FATIGUE CRACKS IN A NORMALIZED CARBON STEEL UNDER MULTIAXIAL LOW CYCLE FATIGUE

H. Bomas, M. Lohrmann, G. Löwisch, P. Mayr*

Fatigue behaviour of thin-walled tubular specimens subjected to tension and torsion loading as well as in-phase and out-of-phase combined tension-torsion loading was investigated using the mild steel Ck 15. In addition to lifetime and deformation behaviour the development of microcracks was observed. Cracks occur in the plane of maximum shear-stress amplitude. The lifetime depends strongly on the ratio between crack initiation and crack propagation lifetime.

INTRODUCTION

The investigation of fatigue properties of materials has normally been done by uniaxial tests. On the other hand the most loadings in service are complex and multiaxial. Therefore multiaxial fatigue is a strongly developing research field since the beginning of the eighties. A large number of studies has been devoted to FCC materials, especially to austenitic steels, while ferritic steels have not been investigated so thoroughly. Especially the microscopic events during complex loading, leading to alterations in the lifetime of the specimen, have not been investigated yet. The aim of this investigation is to analyse microscopic mechanisms like crack initiation and formation of dislocation structures and to relate them to the measured deformation behaviour and the lifetime of the specimen.

MATERIAL, SPECIMEN AND LOADING CONDITIONS

The tests were conducted on a servohydraulic test equipment for axial and torsional loads under normal and shear stress control. In order to produce a homogeneous stress distribution thin-walled tubular specimens with 18 mm inside diameter, external diameter of 21 mm and a gauge length of 30 mm were used. The outer surface was turned precisely. The interior surface was honed. Specimens for microcrack observation were additionally mechanically polished.

The material used was the low carbon steel Ck 15 in a normalized condition. The average grain size was 23 μm. Pure tension-compression, pure torsion and combined tension and torsion tests, either in-phase or 90^0 out-of-phase with a loading ratio $\lambda = \tau_a / \sigma_a = 0{,}5$ were carried out .

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* Institut für Werkstofftechnik, Bremen, Germany

DEFORMATION BEHAVIOUR

The measured stresses and strains were plotted in a von Mises coordinate system . The normal stress and strain respectively were plotted at the x-axis. The shear stress and shear strain respectively were plotted at the y-axis as an equivalent value using the von Mises criterion. The equivalent amplitude is given by the radius of the circumscribing circle in this coordinate system. The plastic strains were calculated similarly using the following equations:

$$\epsilon_p = \epsilon - \sigma/E \text{ and } \gamma_p = \gamma - 2\,\tau(1+\nu)/E$$
$$\text{with } E = 204\,000 \text{ N/mm}^2 \text{ and } \nu = 0.5$$

The elastic-plastic behaviour of low carbon steels under uniaxial loading as described by Pilo [1] was also found under torsional and combined in- and out-of-phase loading. During the first cycles of the loading the material behaves elastically. After a number of cycles a rapid softening occurs followed by a region of mainly hardening behaviour. The rapid softening is established in literature by the removal of fixed dislocations from interstitially soluted atoms. The cyclic stress-strain-curve of the material is plotted in figure 1, using the value of the plastic strain amplitude at $N_f/2$. The used equivalent stress respectively strain criterion leads to the same stress-strain curve for the uniaxial, the torsional and the in-phase loading. Under out-of-phase loading a small extraordinary hardening is observed. An out-of-phase hardening in the order of magnitude as found for austenitic steels does not occur.

CRACKS

The arising plastic deformations during fatigue loading lead to crack initiation in the material after a certain number of cycles. The first cracks can already occur in a very early stage of the fatigue lifetime. For that reason the mechanism of the crack initiation and crack propagation are important for the lifetime of a specimen. In order to investigate these mechanism four specimens for each loading variant were documented by photographs with a light microscope on an area of 1 x 4,8 mm^2 after different numbers of cycles. The magnification was 130 : 1. Only cracks with a minimum length of 55 μm between the crack tips were evaluated. The direction of a crack was defined as the favoured growth direction which was determined at the last observation after failure. The crack direction was determined by the angle between the specimen axis and the perpendicular to the favoured growth direction. The length of the crack was defined as the projection on the crack direction.

The crack initation depends strongly on the applied stress amplitude. For low cycle fatigue loadings the cracks initiate during the first part of the lifetime. During the second half of the lifetime mainly crack growth and coalescence take place whereas the crack initation rate decreases. Hardly any difference is to observe between the crack densities for the different loading conditions as figure 2 shows. For high cycle fatigue loadings the crack density increases linearly right from the beginning. Only a few cracks grow together what can be attributed to the lower crack density. The specimens subjected to torsional and the combined in-phase loadings possess a higher crack density than the other specimens.

With increasing number of cycles the crack length spectrum enlarges and moves in the direction of longer cracks. The number of short cracks decreases simultaneously. The crack lengths respond in sections to a Weibull distribution. Deviations are found at longer crack lengths caused by the linking of cracks and at shorter cracks caused by the smallest considered crack length leading to a lack in the basic frequency.

Many of the observed cracks stopped growing during cycling. Crack growth diagrams were established for those cracks, which showed high growing rates. Figure 3 shows one of all the similar arising diagrams. The crack growth rate is observed to decrease with increasing crack length. It represents the behaviour of shear stress controlled microcracks [2,3] which posess shorter crack lengths than the critical length at which the macroscopic crack propagation starts. This is confirmed by the long crack curve of a similiar steel with equal mechanical properties [4] shown in the diagram.

From a shear stress controlled crack growth it is expected that cracks occur in certain planes. The planes with the maximum shear stresses are for tension loading under 45° to the specimen axis, for torsion loading under 0° and 90° to the specimen axis and for the combined in-phase loading with λ = 0,5 under -22,5° and 67,5° to the specimen axis. For the out-of-phase loading with the chosen parameters all planes are exposed to the same shear stress amplitude. A good coincidence was observed between the expected and the found crack directions.

The crack initiation is supposed to occur through irreversible slip processes in activated slip planes. For the arising deviation between the theoretical and actual distribution of crack directions it is to consider that only a limited number of favourably orientated slip planes exists. For that reason the plane of the activated slip system can considerably deviate from the plane containing the maximum shear stress amplitude.

LIFETIME

The lifetime of the different loaded specimens was compared by means of the equivalent stress amplitude which was described earlier. The arising "Wöhler" diagrams for the different loading variants are plotted in figure 4.

In the low cycle fatigue area the selected equivalent stress amplitude describes the lifetime of the specimens well. In the high cycle fatigue area the lifetime is underestimated for torsion and overestimated for the out-of-phase loading. A modification of the equivalent stress amplitude by using the ratio 0.66 between equivalent shear and normal stress amplitude instead of 0.58 leads to a correct lifetime estimation for torsion and in-phase-loading on the base of push-pull-data. The lifetime under out-of-phase loading remains overestimated.

CONCLUSIONS

For multiaxial out-of-phase loading the lifetime of specimens out of normalized Ck 15 is determined by the mechanisms of crack initiation and crack growth.

Due to the rotating principle axis the dislocation density is enhanced and an additional hardening is reached. Resulting from the smaller plastic strain amplitude the crack initiation starts later respectively higher normal- and shear stress amplitudes can be beared than for in-phase loading when the crack initiation rate is the same. Logically this effect becomes smaller when the plastic strain amplitude is small. After the initiation of a number of microcracks the remaining lifetime is determined only by the shear stress controlled growth of these cracks. For that reason the remaining lifetime is determined by the shear stress which occurs in the crack plane.

For high amplitudes the main part of the lifetime is determined by the growth of short cracks. In this case an equivalent stress criterion describing the maximum value of shear stress amplitude fits the lifetime curve well. At low amplitude loadings the process of crack initiation becomes more significant. We suppose that the crack initiation is determined by the integral load onto the material and not only by the load in a critical plane. Therefore the used critical plane criterion does not fit the value in the high cycle fatigue area. Extending this hypothesis to the area of fatigue strength, which was not investigated here, we suppose that the fatigue strength is only determined by the mechanism of crack initiation and is discribed by a pure integral shear stress criterion as shown by Simbürger [5] and Zenner [6].

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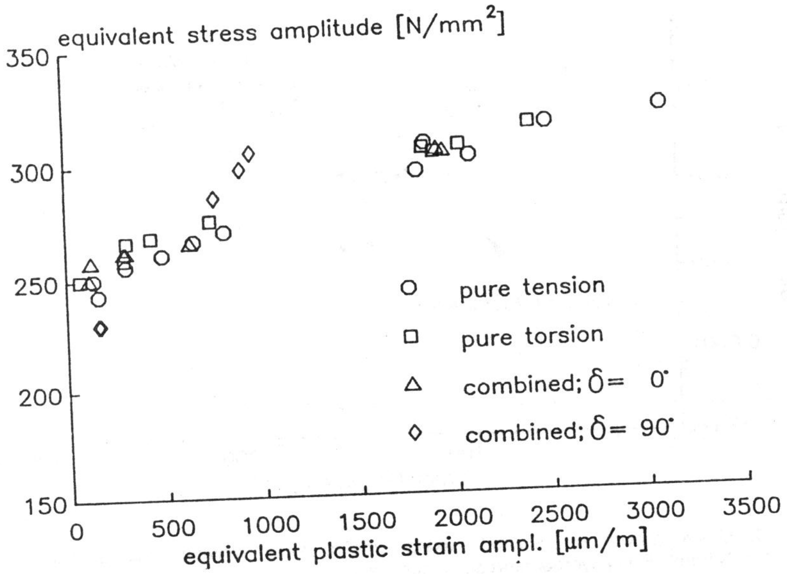
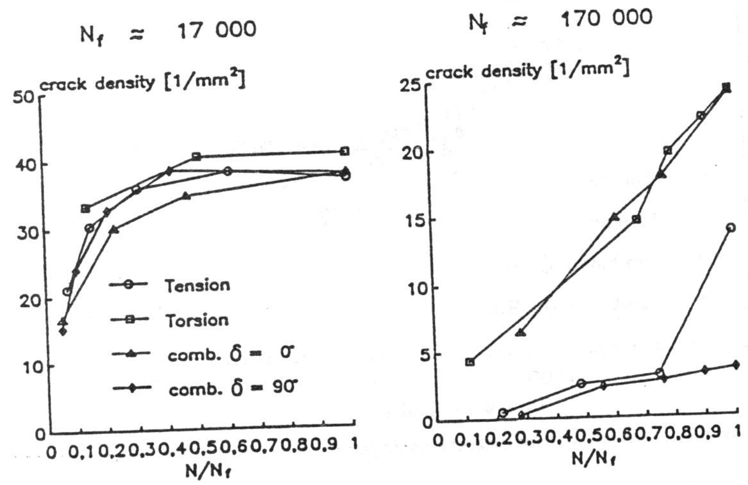


Fig 1: Cyclic stress-strain curve for different loadings


$N_f \approx 17\ 000$

$N_f \approx 170\ 000$

Fig. 2: Crack density during lifetime

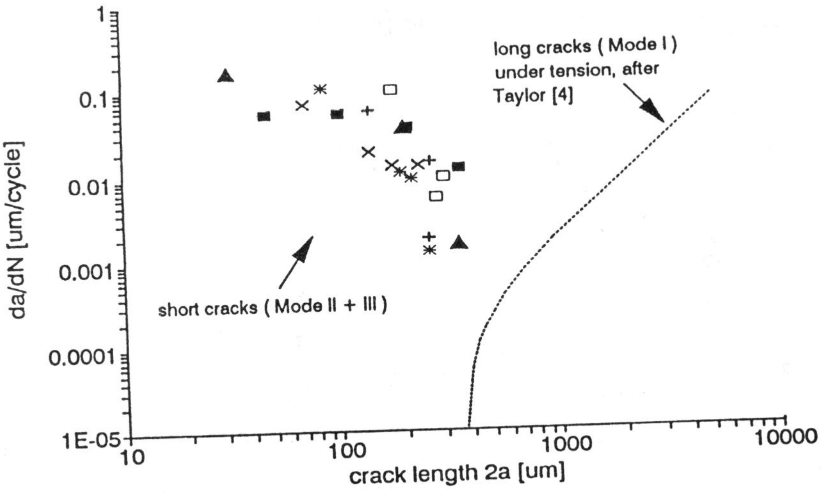


Fig. 3: Crack growth of selected linking cracks under tension loading with σ_a = 300 N/mm². Every symbol represents one crack.

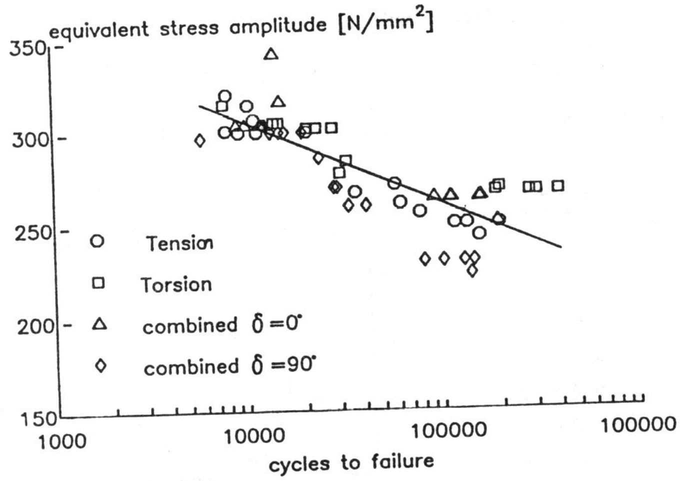


Fig. 4: Wöhler curve of Ck 15 for different loadings