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A two-parameter, heat energy-based approach to analyse the mean stress influence on axial fatigue behaviour of plain steel specimens

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ABSTRACT

Recently, fatigue data generated from fully reversed stress- and strain-controlled tests on plain and notched stainless steel specimens were rationalised in a single scatter band by using the specific heat energy per cycle as fatigue damage index. In this paper, the energy approach is extended to analyse the mean stress influence on the axial fatigue behaviour of un-notched bars made of cold drawn AISI 304L stainless steel or hot rolled quenched and tempered C45 steel. In view of this, stress controlled fatigue tests at different load ratios *R* were carried out. A new two-parameter, energy-based approach is defined to account for the *R*-ratio effects, which combines the specific heat loss and the thermoelastic temperature corresponding to the maximum stress of the load cycle. Such parameters can be readily evaluated at a point of a specimen or a component undergoing a fatigue test by means of temperature measurements, while controlling or monitoring the thermal boundary conditions of the tests is unnecessary. The new two-parameter approach was able to rationalise the stress ratio effect observed experimentally.

1. Introduction

The fatigue damage of laboratory specimens has been monitored by means of surface temperature measurements in the last decades. In fact the temperature of a material undergoing fatigue loadings increases as the applied stress amplitude increases, for a given set of thermal and mechanical boundary conditions (i.e. load test frequency, room and machine grip temperatures, specimen's geometry). In a pioneering work, Stromeyer [1] adopted the dissipated energy to evaluate the fatigue limit of plain steel specimens; in particular he measured the temperature increase of a steady stream of water flowing through the specimen. More recently, temperature has been used for fatigue related studies of metallic materials. Dengel et al. [2] and Curti et al. [3] defined testing protocols oriented to estimate the fatigue limit using temperature measurements. Later on, several temperature-based fatigue studies were performed to estimate rapidly the high cycle fatigue properties or the uniaxial fatigue limit of metallic materials and components [4–14], with inclusion of the fatigue scatter on the basis of a probabilistic model [15–18], to detect fatigue damage and to monitor crack propagation [19–24] and, more recently, to analyse fatigue life under constant amplitude [25–33], multi-stage [34–37] and multiaxial loading [38,39].

It has been noted that the specific heat energy per cycle Q is a more promising fatigue damage index than temperature, because in conventional fatigue tests energy dissipation is a material property for a given load cycle and stress state, while temperature depends on the mechanical and thermal boundary conditions [40–42]. In Ref. [40] a theoretical model and an experimental procedure was proposed to evaluate the energy dissipated as heat in a unit volume of material per cycle, Q, starting from temperature measurements. Fig. 1 shows qualitatively a typical temperature trend measured during a fatigue test of a specimen. At the beginning of the test, temperature rapidly increases and stabilises at a value such that the thermal power due to self-heating of the material is dissipated to the surroundings (note that the thermoelastic temperature oscillations around the mean temperature level have been neglected on purpose in Fig. 1). By applying the energy balance equation, it was demonstrated that Q can be evaluated by stopping the fatigue test at $t = t^*$ after thermal equilibrium has been reached and by measuring the cooling gradient immediately after t^* [40]:

$$Q \cdot f = -\rho \cdot c \cdot \frac{\partial T}{\partial t} \qquad (1)$$

where f is the load test frequency, T is the material temperature, t is time, ρ is the material density and c is the material specific heat.

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Nomenclature

c	material specific heat (J/(kg K))
f	load test frequency (Hz)
f_{acq}	sample frequency of the temperature signal (Hz)
k	inverse slope of the stress-life (σ_a–N_f) curve and of the energy-based (Q–N_f) curve
K_m	material thermoelastic constant (Pa^{-1})
N, N_f	number of fatigue cycles, number of fatigue cycles to failure
N_A	reference fatigue life equal to $2 \cdot 10^6$ cycles
R	nominal stress ratio (ratio between the minimum and the maximum applied stress)
Q	energy released as heat in a unit volume of material per cycle (specific heat loss per cycle) (MJ/(m^3·cycle))
$\overline{Q}$	temperature-corrected Q parameter (MJ/(m^3·cycle))
$Q_{A,50\%}$	characteristic value of Q at N_A with a survival probability of 50%
R_m	tensile strength (MPa)
R_{p02}	proof strength (MPa)
R_y	yield strength (MPa)
t	time (s)
T	temperature (K)
$T_{N,\sigma}$	life scatter index referred to the stress-life curves
$T_{N,Q}$	life scatter index referred to the energy-life curves
$T_{N,\overline{Q}}$	life scatter index referred to the temperature-corrected energy-life curves
T_0	reference material temperature (K)
T_{the}	thermoelastic temperature (K)
α	material thermal expansion coefficient (K^{-1})
ρ	material density (kg/m^3)
σ_a	applied engineering stress amplitude (MPa)
σ_{an}	net-section stress amplitude for notched specimens (MPa)
$\sigma_{A,50\%}$	reference fatigue strength at N_A with a survival probability equal to 50% (MPa)
$\sigma_{\max}$	maximum engineering stress of the fatigue load cycle (MPa)
$\dot{\sigma}$	applied stress rate (MPa/s)
τ_a	shear stress amplitude (MPa)

According to Eq. (1), the specific thermal power ($Q \cdot f$) dissipated in steady state conditions is proportional to the cooling gradient just after the test interruption. Eq. (1) enables one to measure readily and in-situ the specific heat loss Q at any point of a specimen or a component undergoing fatigue loadings. An experimental method to estimate the specific heat loss based on an electrical analogy and applicable to smooth specimens had been previously proposed by Blotny et al. [43,44]. It is interesting to mention that recently also a quantitative evaluation of the amount of heat dissipated at the tip of a fatigue crack has been performed [45].

The Q parameter was used to rationalise about 120 experimental results generated from constant amplitude, push–pull, stress- or strain-controlled fatigue tests on plain and notched hot rolled AISI 304L stainless steel specimens [41,42], as well as from cold drawn un-notched bars of the same steel tested under fully-reversed axial or torsional fatigue loadings [46]. Notched specimens had either lateral U- or V-notches, with root radii equal to 3 or 5 mm, or a central hole with radius equal to 8 mm. Fig. 2 shows all fatigue test results in terms of net-section stress amplitude σ_{an} or τ_a, the mean fatigue curves and the 10–90% survival probability scatter bands. The figure reports also the inverse slope k of the curves, the stress-based scatter index $T_\sigma = \sigma_{a,10\%}/\sigma_{a,90\%}$ (T_τ) and the life-based scatter index $T_{N,\sigma}$ ($T_{N,\tau}$). In the case of strain-controlled fatigue tests, the stress amplitude reported in Fig. 2 is the value that was measured at half the fatigue life.

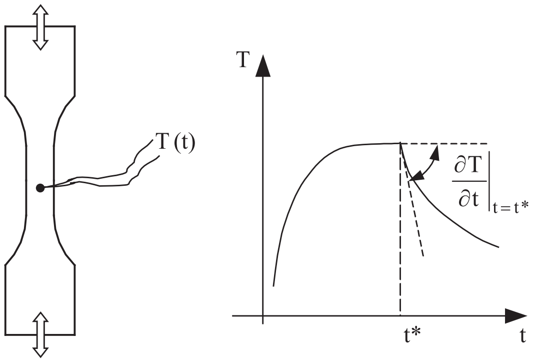

Fig. 1. Evaluation of the cooling gradient Eq. (1) during a fatigue test.

To apply the energy method, temperature was monitored during the fatigue tests in the gauge section of the plain specimens or at the root of the notched specimens. In the former case an infrared camera or thermocouples were adopted, while in the latter case only thermocouples were used. According to Eq. (1), the specific heat loss Q was determined during each fatigue test and it was seen to be fairly constant. By taking the value at half the fatigue life, Fig. 3 shows the same data reported in Fig. 2 re-analysed in terms of the Q parameter. In particular, the 10–90% scatter band shown in the figure was fitted only on the fatigue data published in [42]. However, Fig. 3 shows that the additional data obtained under axial and torsional fatigue tests [46] can be interpreted by the same scatter band. In a different investigation performed recently regarding two-stress level fatigue tests, much better correlation has been obtained using the energy- rather than the stress-based fatigue curves combined with Miner's rule [35]. The reason for that was attributed to the nature of the specific heat loss which measures the actual material response to the external loading, i.e. the actual damage accumulation rate according to the

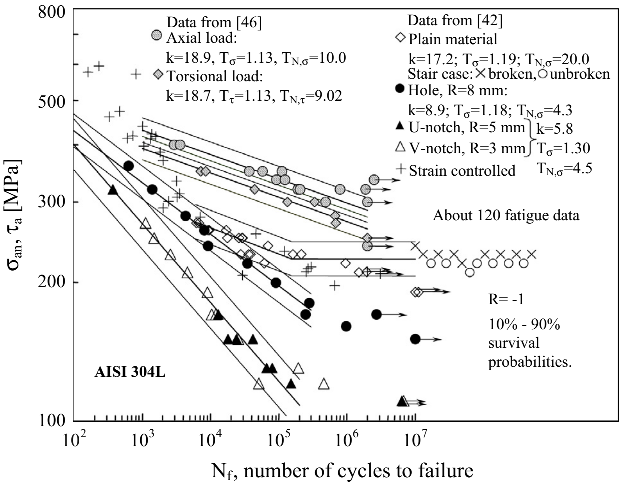

Fig. 2. Completely reversed axial and torsional fatigue test results relevant to AISI 304L steel specimens analysed in terms of net-section stress amplitude (from [46]).