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Quantitative Thermographic Methodology for fatigue life assessment in a multiscale energy dissipation framework

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ABSTRACT

Energy dissipation is an important aspect in fatigue that is closely linked to the microstructure evolution across different length scales. In this work, a novel energy-based method is developed that takes advantage of the shakedown theory and multiscale concept. A key thermal parameter pertinent to dissipation rate is proposed as a measure of the fatigue resistance. It leads to an effective way to evaluate the *S–N* curve. Experimental verification is conducted through the fatigue tests on different materials and structures. Excellent predictions are achieved by comparing to the traditional time-consuming procedure.

1. Introduction

Fatigue is an irreversible process accompanying with microstructure evolution, localized plastic deformation and energy dissipation. It has long been learned that the energy dissipation is very sensitive to the microstructural changes [1] and can, therefore, be related to fatigue damage [2]. Hence, the fatigue phenomenon was proposed to be studied by the energy-based approaches [3–5]. The early applications of the energy criteria mainly focused on the Low Cycle Fatigue (LCF) problem, as the strain energy can be more easily evaluated with the measurable plastic strain on a macroscopic scale. It was remarked in the literatures [3,6–8] that the energy approach was advantageous in investigating the multiaxial fatigue problems [9–11], as the strain energy (or hysteresis energy) allowed characterizing an integrative effect of the complex stress and strain states of deformed materials. The energy methods were also applied to study the fatigue crack initiation and propagation problem combined with the cumulative damage concepts [12,13].

Recently, the interests of the energy approaches were extended to the High Cycle Fatigue (HCF) problem [14–17]. In the HCF domain, the plastic deformation usually takes place on a mesoscopic or microscopic scale. Thus the hysteresis energy is not practically assessable by global measurement means, e.g., using an extensometer. This limitation can be hopefully tackled by employing the infrared (IR) thermography technique [18], which provides a local measurement allowing a precise evaluation of energy dissipation related to the critical regions of fatigue damage. The experiments showed that the temperature increment at the stabilized stage under cyclic loading can be considered as a sensitive indicator of fatigue damage [19–21]. Various methods, based on the stabilized temperature increment or its derivatives, were proposed for fatigue limit evaluation and *S–N* curve assessment, applied to a variety of metallic materials and structures [22–30]. In particular, Crupi [24] correlated the energy dissipation with the internal damping of deformed materials and proposed a unified approach for structural strength evaluation. Wang et al. [26] proposed a Quantitative Thermographic Methodology (QTM) for fatigue life prediction based on a damage accumulation law. Starke et al. [30] developed a so-called PHYBAL method for lifetime prediction based on strain, temperature and electrical measurements. The distinct advantage of these methods is their high efficiency for fatigue parameter evaluation comparing to the conventional methods, for instance, the staircase method. Nevertheless, these predictive models are still in its infancy and are needed to be built on a more solid physical base in order to achieve consensus for its extensive application.

In the framework of the Thermodynamics of Irreversible Processes (TIP) [31], the heat source in the cyclic deformation was derived from the measured temperature fields [32–34], and the underlying mechanisms of heat generation in the fatigue process

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Nomenclature

d	hole diameter (mm)
f	frequency (s^{-1})
h	hole depth (mm)
K_N	inverse slope of the S–N curve in bi-logarithmic scale
K_T	slope of the ΔT_{AS}–σ_a^2 curve in TM
n	constant term of the S–N curve in bi-logarithmic scale
m	inverse of constant term of the ΔT_{AS}–σ_a^1 curve in TM
C	ratio between K_T and K_N
ΔT	temperature increment (°C)
ΔT_{AS}	asymptotic temperature increment (°C)
θ	temperature increment rate (°C s^{-1})
Φ	thermal increment to failure (°C)
E_d	dissipated energy (J m^{-3})
E_s	stored energy (J m^{-3})
E_c	energy to failure per unit volume (J m^{-3})
W_p	plastic work (J m^{-3})
N	number of cycles
N_{AS}	number of cycles after that the asymptotic temperature is reached
N_f	number of cycles to failure
N_{ref}	reference number of cycles equivalent to "infinite" lifetime in fatigue design
R	stress ratio
σ_a	stress amplitude (N mm^{-2})
σ_y	macroscopic yield limit (N mm^{-2})
σ_c	macroscopic critical stress (N mm^{-2})
$\Delta\sigma$	stress range (N mm^{-2})
σ_{TM}	fatigue limit predicted by TM (N mm^{-2})
σ_{SN}	fatigue limit as expected with the S–N curve at 5×10^6 cycles (N mm^{-2})

were discussed in certain studies [19–21,35–38]. In essence, the metal fatigue is a multiscale problem and the dissipated energy manifests across different length scales. Hence, the energy approach is potential to provide an alternative viewpoint to understand the multiscale fatigue phenomenon [39,40], which should be distinguished from the current methods based on the fatigue crack initiation and propagation [41–44]. A basic physical argument in this work is that: if the energy dissipation can perfectly reflect the microstructure evolution, then the microstructure sensitivity with respect to material fatigue properties is also reflective in the surface temperature variation. By this way, the scale effect can be possibly considered in the lifetime prediction model in some way based on the energy (or temperature) variation.

This paper aims to develop an original fatigue assessment method based on energy dissipation and multiscale concept. First, a general framework involving fatigue domains, energy dissipation, and length scales is discussed. Then, the descriptive model and physical arguments of the new fatigue assessment method is elucidated in detail. Finally, the performance of the new method is verified through various fatigue tests applied to different metallic materials and structures.

2. General framework

The fatigue behavior of polycrystals is principally dependent on the loading level and other factors, e.g., temperature, environment, size and location of defects. With increasing loads, different fatigue phenomena will occur and contribute to fatigue damage and crack initiation. For the ease of investigation, the fatigue problem can be normally distinguished by Low Cycle Fatigue (LCF), High Cycle Fatigue (HCF), and Very High Cycle Fatigue (VHCF) [45–48]. These three fatigue domains can be described using a traditional Wöhler curve, as schematically represented in Fig. 1, where N_f refers to the lifetime (or number of cycles to failure) and σ_a the stress amplitude. Here it needs to be noted that it is not easy to describe the VHCF domain by using a traditional Wöhler curve. For the cases in which the VHCF is a great concern, a new statistical model was recently proposed in [49] for a complete description of S–N curves (Duplex S–N curves) both in HCF and VHCF regimes.

In Fig. 1, it should be emphasized that the fatigue domains are naturally associated with different length scales, in which specific fatigue phenomena are dominant. In general, the concerned scales can be classified into three levels: microscale level of dislocations, mesoscale level of grains, and macroscale level of materials and engineering structures. Their corresponding relation with the fatigue domains is shown in Fig. 1. And their intrinsic correlations can be explained as follows.

1. In the VHCF domain, the loading level is very low, which suffices only to activate few or a very limited number of slip systems in the polycrystal. It means that the linear relations between stresses and strains can still be considered valid in each grain. Thus, the macroscopic response of the material is elastic. In this case, only few and local slip bands may occur, and the microstructure evolution is generally confined on a microscopic scale [46,47]. There is, therefore, no important contributing factor to the fatigue damage. Hence, the lifetime can be considered very high in this domain.
2. In the HCF domain, the loading level increases but is still relatively low. For some well-oriented grains, the shear stress may exceed the resolved yield stress, resulting irreversible deformations in certain grains. It will generate a heterogeneous plastic strain field on the mesoscopic scale, and some critical regions with intense slip activations might lead to fatigue crack initiation. In this domain, the lifetime is shorter than that in the VHCF domain, and the fatigue manifestations become pronounced on a mesoscale level.
3. In the LCF domain, the loading level becomes more important. It is high enough to produce significant macroscopic plastic strains. It implies that the irreversible deformation is generalized in all the grains, and one grain is often deformed by multiple slips. Thus, the deformation becomes "homogeneous" on a macroscale level. In this domain, the lifetime of the material

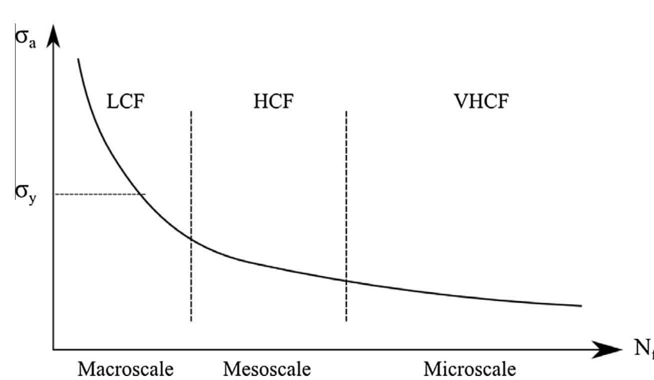

Fig. 1. A schematic presentation of the Wöhler curve (load versus number of cycles to failure) defining the fatigue domains and associated length scales.