Influence of Secondary Phase on Intrinsic Threshold and Path of Shear-Mode Fatigue Cracks in Metals

T. VOJTEK,a,b,∗A. HOHENWARTERC, R. PIPPANd AND J. POKLUDAA,c,f

aCentral European Institute of Technology (CEITEC), Brno University of Technology, Purkyněova 123, 612 00 Brno, Czech Republic
bCEITEC IPM, Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, 616 62 Brno, Czech Republic
cDepartment of Materials Physics, Montanuniversität Leoben, Jahnstr. 12, A-8700 Leoben, Austria
dErich Schmid Institute of Materials Science, Austrian Academy of Sciences, Jahnstr. 12, A-8700 Leoben, Austria
eFaculty of Mechanical Engineering, Brno University of Technology, Technická 2, CZ-61669 Brno, Czech Republic
fFaculty of Special Technology, Alexander Dubček University of Trnecín, Pri parku 19, 911 06 Trenčín, Slovak Republic

1. Introduction

The fatigue crack growth threshold is one of important material characteristics, determining whether the long fatigue crack propagates or not. The resistance to fatigue crack growth should be divided into two components. The intrinsic component, also called the effective crack driving force, is responsible for cyclic plastic deformation of the crack tip leading to crack propagation. The extrinsic component represents crack tip shielding and is mostly realised behind the crack tip, for example, by different types of crack closure. In the near-threshold regime, the extrinsic component is often higher than the intrinsic one. Besides of being on the safe side, the intrinsic threshold data enable us a straightforward comparison with (and verification of) physical models of mechanisms of fatigue crack propagation.

Under mode I loading the intrinsic (effective) thresholds are well predictable and have approximately the same value for a particular metal independent of its microstructure. This value depends only on basic characteristics of the metal, the Young modulus E and magnitude of the Burgers vector b and, for single-phase metals, the following relationship [1] was proposed for the effective mode I threshold \(\Delta K_{\text{eff,th}}\):

\[
\Delta K_{\text{eff,th}} = \frac{\sqrt{E b}}{2 \cos \frac{\alpha}{2} \sin \alpha},
\]

(1)

In the case of shear-mode cracks, however, the effective thresholds depend on the crystal lattice type and microstructure. In previous studies (e.g. [1, 2]) it was shown how the crystal lattice type of single-phase metals influences the local growth mechanism, which in turns influences the effective threshold.

The mechanism related to dominant mode I (opening) crack growth can be either ductile blunting or quasi-brittle tearing, whereas that related to dominant mode II (shear) growth is shear along slip planes more or less parallel with the plane of the maximum shear stress (see [2] for more detail). The tendency to grow under local opening or local shear mode is reflected by the mean angle of deflection of the remote mode II loaded crack from the original precrack plane (the maximum shear stress plane). The following formulae [3], proposed for the prediction of the effective mode II threshold, are functions of the deflection angle \(\alpha\):

\[
\Delta K_{\text{II eff,th}}^\text{theor I} = \frac{E \sqrt{b}}{2 \cos \frac{\alpha}{2} \sin \alpha},
\]

(2)

\[
\Delta K_{\text{II eff,th}}^\text{theor II} = \frac{\sqrt{G b}}{2 \cos \frac{\alpha}{2} (3 \cos \alpha - 1)},
\]

(3)

∗corresponding author; e-mail: tomas.vojtek@ceitec.vutbr.cz
For materials with dominant local mode I growth Eq. (2) should be used while Eq. (3) is for materials with dominant local mode II growth. Only the selected (dominant) mode is considered to contribute to crack propagation and the second (non-dominant) one can be neglected, which represents a new approach to mixed mode loading, different from the classical energetical summation of contributions from each of the modes I, II, and III.

It was shown that the typical angles $\alpha$ for pure bcc, hcp, and fcc metals are 15°, 35°, 50°–65°, respectively. In bcc metals the shear-mode cracks grew under local mode II mechanism [3] due to high density of available slip planes in the lattice which enabled dislocation motion along the remote shear stress direction. This mechanism is very easy and energetically most convenient which is reflected by lower mode II effective thresholds than those of mode I in the bcc and hcp metals [3] (see also Table I).

Since most of the engineering materials are of multiphase structure, the purpose of this paper is to show the dependence of local growth mechanism of shear-mode cracks on the type of the secondary phase. Unlike in the case of mode I effective thresholds, the secondary phase can significantly change the mode II and mode III thresholds due to a change of the growth mechanism. Indeed, the previously published results [4] showed that the intrinsic behaviour of the ferritic-pearlitic steel was very different from that of the pure ferritic steel. Here, the influence of secondary phase type is studied also for the fully pearlitic steel and the Ti6Al4V titanium alloy in more detail. Based on fracture mechanics, a new criterion for mode I crack-branching is formulated and applied to all single- and dual phase metallic materials investigated hitherto.

| TABLE I | Comparison of effective thresholds and local crack growth direction of remote mode II and mode III loading for both ferritic and pearlitic steels as well as for the pure $\alpha$-Ti and the $\alpha + \beta$ titanium alloy. |

| Material characteristic | Steel | Titanium alloys |
|-------------------------|-------|----------------|
|                       | ferritic steel | pearlitic steel | pure $\alpha$-Ti | $\alpha + \beta$-Ti |
| effective threshold [MPa m$^{1/2}$] | mode I | Eq. (1) | experimental | 2.5 | 2.5 | 2.0 | 2.0 |
|                       | mode II | Eqs. (2),(3) | experimental | 2.7 | 3.0 | 2.0 | 2.4 |
|                       | mode III | experimental | 1.4 | 2.2 | 1.5 | 1.5 |
|                       |        |                | 1.5 | 2.8 | 1.7 | 1.8 |
|                       |        |                | 2.6 | 4.5 | 2.8 | 3.1 |
| local crack growth direction | deflection of mode II cracks (70° for pure local mode I) | 19° | 60° | 33° | 30° |
|                       | twist of mode III cracks (45° for pure local mode I) | 16° | 41° | 35° | 32° |
| dominant crack growth mechanism under remote shear-mode loading | local mode II | local mode I | local mode II | local mode II |

$^{a}$ [10], $^{b}$ [3], $^{c}$ [7], $^{d}$ [11], $^{e}$ [12], $^{f}$ [13]

2. Materials

Two alloys with high importance in industrial applications were chosen for investigation. The first material was a titanium alloy ASTM grade 5 (Ti6Al4V) hardened by the $\beta$-Ti phase. The second was a fully pearlitic steel which is, for example, used for the production of rails. The rolling contact fatigue behaviour during the plastically deformed material state ahead of the crack tip and to avoid production of oxide on the fracture surfaces. The ARMCO iron was annealed at 950°C for 90 min and the resulting mean grain size was 110 $\mu$m. The corresponding metallography cut image can be found in [2]. The pearlitic steel was annealed at 850°C for 90 min (metallography cut in [7]). Commer-
Fig. 1. EBSD image of the Ti6Al4V alloy with thin lamellae of the $\beta$-Ti phase. The cut includes the fracture surface of a remote mode II loaded crack on the top of the image.

Fig. 2. Example of a fracture surface of a mode II crack in pearlitic steel. The height profile below is defined by the white arrow on the fracture surface. The deflection and twist angles in the pearlitic steel were much higher than those in ferritic steel, while in Ti6Al4V they were nearly equal to those of pure titanium.
\( \Delta K_{\text{II eff,th}}^{\text{I}} = \Delta K_{\text{II eff,th}}^{\text{II}} \). The angles \( \alpha < \alpha_t \) correspond to values of \( \Delta K_{\text{II eff,th}}^{\text{II}} \) lower than those of \( \Delta K_{\text{II eff,th}}^{\text{I}} \), which means the dominant mode II growth (and vice versa for angles \( \alpha > \alpha_t \) related to mode I dominance). Equating relationships (2) and (3) gives

\[
E (3 \cos \alpha_t - 1) = 4G \sin \alpha_t,
\]

which, for the Poisson ratio \( \nu = 0.3 \), leads to

\[
\cos \alpha_t = \frac{1}{2} \left( \frac{20}{\pi} \sin \alpha_t + 1 \right), \quad \alpha_t = 2 \arctan \left( \frac{1}{3} \sqrt{438 - 10} \right) \approx 45.6^\circ.
\]

The result \( \alpha_t \approx 46^\circ \) is sufficiently accurate for all metallic materials. According to their deflection angles (see Table I) the cracks in ferritic steel as well as in both titanium grades grow under the dominant mode II mechanism (\( \alpha < \alpha_t \)), while those in the pearlitic steel grow in the dominant mode I mechanism (\( \alpha > \alpha_t \)).

![Fig. 3. Illustration of the types of dominant growth mechanisms in single-phase materials (full bars) and in dual-phase materials (shaded bars).](image)

Let us emphasize that, in the previous studies \([3, 16]\), the dominant growth mode was determined by identification of characteristic fractographical patterns on the fracture surfaces of investigated materials. This analysis led to a value \( \alpha_t \) in between 40 and 50 degrees, in a good agreement with \( \alpha_t \approx 46^\circ \), determined by the new criterion. In Fig. 3 the bar chart illustrates the types of dominant growth mechanism in single-phase materials (full bars) as well as in dual-phase alloys (shaded bars). One can see that bcc and hcp single-phase metals exhibit a dominant mode II crack growth while the mode I growth dominates in fcc single-phase metals. The crystallographic reasons for such a kind of branching behaviour are explained elsewhere \([1]\). The arrows in Fig. 3 indicate how the type of secondary phase changes the branching behaviour of the matrix, as already discussed in this section.

5. Conclusions

This work studied the influence of type of the secondary phase on the dominant growth mechanism of fatigue cracks under the remote shear mode loading in metallic materials. It was shown that, in the pearlitic steel, the presence of cementite lamellae caused a change of the local mode II growth mechanism into the local mode I mechanism. Consequently, the effective mode II and mode III thresholds increased in comparison with the purely ferritic steel. On the other hand, a rather coherent phase boundary between the \( \alpha \)-titanium (hcp) and the \( \beta \)-Ti lamellae (bcc) in the Ti6Al4V alloy allowed for dislocation crossing and did not change the local growth mechanism. Thus, the effective mode II and mode III thresholds in this alloy remained approximately equal to those previously measured for the pure \( \alpha \)-titanium. The competition between the local shear and the local opening growth mode was classified by a newly proposed mode I branching criterion based on fracture mechanics. The value of the transition deflection angle determined by this criterion (\( \alpha_t \approx 46^\circ \)) agrees well with the previously published result based on identification of characteristic fractographical patterns on the fracture surfaces of metallic materials (\( \alpha_t \) in between 40 and 50 degrees).

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