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New fatigue life calculation method for quenched and tempered steel SAE 4140

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ABSTRACT

In stress-controlled constant amplitude and service loading tests at ambient temperature mechanical stress-strain hysteresis, temperature and electrical resistance measurements were performed to characterize the fatigue behavior of the quenched and tempered steel SAE 4140. The applied measurement methods use deformation-induced changes of the microstructure in the bulk material and represent the actual fatigue state. A new test procedure combines any kind of load spectra with periodically inserted constant amplitude sequences to measure the plastic strain amplitude, the change in temperature and the change in electrical resistance at the same time. The average values of the measuring sequences are plotted as function of the number of cycles in cyclic 'deformation' curves and represent the summation of microstructural changes caused by service loading. On the basis of generalized Morrow and Basquin equations the physically based fatigue life calculation method "PHYBAL" was developed for constant amplitude and service loading. With only three fatigue tests, Woehler (S–N) and fatigue life curves can be calculated in very good agreement with experimental ones determined in a conventional manner. The application of "PHYBAL" provides an enormous saving of experimental time and costs.

1. Introduction

An exact dimensioning and an optimized material selection are indispensable for safe and economic operation conditions of metallic components. Reliable fatigue life calculations require the comprehensive knowledge of the cyclic deformation behavior and the underlying fatigue mechanisms. Generally, mechanical stress-strain hysteresis measurements are performed to describe the response of metallic materials to an applied cyclic loading on the basis of the plastic strain amplitude [1,2], e.g. [1] presents several experimental techniques for determining cyclic stress strain curves of metallic materials. In recent years, it has become more and more common to complete the acquisition of mechanical data by additional thermal [3–8] and electrical [9–13] measurements. Reference [4] shows the application of thermographic methods on metallic materials and [7] describes the determination of the fatigue limit on the basis of energy dissipation. Apart from the geometry, the electrical resistance depends on the resistivity, which is strongly influenced by microstructural changes resulting in cyclic softening and/or hardening processes. In [9] basic investigations of cyclically deformed copper with respect to the resistivity are summarized.

Especially for material and loading conditions leading to small cyclic plastic deformation, temperature and resistance measurements yield additional helpful information about the actual fatigue state. The plastic strain amplitude $\varepsilon_{a,p}$, the change in temperature ΔT and the change in electrical resistance ΔR are plotted versus the number of cycles N in cyclic 'deformation' curves, i.e. cyclic deformation ($\varepsilon_{a,p}$–N), temperature (ΔT–N) and electrical resistance (ΔR–N) curves. For the characterization of the fatigue behavior under service loading a new test procedure was developed. The basic idea is to combine any kind of load spectra with measuring sequences, using a stress amplitude below the endurance limit to prevent any additional fatigue damage caused by the measuring sequences. The average $\varepsilon_{a,p}$, ΔT and ΔR data measured in these periodically inserted measuring sequences are plotted versus the number of cycles N^* in cyclic 'deformation' curves for service loading. Consequently, under service loading a precise fatigue assessment is possible equivalent as practiced in constant amplitude tests.

The above mentioned physical values $\varepsilon_{a,p}$, ΔT and ΔR can be equally used for a precise fatigue life calculation on the basis of Morrow [14] and Basquin [15] equations in generalized formulations [16–20].

One application of the physically based fatigue life calculation method "PHYBAL" is the short-time calculation of Woehler (S–N) and fatigue life curves of metallic materials. With "PHYBAL" the Woehler and fatigue life curves for different metallic materials and material conditions can be calculated on the basis of only one load

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Table 1
Heat treatments and Vickers hardness.

	Heat treatment parameters	Vickers hardness HV30
HT_0	Austenized at 840 °C, quenched in oil, tempered at 550 °C (120 min)	345
HT_1	Austenized at 840 °C, furnace cooled	195
HT_2	Austenized at 840 °C, air cooled	303
HT_3	Austenized at 840 °C, quenched in oil	511

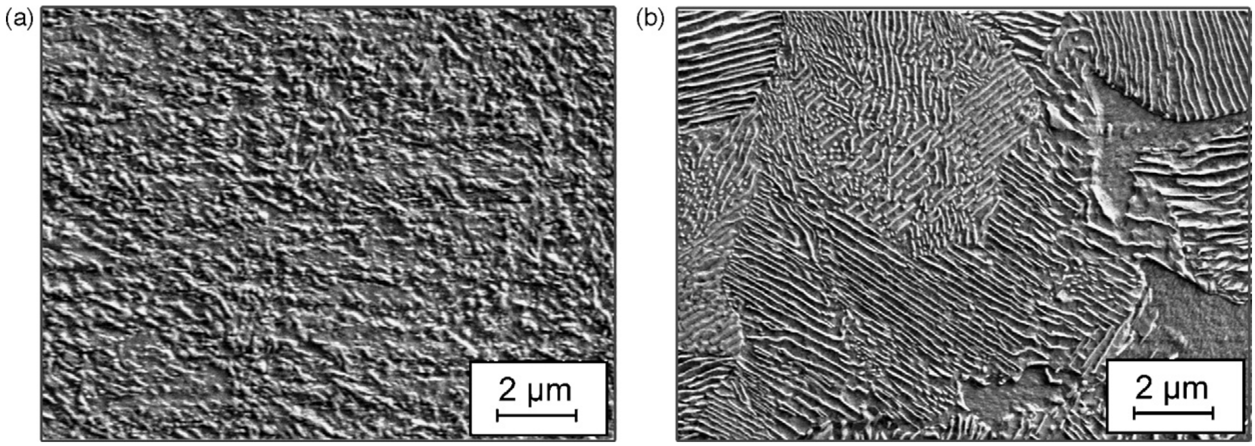

Fig. 1. SEM micrographs of the steel SAE 4140 for HT_0 (a) and HT_1 (b).

increase test and two constant amplitude tests. "PHYBAL" is applied in the following for the steel SAE 4140 (ASTM A 829 M) in the four heat treatment conditions quenched and tempered, normalized, bainitic and quenched. The microstructure is a result of the heat treatment and is mandatory for the cyclic deformation behavior. Therefore, the interrelation of baseline material and fatigue properties is of prime importance and an essential result of this work. The calculated lifetimes are verified in detail in conventional constant amplitude and service loading tests. Scanning electron microscopic (SEM) investigations were performed to characterize the individual microstructure of the SAE 4140 steel.

2. Material

The steel SAE 4140 according to ASTM A 829 M standard (42CrMo4 according to DIN-EN 10083-1) was delivered in form of quenched and tempered round bars with a diameter of 25 mm. The heat treatment by the manufacturer (HT_0) consists of austenizing at $T_A = 840\,^{\circ}C$ and quenching in oil, followed by tempering at 550 °C for 120 min. The chemical composition corresponds to the above-mentioned standards. Table 1 summarizes the different heat treatment parameters and the corresponding Vickers hardness for the different heat treatments (HT) HT_0–HT_3.

Most of the fatigue tests were performed with specimens of the quenched and tempered steel SAE 4140 in the reference heat treatment condition HT_0. HT_0 results in a characteristic microstructure with tempered martensite and ferrite as well as fine dispersed Fe_3C carbides, leading to a Vickers hardness of 345 HV30 (Fig. 1(a)). HT_1 results in a ferritic–perlitic microstructure and a Vickers hardness of 195 HV30 (Fig. 1(b)).

The microstructure of HT_2 (303 HV30) consists of a bainitic matrix with small fractions of martensite and retained austenite, (Fig. 2(a)). HT_3 results in a martensitic microstructure with the maximum Vickers hardness of 511 HV30 (Fig. 2(b)).

3. Experimental setup

Stress-controlled fatigue tests were performed at ambient temperature with a frequency of 5 Hz on servohydraulic testing systems using the experimental setup shown in Fig. 3.

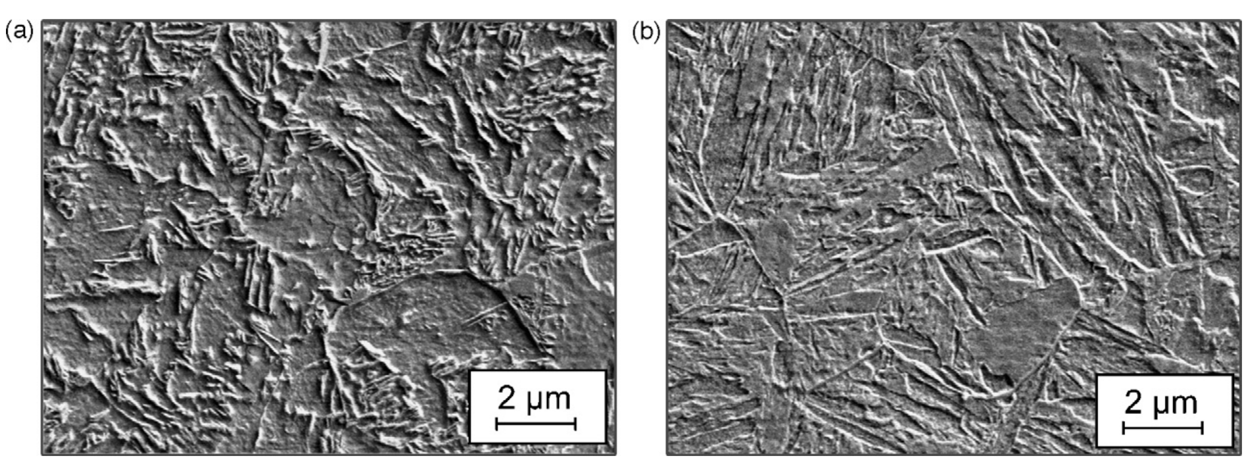

Fig. 2. SEM micrographs of the steel SAE 4140 for HT_2 (a) and HT_3 (b).