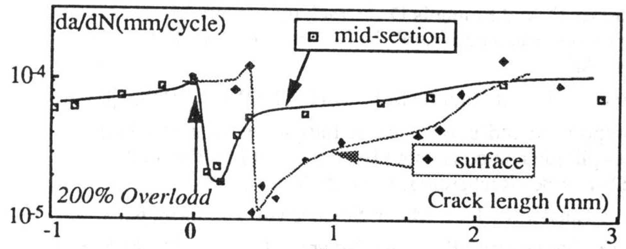

Fig. 12 Crack growth rate (200% overload)

If ΔK_{eff} could explain crack growth rate in the cases of constant and variable amplitudes, disappearance of the crack closure after overloading should produce a higher growth rate da/dN, and not a reduction of the rate. This leads to conclude that da/dN under variable amplitude should not be explained with ΔK_{eff} only.

CONCLUSION

- The movement of the crack closure front is reversible under constant amplitude cycle. An overload blunts the crack tip in such a way that the crack tip behavior becomes different from that without overload. From the second overload cycle on, the ultrasonic response becomes symmetric between loading and unloading. It means that the overload effect from the second overload cycle is relatively limited as compared with the first one.
- Results of MU3F show that overloading eliminates immediately the crack closure in the plane strain region whereas those of CMOD demonstrate that K_{op} remains at a value larger than K_{min} of the fatigue cycle.
- After crack propagation following overloading the crack closure length and the crack opening load increase. The crack surfaces plastically deformed by great overloads remain in contact at low load even after crack growths of several mm.
- Overload produces different growth rates between the plane stress and the plane strain regions. Crack growth rate da/dN tends to be immediately lowered by overload in the plane strain region whereas it is increased over a short range (~0.3mm) and finaly decreases at the surface.
- ΔK_{eff} is not sufficient to explain crack growth rate in case of variable amplitude.
- Ultrasonic investigation is a good tool to assess the validity of the theories describing the behavior of cracks before, during and after the application of overloads.

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