ANALYSIS OF THE PLASTIC ZONE AT THE FRONT OF A FATIGUE CRACK BY X-RAY FRACTOGRAPHY

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The in-depth distribution of the residual stresses and X-Ray diffraction peak broadening are used for measuring the cyclic and monotonic plastic zone sizes. The calibration of the peak-breadth with the monotonic plastic strain gives usefull informations for the analysis.

The X ray fractography is a new method of investigation for the plastic strain at the crack tip Tanaka and Akiniwa (1), Lebrun et al (2) (3), Bignonnet et al (4) have studied the in-depth distribution of residual stresses and peak-breadths. Their evolutions depend on the monotonic and cyclic behaviours. These types of results allow the determination of the cyclic and monotonic plastic zone sizes. We have carried out these measurements on the same quenched steel, tempered for three different levels of ultimate tensile strength. The experimental plastic zone sizes are compared with the analytical solutions. The calibration of the peak breadth against the monotonic plastic strains gives some information about the analysis of the peak breadth evolution and about the plastic process close to the crack tip.

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EXPERIMENTAL PROCEDURE

Materials. The 35CD4 steel studied has been quenched and tempered for three levels of ultimate tensile strength. The chemical composition is : 0.36 % C, 0.98 % Cr, 0.19 % Mo, 0.66 Mn, 0.42 Si, 0.008 % P, 0.008 % S. The three steels have been quenched into a salt bath at 175°C after heating at 850°C for 30 mn, and then tempered for half an hour. The specimens 880, 1150 and 1700 are respectively tempered at 685°C, 550°C and 390°C.

TABLE I : Mechanical properties of the steels investigated.

UTS MPa	σ_{ys} MPa monotonic	$\sigma_{y's}$ MPa cyclic	A%
880	830	455	20
1150	1060	630	14
1700	1450		11

Mechanical tests. Three mechanical tests have been performed :

- crack propagation tests have been realised wich CT40 specimens under constant amplitude load control and a R ratio (Pmin/Pmax) = 0,1. The crack closure was measured at a low frequency with captor in front of the crack.
- low cycle fatigue tests have been performed under constant amplitude strain control.
- tensile tests have been interrupted at different plastic strain levels.

Conditions of X - Ray fractography. These experiments are mainly based on residual stress measurements by X ray diffraction. This technique improved by Maeder et al (5) leads to the knowledge of the half value breadth of the (211) diffraction peak. The main caracteristics of the experiments are a radiation K_αCr 0.229 nm (30 KV, 10mA), a number of angles equals 6, a irradiated area equals 2 x 8 mm^2, a scintillation counter. The tolerance interval on the residual stress measurements is 50 MPa and the standard deviation of the half value breadth is 0,09°.

Electrochemical polishing has been used to remove thin layers of material, the depth has been measured with a micrometer.

FATIGUE TESTS RESULTS

TABLE 2 - Coefficients of the Paris's law

UTS MPa	C mm/cycle	m	C'mm/cycle	m'
880	6.6E-10	3,47	1.03E-7	1.858
1150	8.7E-9	2.73	2.29E-8	2.516
1700	4.87E-8	2		

The fatigue crack propagation behaviour of materials was quite conventionnal. The values c' and m' have been calculated with the effective K determined by the analysis of the crack closure effect. This effect can be seen on the low and medium strength specimens but cannot on the high strength one.

DIFFRACTION RESULTS

Residual stresses : The longitudinal residual stresses σ_L, more important than the transversal ones, are measured in the direction of the crack growth.

Figure 1 shows their distribution on the fracture surface against Kmax, with a maximum value of the residual stress for the low and high strength materials. Kodoma et al (6), Ogura et al (7) observed the same evolution with a Kmax value corresponding to the residual stress maximum that increases with the brittleness of the material. Our results are not in accordance with these observations because our highest Kmax value, superior to 40 MPa $\sqrt{m}$, corresponds to the medium strength steel.

The in depth distribution of residual stresses (figures 2,3,4) shows a decrease below the fracture surface proportional to the square root of the depth ($\sigma_L = a\sqrt{r} + b$) except for the zone close to the surface.

Peak-breadth distribution : On the fracture surface we cannot observe any relation between the peak breadth and Kmax (figure 1).

The in depth distributions of B for the low and medium strength material and for various K values (figures 2,3) are in good agreement with the results of Bignonnet et al (4) (figure 5). In zone A, the peak-breadth increases with the monotonic cold work. In zone B, the peak-breadth decreases with the softening induced by the cyclic plastic strain. In zone C, the peak-breadth increases near the crack tip with the cyclic cold work. The depths for which the peak-breadth reaches its nominal (B_0 on the figures) and maximal values determine respectively the monotonic (r_{pm}) and cyclic (r_{pc}) plastic zone sizes. We use this definition to determine the monotonic plastic strain size of the high strength material. The results are compared in terms of α with the analytical solutions in plane strain. The theoretical value of α equals 0,159.

$$r_{pm} = (Kmax/\sigma ys)^2 \qquad (1)$$

$$r_{pc} = (\Delta K/\sigma y's)^2. \qquad (2)$$

TABLE 3 - Value of for each steel.

UTS MPa	880	1150	1700
α monotonic α cyclic	0,1 0,08	0,135 0,105	0,188

Though the measured values of α monotonic and cyclic are different, they will both increase as UTS increases According to Tanaka and Akiniwa (1), the increase of α is due to the differences in cold work.

The peak-breadth distribution of the high strength material is noticeable (figure 4) ; B increases from the fracture surface to the nominal value. This evolution, observed on other high strength steels by Tanaka and Akiniwa (1) can be accounted for by the restauration of the quenching defect thanks to the internal movement during the strains near the crack type.

The peak-breadth against the monotonic plastic strain (figure 6) shows two types of behaviour. On the one hand, the increase of B with the plastic strain increase, corresponds to the low and medium strength steels and is in keeping with the in-depth peak-breadth distribution (figures 2,3). On the other hand, no evolution of B, is to be seen for the high strength material. On the latter, we drow on figure 4 the cyclic plastic strain sizes calculated (r_{pc}) with the relation (2) in which α equals 0,16 and σ y's is estimated to 1062 MPa. The difference between the cyclic plastic zone limit and the nominal value of the peak-breadth may be important (ΔB = 0,55° and Δr = 254 m for ΔK = 57 MPa$\sqrt{m}$) and can not be explain by the monotonic plastic strain.

At this point, various hypotheses can be formulated :

- a restitution of strain energy for the restoration of the material,
- a difference in scale between the monotonic plastic strains below the fracture surface and the experimentally measured ones on the tensile specimens,
- a uniaxial mode for the tensile specimens that differs from the mode of strain near the crack tip.

CONCLUSIONS

X Ray fractography was applied to the fracture surfaces of laboratory specimens. Three levels of strength material were tested with the same quenched steel tempered at three various temperatures.

The residual stresses on the fracture surface vary with Kmax and exhibit a maximum value. The corresponding value of Kmax does not evolve the same time as the ultimate tensile strength.

Measurements below the fracture surface do express the evolution of the cyclic and monotonic behaviours. The comparison of the measured plastic zone sizes with the analytical solutions give different values of α monotonic and α cyclic ; they will both increase as UTS increases.

The particular evolution of the in-depth peak-breadth, continues increase, for the high strength material cannot be explained either by the calibration curve of B with the monotonic plastic strain or by the cyclic softening.

REFERENCES

(1) Tanaka K. and Akiniwa Y., J.S.M.S. Vol. 31, 1988, p 76-87

(2) Lebrun J.L., Guimard B., Bignonnet A. - Eigenspannungen, Ed. E.Macheraud und V. Hank, 235. Publ. DGM, Oberursel RFA 1983.

(3) Lebrun J.L., Barral M., Bignonnet A., Maillard-Salin C., Nhari A. - Proc. of ICRS, 1986. Residual Stresses in Science and Technology, Ed. E.Macheraud and V. Hank, pp. 109-116. Publ. DGM, Oberursel RFA 1987.

(4) Bigonnet A., Dias A., Lebrun J.L., ICF7, Huston 1989, p. 3457-3463.

(5) Maeder G., Lebrun J.L., Sprauel J.M. - N.D.T. International 1981, 235.

(6) Kurebayashi Y., Kodama S., Misawa H., J.S.M.S., Vol. 31, 1982, p 221.

(7) Ogura K., Miyoshi Y., Kayama M. - Eng. Fract. Mech. 1985, 22, 1, 123.

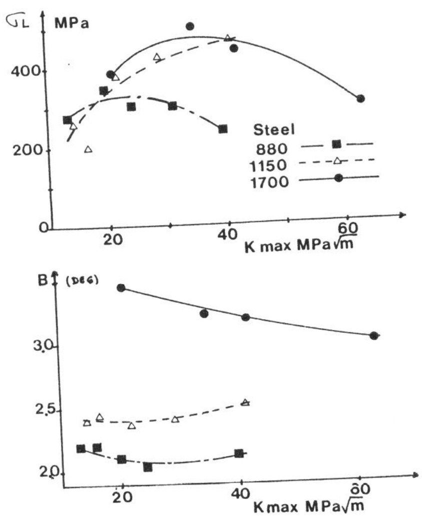

Fig.1 : Fracture surface residual stresses and peak breadths for the three steels.

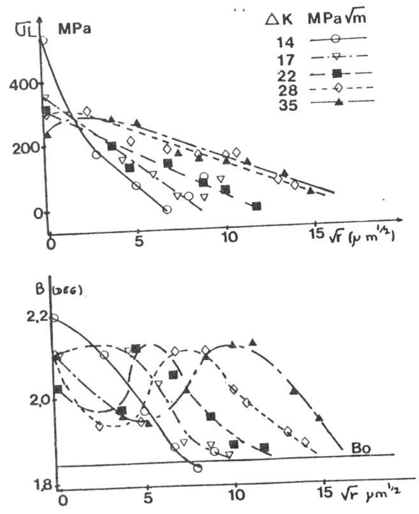

Fig.2 : Distribution of the residual stresses and peak breadths below the fracture surface for the 880 steels.

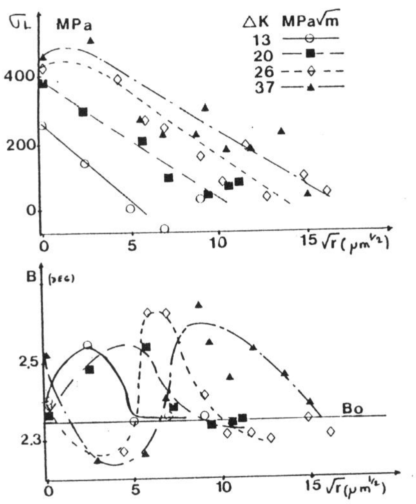

Fig.3 : Distribution of the residual stresses and peak breadths below the fracture surface for the 1150 steels.

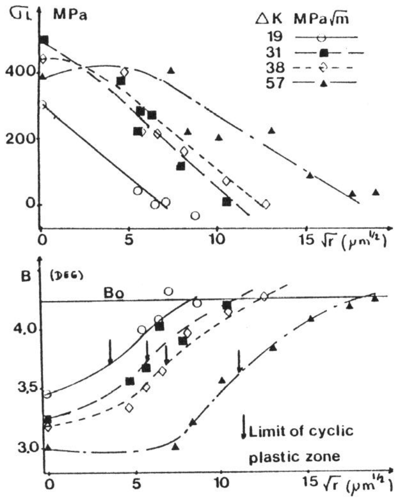

Fig.4 : Distribution of the residual stresses and peak breadths below the fracture surface for the 1700 steels.

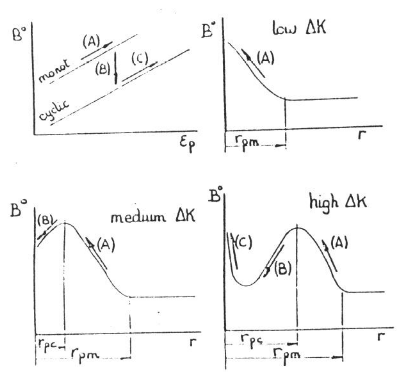

Fig.5 : Schematic representation of peak breadth evolution. Bignonnet et al (4).

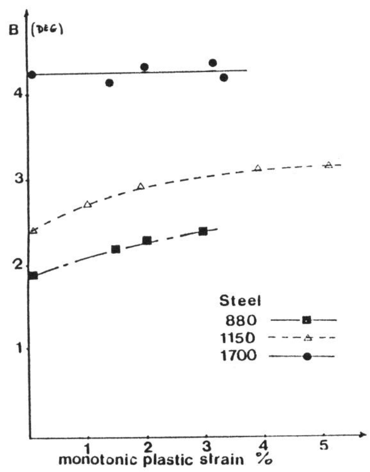

Fig.6 : Peak breadth evolution against monotonic plastic strain.