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Fatigue assessment of metallic materials beyond strain measurement

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ABSTRACT

The comprehensive characterization of microstructural changes caused by cyclic loading is of major importance for the understanding of basic fatigue mechanisms and for an optimized fatigue life calculation of metallic materials. Different mechanical parameters have been considered relevant to describe fatigue processes and to characterize damage accumulation. Among those plastic strain is dominating especially for metallic materials. However measuring this parameter can easily become a challenge because the proportions of plastic strain are usually small when compared to the governing elastic strains. Besides conventional extensometers additional measurement techniques have been introduced over the past years. Even magnetic and ultrasonic sensing which are very much associated with physical parameters being used in nondestructive testing has been moreover considered recently for the determination of fatigue relevant parameters resulting from constant and variable amplitude loading.

Based on these measures obtained in load increase as well as constant amplitude tests a realisable fatigue life calculation according to the PHYBAL method can be performed leading to a significant reduction with respect to the time required for testing and consequently costs. The database provided by PHYBAL can be used for a variety of applications, e.g. the design and lifetime assessment of new as well as aged components and based on this, it offers a huge potential with respect to nondestructive testing.

1. Introduction

Fatigue is a central issue for many technical applications and there exists a large number of current and historical examples that have led to great damage, and in the worst case, the loss of human life. The first systematic fatigue investigations were performed 150 years ago. Among others, August Wöhler was one of the pioneers in this field and is the namesake of the so-called Wöhler (S–N) curves that represent the relationship between the applied load and the fatigue life of a material [1–3].

The paper will give an overview on the information alternative measuring techniques do provide as a result of the cyclic deformation of different metallic materials [4,5]. Beside conventional stress–strain hysteresis, also temperature [4–6], electrical resistance [5,6,8,9] as well as electromagnetic measurements [10–13] will be used for the characterization of the cyclic deformation behaviour of steels and cast irons.

These methods do have a potential to characterize the cyclic deformation behaviour of metallic materials and can indicate fatigue damage significantly earlier than a state-of-the-art strain gauge can do. They may provide an ideal input with regard to materials' parameters and data, which have been originally generated as a database in handbooks [13,14] and consequently significantly enhanced with respect to their generation for the physically based lifetime calculation "PHYBAL" [15]. "PHYBAL" is a procedure where the complete stress–strain as well as S–N-curve of a material are generated by 3 experiments on unnotched specimens only, reducing the amount for experimentation by mainly an order of magnitude when compared to conventional approaches. These materials' data generated build a significant basis for the assessment of any structural component, even when being loaded randomly.

The use of alternative methods to obtain local material properties under cyclic loading provides more specific information with respect to the cyclic deformation behaviour in the range of low stress and very low plastic strains and high number of cycles to failure respectively. It may even be applicable to materials with a very low plastic deformation capability [16]. Furthermore material properties determined by the techniques considered here are independent of a defined gauge length and also applicable to complex geometries like notched specimens. The physical quantities are linked by cross-effects associated with cyclic plastic deformation and directly related to microstructural changes in the bulk material obtained during fatigue loading.

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Nomenclature

$\varepsilon_{a,p}$	plastic strain amplitude	N	number of cycles
ΔT	change in temperature	N_f	number of cycles to failure
ΔR	change in electrical resistance	N_{max}	maximum number of cycles
σ_a	stress amplitude	P_f	failure probability
CAT	constant amplitude test	R	load ratio
DC	direct current	$T_{1,2,3}$	thermocouples
f	test frequency	Z_{GMR}	electromagnetic impedance
LIT	load increase test		

Methods commonly associated with physical parameters being used in nondestructive testing (NDT) are based on physical “processes” or on the interaction between different forms of external energy and the material microstructure are methods to be very much considered, specifically within the context of “PHYBAL” in that regard [15,17].

2. Materials

The investigations presented in this paper were mainly carried out at the Institute of Materials Science and Engineering at the University of Kaiserslautern/Germany [15,17,18]. In the following results from specimens of the quenched and tempered steel SAE 4140 (42CrMo4) [15] as well as of the cast irons EN-GJV-400 and EN-GJS-600 [18] are considered. The steel SAE 4140 was austenitized and quenched in oil, followed by tempering at 550 °C for 120 min. The microstructure of this SAE 4140 is characterised by fine dispersed Fe_3C carbides and ferrite in tempered martensite, resulting in a Vickers hardness of 345 HV30 (Fig. 1(a)) [15].

Fig. 1 shows scanning electron micrographs (SEM) for the cast irons EN-GJV-400 (b) and EN-GJS-600 (c). The ferrite fraction varies from 7.4 (EN-GJL-400) to 14.6 (EN-GJS-600) area % whereas the graphite fraction increases from 11.5 and 9.8 area %. The Brinell hardness is 227 and 235, respectively. The microstructure consists predominantly of a pearlitic matrix with nodular graphite (EN-GJV-400) and compacted graphite (EN-GJS-600). The compacted (EN-GJS-600) and partially the nodular graphite precipitates (EN-GJV-400) are surrounded by ferritic zones [18].

3. Experimental setup

Prior to the fatigue tests, the absolute value of the electrical resistance R_0 was measured in the unloaded condition using the experimental setup shown in Fig. 2 as a photograph (a) and as a schematic drawing (b) respectively [18]. The value R_0 measured is strongly influenced by the specific microstructure of each individual specimen, e.g. characterized by the defect density, ferrite and graphite fraction or graphite shape. As to R_0 it is possible to detect differences between the specimens resulting from the specific density of typical casting defects like micro-pinholes or micro-shrinkage cavities.

Stress-controlled load increase tests (LITs) and constant amplitude tests (CATs) were carried out at ambient temperature with a frequency of 5 Hz on servohydraulic testing systems using a triangular load–time function at a load ratio of $R = -1$. For the LITs the stress amplitude σ_a was increased from $\sigma_{a,start}$ stepwise after 9000 cycles each by 20 MPa until specimen failure. The CATs were performed until failure or to a maximum number of cycles N_{max} of $2 \cdot 10^6$.

During the fatigue tests, which were performed at the Institute of Materials Science and Engineering at the University of Kaiserslautern, the plastic strain amplitude $\varepsilon_{a,p}$, the change in temperature ΔT, the change in electrical resistance ΔR as well as the electromagnetic impedance Z_{GMR} were measured to characterise the microstructure-based fatigue behaviour in detail. All physical quantities are directly related to deformation-induced changes of the microstructure in the bulk material and represent the actual fatigue state. For the measurement of $\varepsilon_{a,p}$ a conventional extensometer was fixed in the middle of the gauge length. The change in temperature ΔT was detected with one thermocouple in the middle of the gauge length (T_1) and two thermocouples at the elastically loaded specimen shafts (T_2 and T_3). For electrical resistance measurements a DC-power supply was fixed at both shafts and ΔR was measured with two wires spot-welded at the transition of the gauge length and the shafts. Apart from the geometry, the change in electrical resistance ΔR strongly depends on the resistivity ρ^* which is directly related to microstructural parameters at the micro scale. In the case of cast irons the measured value ΔR is of major importance, in particular to get detailed information about the actual fatigue state with respect to damage mechanisms like graphite-matrix debonding [6,15,17,18]. The electromagnetic impedance was measured by a Giant Magneto Resistance sensor (GMR), which is commonly used for inspection tasks in the field of NDT. These sensors detect micro-magnetic changes in the bulk material, which occur due to deformation or load-induced microstructural changes. By varying the energizing current of the alternating field the effective working depth of the process can

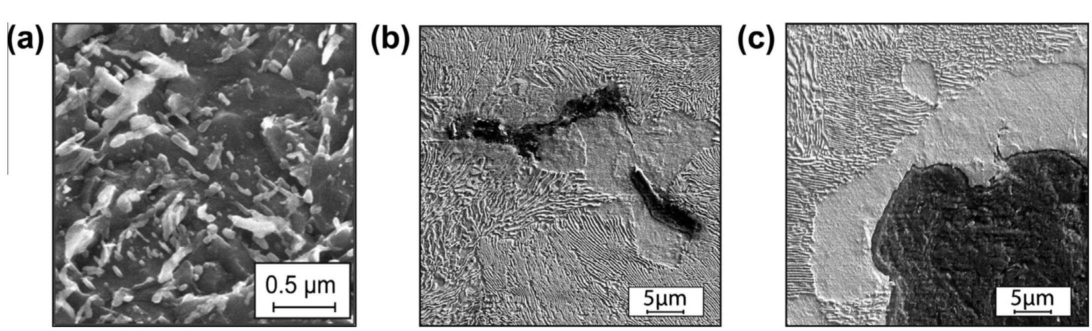

Fig. 1. Micrographs of the quenched and tempered steel SAE 4140 (a) and the cast irons EN-GJV-400 (b) and EN-GJL-600 (ASTM 80-55-06) (c).