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An experimental approach to estimate damage and remaining life of metals under uniaxial fatigue loading

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ABSTRACT

An experimental procedure to estimate damage evolution and remaining fatigue life of metals associated with fatigue loading is presented. Experimental phase involves uniaxial tension–compression fatigue tests performed with solid API 5L X52 and tubular carbon steel 1018 specimens subjected to both constant and variable amplitude loading. A correlation between the so-called damage parameter and the thermal response of a material at different damage levels is proposed. Results demonstrate that the correlation can estimate damage evolution with reasonable accuracy in both constant and variable amplitude fatigue processes. It is shown that under the conditions tested the evolution of damage parameter with respect to the normalized fatigue life is independent of the load amplitude, load ratio, loading sequence, material properties, and specimen geometry. The proposed correlation and the relationship between the damage parameter and the normalized fatigue life are employed to develop a non-destructive method to predict the remaining fatigue life of metallic specimens with prior fatigue damage. The method is applied to both constant and variable amplitude loading and the predicted results are found to be in good agreement with those obtained from the experiments.

1. Introduction

The application of cyclic loading to a material causes irreversible and cumulative damage that diminishes its remaining fatigue life (*RFL*). To quantify damage, one can measure permanent changes to the key *mechanical properties* such as yield strength, modulus of elasticity, cross-sectional area, elongation, tensile strength, hardness, stiffness, and static toughness. For example, Belaadi et al. [1], Abraham et al. [2], and Zhou et al. [3] reported a gradual decrease in the modulus of elasticity with the accumulation of fatigue damage in different materials. Li et al. [4] showed that the reduction in the modulus of elasticity is a useful parameter for the assessment of remaining static strength of self-piercing riveted aluminum joints. Belaadi et al. [1] also showed that plastic strain energy generation per cycle decreases with the progress in the fatigue degradation of a fibrous material. Damage can also be measured by assessing the changes in the *physical properties* such as electric, magnetic, and thermal properties. For instance, Lemaitre and Dufailly [5] presented that the variation in the electrical potential during a fatigue process is useful for estimating present damage in the conductive materials. Basically, these changes affect the materials' *dynamic response* such as stress and strain [6,7]. Azadi et al. [8] and Navaro and Gamez [9] demonstrated that fatigue damage is represented by monotonic accumulation of the total plastic strain energy generation. Thus, to characterize the behavior of materials under cyclic loading, researchers have resorted to monitoring and assessing the evolution of these material properties with time.

From a relevant analytical viewpoint, the continuum damage mechanics (CDM) offers a method to evaluate the progression of damage in mechanical and physical properties and expresses it in terms of a so-called damage parameter, D, defined as:

$$D = 1 - \frac{\widetilde{E}}{E} \tag{1}$$

where E is the modulus of elasticity corresponding to a specimen in its pristine condition and $\widetilde{E}$ represents the modulus of the specimen's present condition after sustaining a certain amount of damage. Among the early works on the application of CDM are Krajcinovic [10] and Chaboche [11] who demonstrated that damage parameter is an useful parameter in predicting present material degradation subjected to constant amplitude cyclic loading (CACL). Varvani–Farahani [12] demonstrated the application of damage mechanics in predicting fatigue failure of metals under variable amplitude cyclic loading (VACL).

A pertinent development to the present study is the work of Duyi and Zhenlin [13] who developed a relationship between D and the number of accumulated loading cycles, N, based on the exhaustion of the *static toughness*. The applications of the concept

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Nomenclature

a_i	specimen dimension (mm)
A	empirical constant
B	empirical constant
C	empirical constant
D	damage parameter
D_c	critical damage parameter
D_k	damage value in kth-stage of loading
D_{k-1}	damage value in $(k-1)$th-stage of loading
$D_{(N_f-1)}$	damage value at the onset of fracture
E	modulus of elasticity of pristine material (GPa)
$\tilde{E}$	modulus of elasticity of material with prior fatigue damage (GPa)
k	number of load stages
L_R	load ratio
m	number of loading stages in a VACL fatigue
n	slope of R_r–N plot (°C/s/cycle)
n_k	slope of R_θ–N plot in kth-stage of loading (°C/s/cycle)
$n_{i,H-L}$	slope of R_r–N plot in ith-stage of loading in High-to-Low load sequence (°C/s/cycle)
$n_{i,L-H}$	slope of R_r–N plot in ith-stage of loading in Low-to-High load sequence (°C/s/cycle)
N	number of load cycles
N_i	number of load cycle in ith-stage of loading
N_f	fatigue life in cycle
R_a	arithmetic average of surface roughness (μm)
R_r	relative slope of temperature rise (°C/s)
R_{rf}	maximum value of R_r (°C/s)
R_{rk}	relative slope of temperature rise in kth-stage of loading (°C/s)
R_θ	slope of temperature rise (°C/s)
$R^c_{\theta 0}$	intercept of R_θ–N plot (°C/s)
s	entropy (MJ/m^3/K)
s_g	total entropy (MJ/m^3/K)
s_{ic}	critical entropy (MJ/m^3/K)
s_{k-1}	accumulated entropy at $(k-1)$th-stage of loading (MJ/m^3/K)
T	temperature (K)
U_{T0}	static toughness of pristine material (MJ/m^3)
W_p	plastic strain energy generation per second (MJ/m^3/s)
σ, σ_a	maximum stress in a cycle (MPa)

of thermodynamic entropy generation associated with a degradation process in predicting damage are reported by Naderi and Khonsari [14,15], Sun and Hu [16], Amiri and Khonsari [17], Amiri et al. [18], and Khonsari and Amiri [19].

Research shows that the thermal response obtained from a short-time excitation (STE) test on a material at different stages of fatigue is useful for predicting fatigue life, N_f. Meyendorf et al. [20] showed that damage associated with the progression of fatigue tends to gradually increase the temperature rise, ΔT. The increase in temperature rise can be obtained from a series of STE tests performed during a normal fatigue test (NFT). The gradual increase in ΔT with the increase in fatigue damage is thus related to changes in the microstructural state and the fatigue life of a specimen [21]. In fact, as reported recently, the slope of temperature rise, R_θ, obtained from STE tests can be utilized to predict the *RFL* of unwelded metallic specimens subjected to constant amplitude rotating-bending fatigue [22] and welded metallic specimens subjected to tension–compression tests [23].

In this paper we report the development of a useful correlation between D and the thermal response of a specimen obtained from STE tests in order to predict its *RFL* when subjected to CACL and/or VACL. The correlation is applied to determine the evolution of D in solid API 5L X52 and tubular carbon steel 1018 specimens. Further, using the relationship between the damage parameter and the normalized fatigue life, N/N_f, we develop a non-destructive testing (NDT) method to predict the *RFL* of metallic specimens with prior history of fatigue damage. A series of uniaxial tension–compression NFTs, subjected to both CACL and VACL, with API 5L X52 and carbon steel 1018 specimens are reported to assess the damage evolution and *RFL* prediction capability of the proposed correlation and methodology.

2. Experimental details

2.1. Materials and equipment

Fig. 1a and b illustrate the schematic of solid, cylindrical dogbone specimens made of API 5L X52 (a high-strength steel) and tubular specimens made of carbon steel 1018 according to the ASTM: E466-07, respectively, and Table 1 presents the corresponding dimensions of the specimens. In order to circumvent initiation of micro-cracks from nicks, dents, scratches, and circumferential tool marks, the entire gage section of the specimens was polished longitudinally to bring the surface roughness to within 0.2-μm R_a (ASTM: E466-07). Uniaxial NFTs are carried out at different stress levels, σ, and load ratios, L_R, (defined as the ratio of minimum to the maximum stress of cyclic loading) in accordance with the ASTM: E466-07. Monotonic static tests are performed at a constant stroke rate of 0.02 mm/s in accordance with the ASTM: E8. A servo-hydraulic fatigue testing machine with the capability of 50 kN axial load and 75 Hz frequency (Fig. 2) is used to perform all of the experiments.

The surface temperature of specimen gage section is recorded using a high-speed infrared (IR) camera with the resolution of 320 × 240 pixel, accuracy of ±2% of reading, temperature range capability between 0 °C and 500 °C, sensitivity of 0.08 °C (at 30 °C) at a data acquisition rate of 1 Hz. A thin layer of black paint was sprayed on the gage section of the specimen to reduce IR reflection and increase thermal emissivity. Specimen surface temperature is recorded over the entire gage section. Since the maximum temperature occurs in the middle of the specimen gage section, average temperature over an approximately 5-mm long line at that location is used in the analysis.

2.2. Fatigue test procedure

Load-controlled and tension–compression NFTs are carried out subjected to CACL and VACL at the frequency of 10 Hz with API 5L X52 and carbon steel 1018 specimens at different stress levels and load ratios. Following the procedure recommended in [22], the evolution of R_θ in an NFT is determined by performing a series of STE tests (typically about 15–20 s) periodically as illustrated in Fig. 3. The STE tests are performed at the load level, load ratio, and test frequency chosen by the operator, which are maintained constant for all the STE tests with a specific material. The STE test loading conditions chosen in the present work are: $\sigma = 402$ MPa, $L_R = -0.56$, and $f = 10$ Hz for API 5L X52 and $\sigma = 395$ MPa, $L_R = -0.6$, and $f = 10$ Hz for carbon steel 1018.

The procedure is as follows. Beginning with a pristine specimen, the slope of temperature rise is measured by an STE test followed