INFLUENCE OF A CONSTANT MODE III LOAD ON MODE I FATIGUE CRACK GROWTH THRESHOLDS

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ABSTRACT: The influence of a superimposed static mode III load on the threshold behavior of mode I fatigue crack propagation was studied for R = -1, 0 und 0.5 with cyclindrical 13% Chromium steel specimens with a circumferential notch. For the tests, the time and energy saving ultrasonic (20 kHz) fatigue testing system has been used the first time. It was found to be most appropriate for such measurements if the alignment of specimen and machine allows symmetric loading of the specimen, thus resulting in concentric crack propagation.
The results may be characterized with either ΔK_{th} or K_{max} as guiding values. It showed that a representation where the results are normalized to the thresholds of mode I fatigue crack propagation without a superimposed mode III load ($\Delta K_{th}/\Delta K_{Ith}$ or $K_{maxth}/K_{Imax\,th}$) is most powerful. Such a representation makes clear that the thresholds are shifted towards higher values if the mode III superimposed loads are increased. This increase of the thresholds is more pronounced for R = -1 than for R = 0 and 0.5. To explain this result roughness induced crack closure is assumed as main mechanism.

INTRODUCTION

The threshold stress intensity value characterizes the condition, under which an existing crack of defined length in some material ceases to grow when it is exposed to a cyclic load in a defined environment. The threshold value therefore is an important parameter for constructors and safety inspectors who have to take care of avoiding failures owing to cyclic fatigue loading.

Numerous detailed informations on threshold stress intensity values of many materials and testing conditions under mode I (crack opening mode) loading are available in the literature nowadays [1,2].

Many components, however, are not only loaded under pure mode I conditions, but usually under mixed mode, which is a superposition of mode I, mode II and mode III loading. But only few threshold values for combined loading are published in the literature, compared to pure mode I loading data. Pook [3] has performed mixed-mode threshold studies on mild steel (mode I + mode II and mode I + mode III) and has represented the results in failure envelopes for various testing conditions. He paid special attention to the development of branch-cracks and treated this problem also theoretically [4]. Hua et al [5] studied mode I + mode II fatigue crack propagation in stainless steel. They tested the influence of mode II loading on mode I fatigue crack propagation and could find good agreement of theoretically predicted and measured threshold values.

The aim of this work is to study the influence of static mode III loading on mode I thresholds at different mean values of stress (R-values). This kind of loading seems to be a very important practical problem, as many rotating parts of cars, trains, airoplanes and power plants are stressed in this way. A pre-cracked shaft for example is loaded in rotating bending (which is cyclic mode I) and simultanously a constant torsion (mode III) is superimposed.

This problem has been studied by Hourlier et al [6] on a Ti-Al-alloy at medium crack growth rates (10^{-6} to 10^{-2}mm/cycle). As a result, a pronounced reduction of the mode I fatigue crack growth rate owing to the superimposing a mode III load has been detected. In addition, the fracture mode changed from a flat fracture surface for mode I loading to a macrofacetted "factory roof" type (change of the main crack to branch-cracks inclined 45° to the specimen axis) for combined loading conditions. The influence of a mode III load on the threshold behavior, however, has not been studied in this work [6] and therefore remained an open question.

EXPERIMENTAL PROCEDURE

Near-threshold fatigue crack growth measurements are very time consuming due to long measuring times with high numbers of cycles. Therefore, a newly developed equipment using the time and energy saving ultrasound technique [7,8] which works at a loading frequency of 20 kHz has been used in this work. It consists of a combination of a conventional hydraulic machine and an ultrasonic equipment. It is possible to superimpose a constant or varying torque and independently also a tensile or compressive static or dynamic load to the high-frequency ultrasonic load in such a way that the individual loads do not influence each other. With appropriate specimen shapes, mode I plus superimposed mode II [9] and mode I plus superimposed mode III loading can be studied. The principle of an appropriate specimen shape is shown in Fig. 1. The maximum deviation of load and strain from pregiven values is atmost 1% for all loading conditions. More experimental details about the testing equipment are given in [9,10].

Testing material was 13% Chromium (ferritic X20Cr13) steel with the following chemical composition (in wt.%): 0.19 C, 0.42 Si, 0.39 Mn, 0.028 P, 0.005 S, 13 Cr. Cylindrical specimens with a length of 120 mm were machined from rods of 20 mm diameter. A circumferential sharp V-notch was introduced into these specimens and a concentrical 0.4 mm deep fatigue crack by a rotating-bending machine with continous registration of the fatigue crack length (measuring accuracy was 0.01 mm). Afterwards the specimens were heat treated in order to remove the plastic zones at the fatigue crack tips: austenitizing was at 940°C 1 hour, followed by oil quenching and tempering at 650°C for 1 hour in neutral environment. Following mechanical properties were obtained by this heat treatment: $R_{po.2} = 550$ MPa, $R_m \hat{=}$ 870 MPa. From heat-treated cylindrical specimens the final hourglass shapes, shown in Fig. 2, were machined for the combined loading fatigue crack growth measurements in the near threshold regime.

The stress intensity factors K_I and K_{III} were calculated according to Tada et al [11] and the ΔK_I or K_{Imax} values for ultrasonic loading according to Stanzl et al [9].

Crack propagation cannot be observed optically with the described specimen and notch configuration; therefore, the D.C. potential drop technique [12,13] was used. The electric potential was determined at 3 points being 120° apart at the edge of the circumferential notch. The resolution for crack-depth measurement was 0.005 mm. Details of the potential drop technique for ultrasound fatigue crack growth measurements with various specimen shapes are reported in [13].

The measuring procedure was the following: The specimens were loaded initially with such a low ΔK value that crack propagation could not take place. Then the ΔK values were raised in steps of 5 - 7% until crack growth took place. Crack extensions of 50 - 200 μm were measured then for increasing ΔK levels. After this stress intensity increasing procedure the ΔK values were reduced in steps of 5%. When no crack propagation was observed during 5.10^7 cycles this value was considered as threshold. Afterwards, the ΔK values were again raised by 5 - 7% and crack growth rates were determined in order to detect an eventual sequence effect.

This load shedding and increasing technique was repeated until a crack length of 0.5 to 1 mm was obtained. The specimen was removed from the testing machine then, cooled down to liquid nitrogen temperature and broken apart for fractographical examination and for a running check of the potential drop measurement.

The above mentioned measuring procedure was used for pure mode I fatigue crack growth and for cyclic mode I + superimposed static mode III crack growth at different R - ratios.

A new specimen was used for each different K_{III} load in order to avoid sequence effects due to a preceding plastic zone. The measurements were performed in laboratory environment at about 20°C.

The cyclic stress intensity value at which no crack extension (resolution of length measurement was 5 μm) took place during 5.10^7 cycles was defined as threshold value. (Assuming a maximum crack extension of 10 μm for this case would result in a crack growth rate of about 2.10^{-13} m/cycles).

RESULTS

The results on the influence of a static mode III load on mode I fatigue crack thresholds at various mean stresses may be represented in different ways. Either ΔK or K_{max} may be used for characterizing the threshold. Both ways allow different interpretations and are therefore used to present the results of this work. In Fig. 3a, the mode I thresholds, ΔK_{th}, are plotted versus the R-values, with K_{III} as parameter. This representation shows that the ΔK_{th} values are increased by superimposing a static mode III load and that this increase is higher for R = -1 than for R = 0 and R = 0.5. Plotting the results as K_{max}-thresholds is shown in Fig. 3b. In this representation, the thresholds again increase with increasing K_{III} values. The slope of the curves however hardly changes with the mode III load; they are almost parallel.

These to some extent different results may be completed by another representation. In Fig. 4, the ΔK_{th} results are plotted versus the superimposed K_{III} values, with the R-values as parameter. From this figure one sees, that the influence of a mode III superposition is most pronounced for R = -1 and becomes smaller for higher R-values. Plotting the K_{max}-thresholds in the same way reveals similar curves.

If the measured ΔK_{th} or K_{max} values for combined loading conditions are normalized with the thresholds for pure mode I loading both representations (ΔK_{th} and K_{max}) give the same curves as shown in Fig. 5. Superimposing a mode III load results in a more pronounced increase of the thresholds at low R-values (R = -1) than at higher R-ratios (R = 0 and R = 0.5). In addition, the thresholds for mixed-mode loading increase monotonically with increasing mode III load at R = 0 and R = 0.5. Contrary to this, almost no influence is observed for R = -1 up to a K_{III} value of 12 MPa$\sqrt{m}$ whereas a steeper curve is found for K_{III} values above 12 MPa$\sqrt{m}$ and for R = -1 than for R = 0 and R = 0.5.

In Fig. 6 the light microscopic photograph of a fractured specimen is shown. One sees the notch and the concentric part of the fatigue precrack owing to rotating bending loading. This fracture part is dark due to oxidation of the fracture surfaces during the heat treatment of the specimens after precracking.

The following concentric area is a bright, newly created fatigue fracture surface, which was formed during measuring. The rough fracture surface in the centre of the specimen is the final fracture. 90% of all precracks and fatigue cracks grew concentrically (parallel to the notch) which indicates that the alignment was perfect and the specimens were stressed uniformly. Specimens which showed more than 0.2 mm difference in their circular crack front diameter, were not used for evaluation of the crack growth rates.

DISCUSSION

An increase of the threshold stress intensity factors due to a superimposed static mode III load means that the fatigue crack growth rates decrease. This decrease is especially effective in the near-threshold regime, where the fatigue crack growth curve (fatigue crack growth rate versus cyclic stress intensity) is very steep. An increase of the threshold stress intensity for example by 20% may result in a decrease of the crack growth rate by several orders of magnitude. This is of special importance for life-time predictions and risk assessments.

Reasons for a reduction of the fatigue crack growth rate by superimposing a static shear load have been discussed in several works of the literature. In [6] the influence of a static mode III load on mode I fatigue crack propagation has been studied, in [14] the influence of a static mode I load on mode III fatigue crack propagation and in [5] and [9] the influence of a static mode II load on mode I fatigue crack growth is reported. In order to explain the reductions of crack growth rates, two mechanisms have been assumed in the above mentioned literature. These mechanisms seem to be similarily relevant for the results of this work.

1. Work hardening at the crack tip

A larger plastic zone is formed at the fatigue crack tip when a mode III load is superimposed. Strain hardening in front of the crack tip therefore takes place, which causes a more pronounced resistance to crack propagation. This mechanism operates like an overload [15], which similarily results in a transient reduction of the fatigue crack growth rate.

This mechanism however does not seem to be the main reason for the observed results of this work. If this mechanism were predominant, the curves with constant R values as parameter in Fig. 4 would be almost parallel, as a plastic zone size influence would be similar for all values (or at least not stronger for R = -1).

2. Closure effects

Shifting of the microscopically rough fracture surfaces by a mode III load results in interlocking and friction of the surface areas. These phenomena reduce the acting nominal to a lower effective stress intensity value at the crack tip. If a crack with rough fracture surfaces is opened by a mode I load and is stressed additionally in mode III, the crack cannot fully close after removal of the mode I load, but is kept open by the relative mis-match of the surface asperities. For cyclic mode I loading, part of the tensile load is not fully transmitted to the crack tip owing to this "crack closure" effect. Only part of the applied cyclic stress intensity value acts at the crack tip and therefore crack propagation is slowed down. Crack closure effects which were found for nominal pure mode I loading conditions [16] have been attributed similarily to mode II shifts of the fracture surfaces during mode I loading.

With this crack closure mechanism, the different influence of a mode III load at different R-ratios can be explained. At R = -1, the nominal cyclic stress intenstiy value is reduced to a much lower effective value than for R = 0.5, obviously because the fracture surfaces are separated more effectively by the positive mean load (tensile pre-load) for R = 0.5 than for R = -1. A quantitative analysis of this results is possible with a model (to be published), in which the rough fracture surfaces are approximated by 45° inclined areas and where the CMOD and CTOD are calculated for mode I and mode III loading at various R-ratios. With these results, effective stress intensity values are obtained.

For practical purposes the question arises, how far the results obtained at the high testing frequency of 20 kHz are relevant for conventional testing frequencies. To answer this, the reader is refered to earlier works of the authors [8,17]. It has been shown there that the fatigue crack growth curves coincide in the threshold regime for low and high frequency loading, if environmental or temperature effects are eliminated and if the pecularities of ultrasonic loading are considered at the stress intensity determination [9].

For the initially mentioned case of a pre-cracked shaft the results of this work imply that the threshold is raised by superimposing a constant torque and that the fatigue crack growth rate is reduced drastically therefore compared to a shaft which runs idle, without torque. Thus, a rotating shaft loaded with constant torque lives longer than one running idle. This result is verified until now only for fatigue crack growth in the threshold regime and has to be checked for higher mode I load and crack growth rates.

CONCLUSIONS

The influence of a superimposed static mode III load on the threshold behavior of mode I fatigue crack propagation was studied for R = -1, 0 and 0.5 with cylindrical 13% Chromium steel specimens with a circumferential notch. Following conclusions could be drawn:

1. For these tests, the time and energy saving ultrasonic fatigue testing system is found to be most appropriate. For such measurements the alignment of specimen and machine must be perfect, so that symmetric loading of the specimen is guaranteed and concentric crack propagation takes place.

2. The results may be characterized with either ΔK_{th} or $K_{max\,th}$ as guiding values. It shows that a representation where the results are normalized with the thresholds of pure mode I fatigue crack propagation without a superimposed mode III laod, ($\Delta K_{th}/\Delta K_{Ith}$ or $K_{max\,th}/K_{Imax\,th}$) is most powerful.

3. Superposition of a mode III static load increases the cyclic mode I threshold stress intensity value. This increase of the threshold is more pronounced for R = -1 that for R = 0 and 0.5. To explain this result roughness induced crack closure is assumed as main mechanism which becomes higher when a CTD_{III} displacement is superimposed, thus resulting in additionally incom-

plete crack closure. This crack closure effect obviously is more effectiveat R = -1 than at R = 0.5. Strain hardening in the plastic zone ahead of the crack tip owing to the superimposed static mode III load is found to be of minor influence.

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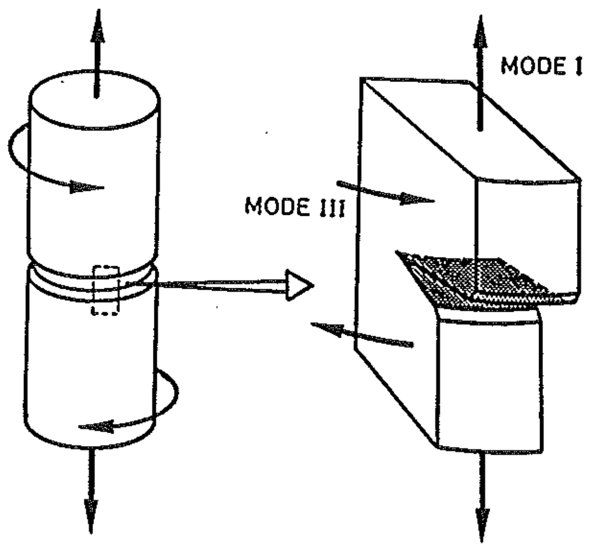

Fig. 1: Principle of specimen shape for fatigue crack growth studies under mode I with superimposed mode III loading conditions.

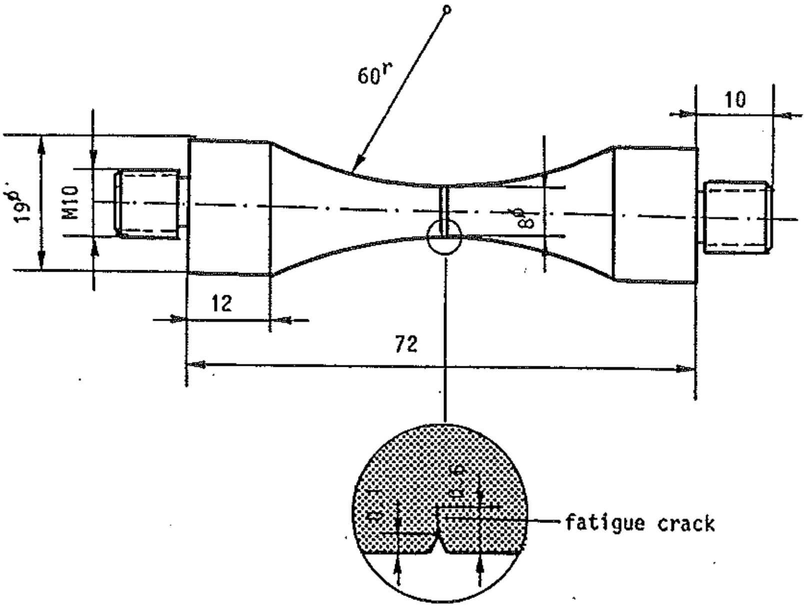

Fig. 2: Specimen shape for high-frequency cyclic loading + superimpoded mode III loading.

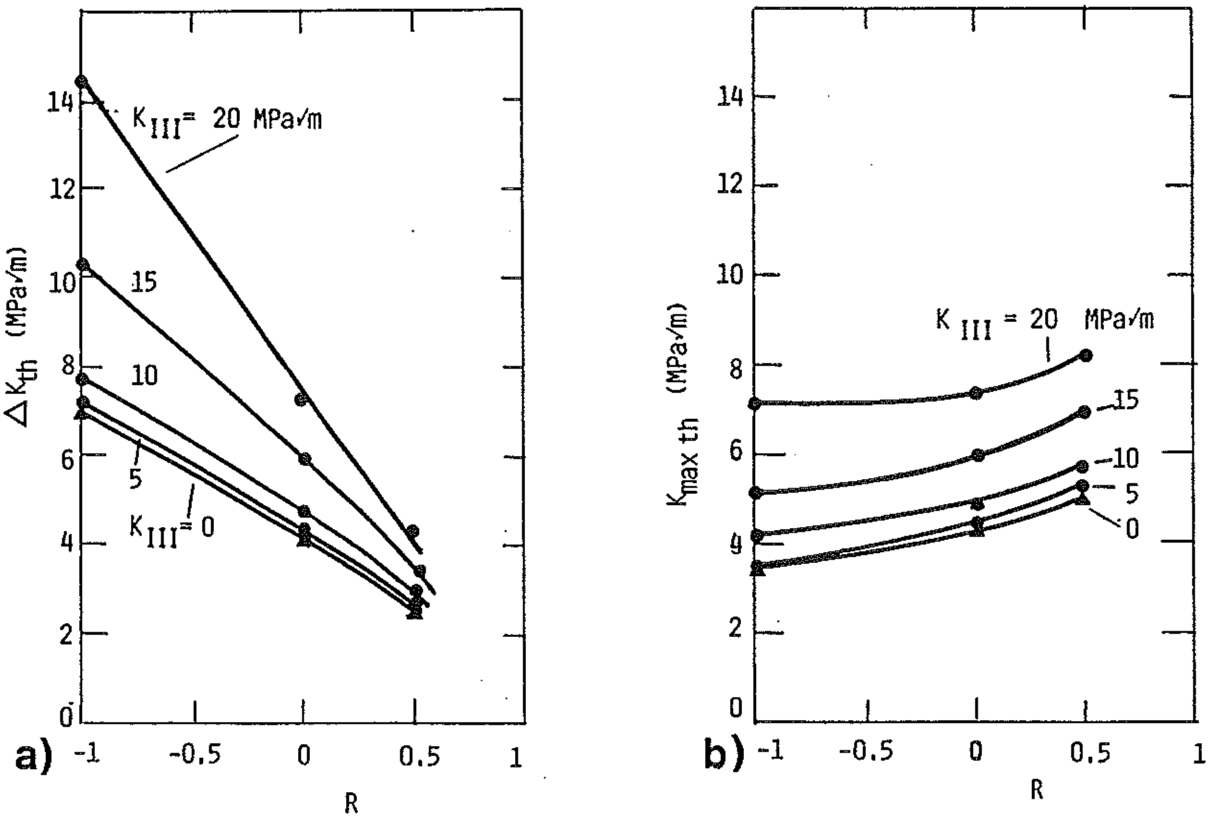

Fig. 3: Static mode III load influence on fatigue crack growth thresholds under different R-ratios.
a) with ΔK_{th} ($K_{max} - K_{min}$) characterizing the threshold value
b) with K_{max} characterizing the threshold value.

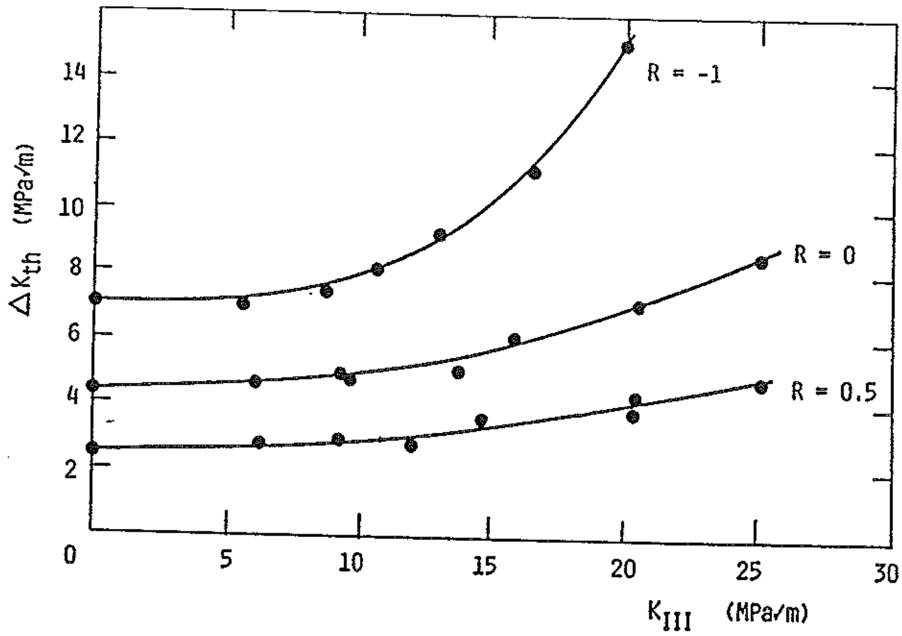

Fig. 4: Influence of static mode III loads on fatigue crack growth thresholds, ΔK_{th}, with different R-ratios as parameter.

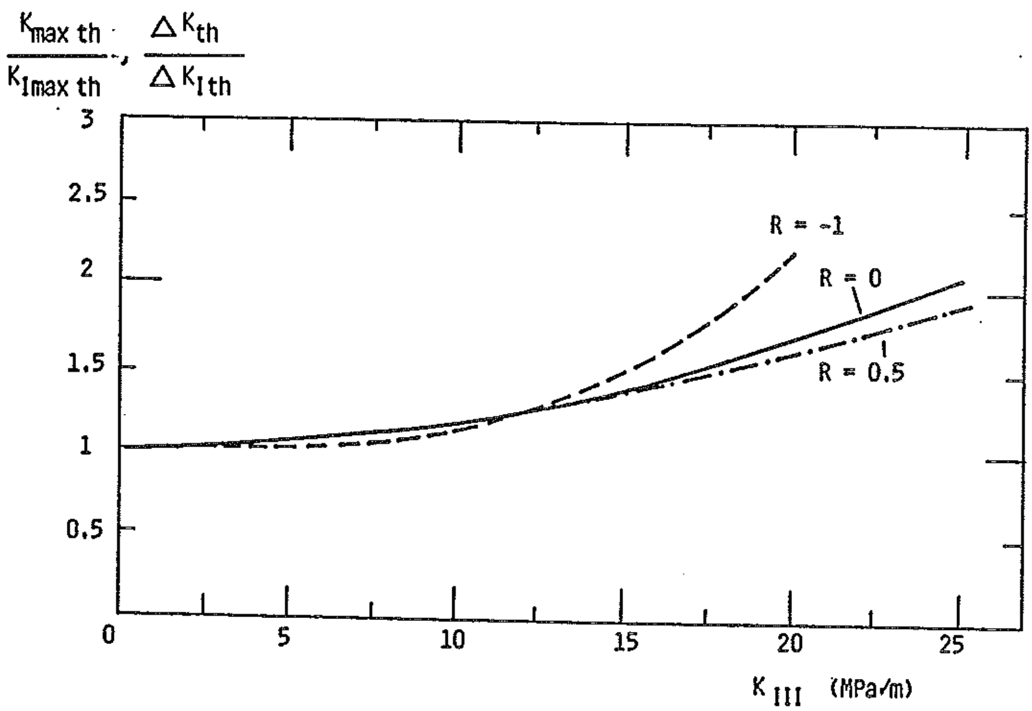

Fig. 5: Influence of static mode III loads on normalized threshold stress intensity values; the R-ratio is parameter.

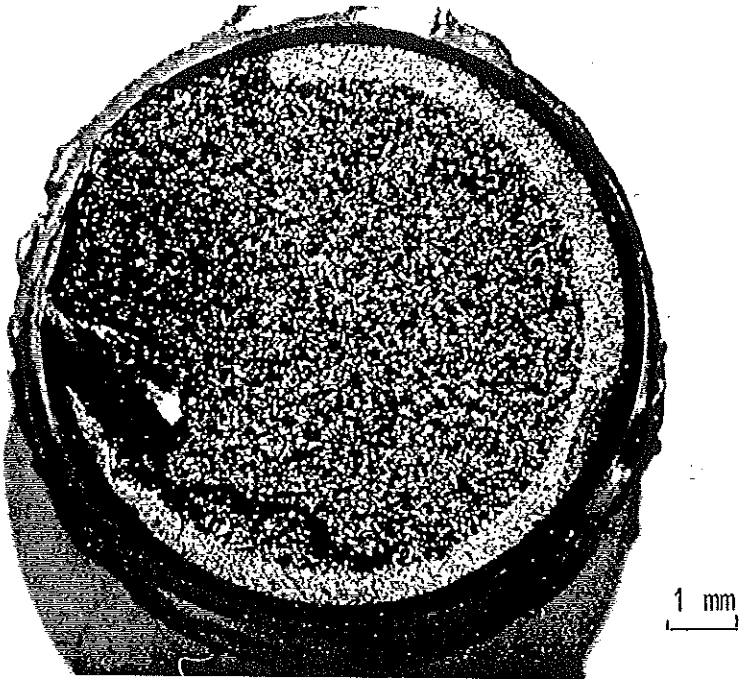

Fig. 6: Fracture surface of specimen with circumferential notch, fatigue precrack, mode I cyclic + superimposed static mode III crack and final fracture.