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Thermo-mechanical measurement of elasto-plastic transitions during cyclic loading

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ABSTRACT

The surface temperature of stainless steel SS304 low cycle fatigue specimens subjected to cyclic loading was studied using infrared thermography technique. The thermal data mapped onto the various stages of cyclic stress–strain curve shows the ability of these measurements to identify the yield points in both the compression and tension loading. Based on the results of this study, it is possible to identify the state of stress for materials such as elastic tension, plastic tension, elastic compression, plastic compression during cyclic loading using infrared thermographic data. The thermo-elastic slope and thermo-plastic slope was observed to be dependent on the prior loading cycles.

1. Introduction

Infrared thermography is a non-destructive, non-contact, real time technique. It offers the advantage of remote/inaccessible/hazardous area measurements [1]. Any object emits energy by radiation according to its surface temperature. Human eyes are capable of detecting this energy only when the object is warm enough and the energy that is emitted is in the visible band (0.4–0.8 μm). In fact, the human eyes are able to recognize the temperature during heating of a metal, when it passes from red (720 °C), to yellow, to white (1350 °C). For low temperature values falling in the infrared region, thermography provides us with artificial eyes and gives us a chance to see invisible radiation [2]. An infrared (IR) system basically includes a camera, equipped with a series of changeable optics, and a computer. The core of the camera is the infrared detector, which absorbs the IR energy emitted by the object (whose surface temperature is to be measured) and converts it into electrical voltage or current. Finally this electrical voltage is converted into thermograms that provide information on the transient temperature behavior of a given point or area on the surface of the test sample at any given time in the loading cycle.

The thermo-elastic effect suggests the existence of a relationship between the amplitude of stress and temperature change in a material during elastic loading. In the elastic region, when a material is subjected to tensile loading, the material undergoes cooling and when a material is subjected to compressive loading, it undergoes heating. Volume dilatation (volume change) takes place in elastic region during tensile loading of material, i.e., atoms get pulled apart slightly and hence, there is a slight increase in bond length. If the loading is done under adiabatic conditions then there is no time for thermal equilibrium to take place between material and surroundings and hence, there is a gross decrease in temperature in this case of elastic tension by a tensile stress [3]. Thermodynamic equation of state and first law of thermodynamics govern these heat effects.

The thermo-elastic equation is expressed as [4]:

$$\Delta T = -\frac{\alpha T}{\rho C_p}\Delta\sigma \tag{1}$$

where α (μm/m °C) is coefficient of thermal expansion, T (°C) is the ambient temperature, ρ (g/cc) is density, C_p (J/g °C) is heat capacity at constant pressure and $\Delta\sigma$ (N/m^2) is the change in stress

Numerous applications of infrared technique have been developed: (a) to find the distribution of stresses in specimens by applying the principle of thermo-elasticity [5], (b) to characterize in situ fatigue damage during testing of the CFRP specimens using a passive thermography by measuring the temperature increase of the specimen due to hysteretic heating during fatigue testing [6], (c) to determine the size and the location of a subsurface defect from the phase image of infrared thermography [7], (d) to determine the fatigue limit of material by plotting the static temperature in temperature response of material versus stress and fitting linear fit [8]. These studies on temperature evolution during cyclic loading tests have showed that, the temperature response curve of the material is sigmoidal nature with three different slopes [9,10]; the initial rapid change in temperature due to the change in the hysteresis loop area, the secondary steady temperature response due to the stabilization of material stress–strain response along with equilibrium with the surrounding temperature and final sudden temperature rise just prior to final fracture due to the high plasticity induced at the crack tip. Isoenergy density theory was applied to fatigue loading, estimating the hysteresis loops of an hour-glass cylindrical specimen and computing the

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non-equilibrium temperature determined from the displacement gradients by considering the simultaneous change of surface and volume energy, without invoking the concept of heat, found to oscillate about the ambient temperature [11–13]. The present work deals with a more detailed study on the variation of surface temperature of test sample corresponding to different segments of stress–strain curve of material undergoing cyclic loading.

2. Experimental details

2.1. Experimental setup

Cyclic loading experiments were carried out on a 100 kN MTS servo-hydraulic testing machine. Fig. 1 shows the experimental set up. The experiments were carried out under completely reversed loading conditions, in displacement control mode for elastic–plastic loading and under force controlled mode for purely elastic loading.

The infrared thermal imaging system used for the temperature measurement is a CEDIP Jade LWIR camera (refer Fig. 1). This consists of an infrared camera cooled by stirring cooler. The camera contains an Hg–Cd–Te detector which is sensitive to infrared radiation in the wavelength range 8–10 μm. The window size used in the experiments is 60 × 56 pixels and an integration time of 200 μs. The camera was positioned on a tripod approximately about 1 m from the specimen surface. The temperature images were acquired in the Automatic Gain Controlled (AGC) mode at a various frame rates and the digital data stored in a computer hard disk. Post-processing software was used for analyzing and extracting the timing graph of temperature data. The temperature values are averaged over a rectangular area along the gage length of the specimen. The temperature variation measured during the experiment is defined as the difference between the temperature at the center of the specimen and the temperature of an unloaded reference specimen. The use of a reference specimen, located next to the loaded sample, eliminates uncertainties introduced by room temperature fluctuations during a long duration test. Polished material surfaces have a small absorptivity and a weak emissivity in infrared spectrum; to overcome the emissivity problem, the specimens were coated with matt-finish black board paint.

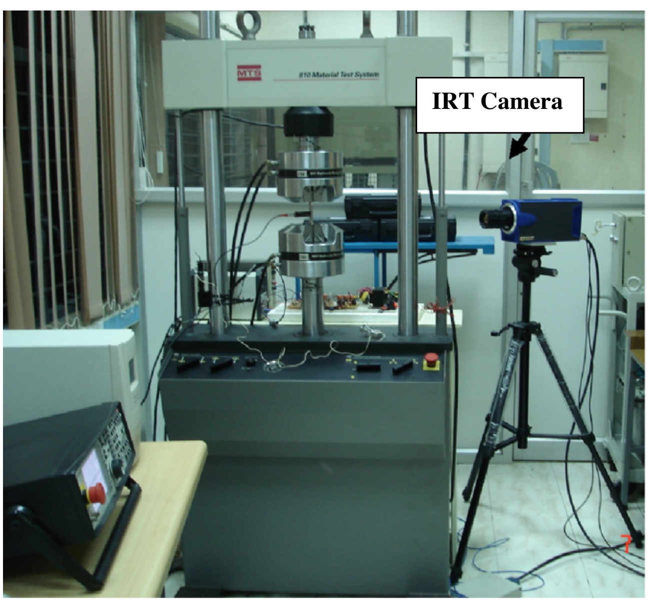

Fig. 1. Experimental set up.

2.2. Material and specimen

Test specimens conforming to ASTM 606 standard [14] with a gage length diameter of 7 mm and a gage length of 27 mm and grip portion diameter of 10 mm were CNC machined as shown in Fig. 2 for as-received stainless steel (Grade 304) material. As a prerequisite of cyclic testing, the surface of the specimens were mirror polished prior to cyclic testing and then painted black, and the specimen was held using hydraulic grips. Axial extensometer with a gage length of 25 mm and a travel of ±5 mm was used to estimate gage section strain.

Table 1 presents the chemical composition of stainless steel used in the experiments which suggests that, the material conforms to ASTM.A.276 SS Type 304.

2.3. Testing conditions

Two types of cyclic loading tests were carried out to study the temperature response variation in a cycle corresponding to various segments of stress–strain curve. Initially to study the material temperature response under fully elastic cyclic loading, the specimen was loaded in the force control with load amplitude equal to 10 kN and stress ratio (ratio of minimum to maximum load) of −1. This load corresponds to a value below yield point load of

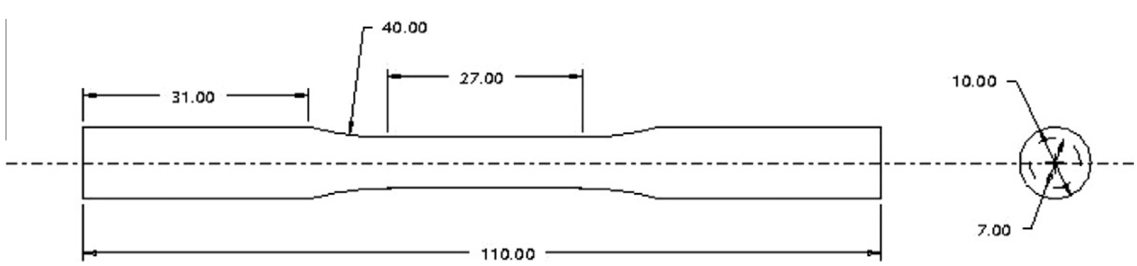

Fig. 2. Specimen geometry.

Table 1
Material chemical composition.[a]

Name of the element	Carbon	Chromium	Manganese	Nickel	Phosphorous	Sulfur	Silicon
Wt.%	0.0370	18.100	1.3100	8.020	0.0273	0.0245	0.3790

[a] Balance Fe.