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Cyclic deformation behavior of a medium carbon steel in the VHCF regime

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Abstract

At the Institute of Materials Science and Engineering an ultrasonic testing facility (UTF) for the fatigue assessment in the very high cycle fatigue (VHCF) regime was developed. The UTF allows to control the test and to measure process parameters like generator power and specimen temperature. In load increase tests (LIT), the critical stress amplitude leading to a first rise of the measured physical values is determined and can be used to identify suitable amplitudes for single step tests in the VHCF regime. The individual design of the UTF allows a defined interruption of the fatigue experiment for detailed microscopic investigations.

Keywords: Very high cycle fatigue; ultrasonic testing facility; microstructure; medium carbon steel; SEM and TEM investigations,

Nomenclature

UTF Ultrasonic testing facility
CAT Constant amplitude test
LIT(s) Load increase test(s)

1. Introduction

The classical description of metal fatigue was developed during the 19th century. The lifetime-oriented fatigue behavior of metals is generally represented in Woehler curves. New investigations during the last decades indicate that the common comprehension of the Woehler curve has to be revised in the VHCF range [1 - 3]. The assumption that the maximum tolerable stress amplitude approaches a mostly horizontal asymptote in and after the high cycle fatigue (HCF) regime was disproved for some cases. In the literature a decrease of the fatigue limit after 10^8 cycles is described for different metals [4 - 9]. A suitable method to perform experiments in the VHCF-regime in an acceptable time is the application of ultrasonic testing facilities (UTF) with a loading frequency of 20 kHz [10, 11].
Although remarkable investigations, studying the damage and failure mechanisms in the VHCF regime, have been realized, there are still significant deficits in the understanding of the fatigue mechanisms in the VHCF-regime.

Fig. 1. Schematic fatigue life diagram [1]

The decrease of the maximum tolerable stress amplitude in the VHCF regime is also related with a change of the failure mechanisms. Up to $10^8$ cycles primarily surface cracks lead to final failure, while for numbers of cycles $>10^8$ often subsurface cracks cause fracture.

2. Experimental Setup

To meet the special requirements of VHCF experiments, an UTF was developed at the Institute of Materials Science and Engineering at the University of Kaiserslautern. To extend the knowledge of the cyclic deformation behavior in the VHCF range, the system was equipped with very sensitive measuring techniques (Fig. 2).

2.1. Ultrasonic Testing Facility

The ultrasonic testing facility is divided in two functional groups: The ultrasonic oscillation system (UOS) and the control unit (Fig. 2a).

Fig. 2. (a) Ultrasonic testing facility and (b) measuring techniques

To guarantee the access of sensitive measurement components, the UOS is mounted in a customized frame. A special control unit realizes the process control, guaranteeing high process stability and a sufficiently high resolution.
of the ultrasonic signal at the same time. Therefore, the control unit is subdivided into a process monitoring device and a measuring device. The measuring device records relevant process data with a sufficiently high recording speed of 500 kHz, allowing a detailed analysis of the ultrasonic signal. The process monitoring defines the loading sequences and records relevant process data at a frequency of 1 kHz. The loading sequence is described by the time relationship of ultrasonic stimulation and sufficient long interruptions to avoid a heating of the specimens. By using an ultrasonic testing facility, the test time for \( N = 10^9 \) cycles can be reduced to about two weeks, including the necessary interruptions to ensure that the temperature increase of the specimens remains e.g. below 10 K [2, 3]. The measurement of physical quantities like the generator power, the specimen’s oscillation amplitude and the temperature allows a detailed evaluation of the cyclic deformation behavior on the basis of deformation-induced changes in the microstructure (Fig. 2 b). Additionally electrical resistivity measurements were performed at defined loading sequences in the load free state by applying a constant direct current [12, 13].

2.2. Material

The fatigue behavior of railway wheel steels in the VHCF regime has been investigated until \( 10^9 \) cycles. The experiments were performed with a loading frequency of 20 kHz at room temperature. The specimens were machined from original wheels of the unalloyed medium carbon steel SAE 1050, with a carbon content of 0.5 wt-%, widely used for high-speed passenger traffic (see Table 1).

Table 1. Chemical composition SAE 1050

<table>
<thead>
<tr>
<th>element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Cu</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>content [wt.-%]</td>
<td>0.50</td>
<td>0.31</td>
<td>0.75</td>
<td>0.23</td>
<td>0.04</td>
<td>0.01</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The industrial heat treatment consists of austenizing, spraying a cooling liquid on the rim and finally annealing. This leads to a characteristic distribution of the Vickers hardness (Fig. 3) and the ferrite fraction as well as cementite lamellae spacing [14].
For a detailed microstructure-oriented evaluation of the cyclic deformation behavior, specimens were machined from defined cross section areas of the rim in rolling direction and electro-polished before the fatigue test.

2.3. Experimental Procedure

To perform tests at constant amplitudes in the VHCF regime, preliminary load increase tests were performed to estimate the critical stress amplitude, which leads to a defined change of process parameters like generator power, dissipated energy or specimen temperature. To correlate the changes of the process parameters with the microstructure scanning electron microscope (SEM) and transmission electron microscope (TEM) investigations were performed after the experiments or at user defined events during the experiments.

The following results, achieved by using non-contact and high-resolution measuring techniques, give an insight to the very complex characterization of the fatigue behavior of a railway wheel steel in the VHCF-regime by using ultrasonic testing facilities

3. Results

3.1. Load Increase Tests (LIT)

The load increase tests start at \( \sigma_{a, \text{start}} = 230 \) MPa at a stress level far below the endurance limit, with a stepwise increase of the stress amplitude (\( \Delta \sigma_a \)) by 5 MPa every \( 10^6 \) cycles (\( \Delta N \)) until specimen failure occurs (see Fig. 4a).

![Fig. 4](image-url) (a) Maximum generator power and energy dissipation during a LIT and (b) SEM investigations

Over 95% of the test time, the course of the process parameters like the maximum generator power, the energy dissipation and the specimen’s temperature don’t show any significant changes. The first rise of the parameters occurs after \( 3.2 \times 10^7 \) cycles, indicating fatigue induced microstructural changes (Fig. 4a). After a pronounced increase of the investigated parameters after \( 3.3 \times 10^7 \) cycles, there is a range, with a nearly horizontal course of the measured values. Specimen failure occurs in the following loading step more than \( 10^6 \) cycles after the first rise of the process parameters was observed. Further SEM investigations show that specimen failure was caused by fatigue cracks emanating from phase boundaries between ferrite and cementite or grain boundaries between ferrite and pearlite (Fig. 4b).
To examine whether the course of the generator power is related to microstructural changes, a load increase test was temporarily stopped in the cycle range of the distinct power increase to perform SEM investigations at the surface of the specimen (Fig. 5).

![Fig. 5. (a) LIT stopped at $P_{\text{max}} = 1000$ W; measured physical values and (b) SEM investigations](image)

The analysis of the observed values shows, in correlation with the other LITs, an almost constant course for over 95% of the experiment. At a loading amplitude of $\sigma_a = 430$ MPa, the dissipated energy and specimen temperature rise shortly before the maximum generator power, indicating an accumulation of microstructural changes. The experiment was interrupted at a maximum generator power of 1000 W (Fig. 5a) for further microscopic investigations.

The SEM investigations show that the formation of persistent slip bands (PSB) as well as intrusions and extrusions at the specimen surface (Fig. 5b) is closely related to the distinct increase of the measured values. It is assumed that in range III in the VHCF regime (Fig. 1) gradual surface roughening can lead to the formation of PSBs. These PSBs can initiate fatigue cracks and finally lead to failure. At lower stress amplitudes an irreversibility threshold according to [1] could exist, but this still has to be confirmed by further experiments.

A series of LITs shows the sensitivity of the applied measuring techniques (Fig. 6). The stress amplitude leading to changes in the microstructure and finally to the failure of the specimens correlates closely with the Vickers hardness, depending on the specimen position in the wheel cross section.

![Fig. 6. LITs: maximum load amplitude for different specimen positions as a function of the Vickers hardness](image)
3.2. Constant Amplitude Tests (CAT)

The LITs were performed to identify suitable stress amplitudes for further constant amplitude tests (CAT). With the stress amplitude of 410 MPa \(N_{\text{max}}=10^9\) cycles were reached without failure. Due to the sensitive measuring techniques, discontinuous courses of the electrical resistivity were observed in experiments exceeding \(10^9\) cycles without failure (compare Fig. 7).

Fig. 7. Electrical resistivity analysis for specimens with different microstructures

To characterize the fatigue and cyclic deformation behavior of metallic materials, electrical resistivity measurements are an appropriate, non-destructive measuring technique to characterize microstructural changes. Results of fatigue experiments with specimens manufactured from the tread compared to specimens taken from the limiting diameter of a wheel show a distinct displacement of the rise of the electrical resistivity (Fig. 7). The significantly later response of the specimen from the tread position is due to the lower ferrite content of 7% at this position compared to 11% at the limiting diameter. This result clearly shows that the influence of the ferrite portion on the cyclic deformation behavior at ultrasonic test frequencies can be evaluated by very sensitive electrical resistivity measurements.

To correlate changes in the microstructure with the course of the electrical resistivity, TEM investigations have been performed at defined fatigue states: in the initial state \((N=0)\), at \(N=10^7\) cycles, at \(N=3\times10^8\) (at the first rise of the electrical resistivity) and at \(10^9\) cycles (Fig. 8 and Fig. 9).

Fig. 8. Defined fatigue states for TEM investigations
The TEM investigations show a significant change in the dislocation structure from the initial state until $10^9$ cycles (Fig. 9).

In the initial state, the ferritic-pearlitic microstructure is characterized by a low dislocation density. The average grain size is about 9-18 µm. During ultrasonic loading, the dislocation density and structure change. The first localized areas with a higher dislocation density can be observed after $10^7$ cycles in ferrite grains. At the first rise of the electrical resistivity, after $3 \cdot 10^8$ cycles, a dislocation cell structure with very small cell diameters of about 300 nm in the ferrite grains and a higher dislocation density in between the single cementite lamellas has developed. This effect is even more pronounced at $10^9$ cycles (see Fig. 10).

Fig. 9. Characteristic results of TEM investigations at $\sigma_a = 385$ MPa

Fig. 10. TEM micrograph and diffraction pattern at $10^9$ cycles with $\sigma_a = 385$ MPa
More detailed investigations show ferrite grains with a large number of very small subgrains (Fig. 11). This assumption is confirmed by the diffraction pattern in Fig. 10 b), showing that a high number of subgrains or low angle grain boundaries have been formed in the ferrite during ultrasonic fatigue.

![Fig. 11. TEM micrographs with details of the dislocation structure (N=10^9, \(\sigma_a = 385\) MPa)](image)

The TEM results in Fig. 11 show small sub grains that have been formed in ferrite grains and prove the existence of the described dislocation structure. The interaction between the dislocations leads to the formation of sub grains or low angle grain boundaries. The rhomboid subgrains have an edge length of about 200-300 nm. In this case the diffraction pattern shows the existence of 20 – 23 different grain orientations (Fig. 10 b). Considering the size of the selected area of diffraction (SAD), calculations lead to a theoretical number of 22 low angle grain boundaries within the observed area, which is in good agreement with the diffraction pattern.

4. Conclusions

With the railway wheel steel SAE 1050, load increase tests have been performed, using an ultrasonic testing facility (UTF). The applied measuring techniques, especially the maximum generator power and the dissipated energy are best suited to indicate changes in the microstructure in an early state of fatigue. Further investigations show that the increase of the measured values is closely related to microstructural changes. Crack initiation was observed in the ferrite or at phase boundaries between ferrite and cementite.

Based on the results of the LITs, constant amplitude tests were realized to determine the cyclic deformation behavior and the fatigue limit in the very high cycle fatigue regime. With TEM investigations at specimens that exceeded 10^9 cycles without fracture, the formation of subgrains and low angle grain boundaries was proved. The combination of the applied measuring techniques leads to a better understanding of the fatigue mechanisms of medium carbon steels in the VHCF-regime.

References


