Crack paths in a superalloy in aged condition

F. Kuhn[1], F. Zeismann[1], A. Brückner-Foit[1], K. Kadau[2], P. Gravett[3]

[1]Institute for Materials Engineering, Quality and Reliability Group, University of Kassel, Moenchebergstrasse 3, D-34109 Kassel, Germany; contact e-mail address: a.brueckner-foit@uni-kassel.de
[2] Siemens AG, Energy Sector, Fossil Power Generation Division, Mellinghofer Str. 55, D-45473 Muelheim an der Ruhr, Germany
[3]Siemens Energy, Inc., Life Methods and Tools, 4400 Alafaya Trail - Mail Code Q3-031, Orlando, FL 32826, USA

ABSTRACT. *The crack paths are analysed of fatigue cracks in aged IN 738 taken from removed turbine blades. Both artificial cracks initiated from notches and service cracks found in removed blades are taken into consideration. Transgranular crack growth is most common in the virgin material, but can still be found in aged material and in service cracks. Under operating conditions, transgranular crack growth is related to re-crystallization of the material along the crack faces. It is suggested that the local plastic deformation plays an important role in this recrystallization process.*

SUBJECT OF INVESTIGATION

Superalloys in gas turbine environment are exposed to very harsh thermal and loading conditions for a substantial amount of time. In addition to that high mechanical cyclic stresses occur during start-up and shut down. Cracks may be initiated at hot spots and extend stably for a certain amount of time with the crack faces being directly exposed to service conditions without any protection.

Crack growth in Ni-base alloys, especially in the widely used alloy IN 718, has been studied extensively over the past two decades. Important influence factors in conjunction with aging are precipitate size and morphology, grain size and grain boundary morphology (e.g. [1] - [5]). The crack path was predominantly transgranular at room temperature and moderately high temperatures, whereas a pronounced increase in crack growth rates together with creep crack growth and intergranular cracking was found at very high temperatures (e.g. [1], [6]). However, this transition in the crack path was observed to be dependent on grain size with fine grained materials being more prone to intergranular cracking.

All tests were performed with virgin material or material aged under lab conditions. Hence, these studies allow identifying influence factors and trends, but do not represent the effect of material aging in a gas turbine at operating conditions. Therefore, a study was initiated by Siemens AG with the purpose of investigating crack growth in aged IN 738. In this study, special emphasis was put on analyzing crack paths and on understanding the extension mechanisms of fatigue cracks. Aged material was available in the form of turbine blades which had been removed during routine in-service inspections of gas turbine plants. Some of these blades contained service cracks at hot spots, whereas others didn't have visible signs of degradation.

EXPERIMENTS

Miniaturized hour-glass specimen (total length 45mm, width in gauge section 8mm) were cut from the blades in the vicinity of the hot spot areas by high precision spark erosion (Fig. 1). Narrow notches were introduced on both sides of the specimens at midsection. The specimen were then mounted in a servo-hydraulic testing machine and subjected to load controlled fatigue loading with R=0.1. Crack extension was monitored during the test using the potential drop method by surface monitoring with a traveling long distance microscope.

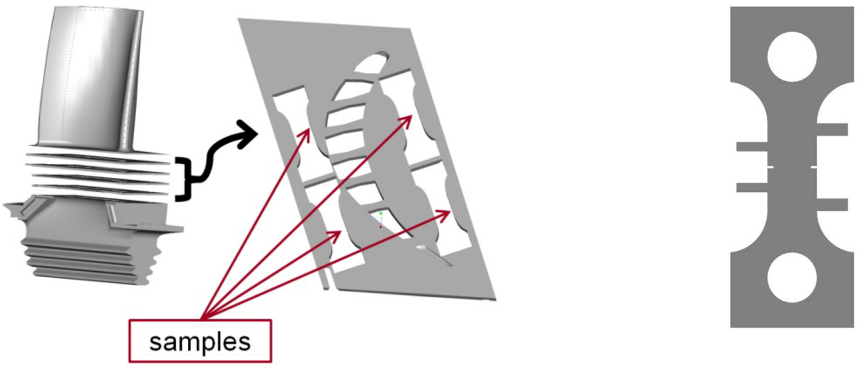

Figure 1: Positioning of specimen within a blade and specimen with notch

The material used was the standard Ni-base superalloy IN 738 in three material conditions. Several blades had been removed from base load gas turbines, i.e. they had been exposed to long hold times at operating temperature, whereas others had been taken from peak load plants which are run with short operating cycles. The number of shut-down/start-up cycles was comparable in both cases. The third material condition was virgin material.

RESULTS AND DISCUSSION

Crack growth curves were obtained at room temperature for three different material conditions: virgin material, base-load aged material, peak-load aged material. The data were collected in a classical da/dN-ΔK-diagram with the range of the stress intensity factor calculated using FE analysis. The crack length inserted the relations obtained was the one following from the potential drop measurements. In general, the data followed a Paris line, but the amount of scatter was quite substantial (up to 2 orders of magnitude for the base load material and one order of magnitude for the peak load and the virgin materials).

Figure 2 illustrates how a typical crack develops in the aged material (peak load blade). The crack path is partly transgranular, partly intergranular with numerous deflection points and crack branching. Interaction with microstructure is very strong, and shear controlled transgranular crack extension is possible at any stage due to the very coarse grains.

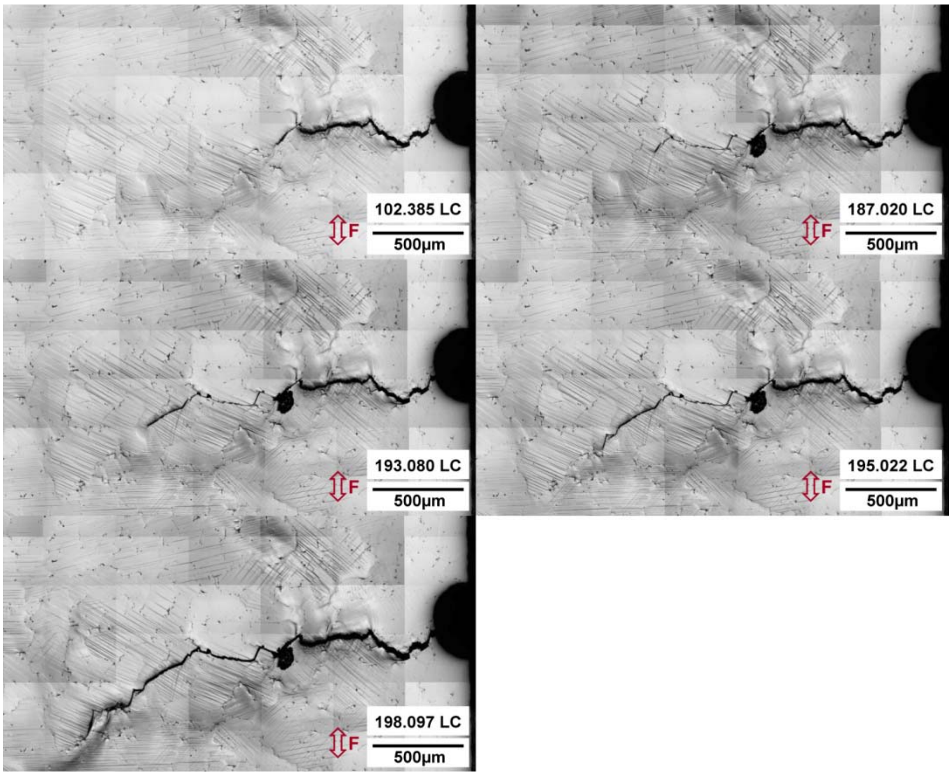

Figure 2: Development of fatigue crack from notch root; peak load blade

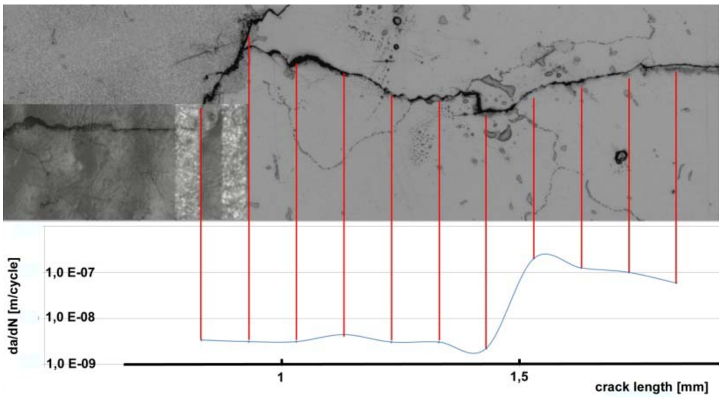

Figure 3: Crack growth rates along crack path; peak load blade

Figure 3 illustrates that the amount of scatter observed in the crack growth rates is directly related to the interaction between the crack and the microstructure. At the beginning observation, the crack possesses an intergranular crack path, and growth rate (measured by increase of crack length on the surface in this case) remains constant for more than 1mm crack extension. Then the crack tip passes through some smaller microstructural features and continues in a transgranular mode with an increase in crack growth rate by two orders of magnitude.

The crack paths found in the peak load material are very similar to those of the base load material. A typical example is given in Fig. 4 which also illustrates the transition between microstructure dominated crack growth with partly transcrystalline, partly intercrystalline crack path, and mode I crack growth with contributions of several activated slip systems. This transition occurs much earlier in the virgin material leading to comparatively straight crack paths and predominantly trancrystalline crack extension.

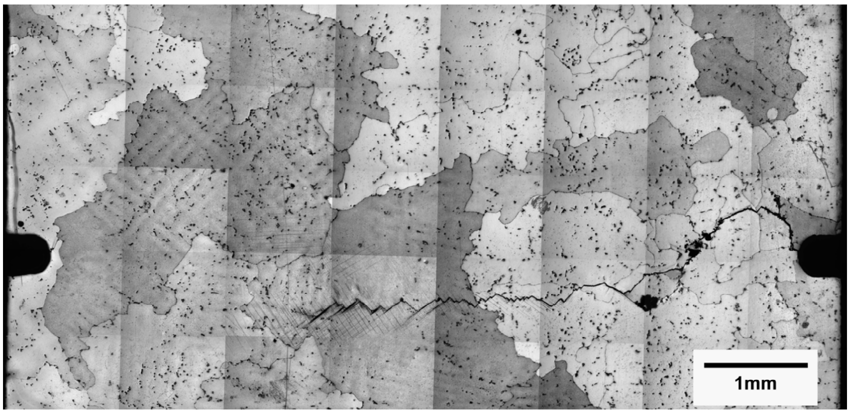

Figure 4: Crack path in base load aged material with transition to mode-I long crack growth

Service cracks have an even more tortuous crack path than artificial cracks in aged material, see e.g. Fig.5. A close-up of the microstructure in the vicinity of the crack tip shows that even though the intercrystalline extension mode is dominant there are also some parts of the crack path which seem to be transcrystalline (on the right hand side in Fig. 5b). Crack branching occurs frequently and sometimes gives rise to “backward” crack propagation.

A closer inspection of the crack faces show that there are some structural changes at the edges (see Fig. 6). First of all there is a zone of very porous material at the very edge. This is very likely material which had been partly molten under operating condition. If the crack is open, there is no protection against the hot combustion gases and the local temperatures are apparently well above design level. This zone of porous material has a width of about 1µm in the straight section of the crack shown in Fig. 6, but may become much wider (up to 50µm) at bends and turns. It is not clear yet whether there is an inhomogeneous temperature distribution along the crack path or whether this observation is related to the oblique in-depth exension of the crack at kinks.

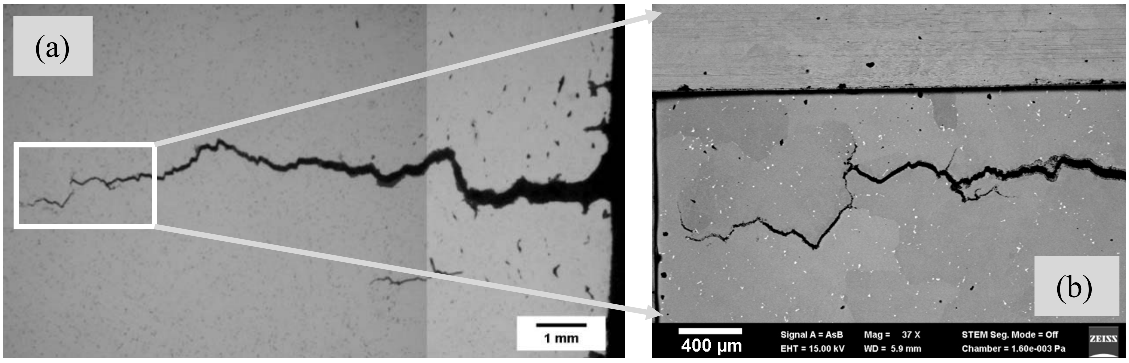

Figure 5: Crack path of a service crack in a base load blade; (a) overview with optical microcope, (b) SEM micrograph BSE

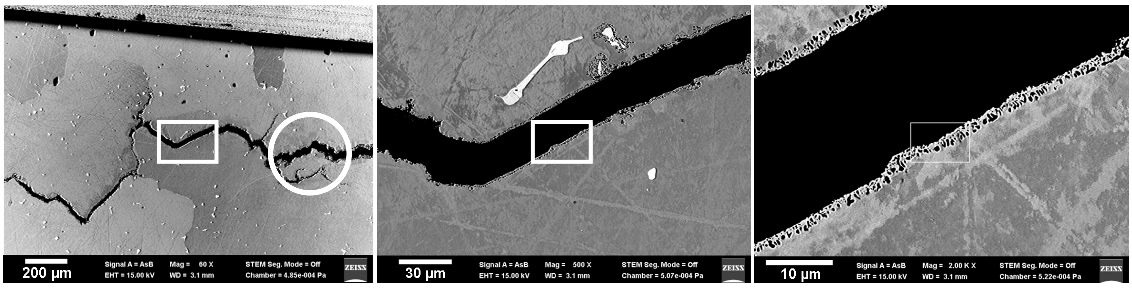

Figure 6: Zone of local remelting at crack face; SEM-BSE micrograph BSE

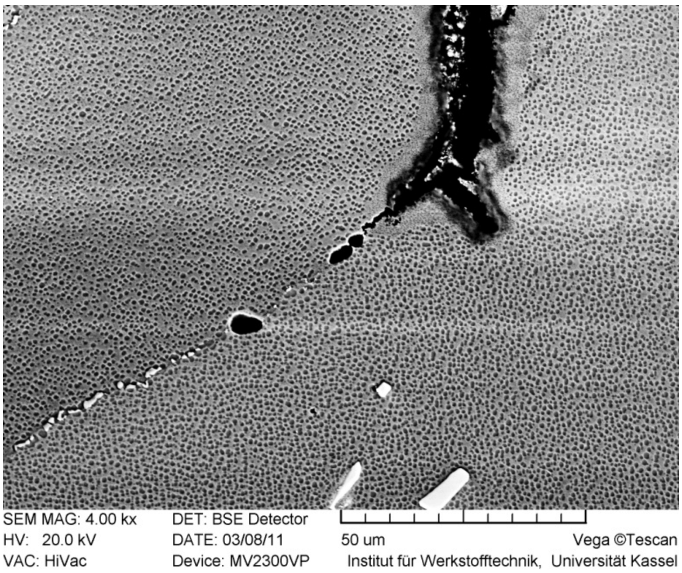

Figure 7: BSE image of crack tip showing zone without γ’-precipitates

In addition to the zone of porous material there is a band of material parallel to the crack faces where the visible γ'-precipitates have disappeared. This band can only be found in specific sections of the crack path; for the service crack shown in Fig. 5 this band exists in the vicinity of the crack tip (see Fig. 7) and in some parts along the crack. An EDX analysis was performed with the purpose of getting more detailed information about the distribution of γ'- precipitates along the crack faces. Fig. 8 shows the result for a crack face in the vicinity of the crack tip, and proves that there indeed no γ'-precipitates in this band.

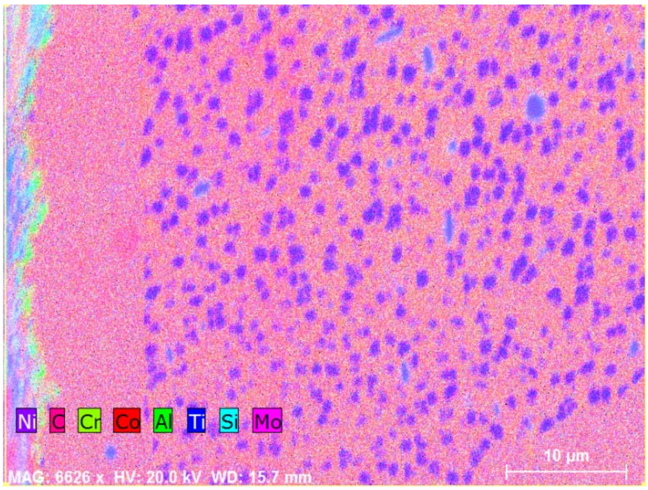

Figure 8: EDX-analysis of a crack face in the vicinity of the crack tip shown in Fig. 7

In the next step, an EBSD analysis was performed in order to find out whether this γ'-free bands can be related to other features of the microstructure. Figure 9 shows that the crack path was predominantly integranular with some transgranular parts at the left hand side in the vicinity of the branching point. There are some finer features visible in the EBSD map which are present along the transgranular crack path and between the two grains which are coloured in similar shades of pink and hence have very little orientation difference.

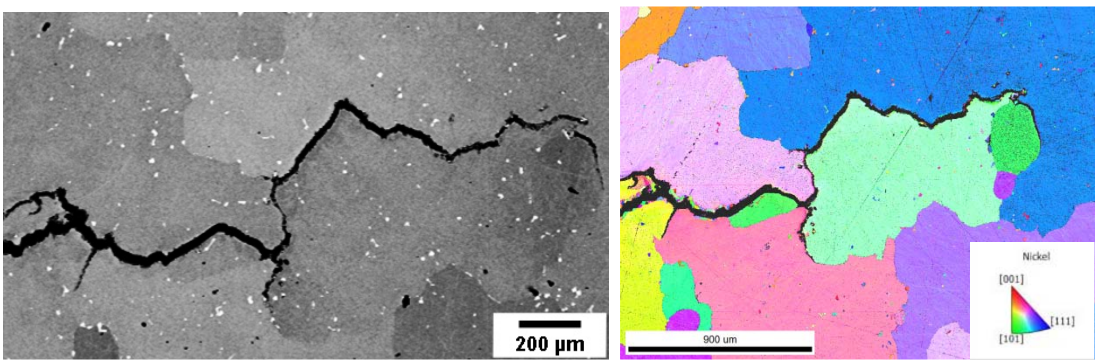

Figure 9: Section around the crack tip of the crack shown in Fig. 5 (rotated by 180°); comparison of micrograph (SEM BSE) and EBSD analysis

Figure 10 shows these features on a larger scale. Apparently there was some re-crystallization along the crack faces. This re-crystallization takes place whenever the crack passes in a transcrystalline extension mode through a grain or when it grows along a low angle grain boundary. A one-to-one match was found when comparing the zones of re-crystallization with the γ'-free bands.

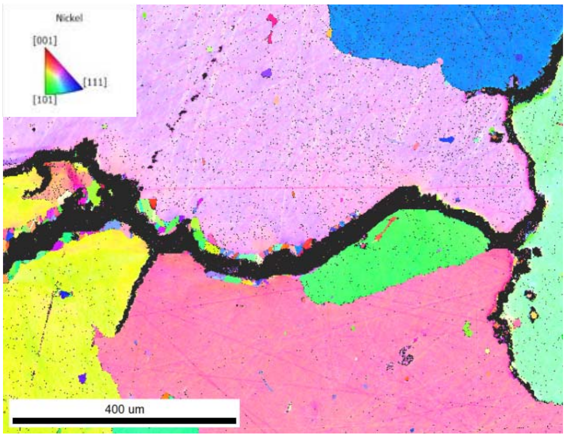

Figure 10: Re-crystallization along crack path

The largest zone of recrystallization was found in the area highlighted by the white circle in Fig. 6. The zone of high temperature damage (partial melting) is particularly large at the kink of the crack, and there is a substantial amount of re-crystallization around it (see Fig. 11). The edges of the crack are decorated by very finely grained layers. A mono-layer of crystals of constant width (about 50 μm) followed. These crystals contain numerous twin boundaries.

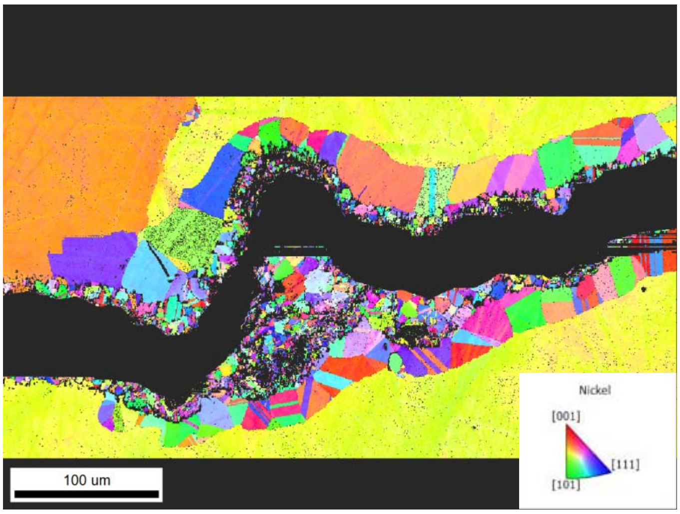

Figure 11: Re-crystallization zone containing twins

The crack discussed in Figs.5-11 was found in a base-load blade which typically experienced long hold times at high temperature. Further micro-analyses were performed with cracks in peak load blades in order to find out whether similar effects can be found there. Figure 12 indicates that this is indeed the case. Hence the re-crystallization process is closely related to the thermomechanical cycling during operation and is not a pure high temperature phenomenon which comes about at long hold times. Additional investigations with hardness indentations suggest that local plastic deformation is also an important influence factor.

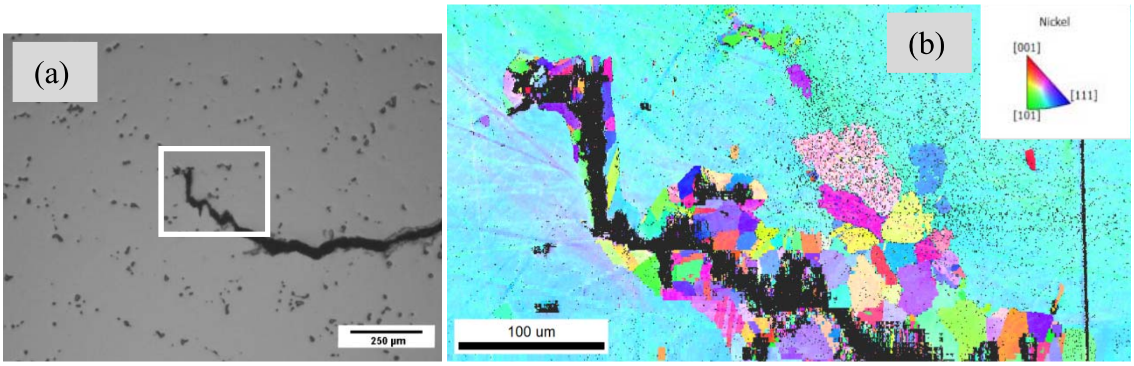

Figure 12: Re-crystallization zone around crack tip of service crack in peak load blade (a) optical microscopy (b) EBSD-analysis (IPF)

ACKNOWLEDGEMENT

Financial support by Siemens AG is gratefully acknowledged. Support of Bruker company (EBSD analysis) and Zeiss company is also gratefully acknowledged

REFERENCES

1. King, J. E. (1987) *Mater. Sci. Technology* **3**, 750 – 763.
2. Ghonem, H., Nicholas, T., Pineau, A. (1993) *Fat. Fract. Engng Mater. Struct.* **16**, 577-590.
3. Boyd-Lee, A.D., (1999) *Int. J. Fatigue* **21**, 393-405.
4. Pang, H.T., Reed, P.A.S., (2003) *Int. J. Fatigue* **25**, 1089-1099.
5. Pang, H.T., Reed, P.A.S., (2008) *Int. J. Fatigue* **30**, 2009-2020.
6. Mills, W.J., James, L.A., (1980) *Fat. Fract. Engng Mater. Struct.* **3**, 159-175.