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Thermomechanical response of metals: Maxwell vs. Kelvin–Voigt models

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ABSTRACT

Temperature changes are exhibited by a material when subjected to mechanical loads in the elastic as well as the plastic regimes. In this paper, we analyze the observed thermo-mechanical phenomenon from elastic cyclic loading tests (stress below yield point) conducted on stainless steel (SS304) using two well-known rheological models *viz.*, Kelvin–Voigt model and Maxwell's models. The Kelvin–Voigt model is shown to be well-suited in characterizing the mechanical as well as the associated thermal response. In seeking a deeper basis for the success of the Kelvin–Voigt model, correlations are sought between the model's key parameter - viscosity and the material's microscopic property *viz.* the grain boundary sliding coefficient. A plausible description is offered for the ability of Kelvin–Voigt model to explain the thermo-mechanical response under elastic cyclic loading. The effect of grain size on thermomechanical response and the variation of grain boundary diffusion coefficient with applied load is demonstrated, theoretically. The new description is used to predict the thermo-mechanical behavior of various other polycrystalline materials such as aluminum. Based on the models developed, experiments are proposed for further research.

1. Introduction

It is now well established that materials, particularly polycrystalline metals, exhibit temperature changes during cyclic loading within the elastic limit (maximum stress below yield strength) [1–6]. On one hand, several studies on the thermomechanical response were undertaken involving macroscopic loading parameters and observing temperature changes [7,8]. One of the earlier studies was carried out on the temperature response of titanium alloy subjected to low-cycle fatigue [7]. Temperature evolution for various specimen geometries during fatigue loading and changes in endurance limit of reactor pressure vessel steel at different frequencies showed promising results [7]. Infrared thermography technique was used to determine the fatigue limit of the pressure vessels by empirically relating the thermal response with load cycle number [8]. The temperature evolution of a sample subjected to elastic cyclic loading revealed the influence of loading frequency and enabled an inverse estimation of the heat dissipated in each load cycle [9]. Attempts to understand the phenomena have been limited to studies involving macroscopic loading parameters and observed temperature changes. The influence of the free surface and mean stress on the heat dissipation in steels under cyclic loading based on Kelvin–Voight model and Maxwell model was determined but not established [10].

On the other hand, fundamental studies on the effects of applied strain involving grain boundary dynamics—grain boundary friction, atomic diffusion across grain boundaries, have been carried out [11–16]. Very few studies have been reported that sought to relate the microscopic processes with the macroscopic observations—particularly the combined thermo-mechanical response. The objective of this work is to seek a microscopic connection between mechanical response and the observed thermo-mechanical phenomena making use of existing studies on the dynamics of grain boundaries in polycrystalline metals undergoing deformation. The plan of the paper is as follows: Section 2 presents details of the experiments on cyclic loading of SS304 samples and the observed temperature changes recorded with an infrared camera. Section 3 describes the application of Maxwell and Kelvin–Voigt models to understand the observed mechanical response and to determine the potential of Kelvin–Voigt model in accounting for the thermo-mechanical response. Section 4 describes how the viscosity parameter in each of these models is used in conjunction with a numerically solved heat diffusion equation to describe the observed temperature changes. Section 5 presents the connection between microscopic grain structure and the phenomenological model parameters. The paper concludes with possible implications of this connection for further work.

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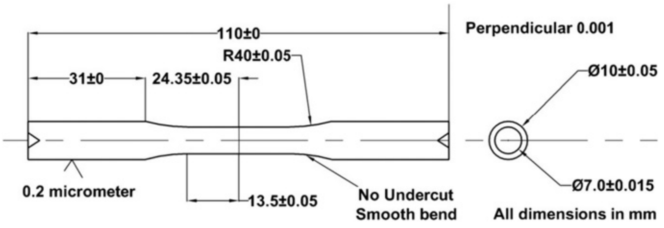

Fig. 1. Schematic showing geometric dimensions of the sample as per ASTM 2.276 for uniaxial testing. The material chosen was Stainless Steel of grade 304.

Table 1
Chemical composition of stainless steel of grade SS304 used for elastic cyclic loading tests.

Element	Ca	Cr	Mn	Ni	P	S	Si	Fe
Wt%	0.04	18	1.3	8	0.027	0.025	0.38	72.102

2. Experiments

Cylindrical specimens of diameter of 7 mm, a gage length of 27 mm and grip portion diameter of 10 mm were CNC machined for an as received stainless steel (grade 304). Fig. 1 shows the schematic of the specimen. The chemical composition of the specimen used is given in Table 1, which confirms to ASTM E 8 2.276 SS type 304. Cyclic loading tests were carried on a 100 kN MTS servo-hydraulic fatigue-testing machine as shown in Fig. 2. In-situ thermal measurements were made from the material's surface using a CEDIP Jade long wavelength infrared (LWIR) infrared thermal camera with a noise equivalent temperature difference capability of 0.02 °C at 25 °C. The camera was positioned on a tripod approximately about 1 m from the specimen at the same height. A window size of 64 × 71 pixels and an integration time of 200 μs were set for this series of experiments. A two-point Non-Uniformity Correction (NUC) has been applied using a blackbody maintained at cold and hot temperature. The digital data given by the IR camera are converted to specific temperature values using calibration function, assuming the

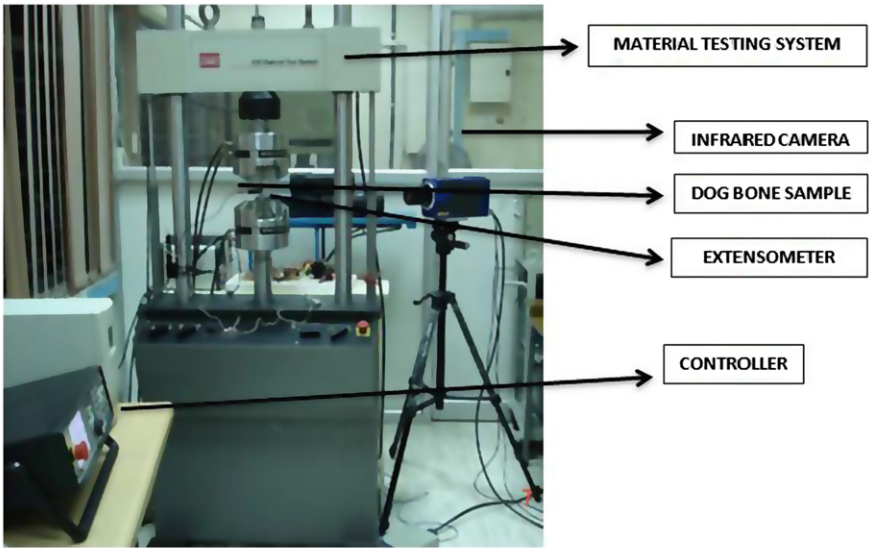

Fig. 2. Experiment setup with all key components in the testing system marked. The extensometer gives the elongation of the gauge-length portion of the dogbone-shaped sample. The total elongation in the sample is recorded by the Material Testing System (MTS). The loading frequency and amplitude was set using the controller.

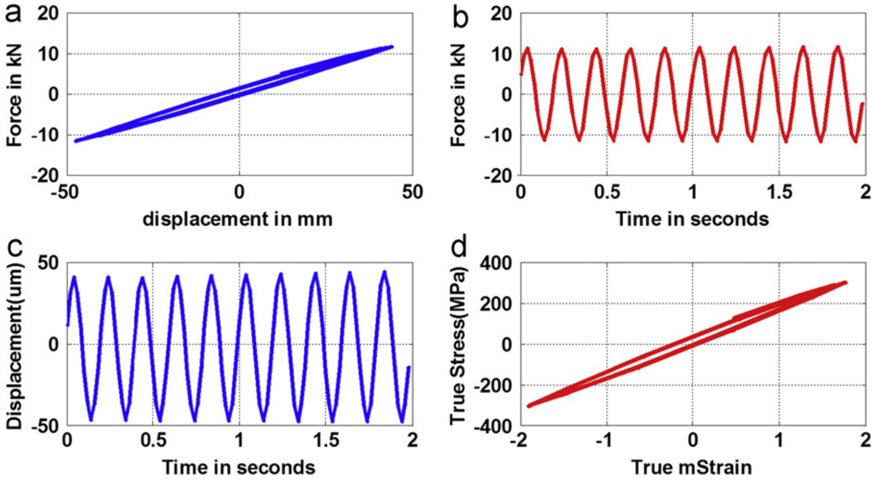

Fig. 3. For an external cyclic load from MTS at 12 kN and 5 Hz: (a) represents the force variation with displacement, (b) and (c) represent the force and displacement variation with time, and (d) represents the corresponding true stress variation with true microstrain.