Fatigue Failure Analysis by X-ray Fractography

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ABSTRACT

The plastic zone sizes of fatigue cracks are measured from in-depth distribution of residual stresses and X-ray diffraction peak broadening. Relationship established between diffraction peak broadening and plastic strain has allowed the analysis of plastic strain at the crack tip.

KEYWORDS

Fatigue crack, plastic zone size, X-ray fractography, residual stress, plastic strain.

INTRODUCTION

Early measurements by X-Ray Fractography performed by Tanaka and Hatanaka (1982) Kurebayashi et al. (1982), Lebrun et al. (1983, 1986) illustrate the interest of the X-Ray Fractography. The local plastic deformation, that occurs at a fatigue crack tip, leaves residual stresses and deformations on the fracture surface. The study of the material deformation and work hardening through the displacement and broadening of X-Ray diffraction peaks, gives useful information on the fatigue process. In-depth measurements allow the determination of fatigue crack plastic zone. In the present study, X-Ray Fractography has been used to investigate fatigue crack plastic zone in the case of a fatigue softening steel. A physical interpretation of the peak breath evolution is also undertaken.

MATERIAL AND EXPERIMENTAL PROCEDURE

Material

The present investigation has been carried out on a chromium alloyed steel (80C4): 0,8% C, 1% Cr, 0,7% Ni. The mechanical properties of this steel are: σ_{ys} = 860 MPa, UTS = 1 200 MPa, elongation = 14%, cyclic yield strength σ'_{ys} = 660 MPa.

Mechanical tests

Interrupted tensile tests were carried out for specimens deformed at different plastic strain levels.

Low cycle fatigue tests have been performed on servohydraulic testing machines operating under constant amplitude strain control.

For the crack propagation tests, CT and SEN specimens have been used under constant amplitude load control. Three R ratio (R = Pmin/Pmax), room moist air and vacuum environment have been chosen for the experiments.

X-Ray Fractography technique

These experiments are mainly based on residual stress measurements by X-Ray diffraction. The technique is well known and has recently been improved both on theoretical and technological points of views (Maeder et al., 1981).

With the experimental conditions used (Cf. Lebrun et al., 1986), the scatter for the stress is about ± 25 MPa.

Local electrochemical polishing has been used to remove thin layers of material, the depth is controlled with a micrometer.

The work hardening of the material was controlled through the simple breadth of the (211) diffraction peak. As shown in the results, it is a very sensitive parameter with high accuracy ± 0.03 (°).

RESULTS AND DISCUSSION

Relationship between plastic strain and X-Ray diffraction peak broadening

Monotonic and cyclic behaviour of the material is shown on the stress versus strain curve Fig. 1. It points out the fatigue softening of this steel. The values of peak breadth corresponding to the range of monotonic and cyclic plastic strain investigated are drawn in Fig. 2. These results show that for a given plastic strain amplitude larger peak breadths are encountered for monotonic loading than for cyclic one's.

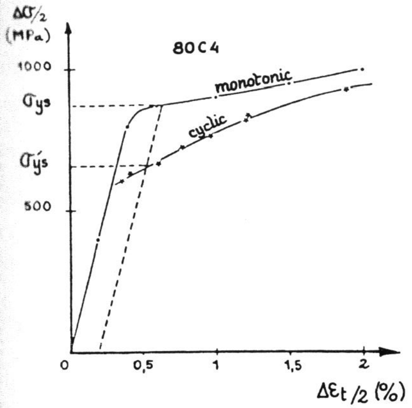

Fig. 1. Monotonic and cyclic stress and strain behaviour of the 80C4 steel

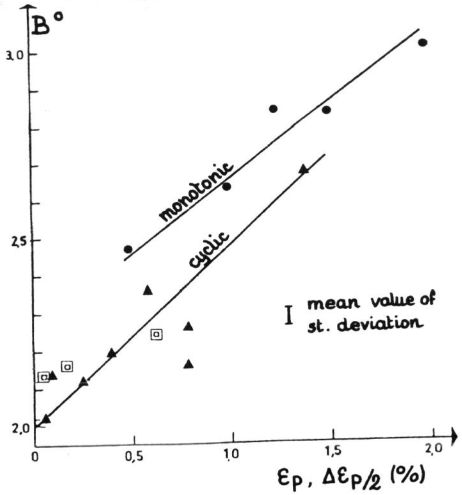

Fig. 2. Relationship between the peak breadth B on the plastic strain

Using transmission electronic microscopy, we have verified that the evolution of peak breadth qualitatively corresponds to the evolution of dislocation density. The difference in peak breadth broadening between monotonic and cyclic loading reflects the fatigue softening of the material observed in low cycle fatigue.

Residual stresses and cold working

X-Ray diffraction measurements on the cracked surface give longitudinal (direction of crack growth) and transversal stresses (σ_L and σ_T) and peak breadth (B). The values of σ_L are always greater than σ_T values. Experimental data are given in Fig. 3, 4, 5 and 6.

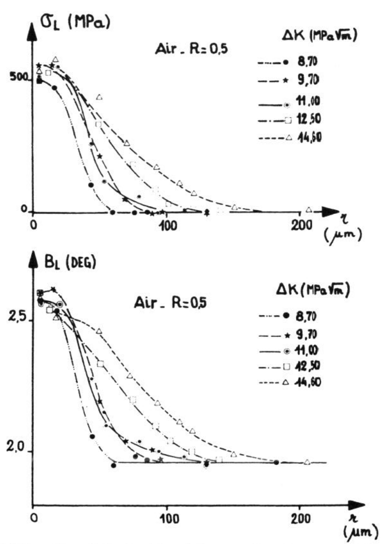

Fig. 3. Distribution of the residual stresses and peak breadths below the surface for test at R = 0.5 in air

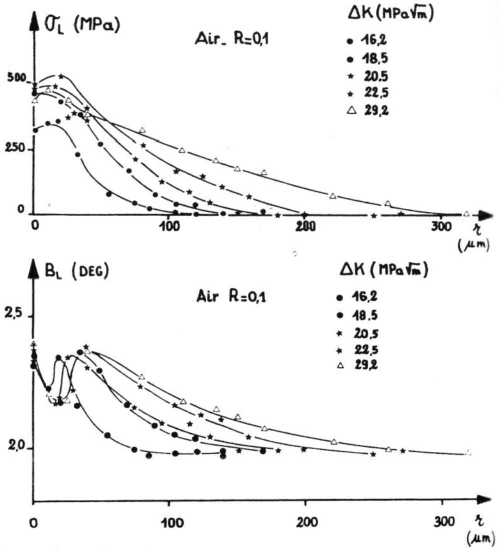

Fig. 4. Distribution of the residual stresses and peak breadths below the surface for at R = 0.1 in air

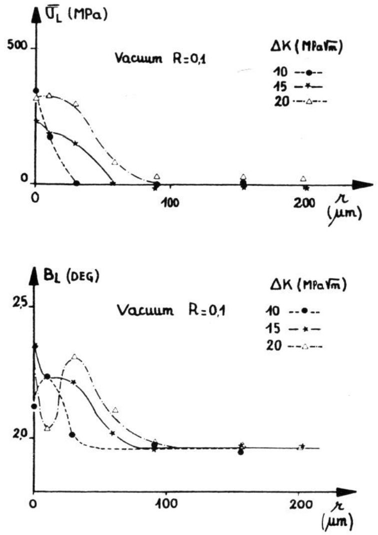

Fig. 5. Distribution of the residual stresses and peak breadths below the surface for test at R = 0.1 in vacuum

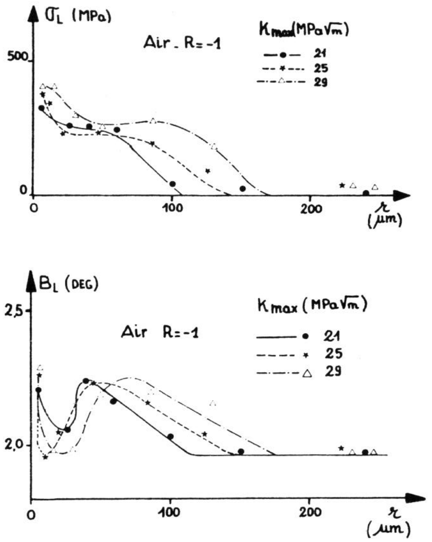

Fig. 6. Distribution of the residual stresses and peak breadths below the surface for test at R = - 1 in air

These results are in good agreement with Lebrun et al. (1983), who have found that residual stresses distribution was inversely proportional to the square root of the depth ($\sigma_r = a\sqrt{r} + b$) except for the zone close to the surface.

Three shapes of peak breadth distribution are usually encountered:

- peak breadth decreases continuously in depth to the nominal value, Fig. 3,
- peak breadth increases below the surface towards a maximum value then decreases to the nominal value, for example Fig. 5 (lower ΔK),
- peak breadth decreases below the surface, then increases and decreases again to the nominal value, for example Fig. 4, Fig. 5 (higher ΔK) and Fig. 6.

A schematic of its behaviour is given in Fig. 7.

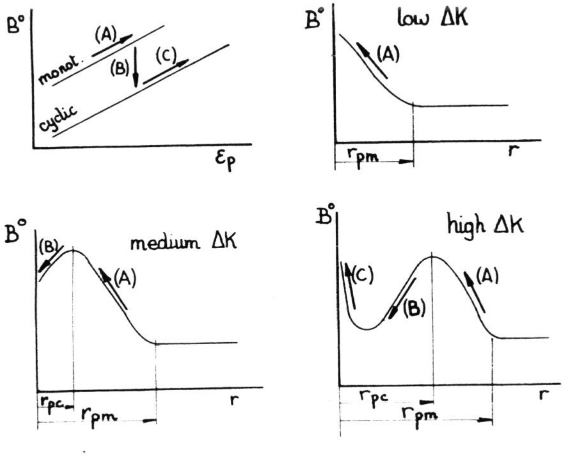

Fig. 7. Schematic representation of peak breadth evolution in depth for different levels of ΔK

These different types of behaviour can be interpreted through the fatigue softening of the material, Fig. 1 and 2, and the different plastic strain level around the crack tip which depends on the stress intensity range ΔK:

- at low ΔK the cyclic plastic strains are too small to induce a softening of the material in the wake of the crack. In such a case the increase in peak breadth toward the cracked surface is due essentially to the monotonic plastic strain, (A) in Fig. 7,
- with a higher ΔK the cyclic plastic zone sizes and cyclic plastic strain increase therefore, fatigue softening at the crack tip becomes more important, (B) in Fig. 7.

This softening occurs in the zone subjected to cyclic deformations, the size of which can therefore be defined by the maximum value of peak breadth below the fatigue cracked surface.

- for the larger ΔK the increase in peak breadth close to the cracked surface corresponds to the larger cyclic cold work at the very crack tip reflecting the very sharp gradient of plastic strain amplitude, (C) in Fig. 7.

Plastic zone size determination

From the in-depth distribution of residual stresses and peak breadths, the limit of the monotonic plastic zone corresponds to the depth where zero stress or the nominal values of B are reached. Moreover, the depth at which the maximum of peak breadth is reached would correspond to the cyclic plastic zone size (Lebrun et al. 1983, 1986) as shown in Fig. 7.

Monotonic plastic zone size. As illustrated in Fig. 8 measurements of r_{pm} from residual stresses or peak breadth value can be expressed by

$r_{pm} = \alpha (Kmax/\sigma_{ys})^2$ with $\alpha = 0.20$.

Cyclic plastic zone size. The process of fatigue crack growth involves a notion of cyclic plastic zone size (r_{pc}) induced during the unloading of the bulk material and which is usually described at $r_{pc} = \alpha(\Delta K/2\sigma'_{ys})^2$. This zone is plastically deformed in tension and in compression at each cycle, and the measurements of r_{pc} are shown in Fig. 9. The value α is again 0.20.

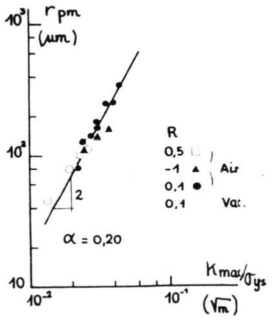

Fig. 8. Relationship between the monotonic plastic zone size and $Kmax/\sigma_{ys}$

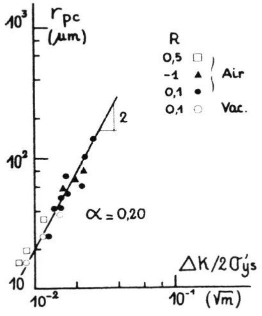

Fig. 9. Relationship between the cyclic plastic zone size and $\Delta K/2\sigma'_{ys}$

CONCLUSIONS

X-Ray Fractography was applied to the fatigue fracture surfaces of steel specimens. Tests were carried out with different stress ratio (- 1, 0.1, 0.5) and environments (moist air, vacuum).

The measurements carried out on fracture surface show tensile residual stresses and variable diffraction peak broadening. There is no clear relation between the surface residual stresses, the surface peak breadth and the ΔK value.

A transmission electronic microscope analysis points out the significance of the peak breadth, B, as a measure of cold working of the material. Subsequently, comprehensive understanding of the different shapes of peak breadth (or cold working) distribution, below the fracture surface, is made as fonction of ΔK level.

Experimental data below the fracture surface allow to determine monotonic, r_{pm}, and cyclic, r_{pc}, plastic zone sizes. The measurements of r_{pm} and r_{pc} can be expressed, respectively, by $r_{pm} = \alpha(Kmax/\sigma_{ys})^2$ and $r_{pc} = \alpha(\Delta K/2\sigma'_{ys})^2$ with $\alpha = 0.20$. It was shown that plastic zone sizes are independent of R ratio and environment (moist air, vacuum).

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