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Rapid estimation of fatigue entropy and toughness in metals

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ABSTRACT

An analytical model and an experimental procedure are presented for estimating the rate and accumulation of thermodynamic entropy and fatigue toughness in metals subjected to cyclic uniaxial tension–compression tests. Entropy and plastic strain energy generations are predicted based on the thermal response of a specimen at different levels of material damage. Fatigue tests are performed with cylindrical dogbone specimens made of tubular low-carbon steel 1018 and solid medium-carbon steel 1045, API 5L X52, and Al 6061. The evolution of the plastic strain energy generation, temperature, and thermal response throughout a fatigue process are presented and discussed. Predicted entropy accumulation and fatigue toughness obtained from the proposed method are found to be in good agreement to those obtained using a load cell and an extensometer over the range of experimental and environmental conditions considered.

1. Introduction

Fatigue is the most dominant mode of failure in components that are subjected to tension–compression in cyclic manner where damage tends to accumulate as a function of time. The rate of progressive damage depends on many factors such as the stress level, σ, load ratio, L_R, (defined as the ratio of minimum to the maximum stress in a load cycle), test frequency, f, ambient temperature, T_a, humidity, and material properties. If the stress is high enough to develop irreversible plastic deformation, then plastic strain energy is generated. Most of this energy is converted into heat and dissipates to the surroundings [1–3]. According to the second law of thermodynamics, the process of irreversible plastic strain energy generation inherently produces thermodynamic entropy, γ, [4]. As the cyclic load continues, the plastic strain energy and the entropy accumulate monotonically. Fargione et al. [5], Risitano and Risitano [6], and Fan et al. [7,8] showed that fatigue fracture occurs when the amount of plastic strain energy generation reaches the fatigue toughness, W_f, (also known as the *critical energy*) of the material. Research shows that fatigue fracture occurs when the accumulation of entropy generated—starting with a pristine specimen and ending with fatigue fracture—reaches a limiting value regardless of the loading sequence [9–13]. The constant value of entropy at fatigue fracture is referred to as the fatigue fracture entropy (FFE), γ_f. This property has been successfully put to use in structural health monitoring system [10]. Development of methodologies for estimating these parameters is useful for the prediction of the present state of material damage.

Experimental results of Meyendorf et al. [14] and Walther and Eifler [15] successfully provided evidence that the level of material damage due to cyclic loading can be predicted by measuring the value of temperature increase, ΔT, with respect to the ambient temperature, T_a. The level of material damage can also be suitably quantified by measuring the slope of temperature rise, R_θ, obtained from the specimen gage section through a series of short-time excitation (STE) tests that typically last 10–15 s [16–19]. Research shows that R_θ increases linearly with respect to the accumulated fatigue load cycle, N, which is found to be useful for predicting the remaining fatigue life of welded- and unwelded-metallic specimens [16,18,19].

Material damage can also be predicted by measuring the variation in the key mechanical properties—e.g., yield strength, modulus of elasticity, tensile strength, hardness, stiffness, and static toughness. For instance, Abraham et al. [20], Belaadi et al. [21], and Zhou et al. [22] showed that the modulus of elasticity decreases gradually with the accumulation of fatigue damage in different materials. Li et al. [23] revealed that the remaining static strength of self-piercing riveted aluminum joints can be estimated by measuring the reduction in the modulus of elasticity. Azadi and Shirazabad [24] demonstrated that fatigue damage affects the stress–strain response of an aluminum alloy. Azadi et al. [25] and Navaro and Gamez [26] showed that fatigue damage is represented by monotonic accumulation of the total plastic strain energy generation. Thus, researchers have found that monitoring and assessing the evolution of these material properties with time

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Nomenclature

$\boldsymbol{A_i}$	thermodynamic forces
C	specific heat (J kg^{-1} K^{-1})
d	diameter (mm)
e	specific internal energy (J kg^{-1})
f	frequency (Hz)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_a	thermal conductivity of air (W m^{-1} K^{-1})
l	length (mm)
L	effective length (m)
L_R	load ratio
n	slope of R_θ–N plot (°C s^{-1} cycle^{-1})
N	number of load cycle
N_f	fatigue life (cycle)
N_{PR}	Prandtl number
$\boldsymbol{q}$	heat flux (W m^{-2})
r	surface normal parameter
R, r_1	radius (mm)
R_a	arithmetic average of surface roughness (μm)
R_θ	slope of temperature rise after N load cycles (°C s^{-1})
$R_{\theta i}$	slope of temperature rise at ith STE test (°C s^{-1})
$R^c_{\theta 0}$	intercept of R_θ–N plot (°C s^{-1}) on R_θ axis
s	specific entropy (J kg^{-1} K^{-1})
t	time (s)
t_f	fatigue life (s)
T	absolute temperature in fatigue test (K)
T_{STE}	absolute temperature in STE test (K)
U	velocity of air (m s^{-1})
$\boldsymbol{V_i}$	internal variables
W_f	fatigue toughness (MJ m^{-3})
W_p	plastic strain energy per second (MJ m^{-3} s^{-1})
ΔW_p	plastic strain energy per cycle (MJ m^{-3} cycle^{-1})
β	a constant
γ	thermodynamic entropy at Nth load cycle (MJ m^{-3} K^{-1})
γ_f	fatigue fracture entropy (MJ m^{-3} K^{-1})
$\dot{\gamma}_N$	entropy generation per cycle at Nth load cycle (MJ m^{-3} K^{-1})
γ_{STE}	thermodynamic entropy in STE test (MJ m^{-3} K^{-1})
ε	strain
$\boldsymbol{\varepsilon}$	total strain tensor
$\boldsymbol{\varepsilon_e}$	elastic strain tensor
$\boldsymbol{\varepsilon^p}$	plastic strain tensor
ε_0	surface emissivity
ν	kinematic viscosity of air (m^2 s^{-1})
ρ	density (kg m^{-3})
$\boldsymbol{\sigma}$	stress tensor
σ	stress level (MPa)
σ_0	Stephan–Boltzmann constant (W m^{-2} K^{-4})
φ	diameter (mm)
$\boldsymbol{\Psi}$	specific free energy (J kg^{-1})

are useful for the characterization of the fatigue behavior of the materials.

In this work, a method is developed to rapidly estimate γ_f and W_f utilizing the evolution of R_θ. A series of uniaxial tension–compression fatigue tests are performed with standard specimens made of low-carbon steel (LCS) 1018, medium-carbon steel (MCS) 1045, API 5L X52, and Al 6061 to assess the validity of the proposed method by comparing the results obtained from the proposed method to those measured from the experiments.

2. Experimental details

2.1. Materials and equipment

Fig. 1a illustrates the schematic and the dimensions of the tubular specimens made of LCS 1018 and Fig. 1b and Table 1 present the schematic and the dimensions of the solid cylindrical specimens made of MCS 1045, API 5L X52 (a high-strength steel), and Al 6061. The specimens are produced from cold-drawn tubes and rods. The specifications of the specimens are in accordance with the ASTM: E466-07. The gage section of the specimens are polished using sand papers progressing through 600, 800, 1200, 1500, and 2000 grit sizes to reduce the surface roughness to within $R_a = 0.2$ μm.

Constant-amplitude, stress-controlled fatigue tests are carried out at the frequency of 10 Hz using an axial-torsion, servo-hydraulic fatigue tester with the capability of a maximum of 50 kN axial load and 75 Hz of frequency. An extensometer with the gauge length of 25.4 mm and travel between −10% and +50% strain is used to measure the strain in the gage section of the specimen during fatigue test. The surface temperature of the 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). In order to reduce IR reflection and increase thermal emissivity, a thin layer of black paint is sprayed on the gage section of the specimen. Specimen surface temperature is recorded over the entire gage section. Since the maximum temperature occurs in the middle of the gage section, average temperature over approximately 5 mm long line at that location is used in the analysis, see Fig. 2.

2.2. Experimental procedure

Fig. 3 illustrates a specimen vertically gripped between the jaws attached to the top and the bottom grips of the fatigue tester, an extensometer mounted on the specimen gage section, and an IR camera positioned to capture the temperature contour on the specimen surface. The bottom grip oscillates vertically to apply cyclic axial load on the specimen and the top grip remains stationary.

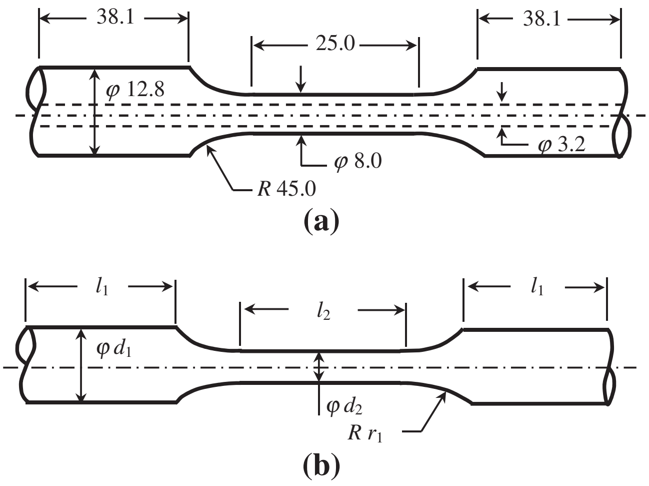

Fig. 1. Schematic illustrations and dimensions of (a) tubular specimens made of LCS 1018 and (b) solid cylindrical specimens made of MCS 1045, API 5L X52, and Al 6061 (all dimensions are in millimeter).