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Experimental and numerical study of the evolution of stored and dissipated energies in a medium carbon steel under cyclic loading

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ABSTRACT

To obtain robust estimations of the fatigue limit from energy-based fatigue criteria, constitutive laws must include a correct description of the energy balance when modeling the cyclic behavior. The present paper aims at providing a better understanding of the evolution of the energy balance at both microscopic and macroscopic scales in a medium carbon steel. First, an experimental procedure is used to estimate the amount of energy which is either stored in the material or dissipated into heat at a macroscopic scale. The energy balance is observed to be very dependent on the stress amplitude and the number of loading cycles. A model is then developed to investigate the energy balance at a microscopic scale. From the simulation results, both the stored energy and dissipated energy fields are found to be strongly scattered. The dispersion is mostly explained by the crystallographic orientation distribution and the two-phased microstructure.

1. Introduction

In-service loading conditions usually generate complex cyclic stress states. As such, the choice of an appropriate multiaxial fatigue criterion plays a crucial role in obtaining correct fatigue predictions. In the case of high cycle fatigue, the observation of the stabilized behavior is generally required to build either stress-based criteria (Crossland, 1956; Sines, 1959; Dang Van, 1973; Papadopoulos, 1994; Morel, 2000) or energy-based criteria (Ellyin, 1974; Leis, 1977; Palin-Luc and Lasserre, 1998; Banvillet et al., 2003). The different energy-based approaches can be classified according to the kind of energy which is assumed to drive the fatigue process. Indeed, the total strain energy is not entirely dissipated into heat since a fraction is stored in the material. While the link between fatigue damage and dissipated energy remains unclear (Chrysochoos et al., 2008), the interest for stored energy approaches is motivated by the correlation that exists between stored energy and fatigue damage accumulation (Warren and Wei, 2010). More specifically, energy storage and fatigue damage are both related to the behavior of dislocations. Energy storage corresponds to an increase of the free energy associated with the multiplication of defects (e.g. dislocations, vacancies) while fatigue damage often results from the evolution of the dislocation substructure (Polák, 2007). Consequently, constitutive laws must include a correct description of the energy balance to obtain robust estimations of the fatigue life under multiaxial loading conditions from energetic approaches.

In order to model the cyclic behavior, different solutions have been proposed. On the one hand, macroscopic plasticity models showed their ability to reproduce several features of the cyclic behavior such as the Bauschinger effect or cyclic hardening and softening (Armstrong and Frederick, 1966; Marquis, 1979). On the other hand, polycrystalline plasticity models have been developed to include the influence of microstructural heterogeneities (Hill, 1965; Hutchinson, 1976; Berveiller and Zaoui, 1979; Lebensohn and Tomé, 1993; Paquin et al., 2001). Indeed, polycrystalline plasticity models are able to

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Table 1
Chemical composition (wt%) of the C35 steel.

C	Si	Mn	P	Cr	Fe
0.38%	0.23%	0.86%	0.02%	0.04%	Balance

account for the anisotropy of single crystal properties which is known to reinforce the heterogeneous aspect of both the elastic–plastic deformation and the dissipative behavior of polycrystalline aggregates (Roters et al., 2010; Mareau et al., 2012). Also, to deal with intragranular heterogeneities, the computation of the stored energy associated with the internal stress field surrounding dislocation structures has been performed from discrete dislocation dynamic simulations (Zehnder, 1991; Mura, 1994; Déprés et al., 2006). Discrete dislocation dynamic simulations are however limited to small volume elements.

In the present paper, it is proposed to study the evolution of the energy balance at both macroscopic and microscopic scales. The studied material is a medium carbon steel which is submitted to a uniaxial cyclic loading with different stress amplitudes. First, the experimental procedure which is used to estimate the evolution of stored and dissipated energies at a macroscopic scale is presented. Then, to gain insight into the energy balance at a microscopic scale, a polycrystalline model is proposed. Finally, the experimental estimations of stored and dissipated energies are discussed and compared to the results obtained from the polycrystalline model.

2. Experimental procedure

2.1. Material description

The material which is studied in the present work is a medium carbon steel (C35) whose chemical composition and mechanical and thermal properties are given in Tables 1 and 2. The material does not exhibit a significant texture and it is made of spherical grains whose size is about 12 μm. The material is two-phased (ferrite and cementite) with a volume fraction of proeutectoid ferrite of about 55% while the volume fraction of pearlite is about 45%.

2.2. Experimental setup

The cyclic tests have been performed with an INSTRON 8850 fatigue testing machine on specimens with a tubular geometry. The specimen geometry is detailed in Fig. 1. Each specimen has been submitted to a load-controlled cyclic loading with a constant load ratio $R = \Sigma_{min}/\Sigma_{max}$ such that the applied macroscopic stress is in the form:

$$\Sigma = \Sigma_m + \Sigma_a \sin(2\pi f_l t) \tag{1}$$

where Σ_m, Σ_a and f_l are respectively the mean stress, the stress amplitude and the loading frequency (20 Hz in the present work). The experimental data consist of:

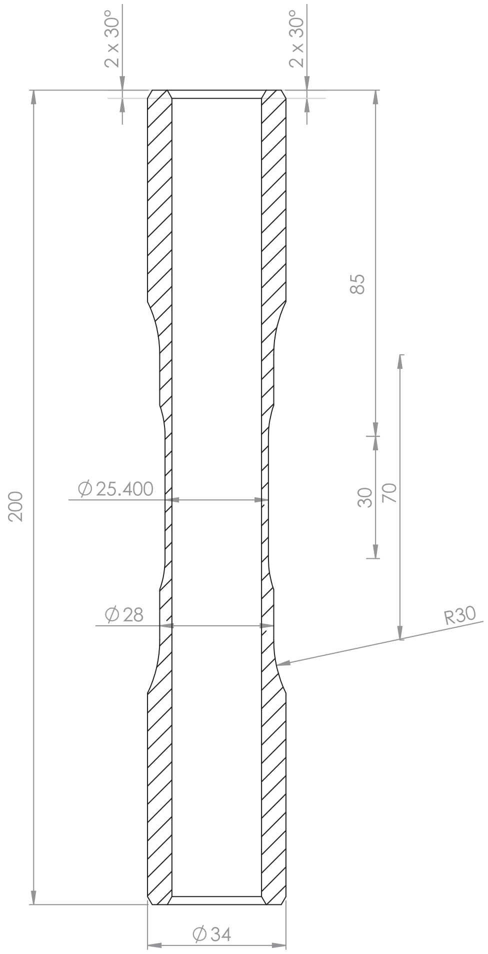

Fig. 1. Tubular specimen geometry.

- the macroscopic stress Σ which is determined from the applied force,
- the macroscopic strain E which is obtained thanks to an extensometer that is attached to the specimen,
- and the temperature T which is monitored around the specimen center with a T type thermocouple.

2.3. Energy balance

The determination of the amount of energy which is either stored in the material or dissipated into heat during cyclic tests is achieved by adopting the thermomechanical framework that was first proposed by Louche and Chrysochoos (2001) and modified by Boulanger et al. (2004) to account for the specific features of high cycle fatigue. Because of the low temperature elevations which are generally observed during our fatigue tests (i.e.

Table 2
Mechanical and thermal properties of the C35 steel: yield stress (σ_y), ultimate tensile strength (*UTS*), Young modulus (E), elongation at break ($A\%$), mass density (ρ) and specific heat (C).

σ_y (MPa)	*UTS* (MPa)	E (MPa)	$A\%$ (%)	ρ (kg m^{-3})	C (J kg^{-1} K^{-1})
430	650	205000	18	7800	450