Experimental investigations on the crack growth behavior in graded ferritic martensitic steel

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Abstract
An experimental approach is presented for characterizing the fatigue behavior of a functionally graded flange shaft. Micro-specimens are defined based on the inhomogeneous phase distribution and microstructure of the flange. Subsequently the experimental setup is described for the investigation of the phase dependent fatigue behavior, and some results are presented. It was found that there is a significant amount of crack retardation in the transition zone in the flange which is located between the soft ferritic phase and the hard martensitic phase. This is verified using a two-sided observation of the propagating crack with two travelling microscopes.
Keywords Graded material, crack growth, fatigue, edge crack

1. Introduction

Functionally graded steel components can play a key-role in the on-going challenges about increase of productivity and saving of resources as they can be tailor-made to the specific requirements in a given application case. However, standard testing and design procedures based on results obtained with homogenous materials may not be sufficient to ensure reliable operation of such components as the interaction of the different regions in the graded component can induce additional damage mechanisms. This is especially true for microstructure-based failure processes such as fatigue failure.

A simple example for a functional gradation is the surface hardening process of a steel component in order to achieve a soft, ductile core and a hard, wear resistant surface. The fatigue behavior of case or surface hardened steel component has investigated (e.g. [1, 2]) recently, and it was found that the failure behavior could not be predicted by just superimposing the results obtained with the constituents in standard tests.

Another, more complex way to produce a functionally graded component is an integrated thermo-mechanical treatment on a steel shaft to form a flange shaft. [3] Such a flange shaft is characterized by a defined local distribution of at least three phases – the soft ferritic-pearlitic base material in an untreated and a deformed state, a hard martensitic phase and a small, mainly bainitic transition zone in between. Under fatigue loading, crack may initiate in the soft phase and propagate towards the hard phase leading to catastrophic failure. In this case, crack initiation and propagation depends not only on the fatigue properties of each phase, but also on their spatial distribution. Obviously, conventional fatigue testing with homogenous specimens will not capture these specific features of the damage accumulation process in a graded component, and may therefore lead to erroneous results. Instead, specimens have to be defined which can directly be cut from the component and contain the phases of interest together with the component specific grading [4, 5].

This paper deals with obtaining valid crack growth data in the flange-shaft mentioned above [3].

The material and the microstructure obtained by the thermo-mechanical forming process are described in the first section. Then the experimental set-up is described which has been developed for obtaining microstructure-dependent crack growth rates. Finally the experimental results are compared with findings of a FE simulation.

2. Material and graded microstructure

The tested material is a low-alloy steel in tempered condition (German designation 51CrV4) with the chemical composition given in Table 1. It has a ferritic-perlitic microstructure and a yield strength of 520 MPa.

Table 1. Chemical composition of 51CrV4

Element	C	Si	Mn	Cr	V	P	S
Weight %	0,47-0,55	≤0,40	0,70-1,10	0,90-1,20	0,10-0,25	≤0,035	≤0,035

An integrated thermo-mechanical forming process, as shown in Fig. 1, was applied to a shaft resulting in a flange shaft with a graded microstructure [3]. First the shaft was heated up above austenitization temperature by induction heating and then put into the molding press to form the flange, which lead to a local martensitic transformation of the original ferritic-perlitic phase.

Figure 1: Integrated thermo-mechanical forming process of the flange shaft [6]

Due to the high natural strain during the forming process a fine grained microstructure is formed, which contains dispersed small defects like inclusions and carbides. The resulting phase distribution is given in the etched micrograph in Fig. 2. It is characterized by the ferritic-perlitic base cold-worked material (grey) in a in the core of the flange shaft and a martensitic phase (dark) at the outside of the flange. The phases are linked by a transition zone (white) of varying width and material properties. For an unambiguously phase identification micro-hardness measurements are used. As shown in Fig. 3, the martensite possesses hardness values above 650 HV (Pos. 1), the transition zone about 450 HV (Pos. 2) and the deformed base material has hardness values below 300 HV (Pos. 1).

Figure 2. Micrograph of the flange shaft, etched

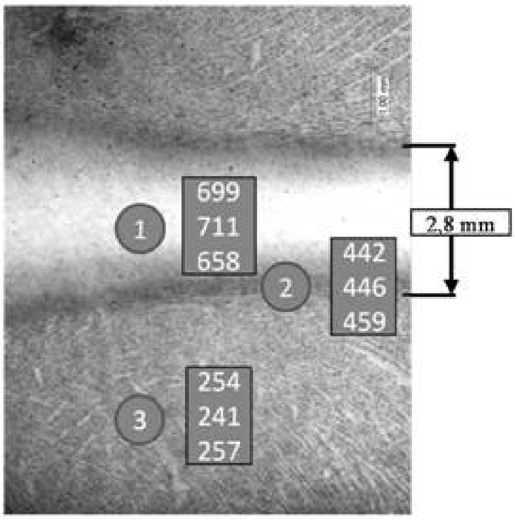
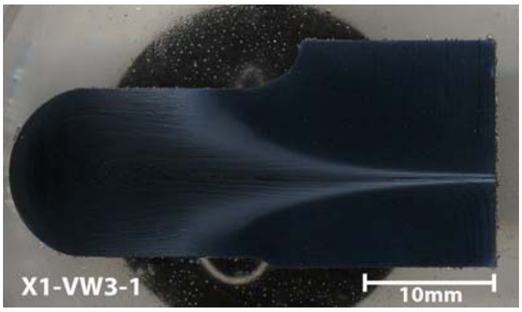
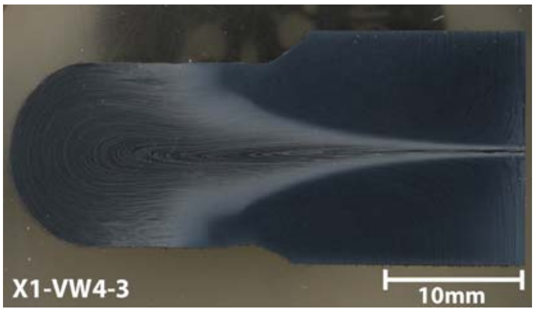


Figure 3. Vickers hardness of the different phases

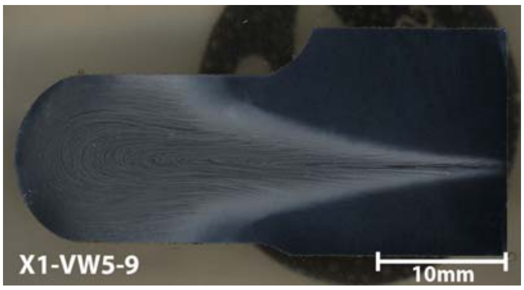
In order to optimize the local phase distribution and its properties in the flange shaft several pre-heating strategies were developed. Beside the standard flange shaft having room temperature at the start of the forming process four pre-heating temperatures were used for the flange. Therefore the flanges were heated up to 300, 400, 500 or 600°C in a convection oven. Then the local induction heating above the austenitization temperature was carried out before forming. The corresponding phase distribution in the flange shaft for each pre-heating temperature is given in Fig. 4 a-d).



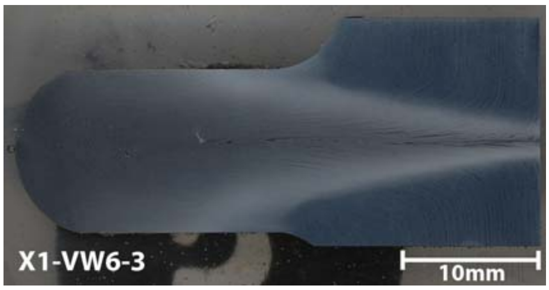
a) pre-heating temperature 300°C



b) pre-heating temperature 400°C



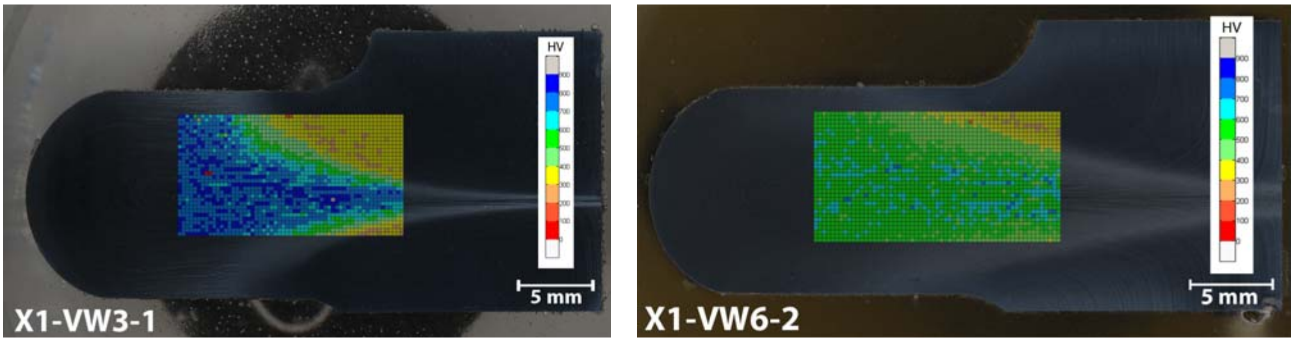
c) pre-heating temperature 500°C



d) pre-heating temperature 600°C

Figure 4. Micrographs of the flange shafts with various pre-heating temperatures, etched

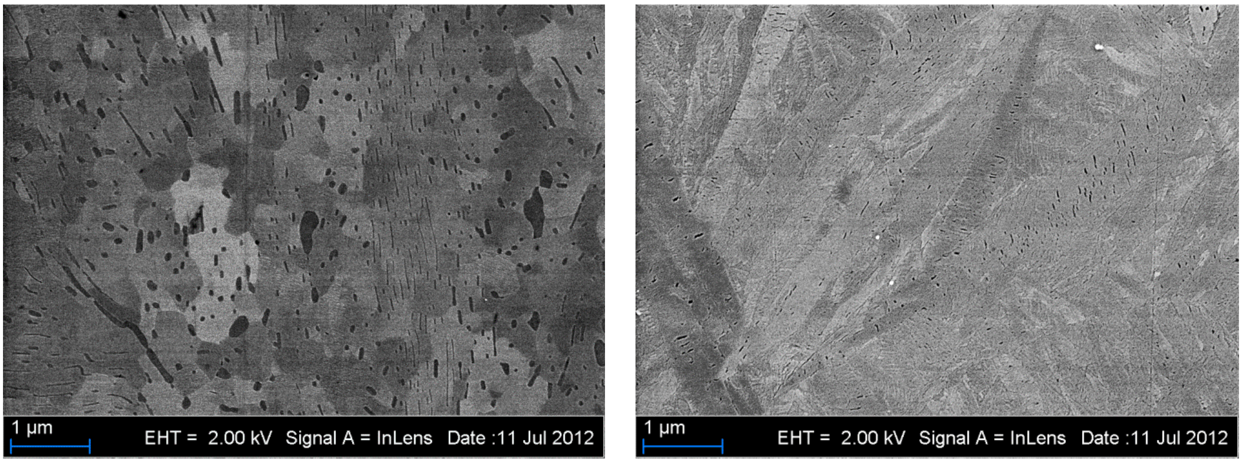
The etched micrographs of the flange shafts, given in Fig. 4 a)-d), reveal that an increasing pre-heating temperature leads to an increasing amount of the transformed phase at the outer part of the flange. The width of the transition zone (white area) increases as well. A second observation of the micrographs is that the etched micrograph becomes brighter in the transformed phase with an increasing pre-heating temperature. This indicates an increasing amount of bainite in the martensitic zone caused by a lower cooling rate during the phase transformation. Verification of this observation can be given by a micro-hardness indentation only, which is shown in Fig. 5 a-b).



a) pre-heating temperature 300°C b) pre-heating temperature 600°C

Figure 5. Micro hardness indentations on 300°C and 600°C pre-heated flange shafts

Pre-heating the flange shaft with a temperature of 600°C decreases the hardness gradient in the flange as expected. As presented in Fig. 5 b), the difference in the Vickers hardness between transition zone and the martensitic zone becomes marginal compared to a 300°C pre-heated flange shaft, given in Fig. 5 a).



c) deformed base material b) martensite

Figure 6. SEM-images from the microstructure of a 500°C pre-heated flange-shaft

Due to the high degree of deformation combined with the high temperature during the forming process a very fine grained and complex microstructure exists in the flange shaft. SEM micrographs show that the grain size is of the order of 1 micron, see Fig. 6 for a 500°C pre-heated flange shaft. The deformed base material, shown in Fig. 6 a), still has its ferritic-pearlitic microstructure, but the original lamellar structure of the pearlite is mainly destroyed. The former cementite lamellae now mostly have a globular shape while the remaining ones are highly deformed. The martensite, shown in Fig. 6 b), is characterized by small carbides in the martensitic needles. It has been observed, that with an increasing pre-heating temperature the amount of carbides increases as well. This observation may support the assumption of a hardness decreasing tempering effect which is caused by significantly slower cooling rate after the phase transformation [7].

Both the increase of the transition zone width and the decrease of the hardness in the transformed phase are desired effects of the pre-heating strategy, but will lead to a variation in the fatigue behavior of the flange shaft. So, a comparison of the fatigue crack propagation in the flange shafts for all four pre-heating temperatures is necessary.

3. Experimental set-up

For analyzing the fatigue behavior of the transition zone micro-specimens were cut out from the flange using high precision spark erosion. A dog-bone shaped micro-specimen (32.5 mm long and about 2.4 mm thick), shown in Fig. 8, was developed with the purpose of performing microstructure specific fatigue tests. As shown in Fig. 8, the center of the specimen consists of martensite (dark) while the white areas mark the transition zone and the deformed base material is in grey again. The preparation of the specimens consisted of mechanical polishing and mechanical-chemical polishing with OPS in the final step.

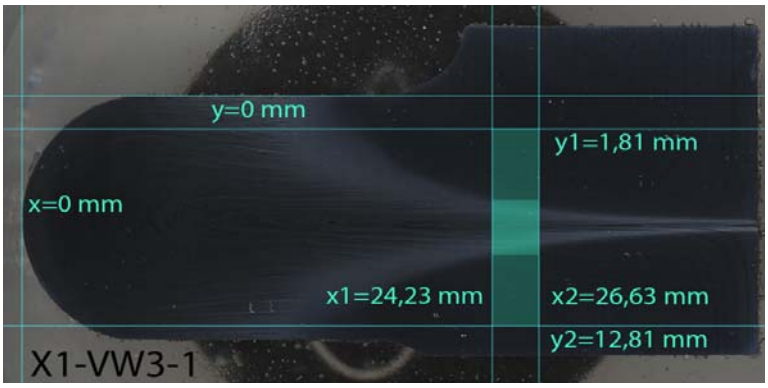


Figure 7. Micrograph taken from a flange shaft to determine the exact specimen position, etched

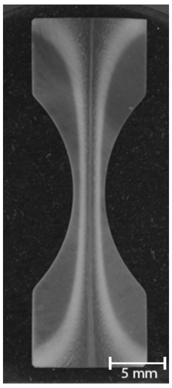


Figure 8. Micro specimen, etched

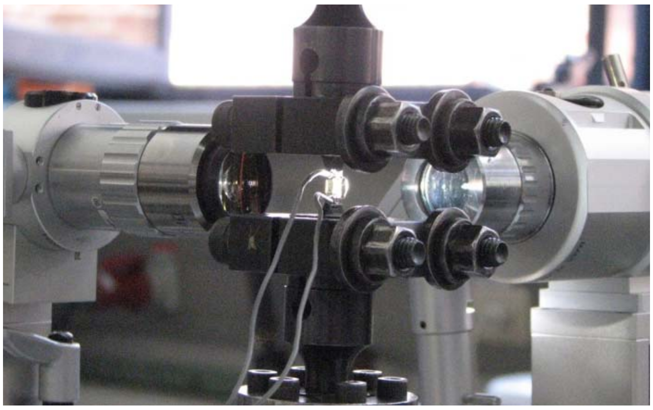


Figure 9. Experimental setup with two long distances microscopes in front of the micro-specimen

All fatigue tests were carried out as uniaxial tests at room temperature on a servo-hydraulic testing machine. The stress ratio was set to R = -1 (i.e. fully reversed) with 500 MPa were chosen as load amplitude. Tests with smooth specimens were monitored using one travelling long distance microscope, whereas two long distance microscopes sitting on motorized three-axis stages were mounted on the rig of the fatigue testing machine to observe the fatigue crack growth at the edge-notched micro-specimen in horizontal and vertical direction, as shown in Fig. 9.

The test procedure itself starts with a scan of the unloaded surface of the micro-specimen. Then the micro-specimen is subjected to fatigue loading with a pre-defined number of load cycles and the surface is scanned again. Repeating this procedure allows monitoring the damage accumulation process on the surface of the micro-specimen and determining the local crack growth rates.

4. Results

Under fatigue loading, microcracks were initiated at inclusions in the base material on the surface of smooth specimens. However, these cracks showed only limited crack extension and never caused failure. Instead, one or two edge cracks were initiated in the vicinity of the notch root. A typical example is shown in Figure 10. It can be seen that the crack paths are fairly rough in spite of the fine microstructure and that the averaged crack line is not exactly perpendicular to the loading direction. These effects can be attributed to texture effects in the deformed base material. First of all, the rods used in the forming process possessed a rather pronounced manufacturing texture and showed lines of enhanced chromium content (dark lines in the shaft in Figure 2). These lines are still visible in the flange after the thermo-mechanical forming process. SEM analyses indicated that crack kinking can also be correlated with local bands of pearlite which survived the forming process. Moreover, there are regions in which the grains in the deformed base material are strongly correlated in their crystallographic orientations (e.g. areas highlighted with white dashed lines Figure 11), i.e. the grain structure shown in Figure 6 is replaced by set of subgrains separated by low angle boundaries. A crack passing through such an area is deviated from its original path due to the local anisotropy of the microstructure (yellow dashed line in Figure 11).

The growth rate of crack #1 is depicted in Figure 12. Apparently, the crack was slowed down after it had reached a length of about 1mm, and picked up considerable speed at about 1.3mm. Comparison with Figure 10 indicates that these changes in the crack growth rate may be related to the graded microstructure. This conjecture was verified using micro-hardness indentation along the crack faces as shown in Figure 13. Figure 12 indicates that there is a clear correlation between an increase in the hardness (corresponding to the transition region) and a decrease in the crack growth rate, and that the sudden rise in the crack growth rate occurs at the maximum of the hardness curve (martensite).

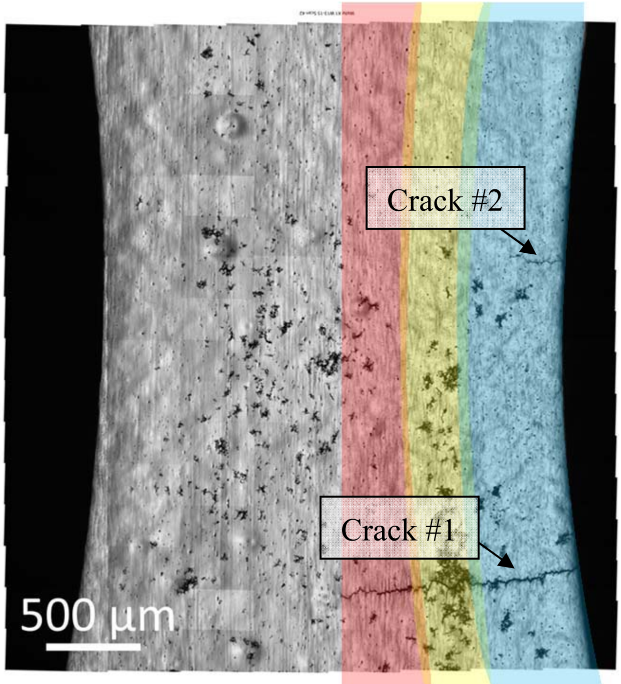


Figure 10. Typical crack paths on the surface of a micro-specimen; phase boundaries are indicated in color

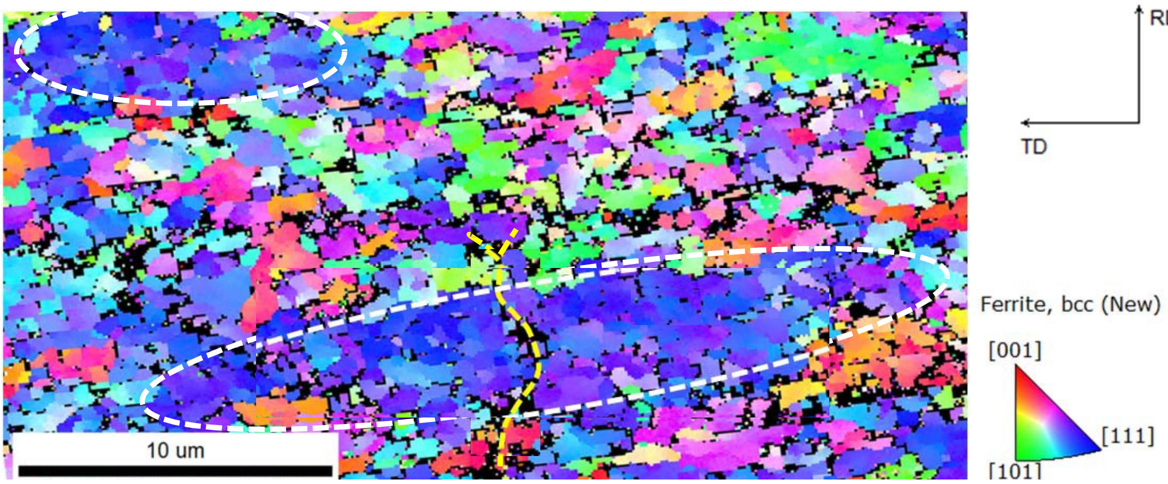


Figure 11. Interaction of crack with areas of local anisotropy

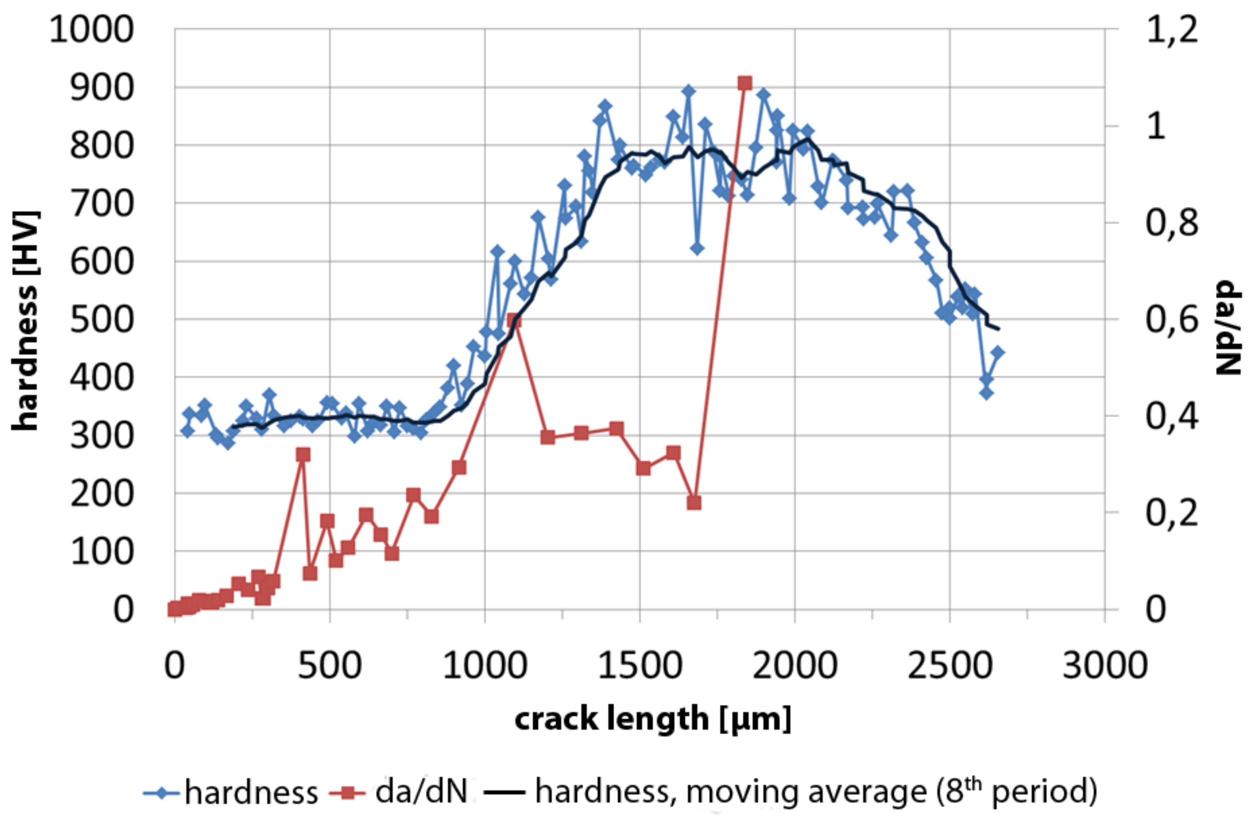


Figure 12. Microstructure dependent growth rate of crack #1

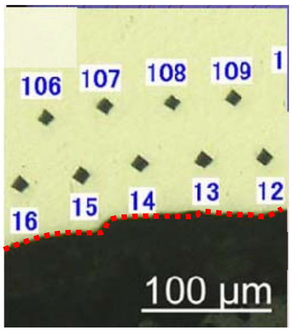
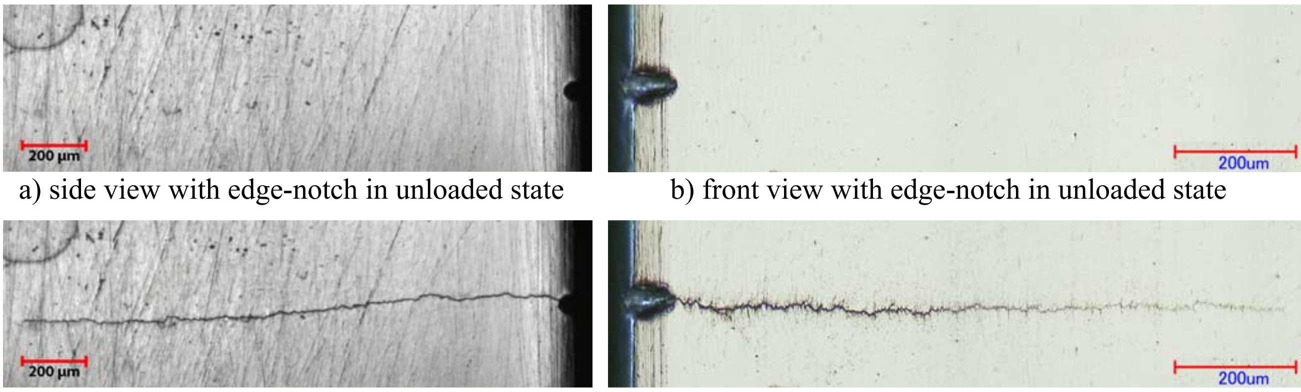


Figure 13. Micro-hardness indentations along section of crack face (dotted red line)

Even though the correlation between the distribution of the phases in the specimen and the acceleration and deceleration of the crack extension process is quite good, it has to be kept in mind that extension of an edge crack is a three-dimensional process, and that conclusions based only on surface observation may be misleading. Therefore a micro-specimen was prepared with an artificial edge notch, and the crack extension from the notch was monitored using the experimental set-up with two travelling microscopes as shown in Figure 9. The initial scans were made in the unloaded state and are given in Fig. 14 a) for the side view (vertical direction) of the micro-specimen and in Fig. 14 b) for the front view (horizontal direction). The fatigue crack initiated at the notch as expected and propagated in both directions. After a total of 45.000 load cycles, which represents approx. 96 % of the lifetime, the fatigue crack has reached a length of 1693.75 µm in the vertical direction (see Fig. 14 c)) and 1002.62 µm in the horizontal direction (see Fig. 14 d)). It seems that the fatigue crack extends more rapidly in the vertical direction than in the horizontal direction. This effect may be related to an inhomogeneous phase distribution in the specimen. This will be clarified by a phase analysis of the fracture surface which is under way.



a) side view with edge-notch in unloaded state

b) front view with edge-notch in unloaded state

c) side view with fatigue crack after 45.000 load cycles

d) front view with fatigue crack after 45.000 load cycles

Figure 14. Data of the test setup gained from the long-distance microscopes with an edge-notched micro-specimen

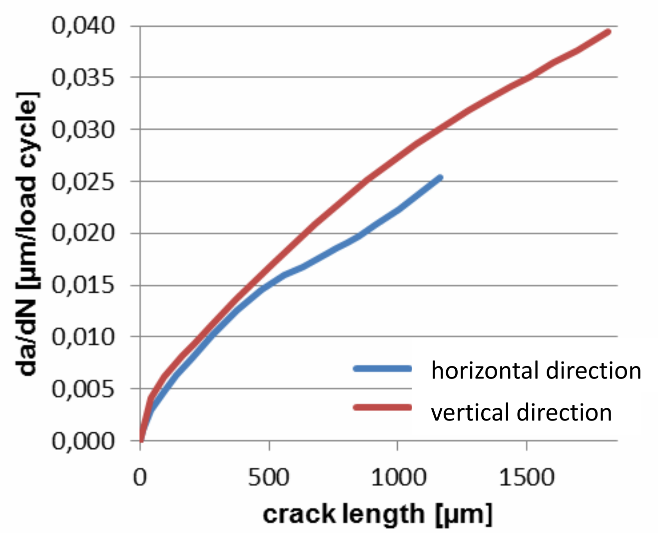


Figure 15. Local crack growth rate of the fatigue crack in horizontal direction (blue) and vertical direction (red)

5. Summary and outlook

The fatigue damage accumulation process in a flange shaft made by a thermo-mechanical forming is dominated by single cracks which are initiated in the soft ferritic phase. Even though in those cases where these cracks are very small they do not propagate as microscopically small cracks as the microstructure is greatly refined due to the forming process with grain sizes of the order of 1 micron or even less. However there is a strong influence of the texture of the material on the crack path leading to pronounced deviations from straightforward mode-I crack propagation. A significant retardation in the crack growth rate was observed when the crack crosses the transition zone between the ferritic and the martensitic phases. This effect will be studied by using different pre-heating strategies which greatly influence the phase distribution in the flange shaft.

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References

[1] D. Firrao, P. Matteis, P. Russo Spena, G.M.M. Mortarino, Fatigue crack growth in inhomogeneous steel components, Int. J. of Fatigue (2010) 864-869.

[2] L. T. Sandor, I. Politori, C.S. Goncalves, A.Y. Uehara, C.V. Leal, M. Sato, I. Ferreira, Fatigue Crack Propagation in Nine Steels, Type SAE 43XX, from 0.20 to 1.00 %, for the Simulation of the Fatigue Behavior in a Carburized Layer of the SAE 4320, Proc. Eng. 2 (2010) 735-742.

[3] K. Steinhoff, U. Weidig, N.Saba, Investigation of Plastic Forming Under the Influence of Locally and Temporally Variable Temperature and Stress States, in: K. Steinhoff, H.J. Maier, D. Biermann (Eds.), Functionally Graded Materials in Industrial Production, Verlag Wissenschaftliche Skripten, Auerbach, Germany, 2009, pp. 35-52.

[4] M. Besel, A. Brueckner-Foit, Surface damage evolution of engineering steel, Fatigue & Fracture of Engineering Materials Structures 31 (2008) 885-891.

[5] A. Brueckner-Foit, F. Zeismann, B. Bode, Y. Xue, Fatigue cracks in a thermal-mechanically processed high-strength steel, Proc. Eng. 2 (2010) 2075-2084.

[6] N. Saba, Untersuchung der plastischen Formgebung unter Einfluss örtlich und zeitlich veränderlicher Temperatur- und Spannungszustände, Dissertation, Kassel University Press, Kassel, Germany (2011).

[7] H. Oettel, H. Schumann, Metallografie - mit einer Einführung in die Keramographie, 15th ed. Wiley-VCH-Verlag, Weinheim, Germany, 2011.