INFLUENCE OF THE MICROSTRUCTURE ON THE CRACK PROPAGATION: IN SITU INVESTIGATION IN THE SCANNING ELECTRON MICROSCOPE

M. Marx and H. Vehoff
Institute of Materials Science and Methods, Saarland University, D-66041 Saarbrücken, Germany

ABSTRACT

Short crack behavior and its origin are still discussed in literature. The aim is to connect the threshold value for crack growth and the crack growth rate with physical values like plastic zone size, crack opening displacement, stress intensity factor K or the maximal stress. One possibility to explain short crack behavior especially crack stopping, is the interaction of microstructurally short cracks with grain boundaries. To measure the influence of those microstructure elements like grain boundaries and phase boundaries, in situ investigations in the scanning electron microscope (SEM) were done. Therefore two techniques were developed which allow initiating microcracks at prescribed positions in the specimen. By a thermal shock microcracks with a length from 50 to 150 µm can be produced and by focused ion beam microcracks with a length from some microns up to several hundred microns can be produced.

Two different materials were investigated. Nickel was used to investigate the interaction of cracks and grain boundaries and the single crystalline Nickel base superalloy CMSX-4 was used to investigate the influence of the precipitates and the influence of the orientation of the crack propagation. Macroscopically the cracks in CMSX-4 showed no typical short crack behavior although crack growth was observed in stage I and in stage II. In the SEM the crack opening displacement and the crack growth rate per cycle could be measured with a resolution of 20 nm. It was found that the crack growth rate could be described by the plastic crack opening displacement while the total crack opening displacement, which is normally measured, depends on the crack length. Crack growth was observed for the <001>- and the <111> orientation that takes place by completely different mechanisms. Additionally the Electron Channeling Contrast Imaging (ECCI)-technique will be used to get further information on the interaction of cracks and grain boundaries.

1 INTRODUCTION

It is well known that short fatigue cracks propagate faster than long cracks at the same level oft the stress intensity factor ΔK and that short cracks start propagating at ΔK values lower than the threshold value of long cracks. Therefore the estimation of lifetime of a broad range of fatigued structures and components on the basis of the stress intensity factor is difficult [1, 2]. The origin of the size effect is distinguished in: (i) microstructurally small cracks, e.g. cracks comparable in length to the grain size in a polycrystall (ii) mechanically small cracks e.g. the crack tip plastic zone size comparable to the crack length and (iii) physically short cracks e.g. crack length in the order of millimeters [3].

Deshpande, Needleman and Van der Giessen showed that the threshold of short cracks is determined by the internal stresses under cyclic loading due to the dislocation structure in the vicinity of the crack tip. They further found that the near crack tip dislocation density, the plastic zone size and the crack tip opening displacement at σ_{max} for near threshold values of ΔK_I are approximately independent of crack size [4]. In this investigation the influence of grain boundaries or phase boundaries was not included. Due to the influence of the dislocation structure, grain boundaries influence the crack propagation what is observed by short cracks stopping in the front of grain boundaries.

One group of materials that is highly influenced by short crack propagation in the low cycle fatigue (LCF) regime is the high temperature materials for turbine blades. For example the excellent mechanical properties of nickelbase superalloys at high temperatures like high crack growth resistance and increasing yield strength are determined by the γ/γ'-microstructure. However, in turbine blades due to processing, repairing and service the microstructure changes continuously from beginning till end of turbine life. Furthermore near laser drilled cooling channels and heat protection layers the γ/γ′-microstructure is resolved and due to high loads the rafting structure may develop. Microcracks can easily be initiated by these defects and the propagation of these cracks determines the LCF-lifetime. Therefore crack growth through different microstructures was investigated macroscopically and locally in situ in scanning electron microscope (SEM).

2 EXPERIMENTAL

2.1 Crack initiation

To investigate the influence of grain boundaries and other microstructural elements like phase boundaries on the crack propagation and two different materials are investigated. One material is polycrystalline nickel with a grain size of about 50 µm to investigate the influence of grain boundaries. The other material is the technical relevant single crystalline nickel base superalloy CMSX-4. In CMSX-4 with cubic γ′-precipitates with a mean size of 500 nm and a volume fraction of 70% the influence of the precipitates and their orientation can be investigated. The specimens are cut by spark erosion and two methods were introduced to initiate surface microcracks. First, artificial microcracks with a length of 50 to 150 µm can be initiated by thermal shock (Figure 1a). Thereby in CMSX-4 a heat affected zone (HAZ) without γ′-precipitates develops [5]. The microstructure can be restored by a heat treatment. Due to this process small areas of the HAZ have disorientation, which are the so-called “freckles”. In this case there is a microcrack with a grain boundary in front of the crack tip.

The second method to produce microcracks is a deep and sharp cut by a focused ion beam (FIB) (Figure 1b). Both methods can be used to initiate microcracks in a predicted place of the sample e.g. near a grain boundary. By the FIB the crack can be placed directly near the grain boundary without any change in the microstructure. In this case a characterization of the specimen by orientation imaging microscopy (OIM) can lead to the measurement of special grain boundaries.

The artificial microcracks with a length of 50-150 µm are microstructurally short in case of nickel and physically short in case of CMSX-4. Therefore the approach of the K-concept that the plastic zone size at levels of the stress intensity factor K near the threshold value K_0 is small compared with the crack length is not suitable anymore. However, so far mainly long crack data are available for single crystalline turbine blade materials measured on standard CT-specimens on the basis of the K-concept. It would be helpful if this data pool could be used for a conservative calculation of LCF behavior of microcracks.

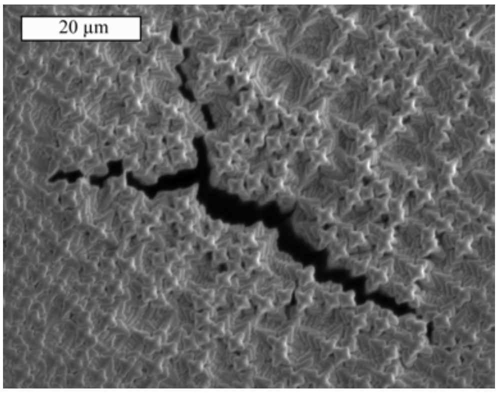


Figure 1a: Crack initiated by thermal shock.

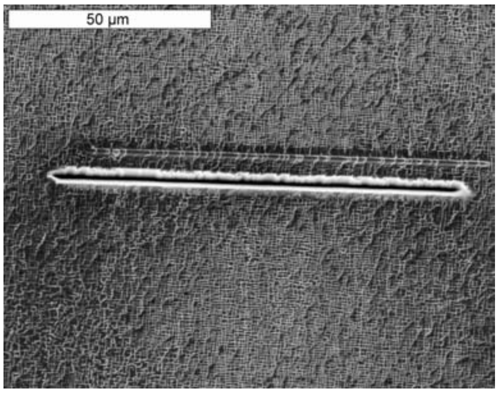


Figure 1b: Crack initiated by FIB.

2.2 In situ crack propagation in the SEM

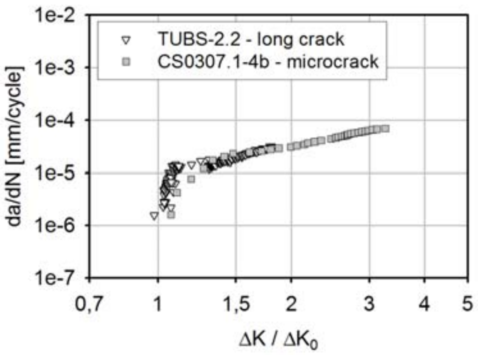
The maximal fatigue frequency of the loading stage for the SEM is 0.01 Hz. Therefore the specimens are pre-fatigued in a servo hydraulic testing machine till crack propagation starts. Following the specimen is mounted in the SEM where the crack propagation rate, the crack opening displacement and the crack path are observed in situ and measured quantitatively for several hundred cycles. This was done for different orientations of the single crystalline superalloy and for different microstructures like the γ/γ´-structure and the HAZ. The second step is to investigate the same procedure in nickel samples. In the servo hydraulic testing machine the crack will be grown till the crack tip is near the grain boundary. In the final step the specimen is also mounted in the SEM and the crack propagation through the grain boundary can be observed in situ and the parameters like crack growth rate, COD and crack path can be compared with the results without grain boundary in the vicinity.

3 DISCUSSION

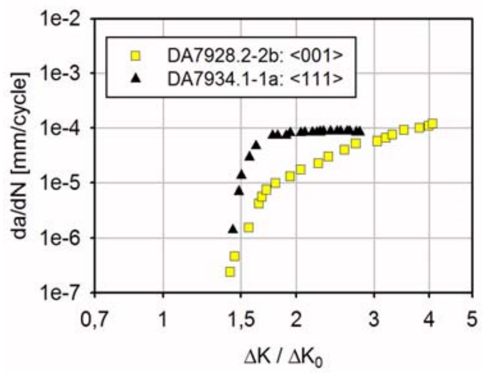
3.1 Macroscopic crack propagation

In CMSX-4 macroscopically no typical short crack behavior was found (Figure 2a). Crack propagation starts at stress intensity factors higher than the threshold value ΔK_0 of long cracks. For ΔK lower than the threshold value even after more than 100.000 cycles no crack propagation could be detected. Therefore the LCF-behavior of microcracks in CMSX-4 can be described conservatively by the K-concept. In addition it was shown that the data pool of long cracks could be used for a conservative calculation of LCF behavior of microcracks from room temperature up to 1223 K [6].

A significant difference was found in the crack propagation rate for different orientations of the single crystal. While the threshold was independent from the orientation the crack propagation rate for <111> oriented specimen was about ten times the crack propagation rate of the <001>-oriented specimen (Figure 2b).



a)



b)

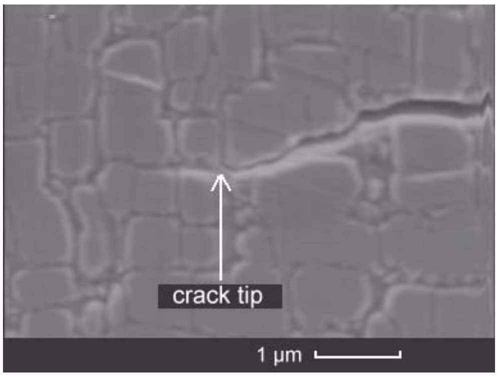
Figure 2a) Crack propagation rate of microcracks and long cracks in CMSX-4 at 823 K.

Figure 2b) Crack propagation rate of microcracks in <001>- and <111>- orientation.

3.2 Microscopic crack propagation

The crack propagation was locally investigated for the <001> and the <111>-orientation, specimens with and without HAZ or rafting structure in situ in the SEM. An example for the influence of the microstructure on the crack propagation mechanism is shown in Figure 3 where different crack opening modes in the <001>- and the <111>-oriented microstructure were found. In <001> orientation the crack path was located in the γ-Matrix, avoiding to cut the γ´-precipitates crack propagation takes place in stage II mode I crack opening while in <111>-orientation the crack propagates by cutting the precipitates on <111>-planes which means stage I crack propagation by mode II crack opening. Animated films comparable to stop motion technique of propagating cracks can be seen on [7]. Macroscopically this difference in the crack propagation mechanism was also found in different crack propagation rates (Figure 1b) whereby the threshold value was identical.

The local physical model for crack propagation, the alternating slip model was also proved which means that the crack propagation per cycle is determined by the plastic crack opening displacement COD although the total COD of short cracks can not be predicted by the established K-concept [8].

a) 

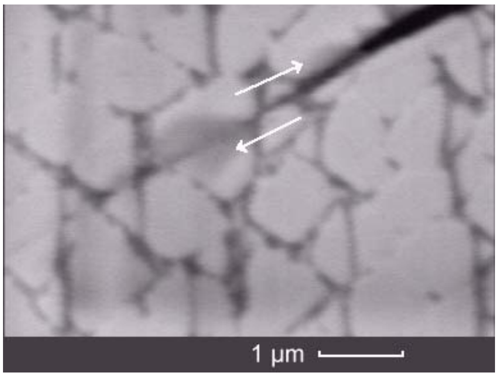
b) 

Figure 3a: Crack propagation in <001>-orientation.

Figure 3b: Crack propagation in <111>-orientation.

4 CONCLUSIONS

Thermal shock and FIB allows the initiation of artificial microcracks. Further more the thermo shock method allows a change in the microstructure of nickel base super alloys and to study the influence of the microstructure. It was found that the plastic COD could be used to describe the crack propagation behavior of short cracks in nickel base superalloys. It was observed that the microstructure leads to completely different crack propagation mechanisms. These artificial cracks can also be placed near grain boundaries to study locally the interaction of cracks with special grain boundaries. The Electron Channeling Contrast Imaging-technique will lead to further information on this interaction.

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