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Straightforward comparison of fatigue crack growth under modes II and III

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Abstract

Low-cycle fatigue crack propagation in double circumferentially notched, cylindrical specimens of austenitic steel was studied by means of special testing device in order to identify local fracture micromechanisms under remote shear modes II and III. Remote mode II crack growth rate was found to be approximately two times higher than that of the mode III. Morphological patterns on fracture surfaces revealed that the mode II and the mixed mode I + II were dominating local crack tip fracture modes operating under both remote modes II and III. No evidence of pure mode III mechanisms was detected on any investigated fracture surface.

Keywords: Mode II; Mode III; Fatigue crack propagation; Mixed mode; Fractography; Morphological patterns

1. Introduction

While the principal fracture micromechanisms of fatigue crack growth in ductile materials under modes I and II are well known, there is a lack of any plausible interpretation in case of a pure mode III crack propagation [1]. The main problem lies in the fact that, from the theoretical point of view, the cyclic movement of geometrically necessary edge dislocations under modes I, II generates new fracture surface along the whole crack front in each cycle. On the other hand, the screw dislocations in the pure mode III generate only ledges on the surface of a plane sample. Although these ledges may then propagate as "local" mode II cracks, the crack front advance per cycle produced in such a way must be negligible when compared with the straightforward crack growth in modes I and II. Real cracks initially growing in macroscopically pure shear modes II and III were usually observed to branch to planes dominated by the maximum tensile stress component (local mode I loading). In the presence of pure mode III loading at the crack front, the mode I branching develops so-called twist cracks [2]. It should be noted that, in fact, the crack growth under remote (macroscopic) mode III can be, on a microscopic scale, produced as a mixture of modes I + III or II + III, since a great majority of crack front elements are not strictly parallel to the applied anti-plane shear stress direction [3]. Moreover, the remote mode III crack growth can be explained by either an alternating mode II model or stepwise mode II mechanisms associated with cracked particles near the crack front [1,3]. Some authors reported a relatively short initial period of crack growth in the shear modes II, II + III and III before the onset of a mode I dominated propagation due to the branching of mode II crack front segments forming a factory-roof fracture morphology [4,5]. However, the presence of a pure mode III growth was deduced only from the macroscopic appearance of the crack growth direction and from the existence of fibrous patterns parallel to the assumed crack front. Since also the above mentioned mode II mechanisms can produce fibrous patterns parallel to the assumed "mode III" front, such conclusions might be completely misleading. Very recently, Makabe et al. [6]

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performed careful analysis of initial crack path and factory-roof patterns at fracture surfaces created in torsional fatigue. Three stages of crack propagation were observed: (i) very short II + III stage; (ii) I + II + III stage; and (iii) pure mode I stage.

It should be noted that all the above mentioned experiments were performed in a pure torsion. However, the main problem of that type of loading lies in its biaxiality. Indeed, initially pure mode II cracks immediately branch to the direction perpendicular to the principal stresses to propagate under the mode I. At the onset of growth, the inclination angle is about 70° (after the Erdogan–Sih criterion) and, after a very short period, it follows the 45° plane of maximal normal stress (see e.g. [7]). The propagation of mode III cracks under torsion was, in fact, never really confirmed. Although such behaviour is more typical for a high-cycle fatigue regime, our low-cycle pure torsion experiments made on high-strength steel specimens proved the above mentioned conclusions as well [1,3]. This was one of the main reasons to develop a new testing procedure (described hereafter) that allowed us to produce mode II and III cracks propagating simultaneously for a sufficiently long time.

A wide international discussion is being in progress (started in Parma at "Fatigue Crack Paths" [3]) in order to sufficiently elucidate micromechanisms of shear mode crack growth. Besides the development of the new testing procedure the second main aim of the paper was to approach a solution of that problem. Thus, an extended 2D and 3D fractographical analysis was performed to identify microscopic fracture mechanisms and crack paths.

2. Experimental device, specimens and loading procedure

The basic idea was to arrange a simultaneous mode II and mode III crack propagation in one specimen. During this experiment, the specimen could only experience macroscopically pure shear loads and deformations; any superimposed normal stresses had to be avoided. Moreover, mode III-like propagation by the stepwise mode II mechanism connecting cracked particles should have been excluded as much as possible. Therefore, a rather clean austenitic steel X5NiCrTi26-15, used, e.g. in aviation industry or as turbine blade material (yield strength of about 600 MPa), was selected as an experimental material. The material was a casted and forged to a diameter of about 60 mm and recrystallized. The chemical composition of the material was as follows (wt%): C 0.05, Si 0.25, Mn 1.50, Cr 15.00, Mo 1.30, Ni 25.30, V 0.30, Ti 2.10, Al 0.25, B 0.005, Fe – the rest. The microstructure of the steel along the crack growth plane is depicted in Fig. 1. As can be seen, the material is almost free of inclusions or precipitates. Nevertheless, some typical non-metallic or intermetallic inclusions are visible. We have not quantified these particles in detail since this was not important with regard to the main aim of the article.

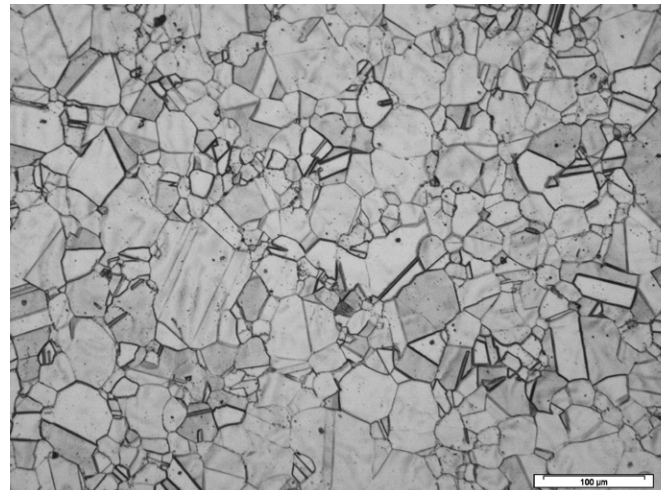

Fig. 1. The microstructure of the investigated steel along the crack growth plain.

The photograph of a cylindrical specimen is in Fig. 2. These specimens were prepared from a rod with a diameter of 50 mm in a way that the crack always propagated in L–R direction (following ASTM notation E 616-89). The diameter of the sample was 8 mm and the notch depth was about 1 mm. Two very sharp circumferential notches were induced by a lathe tool. Specimens were additionally subjected to a compressive loading in order to produce a crack-like notch. Both the compression loading and the following fatigue experiment were performed under full plastic yielding. Therefore, the residual stresses induced by the first compression should have been re-distributed and should had a minor effect on the obtained results.

A further reason for selecting relative large plastic shear displacements was to investigate crack growth rates, which can be determined from the striation spacing on the fracture surface. The experiments were performed displacement controlled since the main aim of the study was to compare the crack growth rates under mode II and mode III fatigue loading of cracks with the same cyclic crack tip displacements. The shear experiment was realized by a special device operating in tension compression loading. Specimens were placed into a fixed rigid holder in the machine, where both side parts of the specimen could be tightly kept. The whole middle part of the specimen (in

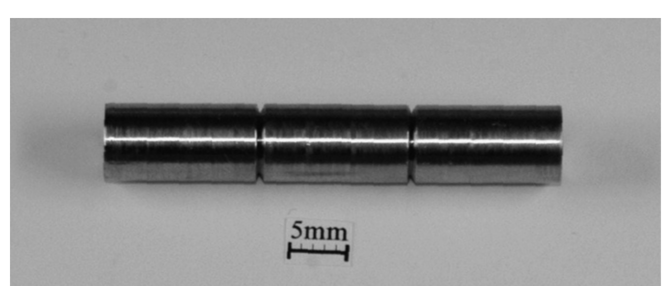

Fig. 2. The experimental specimen.