# Determining Local Crack Growth Rates for Small Cracks in a graded ferritic martensitic steel

T. Stein[1,a], S. Wagener[1], F. Zeismann[1] and A. Brueckner-Foit[1]

[1] Institute for Materials Engineering, Quality and Reliability Group, University of Kassel, Moenchebergstrasse 3, D-34109 Kassel, Germany

[a] stein@uni-kassel.de

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## Abstract

Inhomogeneous or graded materials are useful in many technical applications as different functionalities can be combined. A typical example is a component with a soft phase in the bulk and of a hard phase on the surface with a small transition zone in between. Analyzing the fatigue behavior of such a graded material amounts to investigating the fatigue behavior of each phase or zone. Due to its small size the transition is difficult to analyze separately. A three-step approach for determining the local crack growth behavior is presented. The first step is concerned with specimen definition and specimen preparation with the purpose of positioning the microstructure of interest in the gauge length. Micro notches machined by femtosecond laser ablation are used to promote directed crack growth in the second step. Micro-structure dependent crack growth rates are determined by direct observation of crack extension on the specimen surface using a long-distance travelling microscope.

## Introduction

Many technical components made of steel contain zones of distinctive different material properties. These zones can be the result of the manufacturing process or be introduced on purpose to improve the performance of the component, e.g. by surface hardening or a local heat treatment during forming. A well-known example for such a performance improvement is the combination of a ductile phase such as ferrite or pearlite in the bulk and a hard wear-resistant phase such as martensite on the surface with a small transition zone in between.

The fatigue properties of such a component depend on the fatigue behavior of each phase and its corresponding microstructure including the transition zone. The fatigue behavior of ferrite-pearlite and martensite phases has been subject of numerous investigations, e.g. [1-3]. In general, the ferritic-pearlitic phase has a lower fatigue resistance than the martensite one. However, a closer look shows that this effect is entirely due to the reduced crack initiation probability of the martensite phase. Once a crack has been initiated in the martensite, it extends rapidly. Moreover, the fracture toughness and hence the critical crack size in the martensite phase have comparatively low values. In this sense the martensite phase is rather notch sensitive [4]. Consequently, the worst scenario of the damage accumulation process in a component containing both phases starts with crack initiation in the soft phase followed by crack extension in the hard phase. However, for reaching the martensite a micro crack has to pass the transition zone. Hence the fatigue behavior of this particular zone plays an important role in the fatigue behavior of the component as a whole, and understanding the fatigue behavior of the transition zone is necessary to improve the fatigue resistance of the component.

In general, the width of the transition zone is rather small, such that its properties cannot be determined by a straightforward testing procedure. Local crack growth rates can be measured if a crack is initiated from a micro-notch in the soft phase adjacent to the transition zone. This micro-notch has to small enough to simulate small cracks, and has to be positioned very close to the transition zone in order to grasp the crack extension behavior in a range relevant to the fatigue damage process. Micro notches machined by femtosecond (fs) laser ablation have been used before in several cases [5-7] and seem to be a very versatile tool for analyzing microstructure-dependent crack extension. One of the advantages of machining micro-notches by fs-laser ablation is that the shape of a micro notch (with a diameter of approx. 50 µm or less) can be designed precisely to promote a directed crack growth starting at the ferrite / perlite phase and heading towards the transition zone. The heat transfer to the material during fs-laser machining is negligible due to the extremely short pulse time. Hence no additional residual stresses are introduced by the machining process, and there is virtually no heat affected zone at the notch rim.
A travelling long-distance microscope mounted in front of the testing machine is used for observation of the crack extension under fatigue loading. The phase distribution on the specimen surface follows from a post mortem analysis using micro-hardness indentation. In this contribution, first results of the micro-notch experiments are presented. The investigations are part of an on-going research project analyzing the fatigue behavior of graded materials.

## Material, Sample Preparation & Experimental Setup

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. A detailed discussion of the material is given in [8].

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 was applied to a shaft resulting in a flange shaft with a graded microstructure (see Fig. 1). 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. For details of the forming process see [9].
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 figure 1. 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, which consists predominantly of bainite. The corresponding micro-hardness distribution is given in figure 2. The blue area is the martensite with hardness values above 800 HV, the green / yellow area marks the transition zone and the orange area is the cold-worked base material with hardness values below 300 HV.


Fig. 1 – Cross-section micrograph of the flange shaft, etched

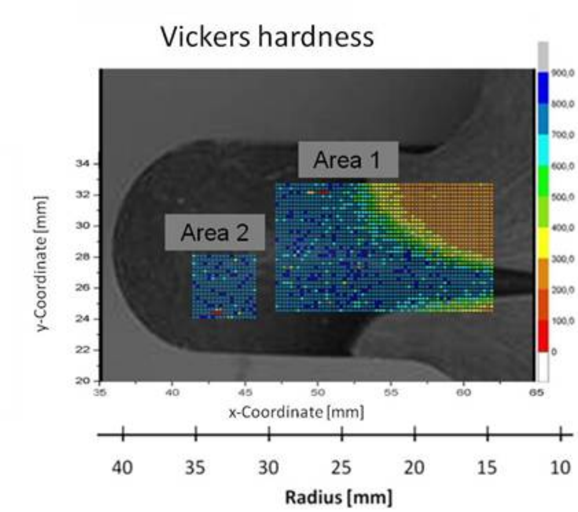



Fig. 2 - Phase distribution identified by using micro-hardness indentation

For analyzing this transition zone specimens were cut out from the flange using spark erosion. A dog-bone shaped micro-specimen (32.5 mm long and about 2.4 mm thick) was developed with the purpose of performing microstructure specific fatigue tests. First a polished micrograph section was cut out from the flange shaft and etched to determine the exact position were the specimens have to be taken from. As shown in figure 3, 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.

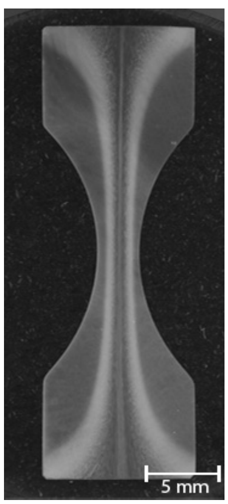



Fig. 3 – micro specimen, polished and etched

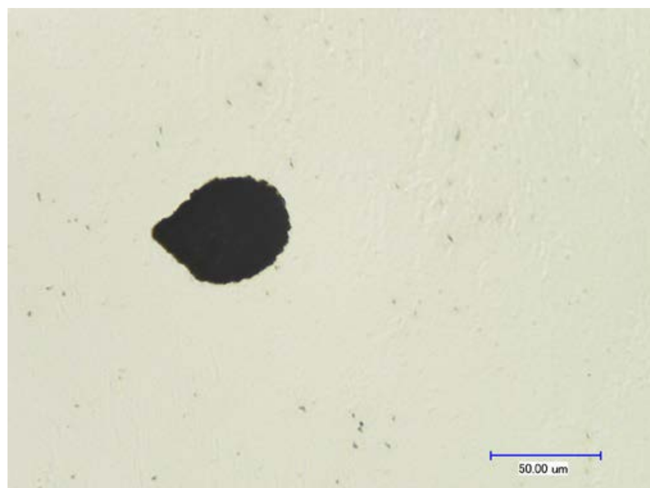



Fig. 4 - Micro-notch manufactured by femtosecond laser ablation

After the preparation several micro-notches were machined on the specimen’s surface using the femtosecond laser ablation. A drop-shaped notch with a diameter of 30 to 50 µm and a depth of approx. 25 µm at the notch tip was chosen as shown in figure 4. The point of maximum at the notch tip was orientated towards the transition zone. While the position of the femtosecond laser was fixed, the shape of the notch was created by moving a computer controlled two-axis stage which holds the specimen. Starting in the middle of the notch the specimen was moved by the stage in a way that the laser followed a concentric line with a steadily increasing diameter. The ablation energy per shot was set to 150 nJ. The root of the notch was relative planar due to the high number of shots for each ablation point.

Fully reversed (R=-1) uniaxial fatigue tests were carried out at room temperature on a servo-hydraulic testing machine. The stress level was set to 250 MPa. A long-distance microscope, manufactured by Hirox, Japan, was used to observe crack extension behavior around the notches. The specimen surface in the gauge length could be scanned as this microscope was mounted on a computer controlled three-axis stage directly in front of the testing machine. After a pre-defined number of load cycles the specimen surface in the vicinity of the notch tip was scanned to document crack initiation or growth as a function of the number of load cycles. Additionally the phase distribution on the specimen surface was determined in a post mortem analysis using micro-hardness indentation as shown (see e.g. figure 2). All hardness measurements were performed with a Fisherscope micro-hardness indenter (Courtesy of B. Scholtes, University of Kassel).

**Results**

Previous investigations on the material carried out at the institute reveals a decreasing local crack growth rate, when a crack starting from the ferritic-perlitic phase reaches the transition zone.

Figure 5 shows a crack, with a total length of about 3 mm, which had been initiated in the ferrit/perlitee phase and propagated towards the transition zone and the martensite phase.

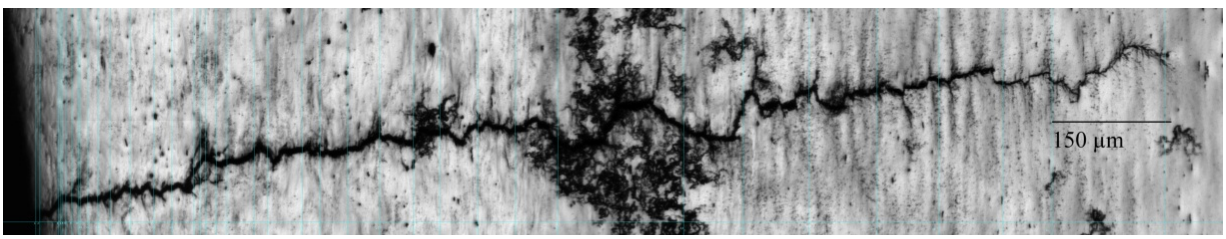



Fig. 5 – Fatigue crack starting from the specimen edge in the ferrite/perlite phase

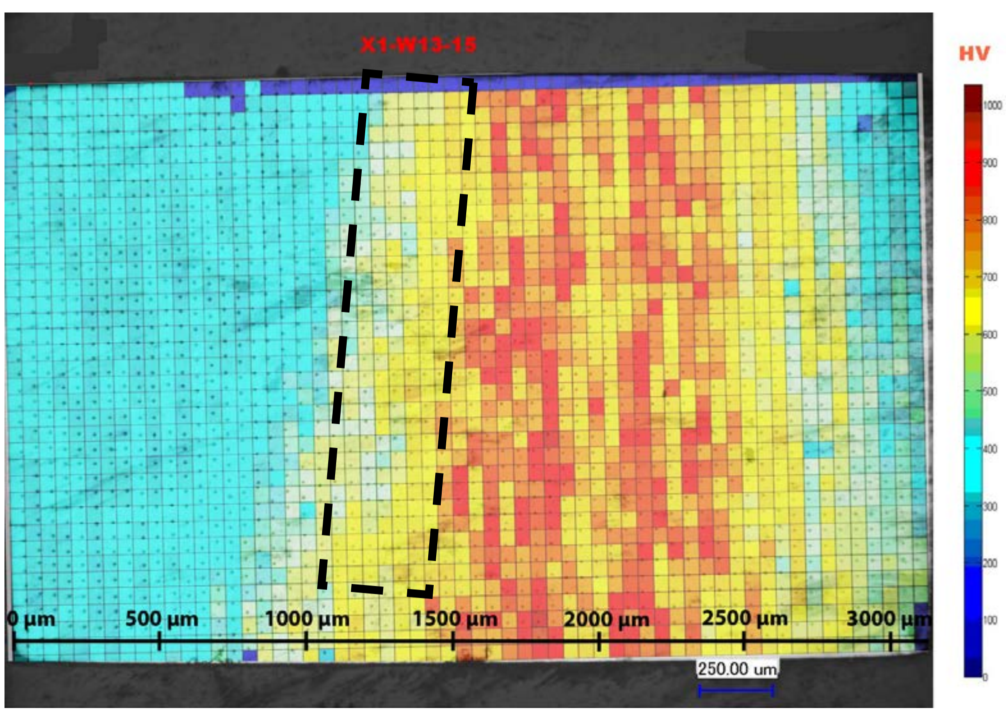



Fig. 6 – Micro-hardness measurement of the fracture surface

A micro-hardness indentation on the fracture surface was performed to identify the phase distribution, as shown in figure 6. The crack started top left in the ferritic-perlitic phase (< 400 HV) and propagates towards the transition zone (400-600 HV), which is marked by the black rectangle in figure 6. The corresponding da/dn-curve of the crack propagation and the hardness related to the crack length are given in figure 7. It can be seen that the crack growth seems to decrease distinctively when the crack reaches the transition zone. Once it reaches the martensite phase failure is imminent as the critical crack size of the martensite phase is rather small.

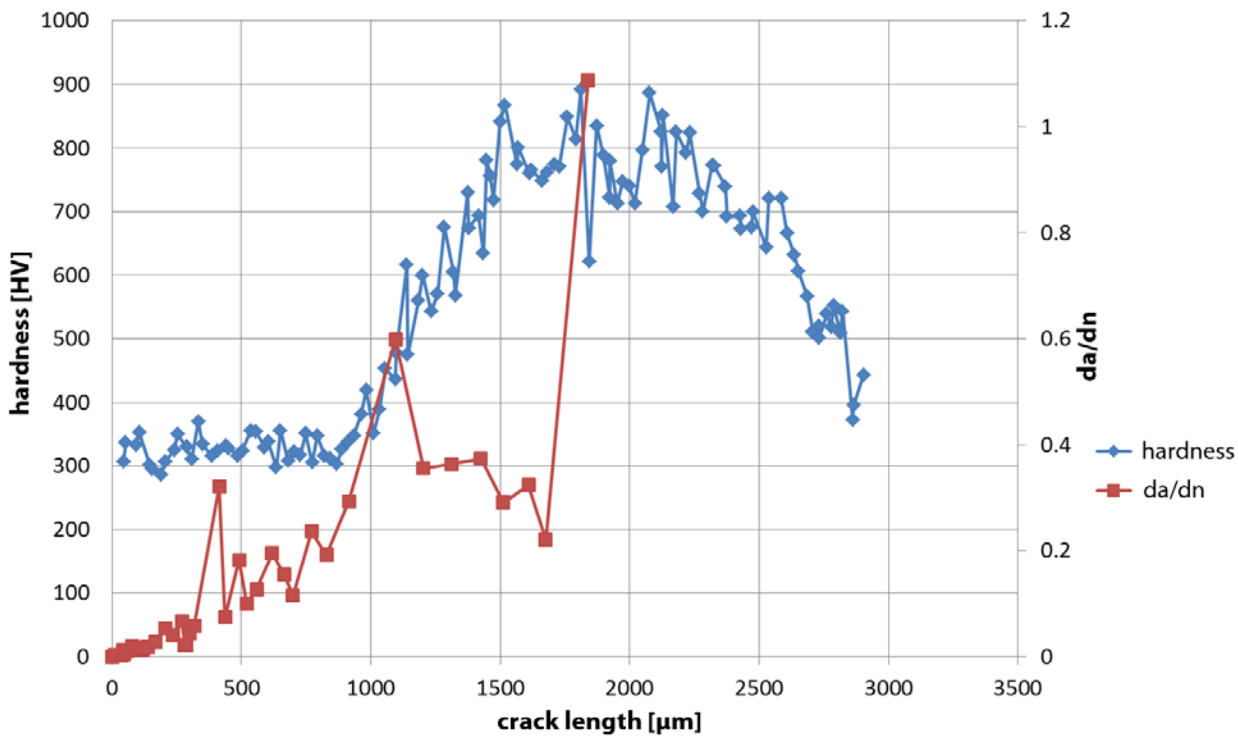


Fig. 7 - Hardness and da/dn-curve related to the crack length

Interpretation of these results is rather difficult because of the three-dimensional nature of crack extension and because of the fact that the phase distribution is not entirely uniform in thickness direction. An edge crack may be retarded on the surface because it is propagating in the transition zone or because it is mainly growing in thickness direction. This effect becomes more pronounced due to the non-uniform phase distribution in thickness direction as illustrated in figure 6. A small crack which starts on the bottom edge will propagate in a graded material in horizontal (surface) direction and in a uniform material in vertical (thickness) direction. Therefore smaller cracks located close to the transition zone are needed for determining the crack growth behavior in the transition zone.

Micro-notches were machined using material ablation by a femtosecond laser. Several geometries with varying diameters were tested. Therefore one specimen was prepared in the area of the highest stress concentration with several notches, as shown in figure 8, and then fatigued. The notches in figure 8 marked with the red rectangle showed micro-crack growth, so a notch diameter of 50 µm turned out to be the ideal compromise between notch effect and machining time. This geometry was used for further investigations.

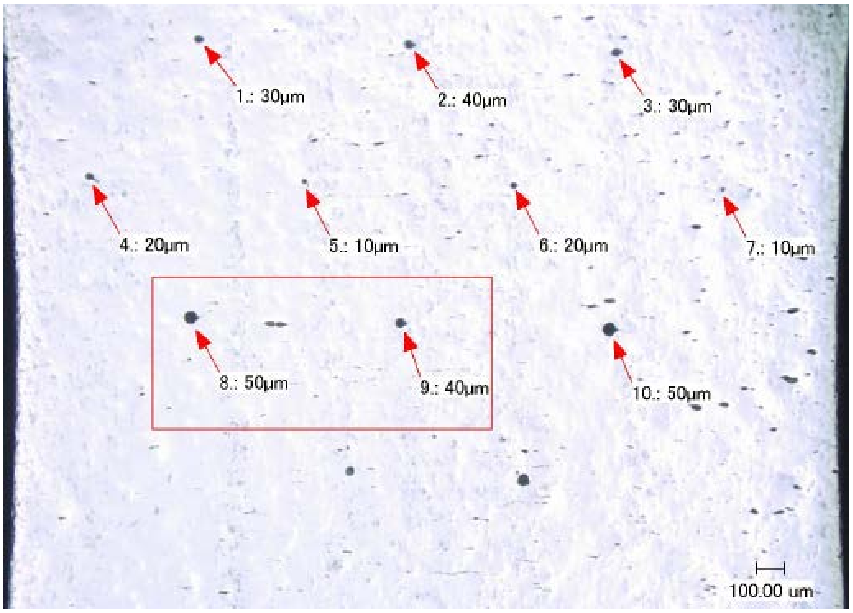
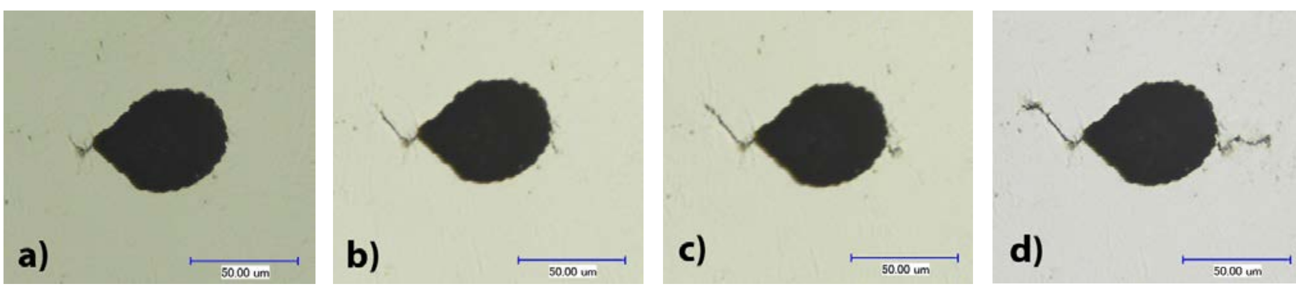


Fig. 8 - Overview notches for geometry tests

Figure 9 shows a micro-notch placed in the ferritic-perlitic phase close to the transition zone. The crack is initiated at the notch tip after approximately 10,000 load cycles (LC) and is propagating towards the transition zone on the left hand side (figure 9a). After reaching a length of approx. 5 µm an obstacle in the microstructure seems to lead to a change of direction of 90°. After additional 10,000 load cycles the crack is still growing in a shear-controlled mode with no additional change in direction (figure 9b). The zigzag crack path looks very similar to a typical stage I extension of a microcrack. However, it has to be kept in mind that the typical grain size both in the ferritic-perlitic phase and in the transition zone is less than 1 µm due to pronounced recrystallization in the thermo-mechanical forming process.



a) after 10,000 LC a) after 20,000 LC c) after 25,000 LC d) after 45,000 LC

Fig. 9 – Crack growth at the notch tip and backside

Although the given goal of initiating directed crack growth is achieved several aspects can still be optimized. The stress concentration on the round side of the notch seems high enough to induce plastic activity, which can be seen after 20,000 load cycles on the right hand side of the micro-notch in figure 9b. A second crack was initiated on this side, and the crack on the left side was almost arrested (figs. 9c and 9d). Investigations are under way to find out whether this arrest is caused by the bainitic phase or by some inclusion in the ferritic-perlitic phase.

**Summary**

1. Using femtosecond laser ablation seems to be a useful way for machining micro notches without influencing the surrounding material mainly in a mechanical or thermal way.
2. Directed crack growth can be induced in a fatigue specimen using micro-notches. This directed crack growth can be used to determine local crack growth rates in a specimen with graded microstructure.

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