EXPERIMENTAL EVALUATION OF FATIGUE LONG CRACK PROPAGATION UNDER REMOTE SHEAR LOADING MODES II AND III

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Abstract

An original experimental setup allowing simultaneous mode II and mode III crack propagation in a single specimen is described in detail and some of the first achieved results are presented. The differences between the long fatigue crack propagation under both modes are assessed by means of the fractographical analysis in circumferentially notched cylindrical specimens made of austenitic steel. It is concluded that, based on the 3D observation and the roughness analysis, the crack propagation mechanism is distinctively different within remote modes II and III regions.

Key words

fatigue, modes II and III, crack propagation, quantitative fractography

INTRODUCTION

It is well known that on the macroscopic scale the long fatigue cracks generally tend to propagate in mode I [1,2]. As a rule, also the high cycle fatigue cracks initially growing in macroscopically pure shear modes II and III usually gradually deflects towards planes dominated by the maximum tensile stress component (local or global mode I loading). In the low cycle fatigue region, the occurrence of a macroscopically flat, shear dominated fracture is more probable [3].

Unlike crack growth under modes I and II, where active micromechanisms are relatively well understood, there is no plausible model interpreting crack propagation process under a pure mode III in ductile metals. The main reason lies in the fact that, when a pure mode III is present, new segments of fracture surface are generated by screw dislocations aside the crack front, i.e. perpendicularly to the crack propagation direction. On the other hand, the crack incremental advance along the whole front is generated by edge dislocations in modes I and II. Although mode III lateral "ledges" might propagate as local mode II segments it is clearly perceived that the overall crack growth rate should be much lower than the straightforward crack growth under modes I and II. These considerations, nevertheless, are inconsistent with an apparent similarity of the threshold stress intensity factor ranges measured for modes II and III as presented e.g. in the paper [4].

A wide international discussion is being in progress started in Parma at the "Fatigue Crack Paths 2003" conference. As it has been pointed out, the presence of a pure Mode III growth is usually deduced solely from the macroscopic appearance of the crack front direction and from the existence of fibrous patterns parallel with the assumed crack front, without any detailed three-dimensional fractographical study of the local crack growth direction being performed [5]. Moreover, the remote mode III crack growth can be explained by either an alternating mode II model or by a stepwise mode II mechanism associated with cracked particles located near the crack front [3,5]. Since both these mechanisms can also produce fibrous patterns parallel with the assumed "mode III" front, a great effort is currently devoted to sufficiently elucidate micromechanisms of the shear-modes long crack growth and to verify experimentally both mentioned models, see e.g. [6]. The aim of the paper is to present a description of the prototype experiment that allows simultaneous mode II and mode III crack propagation in a single specimen, and to discuss some of the first achieved results.

EXPERIMENTAL DEVICE, SPECIMENS, LOADING PROCEDURE AND FRACTURE SURFACE TOPOGRAPHY ANALYSIS

For the purpose of the experimental verification of the fatigue long crack behaviour under modes II and III the original testing setup has been designed and utilized in cooperation with Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, in Leoben. In order to assure both pure remote shear modes II and III crack propagation in a single specimen, a special loading cell was manufactured, Fig. 1. As shown in Fig. 2 a,b, the construction of the specimen holder and its orientation in respect to the loading axis provide a pure Mode II operation at the "top" and "bottom" specimen sites and a pure Mode III at "front" and "back" sites.

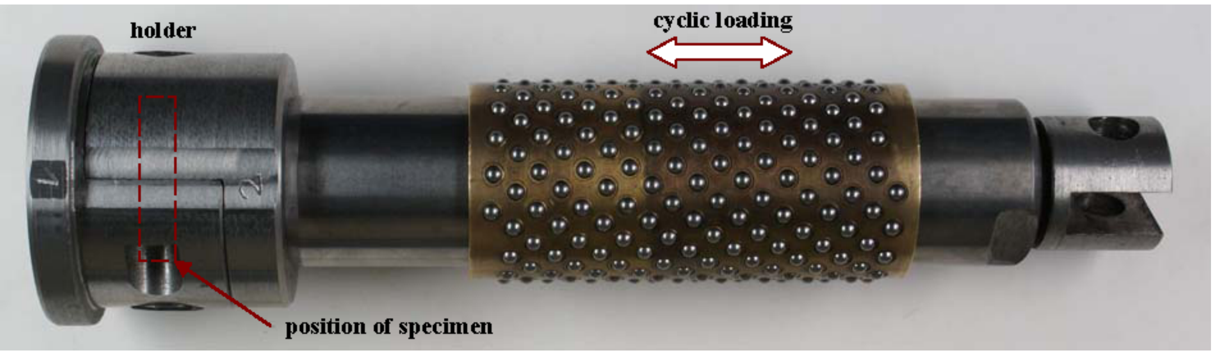

Fig. 1. *A photograph of the loading cell. The position of the specimen in a holder and the loading direction are indicated*

Two cylindrical specimens were made of the X2CrNiMo18-14-3 austenitic steel grade with yield strength σ_y = 200 MPa. Circumferential V-notch was machined by a lathe tool at a specimen mid-length in which a sharp pre-crack was introduced by a blade mechanism, see Fig. 2c. Constant pressure on the gripping frame transferring onto the blade and the specimen undergoing both the rotational and translational motions during procedure guarantee the symmetry and sharpness of the initial pre-crack. Note that although special care was taken during both the notch machining operation and the pre-cracking procedure, the front of the pre-crack could not be considered to be microscopically perfectly smooth. Therefore, the cyclic shear plasticity at the notch-root should be high enough to overlay initial microughness and to produce a rather homogeneous process zone around the notch.

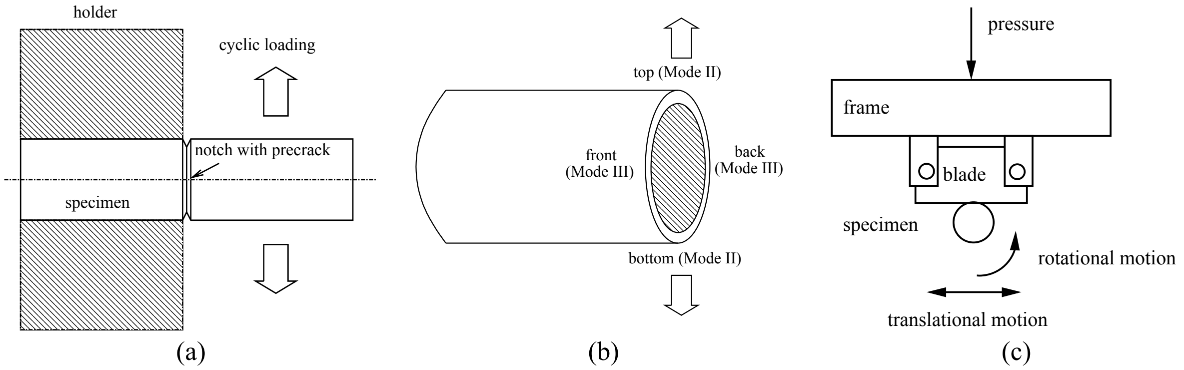

__Fig. 2.__ (a) The loading scheme, (b) the loading modes operating at different specimen sites, (c) a sketch of the pre-cracking procedure

Specimens were tested using shear loading of the amplitude τ_a = 180 MPa and the loading ratio $R = \tau_{min} / \tau_{max} = 0.1$ as the loading regime, where τ_{min} and τ_{max} are minimal and maximal loading levels. Both experiments were interrupted after 380 000 cycles and cyclic tensile loading of the amplitude σ_a = 200 MPa and the loading ratio R = 0.1 was applied afterwards until a final fracture occurred, Fig. 3.

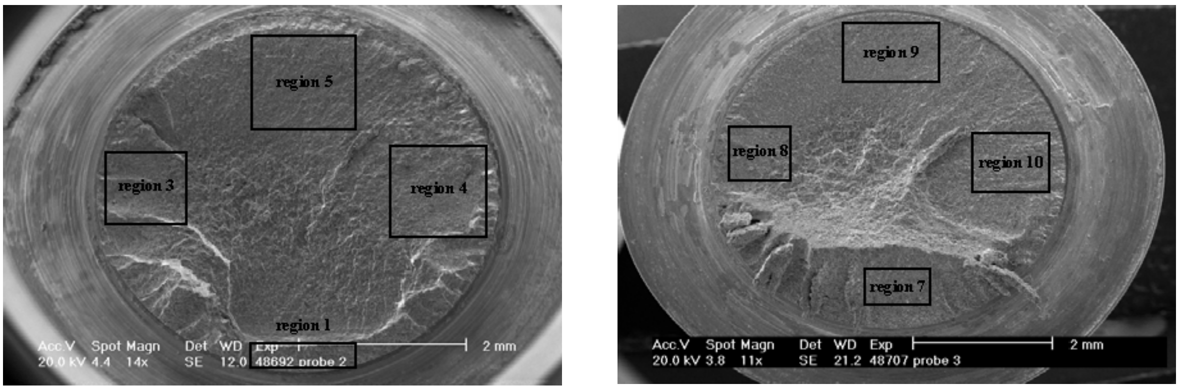

__Fig. 3.__ Fracture surfaces of tested specimens. Rectangular regions chosen for the fractographical analysis are specified and numbered. The remote mode II acts on the crack front located within the regions 1,5,7 and 9, while the remote mode III is present within regions 3,4,8, 10.

The crack path was studied by means of the fracture surface reconstruction of the rectangular regions selected at "top", "bottom", "left" and "right" sites, Fig. 3. Surface topography was measured by the optical profilometer MicroProf FRT, which uses the chromatic aberration method for determination of the surface height coordinate. An example of the fracture surface reconstruction (regions 4 and 8) is given as Fig. 4.

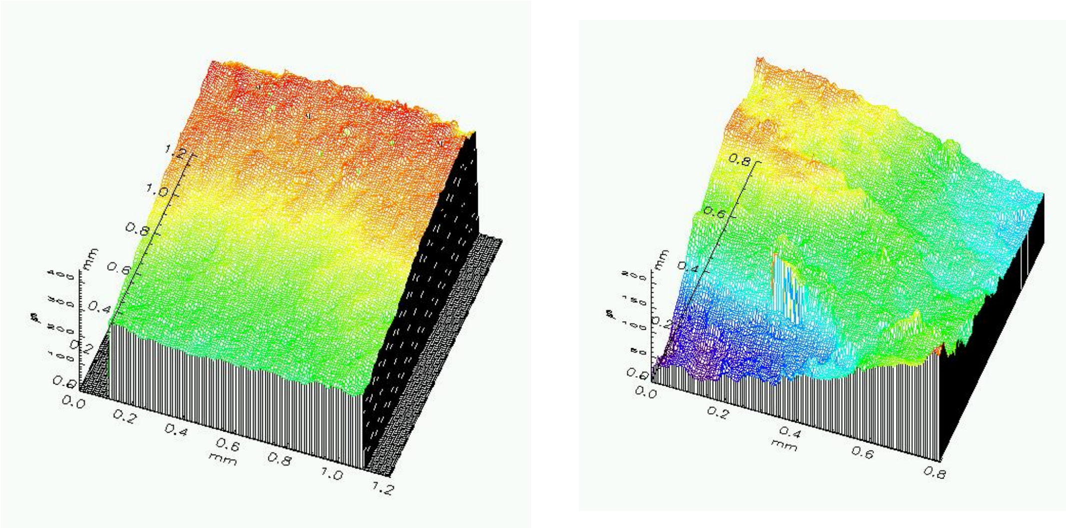

Fig. 4. *An example of the fracture surface reconstruction: Mode II – region 5 (left image) and Mode III – region 8 (right image)*

In the next step, the sets of profiles in both horizontal *x*- and *y*- axes were extracted from a raw 3D data of each analyzed region and the correlation length, *β*, which gives the evidence of the crack path "coherence", was assessed as a quantifying parameter for all profiles. The parameter *β* was calculated as the shift distance for which the value of the autocorrelation function drops to the 1/10 fraction of its original value, *R(0)*. The autocorrelation function is defined as

$$R(p) = \frac{1}{(N-p)} \sum_{k-1}^{N-p} \left(z_k - \langle z \rangle\right)\left(z_{k+p} - \langle z \rangle\right), \qquad (1)$$

where *N* is the number of profile data points, *z* is the height coordinate, $\langle z \rangle$ is the mean height and *p* is the shift distance [7].

RESULTS AND DISCUSSION

Careful study of the surface topography of all analysed regions was carried out by using the software application Mark III, which is supplied with the profilometer MicroProf FRT. It was noted that all the fatigue crack paths exhibited a global deflections from the shear plane within almost all regions, and, therefore, a local mixed mode loading (either modes I+II, I+III, or I+II+III) was experienced by the crack during its propagation. More importantly, qualitatively entirely different topography was observed within the "top" and "bottom" sites and the "left" and "right" sites, see Fig. 4 as a typical example. It is obvious, that while in the first case (remote mode II regions) the crack advances in a more or less steady uniform planar manner, a rather complicated propagation of a relatively torturous crack front is observed in the latter case (remote mode III regions).

In order to quantify these differences, the correlation length, *β*, was used as a conclusive roughness descriptor. The results expressed in terms of the mean values, where the averaging was made over *x*- and *y*- profile sets separately, and the respective standard deviations are collected in Tab. 1. Entries belonging to profile sets representing the crack front at subsequent positions are shown in bold. As can be seen from Tab. 1, distinctive differences of *β*-values are observed for profiles parallel with the growing crack front. On the other hand, nearly equal *β*-values are obtained in the case of profiles perpendicular to the crack growth. This is in accordance with models predicting different growth micromechanisms of mode II and mode III [3,5].

THE CORRELATION LENGTH, β Table1

Mode	Profiles	*β*
II	**x**	**152 ± 34**
	y	111 ± 64
III	x	108 ± 12
	y	**85 ± 32**

CONCLUSION

In the paper, a prototype experiment that allows simultaneous mode II and mode III crack propagation in a single specimen was described and first achieved results were discussed. A deflection of the fatigue crack path from the loading shear plane was found within almost all analysed regions. It is concluded that, based on the 3D observation and the roughness analysis, the crack propagation mechanism is distinctively different within remote modes II and III regions.

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