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Crack growth behavior of low-alloy bainitic 51CrV4 steel

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Abstract

The crack growth behavior of low-alloy bainitic 51CrV4 steel was investigated. The current results indicate that the stress state present during the isothermal bainitic transformation has a strong influence on the crack propagation behavior in the near threshold regime, when the crack growth direction is perpendicular to the loading axis of the original sample undergoing phase transformation. However, the influence of stresses superimposed during the bainitic transformation on the crack growth behavior vanishes when the stress ratio is reduced from R=0.5 to R=0.1. Microstructural investigations revealed a locally pinned crack, indicating that the crack growth behavior in the near threshold regime is also strongly dependent on the local microstructure. Overall, the current results constitute the first step towards establishing a database for understanding and modeling the crack growth behavior in final work pieces exhibiting functionally-graded microstructures.

Keywords: Phase transformation; bainitic transformation; fatigue; crack growth; microstructure; functionally-graded material.

1. Introduction

Steels offer the possibility to tailor mechanical properties by adjusting the temperature-time-deformation path during processing, such that properties, such as high strength and good ductility, can be simultaneously triggered. Thus, steel is mostly the material of choice when it comes to structural components. Especially during forging, high temperature and stress gradients are prevalent, eliminating the possibility to have homogeneous microstructures as a result of the forging process. However, experimental evidence shows that the resulting inhomogeneous microstructure can be advantageous, such that the local microstructure can be aligned with the local loads by using optimized processing routes [1]. Moreover, the production of functionally graded work pieces reduces costs by eliminating further heat treatments typically needed to induce the desired distribution of properties [2]. In order to optimize the local microstructures during the forging process, a deep understanding how different parameters, such as temperature, stresses and strains, affect the overall process, is needed. Especially for steel products, phase transformations have to be considered since they are accompanied by volumetric changes, which might affect the dimensional stability. Therefore, experimental data demonstrating the effect of different influence parameters on the

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phase transformation kinetics and the resulting mechanical properties are indispensable for both understanding the ongoing phenomena and allowing for accurate modeling of the forging process and the final work piece behavior. One key parameter affecting phase transformation kinetics is temperature, and it is well known that the prior austenitization treatment strongly affects the subsequent phase transformation kinetics [3-5]. In addition, stresses superimposed during the phase transformation change the transformation characteristics, as well. For instance, phase transformation starts earlier and proceeds faster as compared to a stress-free transformation [6-8] upon superimposition of stresses even smaller than the yield strength of the supercooled austenite. Especially for bainitic and martensitic transformations, the transformation under stress may result in aligned microstructures, since variants having a preferred orientation with respect to the external loading axis evolve at the expense of other possible variants [9].

However, the question of how an aligned microstructure affects the local mechanical properties of the final work piece remains to be answered for accurate modeling of the lifetime of a work piece under given circumstances. For instance, when the final work piece is subjected to cyclic loads, the endurance limit is often the parameter used for designing [10]. But as small cracks form, the endurance limit can no longer be considered as a safety border since the forming cracks will eventually propagate under cyclic loading. Therefore, concepts based on fracture mechanics approaches come into consideration [11-13], i.e. characterization of the crack growth behavior in the presence of a viable crack. In the near threshold regime, however, parameters, such as the local microstructure, residual stresses or the load ratio, dominate the crack growth behavior [14-16].

The current work approaches this problem from a broader perspective, such that the determination of crack growth rates in both the Paris regime and the near threshold regime were placed under focus for a bainitic microstructure prevalent in the considered forging process. For this paper, a bainitic microstructure was induced in an elastically loaded sample, and miniature compact tension (CT) specimens were then extracted from the transformed region either parallel (0°-oriented) or perpendicular (90°-oriented) to the loading axis of the original sample. The chosen extraction directions allowed for monitoring the crack growth behavior along the two extreme crack growth paths.

One of the key finding is that the crack growth behavior for the 90°-oriented specimens was strongly dependent on the superimposed stress level present during the phase transformation experiments for an R-value of R=0.5, whereas this dependence diminished as the load ratio was reduced to R=0.1. Microscopy analysis in combination with digital image correlation (DIC) measurements revealed that a localized pinning of the crack was responsible for this behavior. For the 0°-oriented samples, the effect of superimposed stresses during the phase transformation was not significant since the local microstructure, exhibiting bands with large amounts of manganese and sulphur, dominated the crack growth behavior, such that the crack growth took place faster due to small cracks initiated ahead of manganese sulphide particles, or slower as pinning of the crack occurred at an obstacle [17]. Overall, the current results identified the main influence parameters affecting the crack growth behavior of the bainitic 51CrV4 steel, which is important for any realistic modeling effort of the crack growth behavior in functionally graded materials.

2. Experimental procedures

The low alloy 51CrV4 steel used in this study showed only minor sample-to-sample variations in the chemical composition. This is crucial to guarantee a good repeatability of the phase transformation experiments, and thus, allows for a good comparability between the fatigue crack growth experiments. All specimens used for the directed phase transformation experiments were machined out of bars from the same production batch. The custom built test rig used for phase transformation experiments utilizes a servohydraulic load frame equipped with an axial extensometer (Figure 1). Direct current heating was used to heat up the specimens within 1 min up to a temperature of 1050 °C. After holding the temperature constant for 2 min the specimens were cooled down via gas quenching to a temperature of 340 °C, where the samples were held for 30 min. This ensured a complete bainitic microstructure upon cooling down to room temperature.

To study the effect of superimposed stresses present during the phase transformation on the subsequent fatigue crack growth behavior, additional experiments were carried out with a stress of 100 MPa superimposed during the bainitic transformation. Following the isothermal bainitic phase transformation experiments, miniature CT specimens similar to those described in the ASTM standards [18] were electro discharged out of the transformed
specimens, such that the fatigue crack growth direction was either perpendicular (Fig. 2a, 90°-orientation), or parallel (Fig. 2b, 0°-orientation) to the loading axis of the specimens. Since the miniature specimens do not meet the thickness criterion to determine the critical stress intensity factor ($K_{Ic}$), the crack growth curves are shown only up to the end of the Paris regime, i.e. the region where linear elastic fracture mechanics is still applicable.

All crack propagation experiments were conducted in laboratory air. The crack length during the experiments was determined using the potential drop method [19], with the current limited to 5 A to avoid any temperature increase in the specimen. The occurring potential drops during crack growth were measured utilizing a voltmeter with nanovolt resolution, such that the actual crack length and the actual stress intensity factor were easily calculated.
using the commercial LabView software. All experiments were performed at a constant frequency of 20 Hz under \( \Delta K \) control and with stress ratios of \( R=0.1 \) or \( R=0.5 \), utilizing an initial value of \( \Delta K=18 \) MPa\( \cdot \)m or \( \Delta K=16 \) MPa\( \cdot \)m, respectively. The \( \Delta K \) value was kept constant until a given crack length was reached, and then reduced in a stepwise manner in order to achieve crack growth rates in the near threshold regime. For the determination of the crack growth rates in the Paris regime for \( R \)-values of \( R=0.1 \) and \( R=0.5 \), initial \( \Delta K \) values of \( \Delta K=18 \) MPa\( \cdot \)m and \( \Delta K=13 \) MPa\( \cdot \)m were used, respectively, followed by a step-wise increase in \( \Delta K \).

In order to shed light on crack opening mechanisms, local displacement measurements were performed utilizing a commercial air brush system to deposit a random speckle pattern onto the samples. Since conventional paint is not suitable to deposit a speckle pattern with small single particles needed for highly accurate local displacement measurements [20], a solution consisting of isopropanol and technical purity silicon (Si) particles was used to deposit the desired random speckle pattern with small Si particles. To monitor the displacement evolution during one load cycle, pictures of the surface were made at different \( K \) values using a Keyence microscope with a long distance lens and a magnification of \( 500 \times \) at a working distance of 85 mm. For the analysis of the local displacements VIC-2D software was utilized. Fracture surfaces were analyzed with a scanning electron microscope (SEM) operating at a nominal acceleration voltage of 20 kV. The roughness of the fracture surfaces was monitored with an Olympus LEXT OLS 31-SU confocal laser scanning microscope (CSM) with a violet laser (\( \lambda =408\)nm).

3. Results and Discussion

Figure 3 summarizes the fatigue crack growth behavior of bainitic 51CrV4 steel depending on several influence parameters, such as superimposed stress level present during the bainitic phase transformation, the crack growth direction with respect to the loading axis during the phase transformation, and the stress ratio. As shown in Figure 3a, a superimposed stress of 100 MPa during prior isothermal bainitic phase transformation had only a minor effect on the subsequent crack growth behavior of the 0°-oriented specimens for a positive stress ratio of \( R=0.5 \). However, a pronounced difference in crack growth behavior for the 90°-oriented specimens, especially in the near threshold region, was visible. The \( \Delta K_{\text{th}} \) value decreases from 5 MPa\( \cdot \)m for a specimen transformed under zero stress to 3.3 MPa\( \cdot \)m for a specimen transformed under 100 MPa. Moreover, the crack growth rate for lower \( \Delta K \) values differed significantly. Specifically, specimens transformed under zero stress exhibited a crack growth rate of \( 3.4 \times 10^{-7} \) mm/cycle at a \( \Delta K \) value of 5.4 MPa\( \cdot \)m, whereas the crack growth rate for the specimens transforming under stress for the same \( \Delta K \) value was more than 10 times higher (\( 4.9 \times 10^{-6} \) mm/cycle). Additional residual stress measurements performed following the directed phase transformation experiments revealed that the specimens transformed under stress exhibited high residual tensile stresses in the 0°-orientation, as well as in the 90°-orientation. For the specimens transformed without superimposed stresses, small residual tensile stresses in 0°-orientation and residual compressive stresses were found in 90°-orientation [21]. The presence of residual stresses influences the effective \( \Delta K \)-value, such that the effective load increases when residual tensile stresses are present, and decreases when residual compressive stresses are present [22], which explains the difference in crack growth behavior in the near threshold regime for the two different specimens that transformed under 0 MPa and 100 MPa. For higher \( \Delta K \) values, at the end of Paris regime, no difference was visible in the crack growth behavior for the 90°-oriented specimens transforming under 0 MPa and 100 MPa. This behavior was expected, since the effect of residual stresses is only effective for small \( \Delta K \) values. When the \( \Delta K \) level increases, the applied external loads also increase, such that the crack growth behavior is no longer dominated by residual stresses but by the externally applied loads [23].

When the crack growth direction was parallel to the loading axis of the bainitic phase transformation sample (0°-orientation), a \( \Delta K_{\text{th}} \) value of 4.5 MPa\( \cdot \)m was obtained for both specimens (0 MPa and 100 MPa). In addition, similar crack growth rates were obtained at the end of the Paris regime. In the Paris regime, i.e. the \( \Delta K \) region between 6 and 20 MPa\( \cdot \)m, no pronounced linear relationship for the specimen transformed under 100 MPa was observed. The reason for the non-linear behavior in the Paris regime for the 0°-oriented specimen that transformed under 100 MPa is attributed to the local microstructure. Figure 4 shows a typical SEM micrograph of the fracture surface of a 0°-oriented sample. Elongated bands are clearly visible, containing a substantial amount of sulphur and manganese, as detected with an energy dispersive spectroscopy (EDS) detector. Since these band structures were already visible in the initial bars used to machine the specimens for the directed phase transformation experiments, it can be concluded that an austenitization treatment at 1050 °C for 2 min was not sufficient to dissolve these...
microstructures. Since elongated structures were detected for all 0°-oriented fracture surfaces, the hard and brittle behavior of the manganese sulfide seems to dominate the crack growth behavior of the 0°-oriented specimens. Moreover, the local amount of manganese sulfide can increase or decrease the local crack growth rate [17]. Thus, the crack growth behavior of the 0°-oriented specimens transformed under 100 MPa can be attributed to the local differences in manganese sulfide content.

Figure 3b shows the crack growth behavior of 90°-oriented specimens depending on the R-value. Obviously the R-value has a strong influence on the crack growth rates, especially in the near threshold area. \( \Delta K \) values of 3.3 and 8.1 MPa\( \sqrt{\text{m}} \) were obtained for specimens initially transformed to bainite under an external stress of 100 MPa with \( R=0.5 \) and \( R=0.1 \), respectively. This behavior is well known and indicates that crack closure mechanisms are active [24].

![Fig. 3. Fatigue crack growth rates as a function of the stress intensity factor \( \Delta K \). a) Influence of the crack growth direction and the superimposed stress during the prior phase transformation on the crack growth rates, b) influence of the load ratio on the crack growth rate of 90°-oriented specimens.](image)

While the superimposed stress present during the prior phase transformation experiment significantly affected the crack growth behavior of the 90°-oriented specimen for a stress ratio \( R=0.5 \), no influence of the superimposed stress...
during the bainitic transformation was visible for the 90°-oriented specimens for a stress ratio of \( R = 0.1 \). To verify why the residual tensile stresses present in the 90°-oriented specimens transformed under stress [21] result in higher crack growth rates in the near threshold regime as compared to the stress-free transformed specimens only for \( R = 0.5 \), additional investigations were necessary. Thus, CSM was carried out on the fracture surface of the 90°-oriented specimen transforming under stress with \( R = 0.1 \), and further SEM investigations were conducted on the fracture surface.

![SEM micrograph showing the fracture surface of a 0°-oriented specimen.](image)

**Figure 4.** SEM micrograph showing the fracture surface of a 0°-oriented specimen. EDS analysis revealed that white shimmering areas contain relatively large amounts of manganese and sulphur.

Figure 5 displays a CSM image of the fracture surface of a 90°-oriented specimen, initially transformed under 100 MPa to bainite. This image was taken from an area where the decrease in crack growth rate was much higher than expected for a stress ratio of \( R = 0.1 \) when \( \Delta K \) was decreased from 14.4 to 12.6 MPa√m (marked with an arrow in Figure 3b). For the specimen that transformed under 100 MPa, the crack growth rate decreased by a factor of 3.2 whereas the decrease in crack growth rate for the specimen transformed under 0 MPa was only 1.6 for the same \( \Delta K \) step. As shown in Figure 5, a significantly large step-like extrusion with a height difference of 91 \( \mu \)m is present in this area. This value is quite high as compared to the monotonic plastic zone, which was calculated to be 40 \( \mu \)m [25,26] and the cyclic plastic zone, calculated to be 8 \( \mu \)m [26]. Moreover the crack opening displacements visualized via DIC showed 100 \( \mu \)m behind the crack tip displacements up to 1.5 \( \mu \)m at \( K = 20 \) MPa√m (Figure 6). This value is in accord with the calculated value for the crack tip opening displacements for \( K = 20 \) MPa√m [10] and is thus much smaller than the observed step-like extrusion on the fracture surface.

To verify the influence of the step-like extrusion on crack propagation in the near threshold regime, additional SEM investigations were performed on the fracture surface of the aforementioned specimen. The SEM analysis evidenced that the occurring extrusion strongly affected the local crack growth behavior, such that the crack propagates much faster in the area without extrusions (right hand side in Figure 7). Thus, the step-like extrusion blocks the crack locally, such that the occurrence of residual tensile stresses due to the superimposition of stress present during the phase transformation has no influence on the crack growth rate in the near threshold regime. In fact, local inhomogeneities overcompensate for the effect of residual tensile stresses on the crack growth rate, such that the crack growth behavior in the near threshold regime is only dominated by the local microstructure.
Fig. 5. CSM image showing the local topography of a 90° specimen. The bainite transformation occurred at a superimposed stress of 100 MPa. The image was taken from an area where the decrease in crack growth rate was much higher than expected from the stress-free transformed 90° specimen.

A thorough understanding of the crack growth behavior in final work pieces requires a good grasp of how different influence parameters, such as load ratio, local microstructures, or the superimposition of stresses present during the phase transformation, affect the local crack growth behavior. The experimental results obtained in the current study revealed that superimposed stresses applied during the previously directed phase transformation experiments result in local residual tensile stresses. Furthermore, the occurrence of residual tensile stresses strongly affects the crack growth behavior, especially in the near threshold regime, as long as local microstructural inhomogeneities are absent. When inhomogeneities are prevalent, the crack can be pinned locally such that the crack growth behavior is dominated by the local microstructure. Overall, the current results clearly demonstrate the necessity of separately monitoring the influence of different parameters on the crack growth behavior in order to accurately model the crack growth behavior in a final work piece, when all influence parameters are simultaneously effective.
Fig. 6. DIC images demonstrating the evolution of displacement with increasing stress intensity factor $K$.

Fig. 7. SEM micrograph showing the fracture surface of a 90°-oriented specimen transformed under 100 MPa and cycled with $R=0.1$. The image shows the transition from low to high $\Delta K$. 
4. Conclusions

The present study was undertaken in order to investigate the influence of stresses superimposed during the isothermal bainitic phase transformation on the subsequent fatigue crack growth behavior. For this purpose, fatigue experiments, digital image correlation (DIC) measurements, and microscopy were performed on CT specimens extracted by electro discharge machining from the specimens that transformed to bainite. Based on the results presented herein, the following conclusions can be drawn:

- Stresses superimposed during the isothermal bainitic phase transformation affected the fatigue crack growth behavior of CT specimens oriented at 90° to the loading axis of the initial sample undergoing phase transformation. The effect became pronounced in the near threshold regime for R-values of R=0.5.
- For lower R-values (R=0.1) no effect of the superimposed stresses present during the phase transformation experiment was detected for the 90°-oriented specimens, mainly due to localized pinning of the crack. This was visualized using both confocal laser scanning microscopy and scanning electron microscopy investigations.
- For the 0°-oriented specimens (R=0.5) no pronounced effect of the stresses superimposed during the phase transformation was monitored. This is attributed to the band-like microstructure with a significant amount of inhomogeneities, such as manganese and sulphur. Therefore, the crack growth behavior was dominated by the local microstructure for this type of specimens.

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