Influence of microstructural barriers on short fatigue crack growth

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Abstract

Increasing the resistance of materials to fatigue crack growth by optimizing the microstructure is one major task of materials science. In this regard, grain boundaries and precipitates are well known to decelerate short cracks, influenced by many parameters like crack length, distance to obstacles or orientation of adjacent grains. A comprehensive understanding of the underlying physical principles is missing.
The focused ion beam microscope offers new possibilities for systematic experiments and three dimensional investigations to quantify the microstructural impact. The ion beam is used to cut micro-notches as initiation sites for cracks. Contrary to natural cracks the influencing parameters can be varied independently for a systematic investigation of the mechanisms.
Additionally, the ion beam is used for tomography of the crack path and the surrounding microstructural elements. Thereby it is possible for the first time to reveal quantitative data of the effect of microstructural barriers on short fatigue crack growth.

Keywords

Microstructural crack propagation, Grain boundaries, Focused ion beam (FIB), Crack tomography

1 Introduction

The fatigue problem is technically described in two different ways: Estimating the lifetime by Wöhler diagrams which is more suitable for high cycle fatigue or calculating the lifetime by the Paris law where the crack propagation rate da/dN is a function of the cyclic stress intensity factor ΔK as given in equation (1):

$$\frac{da}{dN} = D \cdot \Delta K^m \qquad \text{Eq.(1)}$$

Thereby the constants D and m are material-specific fatigue values and have to be measured for every single material. On the other hand the alternating slip model which describes the crack propagation on the scale of dislocations and atom bindings is a simple geometrical consideration: The angle α between the active slip planes at the crack tip determines the crack tip opening displacement (CTOD)

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δ and consequently the crack growth Δa within one cycle can be calculated by equation (2):

$$\Delta \mathbf{a} = (\cot \alpha) \cdot \frac{\delta}{2} \qquad \text{Eq.(2)}$$

Considering linear elastic fracture mechanics with small scale yielding leads to the following relation between crack propagation rate and the cyclic stress intensity factor ΔK:

$$\frac{\mathbf{da}}{\mathbf{dN}} = \mathbf{D}^* \frac{\mathbf{K}^2}{\mathbf{E}\,\sigma_{\mathbf{ys}}} \qquad \text{Eq.(3)}$$

E is the Young's modulus and σ_{ys} the yield strength. This means that there is just one material parameter, the constant D*, which is given by the geometry of the involved slip systems and the amount of brittle fracture. Comparing equation (1) and equation (3) shows that the "material constant" m of equation (1) should be a physical constant of m = 2 which was locally proved by an extensive in-situ investigation. However, the measured values of m vary between 1 and 6 [1]. Additionally the propagation of short cracks is influenced by microstructural barriers like grain boundaries or precipitates. This leads to a fluctuating crack propagation rate, especially to reduced crack growth in front of a grain boundary and sometimes even to a total stop of crack growth. The models that describe the interaction of cracks with grain boundaries are based on the Bilby–Cotrell–Swinden-theory and the Weertman model for cracks, and the model of Tanaka and Navarro and De Los Rios for their interaction with grain boundaries, where dislocations emitted from the crack tip are blocked at the grain boundary. So far a lot of improvements of this simple model have been presented in the literature and several parameters have been discussed to describe the strength of the blocking effect quantitatively. For instance, the misorientation angle of the active slip planes in the adjacent grains is often discussed [1]. However so far this has not been checked systematically. Therefore new techniques were developed to perform such systematic experiments where single parameters can be changed independently. To image dislocation structures and plastic zones in bulk specimen ECCI technique which is known for the imaging of persitent slip bands in cyclically deformed materials was adopted and improved to evaluate the interaction strength of cracks with grain boundaries at least qualitatively. Finally it is not clear how dislocations and the crack pass through the grain boundary. So far this could only be investigated by simulation methods [2], now it can be checked experimentally by the FIB tomography which gives a 3D insight in the passing process.

2 Experimental

2.1 The advantages of artificial crack initiation

For a systematic experiment on the blocking effect of microstructural barriers a technique is needed to vary the parameters independently which influence the crack propagation. These parameters are: Crack length, distance between crack tip and obstacle and in the case of grain boundaries the misorientation of the adjacent grains. Varying only one parameter by keeping the other parameters constant is possible by initiating micro-cracks with the FIB combined with electron back scatter diffraction (EBSD) measurement.

The FIB is the only tool to cut reproducible micro-notches with notch parameters with an accuracy better than 1 µm. Now there are two possibilities: The crack parameters can be kept constant and grain boundary parameters can be changed by selecting different grain boundaries. Or the notch parameters length and distance between initial notch and grain boundary can be changed systematically on the same grain boundary (figure 2a). This should result in a difference in the driving force of the crack at the point when the crack tip approaches at the grain boundary.

The EBSD-technique is also beneficial in two ways: Grain boundaries of special interest for instance with a high or a low misorientation angle between the preferred slip planes in each grain can be selected from the EBSD grain orientation map (figure 1). The second benefit of the EBSD characterization of the specimen is that the easiest mathematical description of the blocking effect implies stage I cracks with a single slip band in front of the crack tip. Exactly the preferred slip plane can be selected from the EBSD data and the starting notch can be cut with the ion beam directly on the plane with the highest shear stress (figure 2b). This is experimentally realized by twisting and tilting the specimen in the FIB microscope. Now we are able to check the often discussed and used models for fatigue crack propagation. Details can be found in [3]

There have been a lot of materials tested. The FIB crack initiation has been proven for nickel based superalloys, steels and aluminium alloys. Especially the nickel based superalloys which are often industrially used in the directionally solidified configuration are a very sophisticated model material because they have long grain boundaries where several cracks with different crack parameters can be introduced near one grain boundary. The best specimen configuration in this case would be a bicrystal which can be seen in [4].

Fig.1: EBSD-grain orientation map of a polycrystalline nickel specimen. Twin boundaries are marked in yellow (not in print version available).

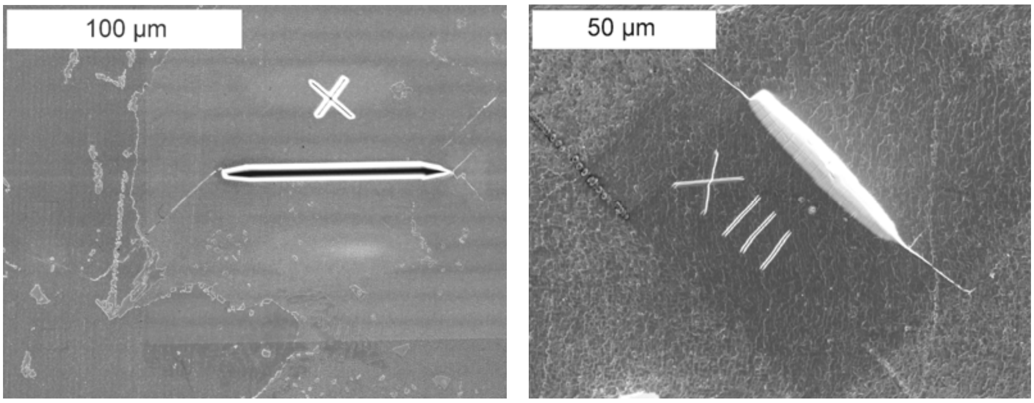


Fig.2 a) FIB notch in front of a grain boundary with a crack emitted from the notch tip cutting the grain boundary.

b) FIB notch initiated directly on the preferred (111)-slip plane calculated from the EBSD data.

2.2 Crack propagation and interaction with obstacles

Fatigue tests were performed using a servo-hydraulic testing machine with a sinusoidal load profile and a frequency of 5 Hz. The stress amplitude was chosen well below the yield strength and the load ratio was -0.1. Several samples of the DS superalloy have been tested to quantify the influence of grain boundaries on crack growth. Therefore the overall crack length in respect to the number of load cycles for one cracks is shown in figure 3a. Additionally in this figure the estimated crack length without the grain boundary ahead of the crack tip is shown (indicated as "calculated"). This data was used to calculate the benefit in life time and the crack growth velocity (figure 3b). Details can be found in [3, 4]. It can be seen that the crack stopped in front of the grain boundary for several thousand cycles. The benefit in lifetime was calculated to 30.000 cycles.

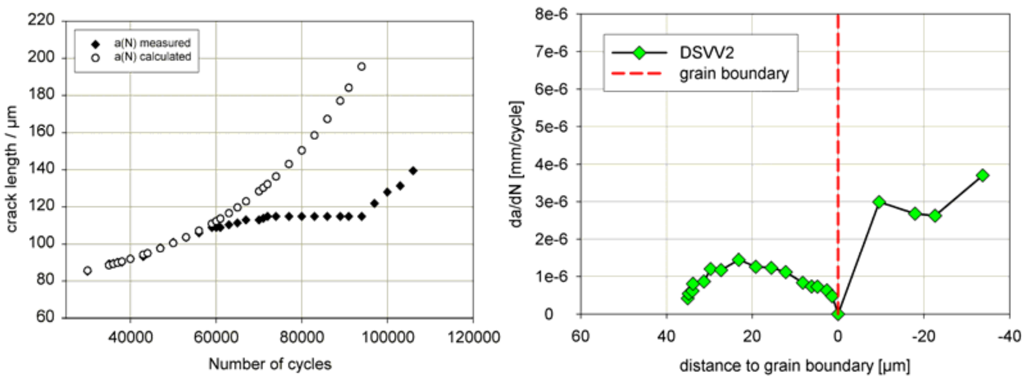


Fig.3 a) Crack length as function of the number of cycles as measured and as calculated for a specimen without grain boundary.

b) Crack propagation rate as function of the distance to the grain boundary for the crack of figure a). For further details see [4].

A special technique to visualize the interaction zone of a crack with a grain boundary is the ECCI technique. This Imaging technique of the SEM can be used to make local stresses and strains visible. Details can be found in [5,6].
In the case of a fatigue crack the plastic zone at the crack tip can be visualized as shown in figure 4. In this case figure 4a was imaged under in situ loading at the maximum stress of the fatigue experiment while figure 4b was imaged at zero stress. The plastic zone can be identified as the diffuse structure around and in front of the tip. It is astonishing that in the unloaded condition there is an additional plastic deformation zone visible in the adjacent grain coming from the point where the plastic zone hits the grain boundary (marked by the arrows). However on second thought this is clear. At maximum load all internal local stresses higher than the yield strength are compensated by forming dislocation structures which are then visible after removing the load due to residual stresses.

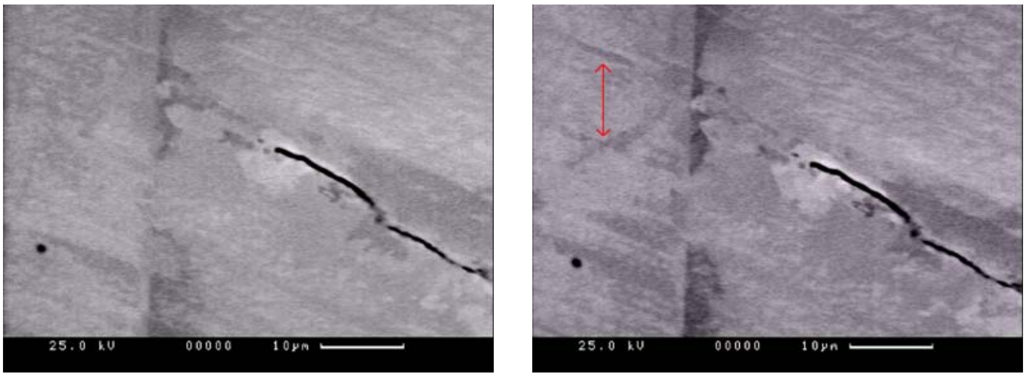


Fig.4:ECCI images of a crack tip in front of a grain boundary (going from the top to the bottom of the images).
a) In situ imaged under maximum load.
b) Imaged at zero load.

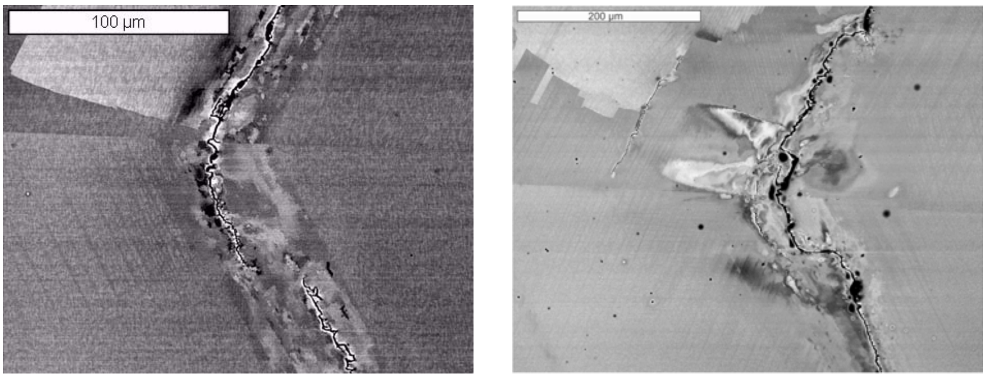
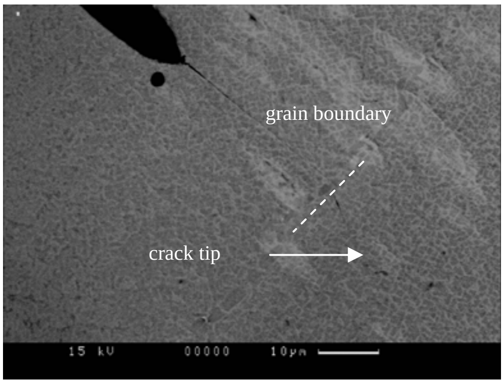


Fig.5: The plastic zone around two different cracks:
a) The crack shows nearly no interaction while passing the grain boundary.
b) Huge spreading of the plastic zone in the interaction region.

The practical value of this fact is, that the whole plastic zone can be imaged under zero load which makes complex in situ loading measurements redundant at least if solely the plastic zone is in the point of interest. To estimate the force of a crack while passing a grain boundary the plastic zone around cracks initiated during fatigue life can be imaged after the fatigue test. The spreading of the plastic zone in the interaction region as illustrated in figure 5 for two different cracks can be used at least as a semi quantitative measure of the resistance of the boundary against crack propagation. More details can be found in [5, 6].

2.3 Fatigue crack growth in case of the bicrystal:

Fatigue crack growth in stage I could be observed at two notches with different initial distance to the grain boundary in a bicrystal. The figures 6a and 6b show backscatter images of both notches after 30,000 cycles. It can be seen that the crack length is much longer for the crack that initiated at the notch further away from the grain boundary. It has to be pointed out that for the notch positioned closer to the grain boundary, crack growth could only be observed on that tip of the notch which is adjacent to the grain boundary until the grain boundary was reached. The crack arrested over a period of 5,000 cycles at the grain boundary until crack growth could be observed at the other tip and it took further 2,500 cycles until the crack overcame the grain boundary. In contrast, no crack arrest was observed for the notch with the higher distance to the boundary.



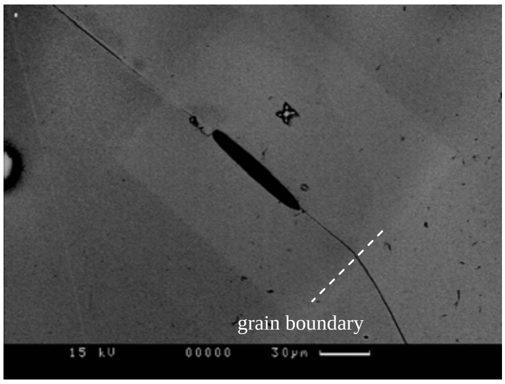
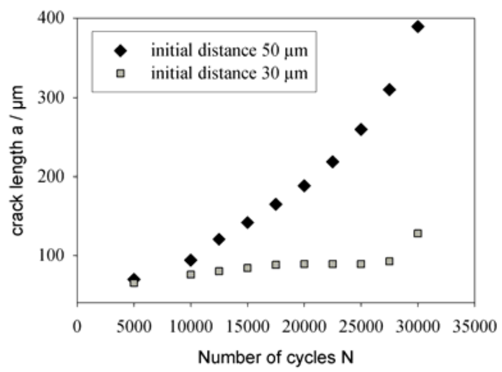


Fig.6 a) The notch has a distance of 30 µm to the grain boundary.
b) 50 µm away from the boundary, the crack was able to spread further.

The overall crack length in respect to the number of load cycles for both cracks is shown in figure 7a. This data is used to calculate the crack growth velocity by a 5-point polynominal fit. The results (figure 7b) show a strong deceleration of the shorter crack which initiated closer to the boundary while for the other crack, no deceleration can bee seen. After the former mentioned crack passed the grain boundary at a length of approximately 90 µm, both cracks show the same velocity. If only the velocity of the crack tip spreading towards the grain boundary is considered, a deceleration can be seen for both crack tips (figure 8), but the deceleration for the crack that initiated closer to the boundary is still more pronounced. No crack advance for the latter crack could be shown after passing the boundary. This is due to the fact that only two replica images of the crack could be made since it passed the boundary. The experiment was stopped afterwards since the length of the other crack was too large so that further loading of the sample could lead to failure.



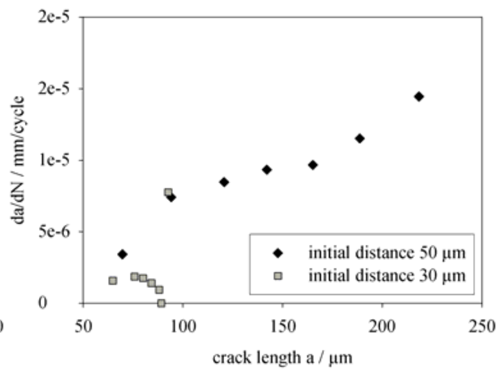


Fig.7 a) Crack length as a function of cycles for both cracks.
b) The calculated crack advance according to figure 7a.

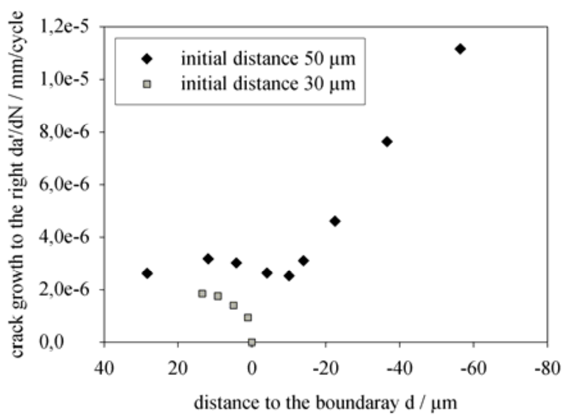


Fig.8: Crack advance for the part of the crack facing the boundary related to the distance

The observations of the two cracks are in good agreement with the theories based on continuous distributed dislocations [7, 8], which was already applied in literature [9], since crack growth is more pronounced for the shorter crack when it approached the grain boundaries and both cracks accelerate after passing the boundary. It has to be pointed out that both cracks approach the same boundary in the same orientation even in the same sample. However, further experiments with bicrystals will be performed to gather more information about the influence of grain orientations and load on the interaction between short cracks and grain boundaries.

2.4 3D investigation of the interaction problem by FIB tomography

How can the resistance of a grain boundary against crack propagation be quantified? One possible parameter introduced in the Zhai model uses the misorientation angle of the active slip planes in the adjacent grains [10]. As mentioned above the grain boundaries of interest can be selected by initiating the cracks directly in front of the boundaries by the FIB. However for a detailed view the problem must be examined in three dimensions because it is a three dimensional problem. The crack has to change its propagation direction in the surface plane and perpendicular to the surface. Therefore several steps must be created at the grain boundary. The surface energy is discussed as a measure for the resistance of a grain boundary against crack propagation because the energy is proportional to the additional crack surface resulting from these steps (figure 9). The three dimensional geometry of the cracks and the grain boundaries can be reconstructed by FIB tomography (Figure 10) to measure the inclination angles between the surface, the crack plane and the grain boundary. Details can be found in [3,11]. However in this case the reduction of the crack propagation rate near the grain boundary was not due to the inclination angle between the slip systems but due to the precipitates which had to be overcome by producing additional surface steps which is nearly the same effect as described above.

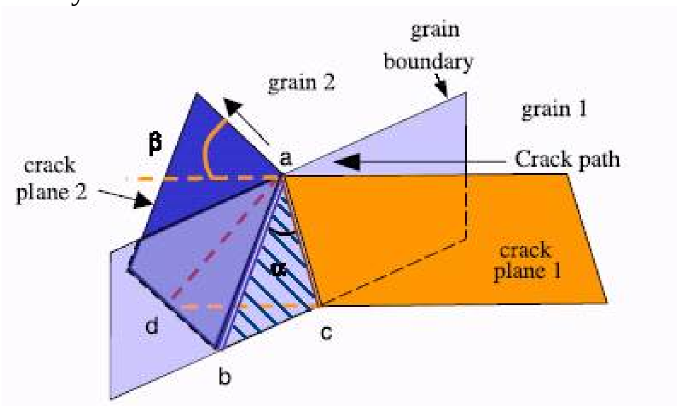


Fig.9: 3D geometry of a crack intersecting a grain boundary. Normally only the surface is visible. The additional surface is given by the hatched area [10].

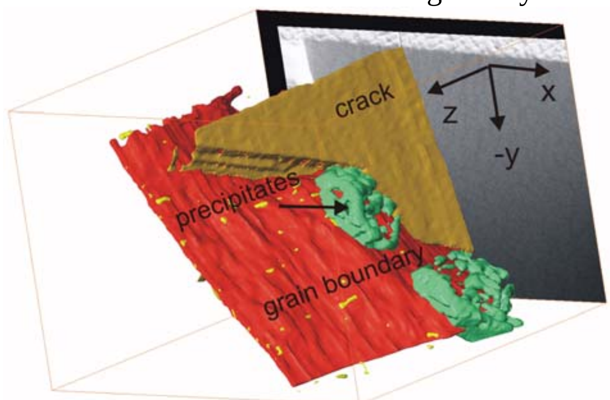


Fig.10: 3D-reconstruction of a crack plane and a grain boundary decorated with precipitates.

3 Conclusions

It has been shown that the influence of grain boundaries on the propagation of short fatigue cracks can be imaged by the ECCI-technique which can also be used for a semi quantitative estimation of the interaction strength. Additionally by using the FIB and a sophisticated experimental set up the influence of different parameters which influence the interaction of short fatigue cracks with microstructural obstacles can be investigated independently. Combining these techniques with local in-situ investigations of the CTOD will be helpful to improve the models for the crack propagation by replacing material parameters by general parameters based on the microstructure to avoid at least some complex and expensive fatigue tests by simple metallography.

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