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HIGH FREQUENCY FATIGUE OF METALS, CRACK INITIATION AND PROPAGATION

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INTRODUCTION

The ultrasonic fatigue testing method has been in use for several years [1]. It has been shown that similar effects to low frequency tests result, if a metal is subjected to ultrasonic vibrations. For instance similar dislocation arrangements have been found [2 - 5]. Also the SN-curves are similar at high and low testing frequencies [4]. So it becomes possible to save much experimental time by applying the ultrasonic method. Since 1973 we have undertaken experiments concerning crack initiation and propagation under ultrasonic stress and thus the purpose of this paper is to present details of our work in this area since ICF3.

EXPERIMENTAL PROCEDURE

An ultrasonic resonance system was used by means of which the sample is push-pull stressed with the mean stress equal to zero. The peak stress and strain level are proportional to the displacement amplitude, which is measured with an electrodynamic converter. The length of the samples is $\lambda/2$ (λ = ultrasonic wavelength in metal) or the samples are dumb-bell shaped. The ultrasonic amplitude is stabilized by a control system and interrupted at preselected intervals in order to prevent any undesirable temperature rise in the sample, caused by internal friction. The stress is calculated from the measured amplitude by Hooke's law.

HIGH SPEED FILMS OF CRACK INITIATION AND PROPAGATION

With a high speed camera (type Fastax and Millican) the surfaces of the following b.b.c. metals being stressed with ultrasound have been filmed:
a) mild steel (0,04%C, recrystallized, σ_B = 300 MPa)
b) Chromium steel X20Cr13 (0,2%C, 13%Cr, hardened and annealed respectively, σ_B = 700 MPa)
c) technically pure Molybdeium ($\sigma_B \sim$ 900 MPa)

All samples had a cross-section of 10 x 1 mm and were notched in the middle of their length to get an exactly defined starting point for the crack during filming.

The shape of the notches (which is not exactly the same in all cases) does not matter, because there is used the tip of an already formed fatigue crack as starting point for all calculations.

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The sample surfaces were filmed differently enlarged with 150 slides/sec. With a second objective (of the same camera) the oscilloscope screen showing the converters amplitude signal, was filmed synchronously. Thus it is possible to correlate the amplitude to each crack stage.

DEPENDENCE OF CRACK VELOCITY AND STRESS INTENSITY

Each crack length is measured directly from the film slides. The number of cycles corresponding to that crack length is calculated by means of the known film speed and the ultrasonic frequency.

The stress intensity K also can be determined for each stage of crack length, because the amplitude is filmed synchronously to the crack propagation.

The stress intensity is calculated by $K = \sigma\sqrt{a}\, y$ (σ = stress, a = length of notch + crack, $y = f(a/w)$, w = width of the sample). The calculations are done as far as to a ratio a/w of at most 0,6. Sometimes the resonance system gets out of tune before a/w is 0,6. In that case the calculations aré done for shorter crack lengths only.

In Figure 1 there is reproduced the dependence: crack propagation velocity on stress intensity.

The ultrasonic results for mild steel and X20Cr13 steel, tested at temperatures between 90K and 470K in liquid nitrogen, water and oil respectively, are given in the right scatter band. The ratio of K_{min}/K_{max} has been -1, i.e. the mean stress has been equal to zero.

The outlined curve is the result of low frequency testing with 10 Hz in vacuo with R = 0. These tests were carried out by M. O. Speidel with the same X20Cr13 steel.

Comparing those two results shows that the dependence of crack propagation velocity and stress intensity is similar for both frequencies, though the surrounding medium has been different (20 kHz: water, oil, 10 Hz: vacuum). This effect might be explained by the short testing time at the ultrasonic fatigue test, so that there is not enough time for corrosion influence.

But corrosion becomes effective in ultrasonic tests too, when there are used salt baths. The cracks propagate faster, Figure 1 left scatterband. There have been used different salt baths between 290K and 370K.

The influence of temperature is not differentiated in both scatterbands of Figure 1, because the difference is too small; further experiments are necessary.

ELECTRON SCANNING MICROSCOPE RESULTS OF THE FRACTURE SURFACES OF FILMED SAMPLES

By means of high speed filming one comes to know crack velocity and stress intensity for each stage of the crack, i.e. for each crack length. Therefor one is able also to correlate crack velocity and stress intensity to each spot of the fracture surface, looked at with the scanning microscope.

Doing this one can find that e.g. in the case of mild steel, having been ultrasound stressed in the temperature range of 290 - 470K, the formation of the fracture surface strongly depends on stress intensity and crack propagation velocity. E.g. there are formed brittle intergranular cracks only at low stress intensities ($\Delta K < 20\ \mathrm{MPa \cdot m^{1/2}}$), low crack velocities and only being stressed in the temperature range of 290 - 320K. This is shown schematically in Figure 2.

At somewhat higher stress intensities ($\Delta K \sim 28\ \mathrm{MPa \cdot m^{1/2}}$) and crack velocities there are formed striations and microcracks. Further increase of those parameters ($\Delta K > 35\ \mathrm{MPa \cdot m^{1/2}}$) causes more ductile modes of fracture.

When mild steel is stressed by ultrasound in liquid nitrogen (~90K) or in liquid Helium (4K), the whole fracture surface looks similar. Figure 3 shows the transcrystalline brittle fracture of mild steel, stressed in liquid Helium.

PLASTIC DEFORMATION IN FRONT OF THE CRACK TIP

Former investigations [5, 6] based on recrystallisation tests of 20 kHz and 8 Hz fatigued mild steel have shown, that in front of the crack tip there is formed a plastically deformed area, the shape of which looks like a butterfly.

With the method of high speed filming one can observe directly, how this plastic deformation increases with the increase of the crack length.

Figure 4 shows one stage of the plastic deformation on the sample surface of ultrasonic stressed mild steel. This figure has been made with re-emitted (REM) electrons with 5 eV acceleration voltage.

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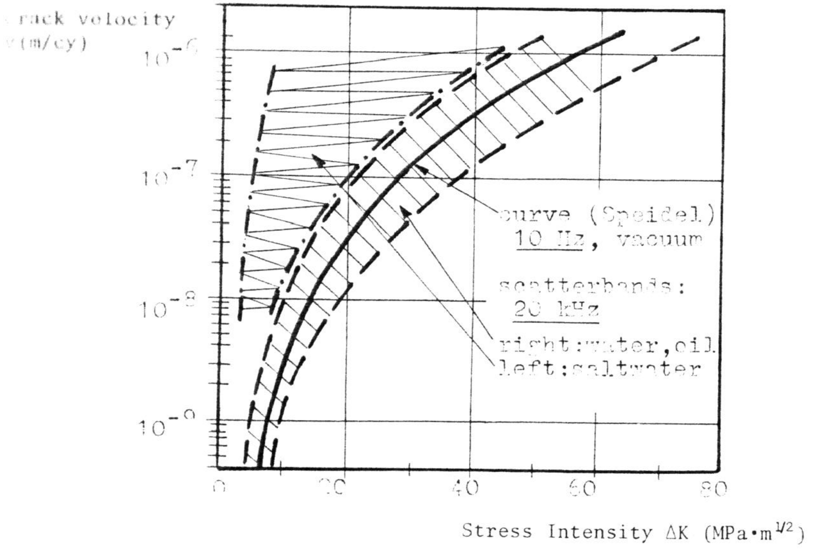
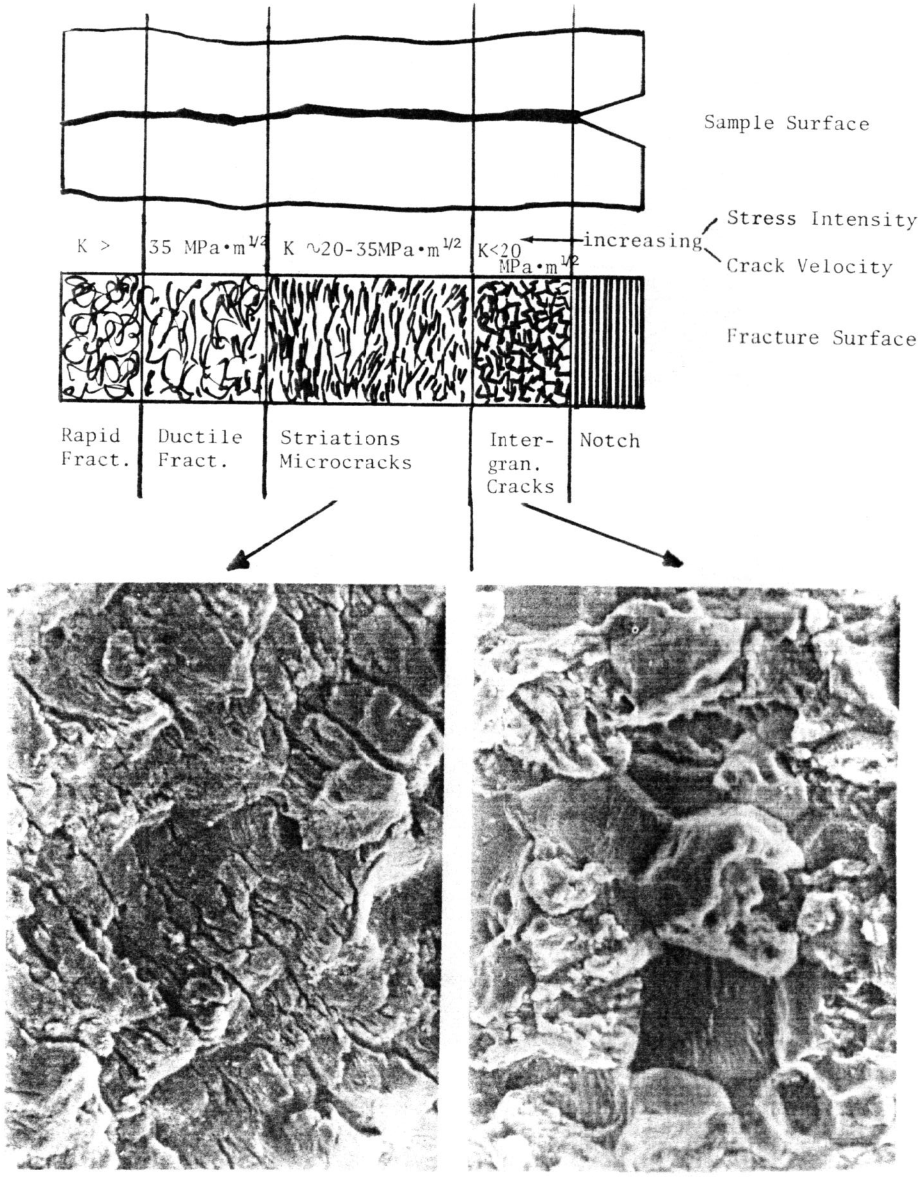


Figure 1 Frequency Influence on the Dependence of Crack Velocity and Stress Intensity. Curve (Speidel): 10 Hz, R = 0, X20Cr13, Vacuum. Scatterbands: 20 kHz, R = -1, X20Cr13, Mild Steel, Right Band: Liquid Nitrogen, Water, Oil, 90 - 470K, Left Band: Salt Water, 290 - 370K



SEM, 600X, Microcracks and Striations

SEM, 1000X, Intergranular Cracks

Figure 2 Influence of Stress Intensity and Crack Velocity on the Fracture Surface of Mild Steel, 20 kHz Fatigued at 320K

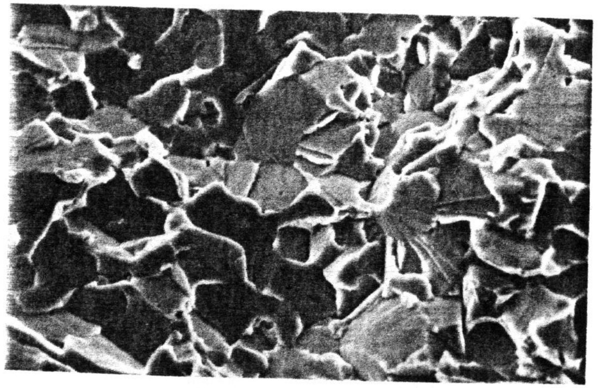


Figure 3 SEM, 750X, 20 kHz Liquid He, Mild Steel

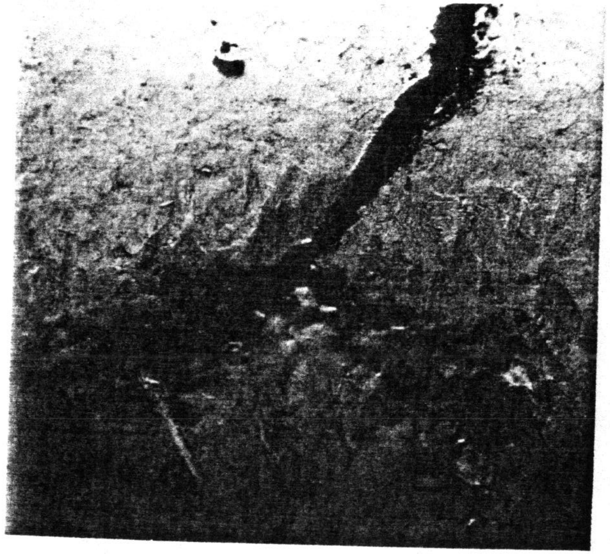


Figure 4 REM, 130X, 5 keV, Mild Steel, 20 kHz, 320K