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ScienceDirect
Acta Materialia 58 (2010) 2079–2090
Acta MATERIALIA
www.elsevier.com/locate/actamat

Creep damage characterization using non-linear ultrasonic techniques

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Received 25 July 2009; received in revised form 18 October 2009; accepted 27 November 2009
Available online 6 January 2010

Abstract

This paper describes the use of non-linear ultrasonic techniques for the characterization of material degradation in 99.98% pure copper due to high-temperature creep. Flat dog-bone-shaped specimens were subjected to constant load creep testing at different stress and temperature levels. Creep damage progression was monitored by conducting continuous and interrupted mode creep tests. In the case of continuous loading non-linear ultrasonic (NLU) measurements were conducted after fracture at different locations along the gage length of the sample. For interrupted tests the NLU measurements were conducted on different creep life fractions, through periodic interruption of the creep test. In all cases a through transmission NLU measurement technique was employed. Three different non-linear measurements, namely static displacement, second harmonic and third harmonic, were taken and their responses compared. The NLU measurements were found to be significantly sensitive to the extent of creep damage (∼200–2500% of base level), while the linear ultrasonic measurements, representing the change in longitudinal velocities, were only in the range 10–30% for a comparable creep damage level. NLU measurements carried out on fractured samples suggest that the NLU response was locally high at locations where the creep damage was concentrated, compared with other locations, even within the gage length of the specimen. This was confirmed using micrograph observations. Of the three non-linear measurements, the third harmonic data was most sensitive to creep damage.

Keywords: Non-linear ultrasonic; Second order harmonics; Third order harmonics; Creep damage; Copper

1. Introduction

Creep is the time-dependent plastic deformation which occurs when a material is subjected to a constant stress and temperature for an extended period and which may lead to catastrophic failure [1] of components that are operating at elevated temperatures. Creep in polycrystalline materials occurs as a result of the motion of dislocations within grains, grain boundary sliding and diffusion processes [2]. The formation of voids, multi-poles, micro-cracks and, finally, macro-cracks leading to complete fracture are the manifestations of the creep damage process. Critical parts in the power generation industry, such as turbines, heat exchangers, condensers, are prone to such creep degradation. As the demands on industry grow, prolonged service lives of machinery and the ability to perform at higher operating temperatures have become necessary. To assess creep damage within a material and to assess the remaining lifespan of critical components both quasi-destructive (in situ metallography) and non-destructive methods can be used.

Different non-destructive evaluation (NDE) techniques, such as acoustic emission, infrared thermography, eddy current and linear ultrasonic measurements, have been used for the measurement of different types of damage in metals [3]. Non-linear ultrasound has emerged in recent years as a potentially effective tool for non-destructive evaluation of material property degradation. This technique relies on measuring the higher order harmonics generated by a damage gradient. Recent studies have shown that non-linear ultrasonic measurements are sensitive to subtle damage in a material and can be used to observe damage at an early stage and can be correlated with certain micro-structural changes leading to micro-void nucleation and growth [4–7].

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doi:10.1016/j.actamat.2009.11.050

Ogi et al. [8] monitored the ultrasonic surface wave non-linearity of fatigued steel samples and observed that early damage indications could be picked up by the non-linear ultrasonic (NLU) technique. Sagar et al. [9] employed a NLU technique to evaluate the various stages of fatigue during high cycle fatigue testing of a structural steel. It was observed that the second harmonic amplitude became comparable with the amplitude of the fundamental harmonic at nearly 95% of the expended fatigue life, which could be due to fatigue crack initiation. Jaya Rao et al. [10] characterized the fatigue damage in a flat hourglass-shaped specimen made out of a high strength Al–Cu–Zn–Mg alloy (AA7175-T 7351) using an NLU harmonic generation system and determined the non-linear parameters as a function of percentage fatigue life. Their study showed the presence of two peaks, the first at between 40% and 50% fatigue life and a second at between 80% and 90% fatigue life.

Jaya Rao et al. [11] characterized the residual plastic deformation in dog-bone-shaped samples of high strength Al–Cu–Zn–Mg alloy (AA7175-T 7351) and noted an increase in non-linear parameters as a function of percentage residual strain. They interpreted their results using the two stage dislocation dynamics observed during plastic deformation. Kang et al. [12] assessed the remaining creep life of a directionally solidified nickel base superalloy and observed a strong and unique correlation between the third order harmonic of the transmitted wave and the spent creep life fraction. They also showed a strong correlation between plastic deformation accumulated during monotonic loading and the second harmonic non-linear parameter of the transmitted ultrasonic wave. However, interestingly, no correlation was found between plastic strain and the third order harmonic non-linear parameter. Ohtani et al. [13] evaluated creep damage accumulation in steel welds using the second harmonic non-linear ultrasonic method and micro-structural observations. Using an immersion technique, they observed increased amplitudes of harmonics around the heat-affected zone (HAZ), which corresponded to the regions of high creep void density, as confirmed through microscopy. Baby et al. [14] studied the non-linear response of creep damage in a titanium alloy. Creep damage was observed in the form of micro-voids at interfaces and the volume fraction of these voids was found to increase progressively with creep damage. A 200% change in the second harmonic non-linear parameter β was observed as a function of creep fraction life, which clearly substantiates that β is more sensitive to damage accumulation during creep deformation when compared with linear ultrasonic longitudinal velocity measurements.

A new technique in the field of NLU measurements which has been receiving keen attention in recent times is the static displacement generation based measurement of the non-linearity parameter. Originally reported by Thurston and Shapiro [15], and later studied by Cantrell [16,17], Yost and Cantrell [18], Jacob et al. [19] and Karthik et al. [20], this technique uses the complementary phenomenon of acoustic radiation-induced static displacement generation during finite amplitude ultrasonic wave propagation in solids. Karthik et al. [20] proposed an experimental technique to measure the static displacement and, hence, the non-linearity parameter. This technique has the advantage that the non-linearity parameter can be obtained directly from the time domain measurements; the receiver side instrumentation is reduced by avoiding the use of filters, as these could possibly interfere with the non-linearity parameter measurements [19–22].

Most of the non-linear studies have been confined to plastic deformation and fatigue damage and less information is available with respect to creep damage assessment. The present study deals with the characterization of creep damage in a pure copper material, using non-linear ultrasonic techniques. Copper is a well-documented material with a relatively simple lattice system. There is a wide literature on the creep behavior of copper and, hence, this might be useful in assessing the non-linearity of creep in copper [23–25]. Measurements of non-linear parameters, i.e. static displacement, second harmonic and third harmonic, and have been carried out on both continuous test and interrupted test specimens. In addition, metallographic studies have also been performed and the void densities at different locations were determined and correlated with the NLU and linear ultrasonic measurements.

2. Experimental work2. Experimental work

2.1. Material specification and creep tests

Dog-bone-shaped specimens prepared from a strip of 99.98% pure copper, oriented along the rolling direction, were used in the present study. The samples were flat and were of two different dimensions, one set having nominal dimensions of 145 (length) × 25 (width) × 6 mm (thickness) with a gage section area of 36 mm^2 (6 × 6 mm) and the other set having dimensions of 120 (length) × 25 (width) × 4 mm (thickness) with a gage section area of 40 mm^2 (10 × 4 mm). Fig. 1 shows the schematic of specimens used for creep damage studies. Creep tests were performed on a 30 kN constant load, single beam balancing creep test system at different temperatures and at stress levels as listed in Tables 1 and 2. A few of the samples were preserved as reference samples. A resistance furnace with ceramic thermal elements and a controller capable of maintaining temperature to within ±2 °C of the set point value was used to heat the specimen. The creep strains as a function of time were estimated based on the readings taken from a dial gage mounted across the loading train. During the creep test it was assumed that there was a uniform elongation of the specimen along the gage section. Continuous creep tests were carried out until fracture. Fig. 2a shows the typical creep curve of copper tested at a temperature of 823 K and stress level of 20 MPa under continuous loading. The melting point temperature of the copper used (T_m) was 1356 K. Fig. 2b shows the micro-structure of the reference sample. The creep curve in Fig. 2a clearly