

Creep damage assessment in titanium alloy using a nonlinear ultrasonic technique

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This paper deals with nonlinear domains (second harmonic amplitude) in order to evaluate creep damage in titanium alloy. Creep damage has been observed in the form of microvoids at primary α /transformed β interface and the volume fraction of voids increases progressively with creep deformation. A good agreement between the experimental results and metallographic studies indicate the usefulness of the method for in-service evaluation of creep damage. A nonlinear ultrasonic technique was found to be significantly more sensitive for the assessment of creep damage.

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Most aeroengine components operate at elevated temperatures under complex loading conditions and extremely hostile environments. Under such loading conditions, several damage mechanisms, including fatigue and creep, become operative, leading to a marked deterioration in the lifespan of the components. In-service assessment of the damage state in a component is important for ensuring safe operation, predicting the remaining life and promoting the life extension program. Creep is one of the main phenomena responsible for the failure of structural materials operating at elevated temperatures. At high temperatures, creep deformation is associated with the synergistic effect of both microstructural changes and strain accumulation, which leads to nucleation of microvoids, growth and coalescence, and subsequently to failure. Different nondestructive evaluation (NDE) techniques, such as acoustic emission, infrared thermography, ultrasonic attenuation and velocity measurements, acoustic harmonic measurements and eddy current, have been used for measurement of these types of damage [1]. Ultrasonics is one of the means proposed for monitoring creep damage evolution in high-temperature components [2–7]. These investigations have shown that ultrasonic velocity is

more sensitive than attenuation to the damage [2]. However, most of these conventional ultrasonic methods, based on velocity or attenuation measurements, are quite sensitive to gross defects, but much less sensitive to early creep damage stages that manifest in the form of microstructural changes. Recent studies have shown that nonlinear ultrasonic measurements are sensitive to the damages in the materials at an early stage and can be correlated to certain microstructural changes leading to microvoid, nucleation and growth [8–11]. A nonlinear ultrasonic technique has proved an effective means of characterizing the damage in structural alloys by investigating the magnitude of higher harmonics caused by nonlinear material behavior. Burke et al. [12] have evaluated the efficacy of the nonlinear parameter β associated with nonlinear acoustic behavior as a fatigue damage precursor in nickel base superalloys. Yost et al. [13,14] presented the experimental evidence as well as an analytical model, which suggests a strong nonlinear interaction of acoustic waves with dislocation dipoles in metals subjected to fatigue. The effect of artificial aging and fatigue damage on acoustic harmonic generation was reported in the case of a precipitation-hardened 2024 aluminum alloy. The noncontact monitoring of surface wave nonlinearity for predicting the remaining life of fatigued samples was studied by Ogi et al. [15]. Campos-Pozuelo and Gallego-Juarez [16] studied the nonlinear behavior of intact and

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fatigued metallic samples by means of a new experimental procedure for ultrasonic fatigue damage initiation and detection. The results have shown a notable increase (5-fold) of the nonlinear characteristics of the fatigued samples with respect to the intact samples. In particular, the variation of the third harmonic becomes much more important than the second one. Sagar et al. [17] utilized a nonlinear ultrasonic technique to evaluate various stages of fatigue, during high-cycle fatigue of a structural steel. It has been shown that the second harmonic amplitude becomes comparable to the amplitude of the fundamental harmonic at nearly 95% of the expended fatigue life, which could be the signature of fatigue crack initiation of in-service components. Nagy [9] employed a nonlinear ultrasonic technique to assess the degradation of the material due to fatigue loading. Jhang and Kim [8] conducted experiments on SS 41 stainless steel to confirm the correlation between the magnitude of the second-order harmonic frequency and material degradation. Most nonlinear studies have been confined to fatigue damage [13–20] and less information is available with respect to creep damage assessment, especially in titanium alloys. The present study deals with the characterization of creep damage in one of the recently developed high-temperature near- α IMI 834 titanium alloys used for aeroengine compressors, using a nonlinear ultrasonic technique. Measurements of the nonlinear parameter have been carried out on interrupted creep specimens. In addition, metallographic studies have also been performed in order to understand the various damage mechanisms that operate in this alloy.

When an ultrasonic wave propagates through a material, a strong nonlinear effect will be generated due to the nonlinear elastic properties of that material. Therefore, the damage to the material can be evaluated by measuring the nonlinearity of the ultrasonic wave propagated through the target material. Nonlinear measurements often use the phenomenon of harmonic generation. A longitudinal ultrasonic wave of finite amplitude tone burst of amplitude A_0 at frequency ω_0 is launched on one side of the specimen under examination. If A_0 is sufficiently large, the wave detected on the other side of the specimen will contain many harmonic components, i.e. the detected wave possesses a component of amplitude A_1 at the fundamental frequency ω_0 , a component of amplitude A_2 at the second harmonic frequency $2\omega_0$, etc., as shown in Figure 1. As a measure of nonlinearity, the parameter β is defined as a combination of the second- and third-order elastic moduli C_{ij} and C_{klm} . For in-

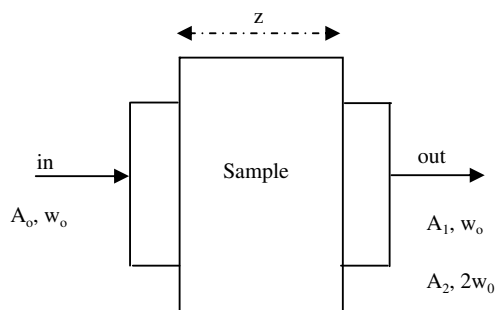


Figure 1. A conceptual diagram of harmonic generation.

stance, $\beta = 3 + (C_{111}/C_{11})$ for longitudinal waves in an isotropic material. The parameter β can also be expressed in terms of amplitudes A_1 and A_2 of the fundamental and second harmonic displacements [11].

$$|\beta| = (8v^2 A_2) / w_0^2 z A_1^2, \quad (1)$$

where v is the ultrasonic phase velocity, z the specimen thickness and w_0 the fundamental frequency. Eq. (1) implies that $|\beta|$ may be determined by measuring A_1 and A_2 of the fundamental and second harmonic displacements in a harmonic generation experiment.

A near- α high-temperature IMI 834 titanium alloy having the composition, Ti–5.75 Al–4.03 Sn–3.5 Zr–0.7 Nb–0.5 Mo–0.31 Si, was used in this study. This alloy was solution treated at 1303 K for 2 h and then oil quenched. The solution-treated alloy was subsequently aged at 973 K for 2 h. The microstructure of the alloy consists of $\sim 12\%$ volume fraction of primary α within transformed β matrix as shown in Figure 2. Kroll's reagent containing 100 ml distilled water, 1–3 ml hydrofluoric acid and 2–6 ml nitric acid was used to etch the alloy for microstructural examination. For examination of creep damage, the samples were cut from the specimens crept for different time fractions, mounted first in bakelite and then polished following standard metallographic practice. Subsequently the samples were etched using Kroll's reagent and damage was examined using optical and scanning electron microscopy (SEM). Flat creep specimens of thickness 4 mm, width 11 mm and gauge length 44 mm were fabricated from the heat-treated coupons by wire-cut electrodischarge machining (EDM). Constant load creep tests were conducted in air at a temperature of 873 K and a stress of 300 MPa. An extensometer was mounted on the specimens and two linear variable differential transducers (LVDTs) were attached to the extensometer outside the furnace. The average of both transducers was used to plot the creep curve. A complete creep test was carried out until fracture (122 h rupture time). The creep curve (Fig. 3) exhibits all the three stages, i.e. primary, secondary and tertiary creep regimes; however, the tertiary is more predominant as typically observed in many engineering alloys, especially titanium alloys. Based on the results of the test, other specimens were interrupted at different strain levels. In general, two specimens at the same strain level were used for damage evaluation. For all creep tests, reference specimens were held in the furnace along with the creep specimens. Reference specimens sustained no load. Each pair underwent exactly the same thermal history.

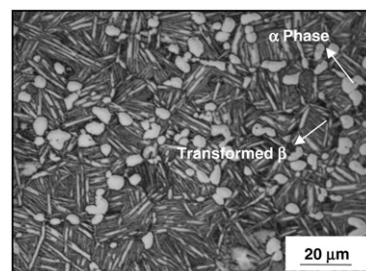


Figure 2. Microstructure of IMI 834 Ti alloy under heat-treated condition.

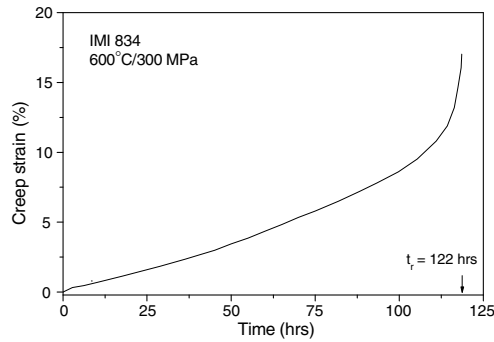


Figure 3. Creep curve of IMI 834 titanium alloy.

A computer-controlled transmitter–receiver (Model RAM-5000, M/s. RITEC, USA), generating sine waves with an adjustable number of cycles at a single frequency, was used to drive the transducer. The RAM-5000 system is fully computer controlled and contains two gated amplifiers of different frequency ranges, a superheterodyne receiver having capabilities of filtering, reversing phase and frequency sweeping of fundamental, second and third harmonics. The signal is received by a RITEC broadband receiver. The experimental setup is as shown in Figure 4. The purpose of this experimental setup was to transmit a radiofrequency (RF) tone burst of a certain frequency and pulse width into the material under study through an ultrasonic transducer, and to receive the distorted signal through another broadband ultrasonic transducer. A pair of transducers was placed on either side of the material under inspection. One of the transducers acts as a transmitter sending pulses across the material, which was collected by the other acting as a receiver. The central frequency of the receiving transducer was chosen such that its value is two or three times that of the frequency of the transmitting transducer. In the present study, a 5 MHz ultrasonic transducer (−6 dB bandwidth of 2–8 MHz) with a diameter of 8.8 mm was used as a transmitting probe. A 15 MHz broadband ultrasonic transducer (with −6 dB reception bandwidth between 7 and 20 MHz) with a diameter of 8.8 mm was used as a receiver. In order to obtain a high-power RF tone burst, a RITEC RAM-5000 (with maximum power output of 5 kW) gated amplifier was used and the output from the broadband receiver was fed to the digital storage oscilloscope, which digitized the data at a sampling rate of 200 MHz. For further analysis of the data, the digitized

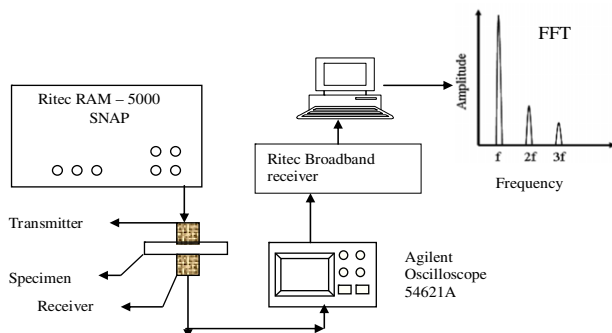


Figure 4. Experimental setup using a RITEC RAM-5000.

data from the oscilloscope was transferred to a computer with nearly 2000 data points per data file. Before the commencement of experiment, the variation of the power level of the RITEC RAM-5000 with the dial setting was calibrated. The frequency of excitation was 6 MHz and the second harmonic as well as the fundamental frequency signals were detected by using the receiver transducer at the other end of the specimen. The longitudinal wave response was monitored at different locations along the gauge length of the creep specimens. The direction of propagation of the longitudinal wave was across the shorter thickness of the test specimens.

The nonlinear parameter β which is represented as the slope of A_2 vs. A_1^2 (Eq. (1)), varies with creep exposure time as shown in Figure 5a. It can be inferred from Figure 5b that A_2/A_1^2 increases to a maximum level with increasing creep deformation and at final stage towards rupture β decreases with increase in creep fraction life, defined in terms of t/t_r , where t is the instantaneous time and t_r is the total creep rupture time. It can be observed that there is a significant increase in the β response to creep damage up to ~ 0.6 creep fraction life and the response drops towards a higher creep fraction life (~ 0.8). Moreover, a 200% change in the nonlinear parameter (Fig. 5c), clearly proves that β is more sensitive to creep damage than conventional ultrasonic longitudinal velocity measurements (which show a maximum of 15% change) [21]. A small variation in β was also observed along the uniform gauge length of the creep-damaged specimens. This could be due to the variation in creep damage in the gauge length of the specimen. The significant increase in the β response to creep damage can be explained by the increase in the microstructural damages such as voids, nucleation and growth during creep deformations as shown in Figure 5d. Since the nonlinear ultrasonic response is a function of the scale of the damage, there appears to be an optimal scale of damage that provides the highest nonlinear ultrasonic response. Any further increase in the scale of damage would cause a reduction in this response. Similar observations have also been made by Ogi et al. [15] for fatigue damage in steels and by Jayarao [22] in aluminum alloys. A detailed metallographic analysis of the interrupted creep-damaged specimens reveals that this decrease can be related to the presence of creep damage features such as micropores and microcracks as shown in Figure 6. Figure 6a and b shows the optical and secondary electron images of the specimens corresponding to a creep fraction life of ~ 0.3 . As seen from Figure 6a, the microvoids are not clearly revealed by optical microscopy. However, a secondary electron image as shown in Figure 6b reveals the existence of microvoids at the primary α /transformed β interface. This is due to the fact that the microvoids are too fine to be resolved by optical microscopy during the early stages of creep damage. As can be seen from the micrograph (Fig. 6c), not only the size of the microvoids increased but their volume fraction also increased, as evident in Figure 5d. The increase in volume fraction as well as the growth and coalescence of these voids with continued creep deformation would eventually lead to fracture of the specimen.

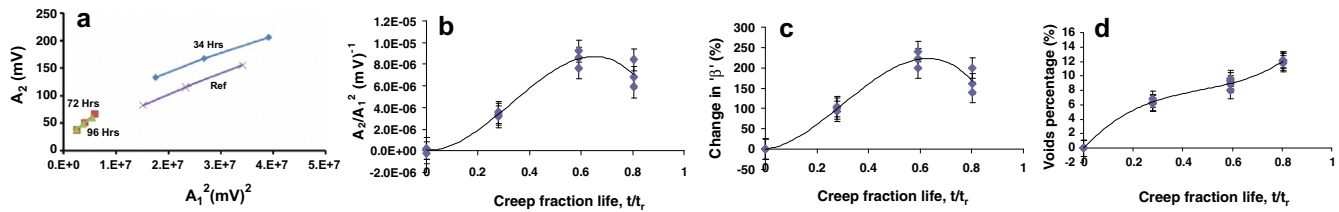


Figure 5. (a) Variation of A_2 with A_1^2 , (b) variation of A_2/A_1^2 with creep fraction life, (c) variation of percentage change in β , (d) voids percentage vs. creep fraction life. t_r = total creep rupture time.

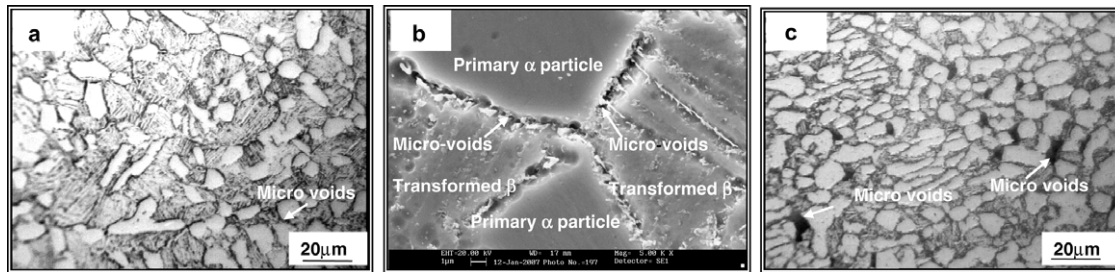


Figure 6. Creep damage micromechanisms at creep fraction life of (a) ~ 0.3 , optical micrograph; (b) ~ 0.3 , secondary electron image; (c) ~ 0.6 , optical micrograph.

A nonlinear ultrasonic technique has been used to characterize effectively the damage by investigating the magnitude of higher harmonics caused by nonlinear material behavior. Good agreement between the results and data obtained from metallographic studies demonstrates the usefulness of the method for in-service evaluation of creep damage in engineering components. Measurements of the nonlinear parameter have been carried out on interrupted creep tested specimens at a temperature of 873 K and under a constant stress of 300 MPa. A 200% change in the nonlinear parameter β is observed as a function of creep fraction life, which clearly substantiates that β is more sensitive to damage accumulation during creep deformation than longitudinal velocity measurements.

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