CRACK INITIATION AND CRACK PROPAGATION BY TORSIONAL FATIGUE IN LOW CARBON STEELS

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Crack initiation in unnotched and notched specimens was studied. Depending on cyclic strain, transcrystalline or intercrystalline initiation was found in low carbon ferrite.

Crack formation leads in smooth specimens to an abrupt drop in torque (constant twist angle) whereas in notched specimens cyclic strain hardening can be observed even after crack formation due to large plastification over the entire cross section.

Recrystallization treatments were performed to show the extent of plastic deformation.

INTRODUCTION

In many fields of technology machine members are stressed in torsion, e.g. driving shafts and transmission shafts. Despite that we know hardly anything about the fracture and strain processes, especially if notches or cracks are present in the component. One reason for this lies in the difficult experimental determination of the plastic zone around the crack tip and inside the specimen.

Fig. 1 illustrates the state of stress at a point on the surface of a smooth bar subjected to torsion. The maximum shear stress occurs on two mutually perpendicular planes. A ductile metal fails by shear along one of the planes of maximum shear stress. Generally the plane of the ductile fracture is normal to the longitudinal axis whereas brittle material fails in torsion along a plane perpendicular to the direction of maximum tensile stress. Since this plane bisects the angle between the two planes of maximum shear stress and makes an angle of 45° with the longitudinal and transverse directions,it results in a helical fracture (1).

Previous works concerning torsional fatigue (2-5), predominantly deal with the determination of WOEHLER-diagrams and life-time evaluations (2,6,7).

Another problem which arises with the handling of notched torsion specimens is that in most cases only elastic solutions exist, which are restricted to special specimen geometries (8-11).

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There are only a few papers taking the influence of the microstructure into account (4,5,12,13) and even fewer authors worked on torsional fatigue of iron samples (5) or at monotonic torsional loading (13).

Ritchie et.al. (5) studied in spheroidized AISI 4340 different initiation and growth mechanisms depending on loading conditions. They found that at low shear stresses Mode I initiation and growth of cracks occurs, whereas at higher shear stresses (shear stress greater than 0,85 times the yield shear stress in torsion) combined Mode III + II can be observed.

A powerful aid to show localized plastic deformation seems to be the method of recrystallization of deformed specimens (14, 15). This is one of the few methods which is really applicable to torsional fatigue.

EXPERIMENTAL DETAILS

Fatigue tests were undertaken using a SCHENCK-torsion and bending fatigue testing machine on smooth and notched samples (Fig. 2) of normalized low carbon steels with 0,0014% and 0,02% carbon and a mean grain size of 100 µm and 45 µm, determined by the linear intercept methode. The microstructure of the samples is ferritic with a few precipitated cementite plates at the grain boundaries.

Twist angles from about ± 0,5 to about ± 6 degrees were applied to 35 mm long specimens. Torque-twist hysteresis loops (Fig. 3) were recorded on an XY-recorder.

During the experiments the polished surfaces of smooth and notched specimens were observed using an optical microscope. Notches were introduced to the specimen to localize the strain in a region observable with the installed microscope on the torsion machine. Additionaly this also raises the possibility to study the effects of the notch directly.

After the fatigue loading some of the specimens were recrystallized at 680°C for 5 hours. After this treatment the extent of the plastic zones were studied by sectioning the specimens layer by layer.

RESULTS

It can be argued that crack initiation occurs more easily in more highly deformed material. The crack initiation in a torsion test will therefore be observable at the surface because the stresses and the strains increase with the radius and are highest at the surface. Microscopic stress and strain raisers (inclusions) seem to have no obvious influence on the fracture process at higher strain amplitudes.

The performed twist angles of ± 0,5 ... ± 6° lead to different deformations on smooth and notched specimens which result in various fracture initiation mechanisms and crack growth.

In smooth specimens only cracks are observable at the specimen surface which are orientated parallel or perpendicular to the torque axis (Fig. 4), the directions of maximum shear stresses. Besides these cracks there are almost no signs of deformation. It is supposed that the deformation process is very localized in well spaced out fatigue bands, which similarly to the case of fatigue in tension leads to cracks in nearly all fatigue bands after only a few cycles. One of these perpendicular cracks will be selected and propagates in a transcrystalline fashion until the failure of the specimen occurs.

Cyclic stress strain curves are depicted in Fig. 5. From these curves a distinct cyclic strain hardening behaviour of the ferrite can be seen. A softening process is obviously not detectable at amplitudes over the yield stress. This corresponds to the observations of Mayr and Macherauch (16) in fatigue tests under tension-tension conditions. The reduction in torque coincides approximately with the first cracks observed by the optical microscope.

The introduction of notches to the specimens (Fig. 2) leads to stress and strain concentrations in the notch root and at the end of the notch. Fig. 6a and b show a schematic representation of iso-stress lines of the notched specimen according to Neuber (8).

Highest deformation occurs at the ends of the notch indicated by slip bands (Fig. 7) and on a macroscopic scale an orange peel effect (Fig. 8) in this region. The perpendicular slip bands within the grains in Fig. 9 can be explained by the fact that slip occurs preferably in slip systems which are well orientated to the directions of maximum shear stresses. Only a few grains show multiple slip or cracks perpendicular to other slip bands within a grain (Fig. 10). Grain boundaries are usually those sites at which the cracks initiate.

Many small cracks, nucleated in this way, propagate and often form a branched main crack. This is in accordance with the observations in tension where at high cyclic amplitudes cracks appear at grain boundaries (16). These cracks grow from the notch root to the specimen interior to some extent before growing around the circumference.

By cycling of notched specimens on a first stage the orange peel can be seen in the notch root and the ends of the notch. This orange peel marks the highly deformed zones on the specimen, whose shape depends on the geometry of the notch. The investigations show in a second stage cracks beginning to grow further along the boundary between the highly deformed and the sligthly deformed region. In specimens with sharp notches both crack branches grow at the interface between the plastic zone and the almost undeformed region and combine at the surface after some stable crack propagation. This process eventually leads to failure of the specimen (Fig. 11a). In Fig. 11b it can be seen that in specimens with larger root radii, one or both cracks grow around the circumference of the specimen without any recombination. Also secondary cracks having a longitudinal direction can be seen lying within the highly deformed zones between the two crack branches (Fig. 8). Fig. 6c shows crack fronts after various amounts of stable crack extension, which are in a good agreement with the iso-stress lines of the elastic approximation (Fig. 6b); some partly fatigued specimens are shown in Fig. 12a, b (final fracture was performed in liquid nitrogen). Striations were observed in the corners of the fracture surface where the notch ends met the specimen circumference. These striations had not been erased by any rubbing effect during fatigue und therefore could confirm a Mode I crack propagation in these particular areas (Fig. 13).

Unlike the unnotched specimens, the notched specimens exhibit hardening even after cracking has been observed by means of the microscope, indicating that strain hardening outweights the loss in cross section due to crack propagation (see arrows in Fig. 5).

To show the plastic deformation a recrystallization treatment was performed. Figure 14 shows a specimen recrystalized in this way. This method gives a small grain size (< 20 μm) in the highly deformed ferrite and a large grain size (>200 μm) in the ferrite which is deformed for a few percent (15). It seems that the heavily deformed region ahead of the crack tip doesn't vary appreciably during crack growth. This can obviously be explained by a balance of the reduction of torque with the increase of crack length and therefore geometry factor. These problems will be discussed in a further paper.

CONCLUSION

Crack initiation in low cycle fatigue torsion tests was studied. The predominant failure mechanism of smooth specimens is the nucleation of cracks within the grains due to well spaced out slip bands. It was found that crack initiation occurs preferentially parallel and perpendicular to the torsion axis depending on the macroscopic stress field at the surface of the specimen. The specimen fails by the growth of one of these perpendicular cracks through the material.

In notched specimens crack nucleation at the ferrite grain boundaries dominates, which might be due to the higher strain at the notch root compared with the smooth specimens. Two crack branches grow in a transcrystalline fashion along the interface between the slightly and the highly deformed regions at the notch root.

The formation of the main crack in smooth specimens can be observed at low cycle fatigue just befor the abrupt drop in the cyclic stress-strain curve, whereas with notched specimens a crack is observable from the beginning of the cyclic stress-strain curve.

The applied method of recrystallization shows, that the plastic zone does not increase during crack propagation.

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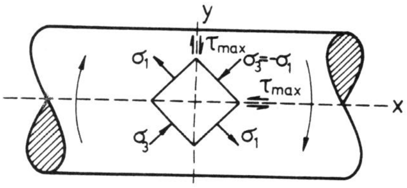
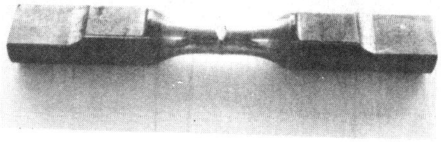


Fig. 1 State of stress in torsion



DIAMETER 15 mm
NOTCH DEPTH 2 mm
GAGE LENGTH 35 mm

Fig. 2 Notched torsion specimen

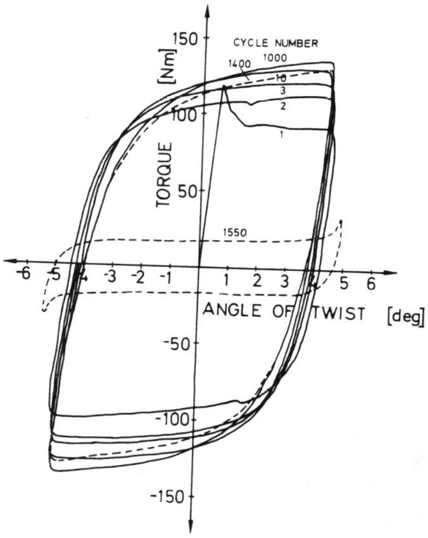


Fig. 3 Torque-twist hysteresis loops for a smooth specimen

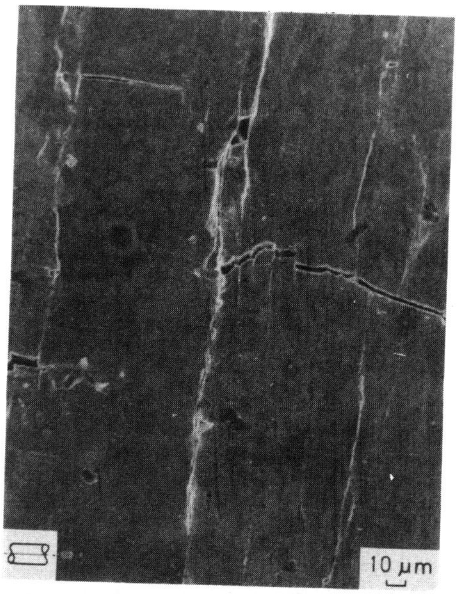


Fig. 4 Cracks at a surface of an unnotched specimen

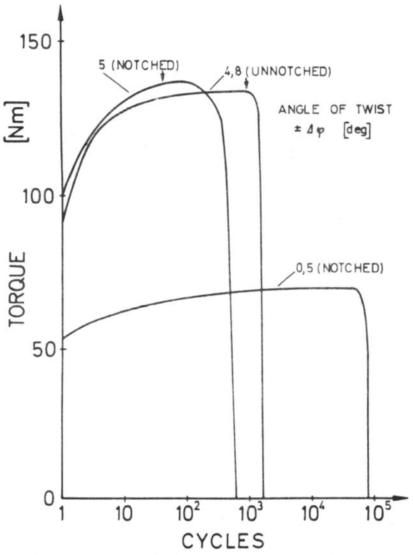


Fig. 5 Cyclic strain hardening behaviour of smooth and notched specimens

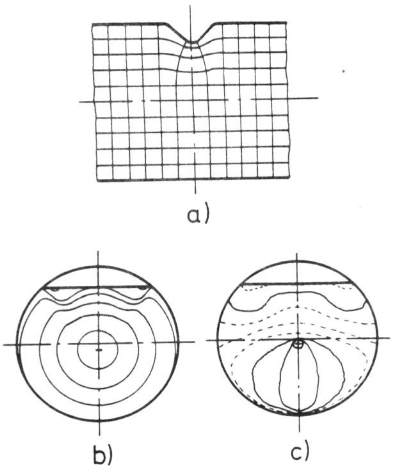


Fig. 6 a,b) Schematical drawing of iso-stress curves and c) for comparison the crack fronts after various cycles

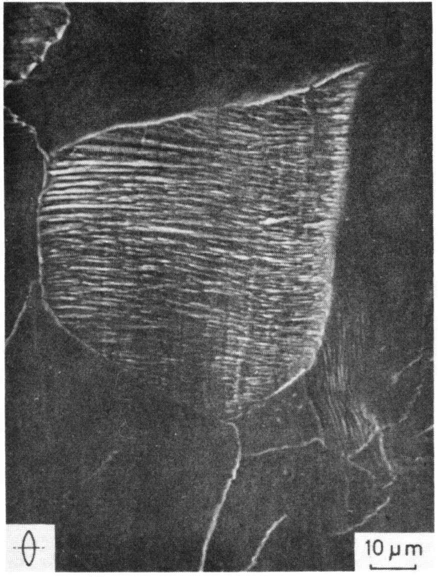


Fig. 7 Slip bands within a grain

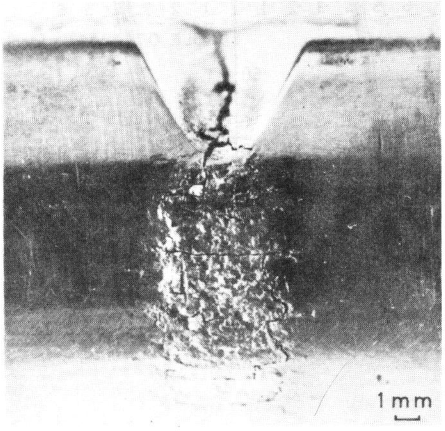


Fig. 8 Orange peel at the highly deformed region

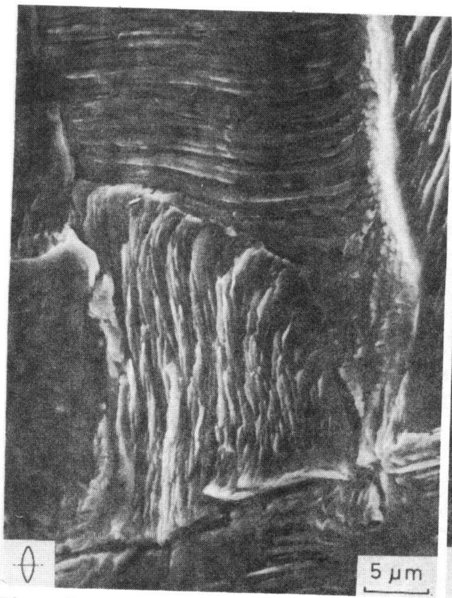


Fig. 9 Slip bands and cracked boundaries at the notch root

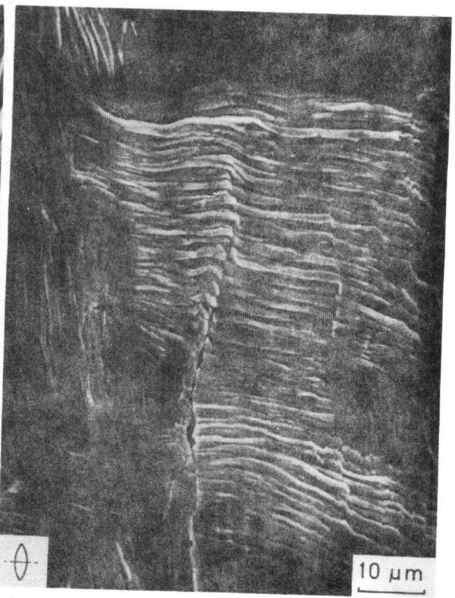


Fig. 10 Growth of a crack perpendicular to the slip bands

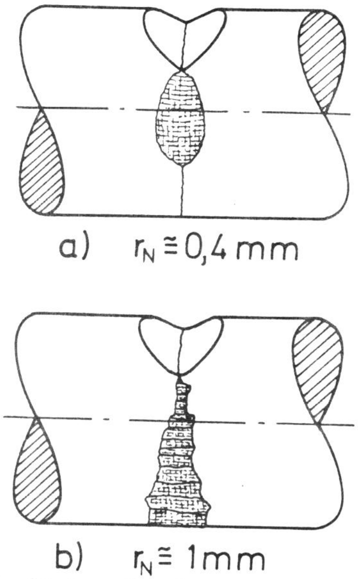


Fig. 11 Growth of cracks along the boundaries of the plastic zone (schematically, r_N=notch radius)

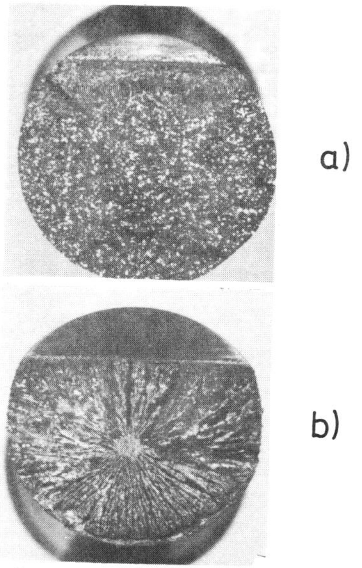


Fig. 12 Marked crack fronts after several cycles

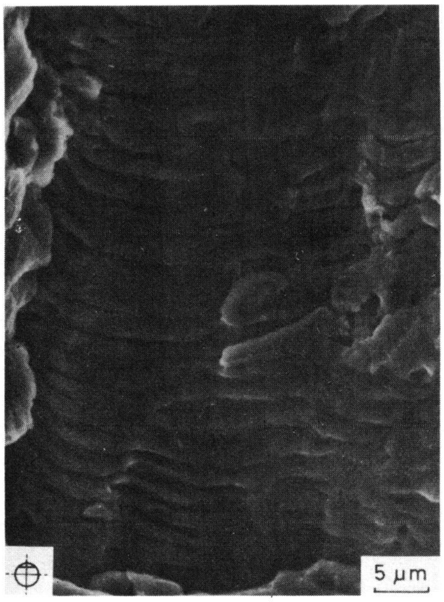


Fig. 13 Striations at the fracture surface

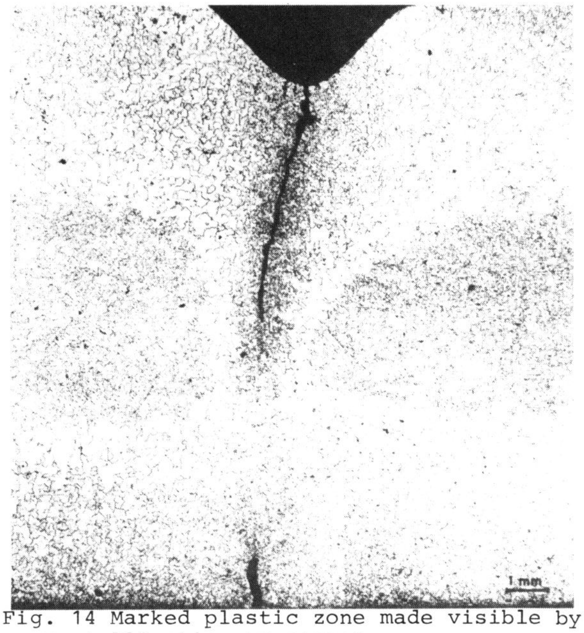


Fig. 14 Marked plastic zone made visible by recrystallization treatment