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On the anelasticity and fatigue fracture entropy in high-cycle metal fatigue

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ABSTRACT

The concept of thermodynamic entropy generation in a degradation process is utilized to study the high-cycle fatigue of medium carbon steel 1018. Uniaxial tension–compression fatigue tests are carried out with tubular dogbone specimens at different stress levels and loading frequencies. It is shown that a phase lag between the stress and the strain caused by the internal friction includes a considerable amount of non-damaging anelastic energy in a hysteresis loop when the amplitude of cyclic load is substantially smaller than the yield strength of the material. A methodology is proposed to determine the anelastic energy associated with metal fatigue at a stress level lower than the yield strength of a material. Finite element simulations are carried out with a 3-D model of the specimen to determine the validity of the proposed methodology. The evolutions of the plastic strain energy and temperature are discussed and utilized to calculate the entropy accumulation. It is shown that the accumulation of entropy generation in the HCF of the material—beginning with a pristine specimen and ending at fatigue fracture—is nearly constant within the experimental and loading conditions considered. The concept of tallying entropy is useful for the prediction of the fatigue life evolution of a material undergoing cyclic loading.

1. Introduction

There are many applications where a component undergoes cyclic mechanical loading where the stress level, σ, is substantially below the material's yield strength, σ_y. In these applications, the number of cycles to failure is quite large and the corresponding degradation process is often referred to as the high-cycle fatigue (HCF). Although the level of stress in an HCF test remains within the elastic limit, the material experiences local micro-scale plastic deformations [1–3]. As a result, metallic materials do not exhibit truly infinite fatigue life [4–9]. Therefore, each load cycle must necessarily introduce a certain amount of irreversible degradation, albeit small, in the material regardless of the amplitude of stress [10–13]. Indeed, as demonstrated by Esin and Jones [10], at low stress levels a material experiences inhomogeneous local plastic deformations. This phenomenon, known as the microplasticity, has been observed in experiments with different materials subject to HCF [1,2,14–19]. Although the irreversible changes in an HCF test is small, this process generates local plastic strain energy. Most of the plastic strain energy converts into heat and dissipates to the surroundings.

Recent research shows that tallying up the accumulation of the amount of entropy generation in a low-cycle fatigue (LCF) degradation process yields a useful parameter for the assessment of the fatigue life [20–22]. Specifically, the total amount of thermodynamic entropy generation—starting with a pristine specimen and ending at the fatigue fracture—in LCF is relatively constant and remains within a narrow band for various operating condition. Naderi et al. [20] referred to this value as *fatigue fracture entropy* (FFE). Experimental results show that, within a wide range of operating conditions tested, the FFE is independent of the amplitude and the frequency of load, the geometry of the specimen, and the type of fatigue load [20,23–25]. The application of this concept in HCF requires further research to develop a methodology for the estimation of the plastic strain energy generation at low stress levels.

According to the published literature [1,26,27], most of the area of a cyclic hysteresis loop in HCF represents a non-damaging anelastic energy generated by the magnetoelastic coupling, thermoelasticity, atomic diffusion, etc. The presence of the anelastic energy in a hysteresis loop occurs due to the effect of internal friction in the material, Q^{-1}, that causes a phase lag, ϕ, between the stress and the resulting strain [26,28,29]. Wertz et al. [26] successfully showed that the anelastic energy from a hysteresis loop can be eliminated by gradually decreasing the loading

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Nomenclature

A_i	thermodynamic forces associated with internal variables
C	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
E_s	elasticity modulus at magnetic saturation (GPa)
E_0	elasticity modulus at zero magnetism (GPa)
f	frequency (Hz)
h	heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
L_R	load ratio
n	surface normal parameter
N	number of load cycle
N_f	fatigue life (cycle)
$\boldsymbol{q}$	heat flux ($\mathrm{W\,m^{-2}}$)
Q^{-1}	internal friction
R_a	arithmetic average of surface roughness (μm)
T	specimen temperature (K)
T_a	ambient temperature (K)
$\Delta W_{el,max}$	maximum elastic strain energy per cycle ($\mathrm{MJ\,m^{-3}\,cycle^{-1}}$)
ΔW_H	hysteresis energy per cycle ($\mathrm{MJ\,m^{-3}\,cycle^{-1}}$)
ΔW_p	plastic strain energy per cycle ($\mathrm{MJ\,m^{-3}\,cycle^{-1}}$)
γ	fatigue fracture entropy ($\mathrm{MJ\,m^{-3}\,K^{-1}}$)
$\dot{\boldsymbol{\varepsilon}}^p$	time rate of plastic strain tensor ($\mathrm{s^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)
$\boldsymbol{\sigma}$	stress tensor
σ	nominal stress (MPa)
σ_y	yield strength (MPa)
ϕ	phase lag (°)

frequency, f, to a value such that further decrease of the frequency does not reduce the area contained within the hysteresis loop. Application of this novel method requires one to repeat an HCF test at different frequencies with identical stress level and load ratio (defined as the ratio of minimum to the maximum stress in a load cycle), L_R.

In order to determine the usefulness of the concept of the FFE in an HCF test, we propose a methodology to estimate the plastic strain energy generation in an HCF process that does not require one to repeat a fatigue test at lower frequencies. The methodology is applied to the results obtained from the experiments carried out with tubular specimens made of medium carbon steel (MCS) 1018 subject to uniaxial tension–compression fatigue load. The evolutions of plastic strain energy and temperature are then utilized to calculate FFE. Finite element simulations are performed with a 3-D model of the specimen to study its thermal response under cyclic load to validate the proposed methodology of the plastic strain energy measurement, and to predict the FFE of the material subject to a range of stress levels.

2. Analytical

2.1. Energy balance and entropy accumulation in fatigue

In the case of a cyclic loading test, the applied load generates plastic strain energy, $\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^p$, that converts into heat where $\boldsymbol{\sigma}$ and $\dot{\boldsymbol{\varepsilon}}^p$ denote the stress and the time rate of plastic strain tensor, respectively. A part of the heat energy tends to increase the specimen temperature estimated as $\rho C\dot{T}$ and dissipates to the surroundings via convection where T represents the specimen temperature, ρ is the density, and C stands for the specific heat. The rest of the heat energy conducts to the gripping jaws of the fatigue tester calculated as $k\nabla^2 T$ where k is the thermal conductivity. Thus, the principle of the conservation of energy can be applied for a fatigue specimen as follows [20]:

$$k\nabla^2 T = \rho C\dot{T} - \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^p \tag{1}$$

The time rate of volumetric entropy production, $\dot{\gamma}$, associated with the plastic strain energy generation in the gage section of the specimen can be calculated according to the second law of thermodynamics postulated by the Clausius–Duhem inequality [30]. Let $N = 0$ denotes the beginning of a fatigue test and N_f the number of load cycles required to fracture the specimen, then the total entropy generation in a fatigue test is [20]:

$$\gamma = \int_0^{N_f} \left(\frac{\Delta W_p}{T}\right) dN + \int_0^{N_f} \left(\frac{k}{T^2} . grad\, T\right) dN \tag{2}$$

where $\Delta W_p = \frac{\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^p}{f}$ denotes the cyclic rate of plastic strain energy generation and γ represents the fatigue fracture entropy, i.e., FFE = γ when $N = N_f$. Thus, FFE is the summation of entropy generation due to the plastic strain energy generation and the axial heat conduction from the pristine specimen until fracture occurs.

2.2. Internal friction, damping, and phase lag

The application of mechanical load on a metal develops strain that tends to cause several other changes in the material [27,31,32]. If the stress is less than the yield strength, the material tends to resist these changes due to the presence of internal friction according to the mechanism of damping. According to Blanter et al. [28], damping manifests itself by a phase lag between the stress and the resulting response such as the strain. The damping and the resulting internal friction transforms the mechanical energy into non-damaging internal energy which is known as the anelastic energy [1,27]. In such a process, the area of a hysteresis loop represents both the damaging plastic strain energy and the anelastic energy. The amount of the anelastic energy depends on several factors and internal processes such as the amplitude of vibration/oscillation, temperature, frequency, thermal current, dislocations, and ferromagnetism briefly discussed as follows.

According to Zener [27], the effect of the internal friction is independent of the amplitude of oscillation/vibration if the strain amplitude is less than 10^{-5} and considerable at larger strain amplitudes. Foppl [33] stated that the internal friction associated with the strain amplitude is primarily a measure of the capacity of a metal to undergo plastic deformation. Usually, cold work makes a metal more resistant to plastic deformation; it decreases the internal friction at larger strain amplitudes and increases the internal friction at small strain amplitudes [34].

Forster and Koster [35] showed that the internal friction of different metals increases substantially when the temperature is greater than 200 °C. The rapid rise of the internal friction is attributed to the onset of slip between the crystals at high temperatures due to a considerable thermal expansion of the material.

The effect of frequency on the internal friction is reported to be substantial for a range of the metals. The experimental work of Wegel and Walther [31] showed that the internal friction increases at higher frequencies. Wertz et al. [26] revealed that the area of a hysteresis loop decreases by several fold as the frequency of