Ultrasonic fatigue of a high strength steel

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Abstract At the Institute of Materials Science and Engineering at the University of Kaiserslautern an ultrasonic testing system for the fatigue assessment of metallic materials in the very high cycle fatigue (VHCF) regime was developed. The ultrasonic testing system allows to control the test and to measure detailed fatigue data. The achieved results can be used to describe the cyclic deformation behaviour of wheel steels at ultrasonic frequencies. In load increase tests (LIT), the critical stress amplitude can be determined, which leads to a defined change of process parameters like generator power, dissipated energy and specimen temperature. With SEM investigations it was proved that the change of the process parameters correlates with irreversible changes in the microstructure. It can be shown that the stress amplitude, leading to first irreversible changes in the microstructure, strongly depends on the depth position within the original wheel rim. New and basic results on the fatigue mechanisms of high strength steels in the VHCF-regime can be achieved.

1. Introduction
During the 19th century, the classical description of metal fatigue was developed. In general, the main aspects of the lifetime-oriented fatigue behaviour of metals are described in Woehler curves which are generally used in the most industrial fields for the design of reliable constructions under cyclic load. But during the last decade, new research works indicate that the common comprehension of the Woehler curves has to be revised in the VHCF range [1, 2].

The assumption that the fatigue limit of bcc-metals is reached mostly after $2 \cdot 10^6$ cycles was disproved. In the literature a decrease of the maximum tolerable stress amplitude after $10^8$ cycles is described for different metals. A possibility to achieve these results in an acceptable time range yields the application of ultrasonic oscillation systems with a frequency of 20 kHz. By using an ultrasonic oscillation system, the test time for $N = 10^9$ cycles can be theoretically reduced to less than one day, in the experimental realisation it requires about two weeks, since the loading sequence is divided into ultrasonic stimulation and sufficient long interruptions to ensure that the temperature increase of the specimen remains below 10 °C in the crack-free state [2, 3].

The following results, achieved by using non-contact and high-resolution measuring techniques, give a first insight to the very complex characterization of the fatigue assessment of a railway wheel steel in the VHCF-regime by using piezoelectric testing facilities.
2. Experimental setup

To extend the knowledge of the cyclic deformation behaviour in the VHCF range a commercial ultrasonic oscillation system (UOS) was developed at the Institute of Materials Science and Engineering to meet the special requirements of VHCF investigations (Figure 1 a):

2.1. The VHCF-testing facility

![Figure 1: VHCF testing facility (a) and applied measuring techniques (b)]

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

The UOS is mounted in a customized frame that guarantees by its open design the access to the necessary measurement components. The process control is realized by a specially developed control unit. In order to guarantee a high process stability with a sufficiently high resolution of the ultrasonic signal, the control unit is subdivided into a process supervision device and a measuring device. The process supervision defines the loading sequences and records relevant process data. The measuring device records relevant process data with a sufficiently high recording speed, allowing a detailed analysis of the ultrasonic signal.

2.2. Measuring techniques

The measurement of important process parameters like generator power, specimen’s oscillation amplitude and temperature with a very high resolution allows a detailed evaluation of the cyclic deformation behaviour on the basis of deformation-induced changes in the microstructure and an improved understanding of the fatigue mechanisms in the VHCF regime.

2.3. Test material

The fatigue behaviour of railway wheel steels has been investigated in the Very High Cycle Fatigue regime until \(10^9\) cycles with a frequency of 20 kHz at room temperature. The specimens are 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 [4]. The industrial heat treatment consists of austenising, spraying a cooling liquid on the rim, the so-called ‘rim chilling’, and finally annealing, leading to a typical distribution of the hardness in the wheel (Figure 2). As a result of this process the hardness decreases with increasing distance from the rim surface and the ferrite fraction and cementite lamellae spacing increase.
For a detailed microstructure-oriented evaluation of the cyclic deformation behaviour, specimens were machined from defined cross-section areas of the rim in rolling direction.

3. Results of load increase tests in the VHCF-regime

Load increase tests allow to estimate the endurance limit with only a few specimens. LITs are commonly used for fatigue investigations in the high-cycle-fatigue range (HCF) with servo-hydraulic and resonance vibration testing systems. For the realization of LITs with piezoelectric testing systems, the VHCF-testing facility was improved in order to apply defined varying loads.

The load increase tests start at a damage-free stress level of 230 MPa with a stepwise increase of the stress amplitude of 5 MPa every $10^8$ cycles. In order to describe the fatigue assessment the maximum generator power and the dissipated energy during every ultrasonic pulse were determined (Figure 3).

Over 95% of the test time, the curves for the maximum generator power and energy dissipation don’t show any significant changes (Figure 3 a). The first increase of the parameters occurs after $3.2 \times 10^7$ cycles, indicating first irreversible changes in the microstructure (Figure 3 b). After a distinct increase of the investigated parameters after $3.3 \times 10^7$ cycles, there is a range, where the course of the parameters is nearly constant. Specimen failure occurs in the following loading step, caused by fatigue cracks that start preferentially in the softer phase, ferrite and grow along the phase boundaries between ferrite and pearlite (Figure 4).
A series of LITs shows the sensitivity of the applied measuring techniques (Figure 5). 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.

4. Conclusion
Load increase tests have been successfully performed with the railway wheel steel SAE 1050 by using UOS. The applied measuring techniques, especially the maximum generator power and the dissipated energy during an ultrasonic pulse are best suited to indicate changes in the microstructure up to $3 \times 10^6$ cycles before failure. Based on the results of the LITs, constant amplitude tests are performed for an appropriate description of the cyclic deformation behaviour and damage mechanisms in the VHCF-regime.

References
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