SHORT TIME EVALUATION OF METALLIC MATERIALS' FATIGUE POTENTIAL COMBINING DESTRUCTIVE AND NON-DESTRUCTIVE TESTING METHODS

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Abstract. Fatigue of engineering structures is an issue from an engineering design point. The lifetime of materials being subject to repeated mechanical loads is limited. Different examples of failures and fateful air accidents have caused significant cost and claims to the operators as well as manufacturers in excess of fatalities. Criticality of failure increases with increasing age and the uncertainty of operational loads applied. In such a case a reassessment of a structural materials' condition is in big need should damage tolerance criteria still be met, being the essential ground rule for aeronautical structural design.

It is therefore the challenging aim to use a metallic material's microstructure characterizing non-destructive testing (NDT) parameter or a combination of those as a parameter to be scanned over a defined surface of the component considered to more realistically characterize the damage condition and to use this information twofold: a) to more precisely assess the structural component's residual life and b) to feed the information recorded back into a specific database belonging to an approach named PHYBAL.

The physically based fatigue life evaluation method (PHYBAL) is a short-time procedure for the evaluation of fatigue data based on a small number of fatigue tests performed on un-notched specimens only. This method significantly reduces the effort for experimentation in terms of time and cost by around 90 % and inhibits remarkable scientific as well as economic advantages.

The paper highlights the high capability of PHYBAL as well as the suitability for assessing the residual life of aeronautical components also with respect to the application of this approach in the light of structural health monitoring issues.

1. Introduction

Fatigue of engineering structures is an issue from an engineering design point of view since around 150 years now. The lifetime of materials being subject to repeated mechanical loads is limited. Numerous examples in the aeronautical industry but also other engineering disciplines including civil, mechanical, power, offshore, automotive, naval or rail are exposed to fatigue-induced material failure of components, which can cause significant cost and claims and in the worst case human lives.

Traditionally, material response to cyclic mechanical loading is characterized by the plastic strain amplitude $\varepsilon_{a,p}$, determined in mechanical stress-strain hysteresis measurements [1]. Complementary temperature ΔT [2], electrical resistance ΔR [3] as well as magnetic measurements [4] have been used for a detailed characterization of the fatigue behaviour of structural metallic materials for different applications. Those resulting physical quantities are directly influenced by deformation-induced changes in the materials' microstructure and offer the possibility to obtain more precise information regarding the actual fatigue condition.

Generating fatigue life curves of a material still requires a significant effort and may require around 20 to 30 experiments to be performed in case the curve determined should be considered to be sufficiently proven. In the 1980ies materials data for cyclic loading were collected and compiled in a database in a first approach, which was made available to the engineering designer [5]. With this as an initial point, it is of prime interest to reduce the efforts required for determining a stress-strain and fatigue life curve of a material.

In recent years, the PHYsically BAsed fatigue Life evaluation method (PHYBAL) has been developed and applied for different un-, medium- and high-alloyed carbon steels as well as cast irons and light-weight materials [6]. PHYBAL is a short-time procedure for the calculation of fatigue data based on a small number of fatigue tests only. This method significantly reduces the effort for experimentation in terms of time and cost by 90 % and inhibits remarkable scientific as well as economic advantages.

Within the scope of the work presented here, examples for applying the PHYBAL approach for calculations of the steels SAE 1045 and SAE 4140 including magnetic and thermography measurements will be given. However, the approach is also well applicable to aeronautical metallic materials too. The examples provided will highlight the high capability of the procedure presented as well as the approach's suitability for engineering structures' integrity management including potential systems with respect to the application of structural health monitoring aspects for aeronautical industry applications.

2. Experimental setup

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 sinusoidal load-time function at a load ratio of R = -1. For the LITs the stress amplitude was increased stepwise or continuously until specimen failure.

During fatigue tests, the plastic strain amplitude $\varepsilon_{a,p}$, the change in temperature ΔT as well as the electromagnetic impedance Z_{GMR} were measured to characterise the microstructure-based fatigue behaviour in detail. All physical quantities are directly linked to deformation-induced changes of the microstructure related to their defects (Fig. 1) in the bulk material and represent the actual fatigue state.

Within the continuous LIT the change in 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 types of 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 be adapted. This contact free measurement technique is very well suited to detect microstructural changes in very early fatigue states. Compared to conventional techniques the use of those techniques mentioned above which are more known within the context of nondestructive testing (NDT) result in a gain of information even with respect to the characterization of the cyclic deformation behaviour of metallic materials [8]. For conventional stress-strain hysteresis measurements a commercial extensometer with a measuring length of 10 mm, a range of +/-8 % and a resolution of $5\cdot10^{-6}$ from MTS was used.

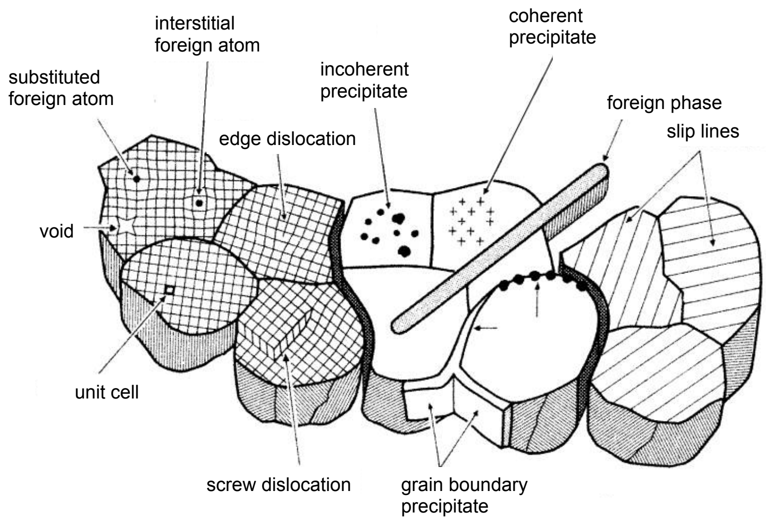

Fig. 1. Microstructural defects in metallic materials, according to [7]

Within the stepwise LIT, the change in temperature ΔT was measured by means of an infrared camera type thermoIMAGER TIM 160 from Micro-Epsilon. This system provides a spectral range of 7.5-13 μm, an optical resolution of 160×120 pixels, a $23°\times17°$ objective and a thermal resolution of 0.04 K. For the temperature measurement, the specimen was prepared with a matt black finish to avoid reflections on the surface and to realize an emission grade of $\approx$ 1. The experimental setup for the LITs with the applied measurement techniques based on thermography and magnetics is shown in Fig. 2.

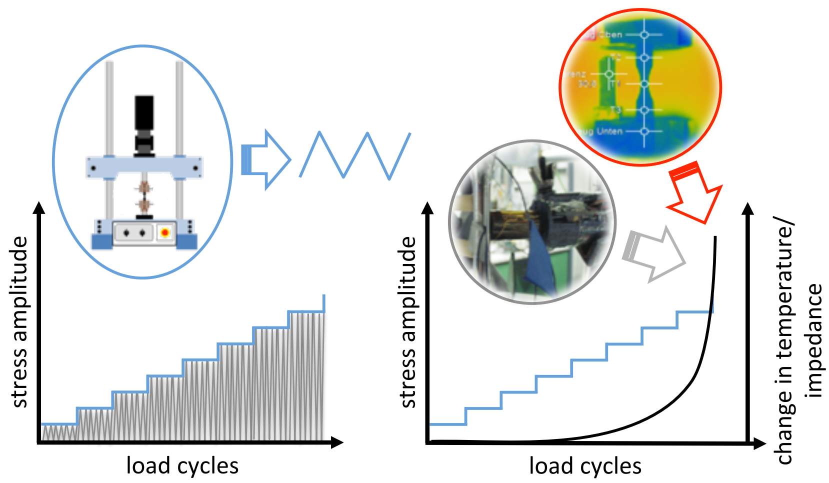

Fig. 2. Experimental setup for load increase tests, schematically

3. Results

Fig. 3 shows a continuous LIT for the SAE 4140 steel starting at a stress amplitude (σ_a) of 100 MPa. At this load level, which is approximately 10 % of the yield strength, no plastic deformations occur during cyclic loading. σ_a was increased continuously by $2.1\cdot10^{-3}$ MPa per cycle until specimen failure at σ_a = 683 MPa.

First changes in the slope of $\varepsilon_{a,p}$ as well as Z_{GMR} can be observed at a stress amplitude of 470 MPa and 495 MPa, respectively, which corresponds quite well with the endurance limit 490 MPa determined conventionally from CATs [6]. Fig. 3 shows that the GMR signal provides a highly accurate feedback in terms of a stress-measurand-relationship, which is related to first microstructural changes based on dislocation reactions in the specimen gauge length due to the continuously increased stress amplitudes within the LIT.

This similarity observed is quite remarkable keeping in mind that the endurance limit in the LIT can be estimated with only one single fatigue test. This underlines that measurement techniques widely used in the field of NDT do have a potential to characterize the cyclic deformation behaviour of metallic materials and that those can indicate fatigue damage significantly earlier than a state-of-the-art strain gauge can do. Apart from this, GMR sensors can be also applied in the case of notched specimens or even components without an availability of a defined specimen gauge length.

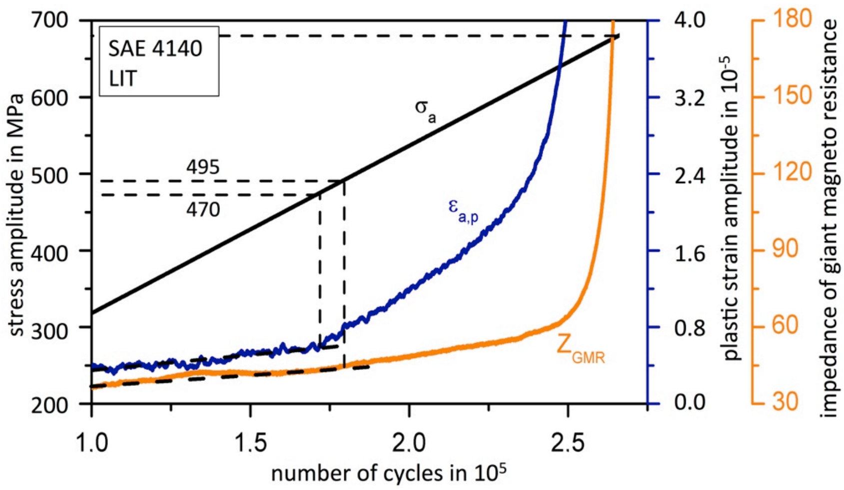

Fig. 3. Behaviour of a quenched and tempered SAE 4140 along a continuous load increase with respect to plastic strain amplitude as well as the electromagnetic impedance

PHYBAL mentioned above is a short-time procedure for the rapid evaluation of fatigue data based on one LIT and two CATs. It is therefore a basic requirement that the cyclic deformation behaviour in LITs as well as CATs is characterized by means of high precision measurements techniques, which describe the damage evolution in the bulk material due to the applied loads. Apart from conventional strain measurements, NDT related techniques provide the possibility to evaluate microstructural changes in very early fatigue stages even before changes on the macro-scale appear. PHYBAL significantly reduces the effort for experimentation in terms of time and cost by approx. 90 % because it virtually only requires three fatigue experiments to obtain a complete fatigue life curve of a material [5,6]. It therefore inhibits remarkable scientific as well as economic advantages. According to this short-time procedure, Fig. 4 shows a stepwise LIT for the SAE 1045 steel starting at a stress amplitude of σ_a = 100 MPa. Thereafter, σ_a was increased each $9{\cdot}10^3$ cycles by 25 MPa until specimen failure at σ_a = 375 MPa. The deformation behaviour within the LIT was measured by means of an infrared camera. Therefore five measuring fields (1×1 pixel) were defined along the specimen, one along the gauge length and two at each shaft. The difference from ambient temperature is determined in a way that the temperature recorded on a short black painted specimen of the same material placed next to the specimen being loaded is taken as a reference. The change in temperature was calculated in accordance to equation (1) below:

$$\Delta\Theta = \Delta\Theta_1 - \frac{1}{2}\cdot(\Delta\Theta_2 + \Delta\Theta_3) \qquad (1)$$

If there is a shift of the fracture zone along an axis defined as the z-axis, the calculation of the change in temperature can be imprecise. Therefore an integral approach based on the fin/bar-model was developed, which is used for many technical applications with respect to heat conductivity and flux processes [9]. Simplifications with respect to the specimen geometry, material, elastic-plastic deformation as well as additional heat sources lead to the following equation (2):

$$\theta(z) = \theta(z=0)\cdot\frac{\sinh[\mu(L-z)]}{\sinh(\mu L)} + \theta(z=L)\cdot\frac{\sinh(\mu z)}{\sinh(\mu L)} \qquad (2)$$

with μ (equation (3)) for the steel SAE 1045 to be:

$$\mu = \sqrt{\frac{4\alpha}{\lambda\cdot D}} = \sqrt{\frac{4\cdot 1.62}{48.3\cdot 6\cdot 10^{-3}}} = 4.73\ \left[\frac{1}{m}\right] \qquad (3)$$

α: heat transfer coefficient in W/(m²·K); D: diameter of the gauge length in m;
λ: thermal conductivity in W/(m·K); μ: fin parameter in 1/m

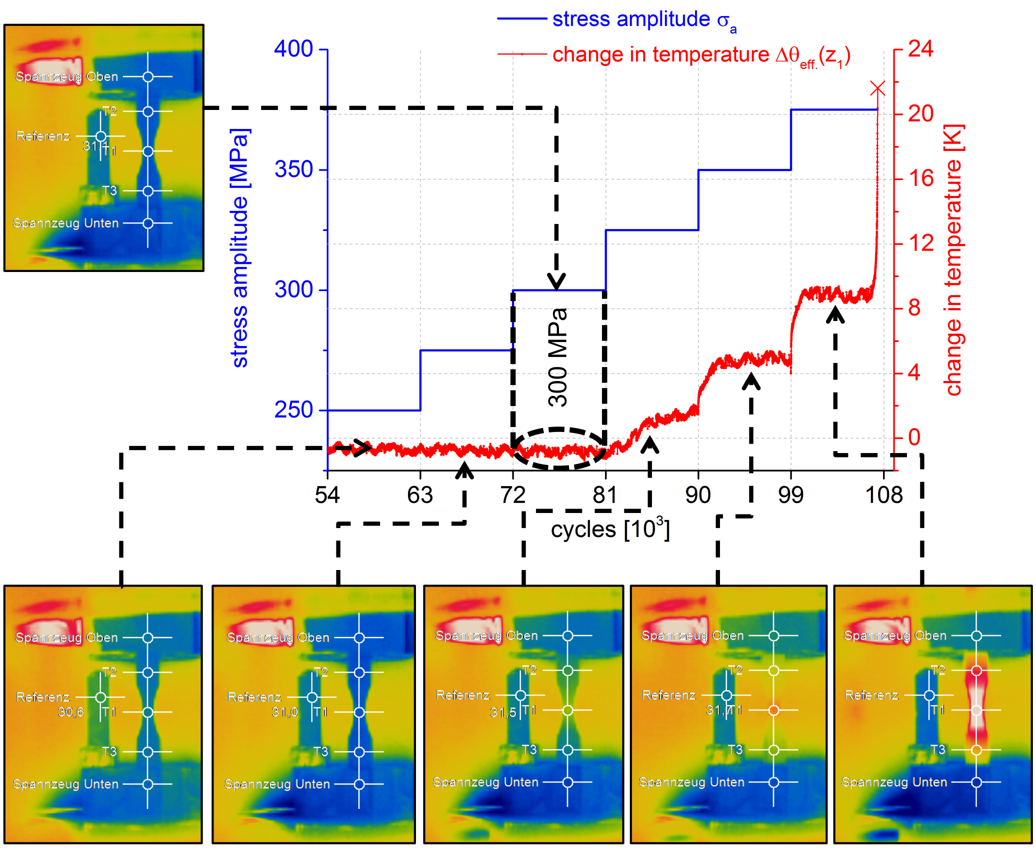

Fig. 4. Load increase test with the courses of the stress amplitude and the change in temperature as well as related thermographs for normalized SAE 1045

After a first linear decrease of the temperature values of $\Delta\Theta_{eff}$ at $7.2\cdot 10^4$ cycles caused by thermo-elastic effects a change in the slope of the temperature related data can be observed at σ_a = 300 MPa, which can be related to the first plastic deformations in the specimen's gauge length. This value corresponds quite well with the fatigue limit of normalized SAE 1045 in literature [10] with approx. 290 MPa, which is a value slightly below, keeping in mind that those values can easily scatter by +/- 5%.

Besides the LIT's diagram, Fig. 4 shows for the range of $250 \le \sigma_a \le 375$ MPa related thermographs giving an overview of the temperature evolution along the specimen due to cyclic loading. From $\sigma_a = 325$ MPa onwards, the temperature change in the subsequent fracture zone is significantly more pronounced than in the rest of the specimen which is related to increasing plastic deformation processes.

In accordance to the PHYBAL method, two constant amplitude tests were performed with stress amplitudes in the range of the estimated endurance limit and slightly below the load level that led to specimen failure in the LIT respectively. Cyclic softening which goes along with an increase of $\Delta\Theta_{eff}$, dominates the cyclic deformation behaviour until it reaches a local maximum at approx. 25-30 % of the lifetime, followed by cyclic hardening and consequently decreasing $\Delta\Theta_{eff}$ values. The last 10 % of the specimen's lifetime is dedicated to the macro-crack propagation within the fictional cyclic softening process, which is also accompanied by a temperature increase. The cyclic deformation curves for $\sigma_a = 300$ and 350 MPa based on the change in temperature of the two CATs are given in Fig. 5.

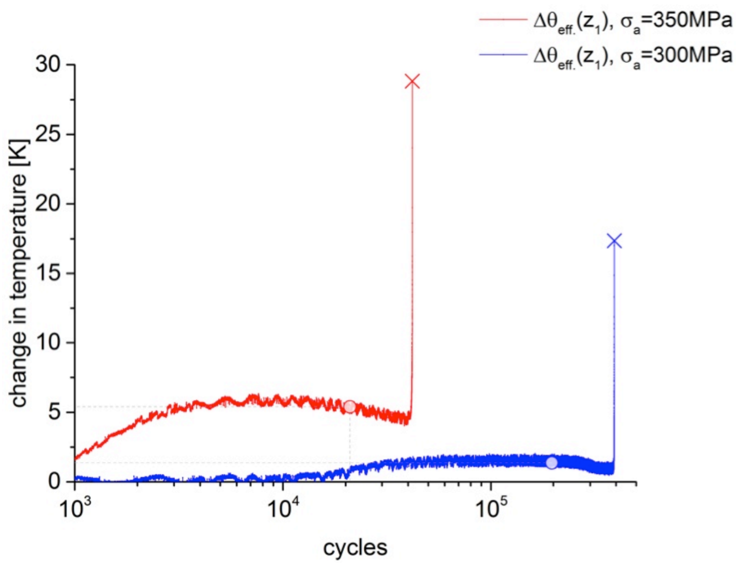

Fig. 5. Temperature based cyclic deformation curves for normalized SAE 1045

The stress-temperature relationship from the LIT is affected by the pre-damage of the previous load levels, such that the two CATs have to be performed to provide anchoring points for the interpolation from the cyclic stress-temperature relation of the LIT to the one for CATs, which can be described by a generalized Morrow [11] equation and is not limited to a specific material. The material response values from the CATs have to be extracted at defined fatigue states depending on the cyclic softening/hardening behaviour of the material investigated. In the case of the normalized SAE 1045, which is characterized by cyclic softening followed by cyclic hardening, the characteristic temperature values were taken at half lifetimes $N_f/2$.

The exponents of the Morrow [11] and the Basquin [12] equation interpolated for constant amplitude loading are directly linked to each other by an empirical relation, which also goes back to Morrow. With the stress amplitude and the lifetime of the CAT resulting in fewer numbers of cycles to failure when compared to the LIT still the Basquin's fatigue strength coefficient can be determined and from this the S-N curve can be calculated in a very good accordance to the conventional procedure of determining materials' data for cyclic loading [5,6].

Fig. 6 shows the conventionally determined lifetimes of the two CATs and the

PHYBAL calculation based on $\Delta\Theta_{eff}$ for normalized SAE 1045. This diagram provides a first view into the very good match of the PHYBAL approach with experimental data. In forthcoming investigations, the results will be verified in a more statistically manner.

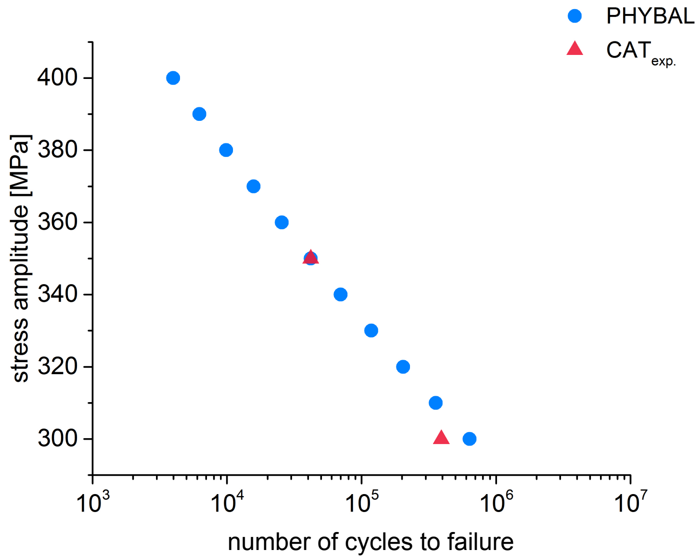

Fig. 6. Experimental lifetimes (CAT$_{exp.}$) and PHYBAL curve calculated on the basis of the change in temperature for normalized SAE 1045

4. Conclusions

Apart from extensometer and strain gauges, additional measurement techniques have been introduced in recent years. Even magnetic sensing and thermography which are very much associated with physical parameters being used in nondestructive testing have been moreover considered for the determination of fatigue relevant parameters recently, specifically within the context of the PHYsically Based fatigue Life calculation "PHYBAL". The flavour of the approach taken is to build a bridge between the physical parameters measured in NDT and to relate those to parameters and phenomena such as stress and strain measurements classically used in materials' fatigue assessment.

The basic requirement for the applicability of PHYBAL is to characterize the cyclic deformation behaviour by means of high precision measurement techniques based on parameters such as related to temperature, electrical resistance and electromagnetics. These techniques are highly sensitive to first microstructural changes based on dislocation reactions and offer significant advantages when compared to conventional methods based on techniques such as stress or strain measurements. Furthermore materials' properties determined by these techniques are independent of a defined gauge length and also applicable to complex geometries like notched specimens or even components. The physical quantities can be transferred from those localized but potentially critical spots and be directly related to microstructural changes in a bulk material of which the fatigue loading properties have been obtained with an approach such as PHYBAL.

PHYBAL is a short time procedure where the complete stress-strain as well as S-N curve of a material can be provided by one single load increase test and two constant amplitude tests only. Even with this increase in experimentation effort PHYBAL still generates an information that would have required a possibly tenfold effort when considering conventional terms.

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