# LIFE ASSESSMENT OF CREEP DEGRADED SUPER ALLOY MATERIALS USING ULTRASOUND

J. Saniie, B. Panda, T. Wang, and D. T. Nagle

Electrical and Computer Engineering Dept. and IIT Research Institute

Illinois Institute of Technology
Chicago, Illinois 60616

## ABSTRACT

There has been a growing need to assess the remaining life of aging super alloy components used in combustion turbines. Components such as blades, vanes and rotors are subject to high temperature deformation known as creep which tends to change microstructure and undermine the mechanical properties. Therefore, it is important that any deterioration and microvoid formation be detected and characterized to accurately predict the remaining life of the components. In this investigation, several samples of IN-738, a super alloy used in many gas turbines, were heat treated at a temperature of 1520°F under 40kpsi stress for times ranging from 500 to 900 hours. Both ultrasonic attenuation and velocity measurements using a 20 MHz transducer were employed for characterizing the samples. Our findings indicate that velocity measurements lack quantitative value since significant variability exists in the samples prior to creep damage. However, attenuation measurements clearly distinguish between fresh specimens and samples with creep damage.

## INTRODUCTION

Gas turbines constitute a significant portion of land based turbines for power generation. Currently, there are a large number of gas turbines ready to be retired because they are suspected of being aged. There are, however, substantial costs associated with the replacement of these turbines, and utility companies are generally skeptical about the recommendations of turbine manufacturers due to the intermittent use of these turbines. Life assessment of hot section components such as blades, vanes, and disks has recently been given considerable attention in the field of nondestructive testing and may greatly facilitate the decision making process of whether to retire or continue using a specific turbine.

For proper assessment, material degradation mechanisms must be understood. Material degradation can be broadly characterized as mechanical property degradation and degradation due to oxidation, of which, mechanical property degradation due to creep and the associated changes in microstructure is recognized as the dominant degradation mechanism. Exposure to high temperature and stress coarsens the strengthening precipitates in these materials often changing their morphologies. Extensive degradation results in the generation of fine, grain boundary voids drastically reducing the strength and ductility of the material. In superalloys, which are the preferred materials for turbine components, the above changes occur under a very thin oxide layer. The thickness of this oxide layer changes, but rather slowly over time for this group of alloys.

These hot section components constitute a large portion of the total material cost of the turbine. Therefore non-destructive assessment of material degradation, which can be correlated to the remaining life, has become a major priority among utility companies. Currently, metallographic polishing and replication is the only reliable method for degradation assessment. This paper presents the viability of ultrasonic testing as a technique to study this degradation.

## ULTRASONIC IMAGING AND MICROSTRUCTURE CHARACTERIZATION

Current testing methods of creep degraded superalloys require sectioning sacrificial components to detect microvoids and changes in microstructure. Therefore, an NDE method, such as ultrasound, which can provide the needed information without sacrificing components is highly desirable. Ultrasonic imaging for microstructure characterization has two objectives: flaw detection and evaluation of microstructure. Changes in the microstructure are reflected in the attenuation and velocity of ultrasound in the given medium. This study utilizes the pulse-echo (A-scan) imaging technique in which a extremely short burst of ultrasonic energy is transmitted into the sample so that the returning echoes can be monitored and analyzed. The boundaries of inhomogeneities in the material produce reflections in which the time of flight pertains to the depth of the material and the intensity of the backscattered echo yields information about the gradient of the impedance and size of the reflector. The prepared creep-damaged samples are a thin layer (thickness is approximately 6.3mm) in which ultrasonic examination produces reverberant echoes. Therefore in the next section an explicit model of attenuation and the backscattered signal from a thin layer is given in which attenuation and velocity measurements are made in order to estimate creep damage in super alloy components.

## BACKGROUND THEORY

The model of an ultrasonic signal penetrating a thin layer is shown in Figure 1 (immersion technique). It can be seen

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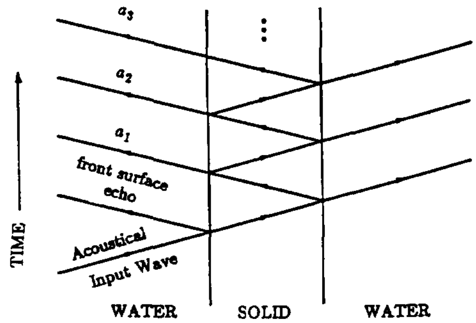



Figure 1. Model of single reverberating ultrasonic echo in a thin layer with normal incidence penetration.

from this figure that the resulting backscattered signal, $y(t)$, is composed of a sequence of evenly spaced echoes given by:

$$y(t) = a_0\, h(t) + \sum_{i=1}^{\infty} a_i\, h(t - i\,\Delta T) \quad (1)$$

where $t=0$ corresponds to the instant of signal reception, $a_i$ are the amplitudes of the received echoes ($a_0$ corresponds to the front surface echo as in Figure 1), $h(t)$ is the impulse response of the system, and $\Delta T$ represents the time separation between received echoes. $\Delta T$ can be expressed as:

$$\Delta T = \frac{2d}{v_L} \quad (2)$$

where d is the thickness of the solid and $v_L$ is the longitudinal velocity of sound in the medium. Assuming the material is homogeneous, velocity can be easily estimated from the above relationship. The respective intensities of the returning echoes, $a_i$ (see Figure 1), are dependent on the acoustical impedance and attenuation of the material [1-2]:

$$a_0 = \frac{Z_s - Z_w}{Z_s + Z_w} \quad (3)$$

$$a_i = \left[\frac{4Z_w Z_s}{(Z_w + Z_s)^2}\right] \cdot \left[\frac{Z_w - Z_s}{Z_s + Z_w}\right]^{2i-1} [e^{-2\alpha(f)d}]^i \ \text{ for } i>0 \quad (4)$$

where $i$ is the index of received echoes, $\alpha(f)$ is the composite frequency-dependent attenuation coefficient, and $Z_w$ and $Z_s$ is the acoustical impedance for water and solid, respectively. The general acoustical impedance, $Z$, is

$$Z = \frac{1}{\rho v_L} \quad (5)$$

where $\rho$ is the density of the propagating medium.

The longitudinal velocity, $v_L$, is given by:

$$v_L = \left[\frac{Y(1-\sigma)}{(1-2\sigma)(1+\sigma)\rho}\right]^{\frac{1}{2}} \quad (6)$$

where $Y$ is Young's Modulus and $\sigma$ is Poisson's Ratio.

The attenuation of ultrasonic wave in solid materials is rather complex [3-5] and can be modeled as the sum of two components:

$$\alpha(f) = \alpha_s(f) + \alpha_a(f) \quad (7)$$

where $\alpha_s(f)$ is attenuation due to scattering and $\alpha_a(f)$ is attenuation due to absorption. In the Rayleigh region (the wavelength, $\lambda$ is large in comparison with the mean grain diameter, $\bar{D}$), the attenuation of ultrasound is expressed as

$$\alpha(f) = a_1 f + a_2 \bar{D}^3 f^4, \quad (8)$$

where $a_1$ is the absorption constant, $a_2$ is the scattering constant, and $f$ is the transmitted frequency. In the Rayleigh region, the absorption characteristic of a solid is generally much smaller than the scattering component, $\alpha_s(f)$.

The microstructure changes resulting from creep damage may influence these physical parameters presented in Equations 4,6, and 7. This would suggest that velocity measurements and the values of the reverberant echoes, $a_i$, are potentially useful for evaluating creep damage. Simulated envelopes of the echoes, $a_i$, are shown in Figure 2 for different values of acoustical impedance of the thin layer and for $\alpha=0$dB/cm. This shows that higher impedances of the thin layer prolongs the reverberations in the material, while allowing less energy to penetrate the layer. The effect of attenuation does have a significant role in reverberation patterns as is shown in Figure 3 for various $\alpha$ and $Z_s$=75 kg/cm$^2$sec. The changes in the attenuation have a direct effect on the received energy of the reverberant echoes. The larger attenuation severely diminishes the reverberations which will decrease the SNR of the information signal. It is our objective to characterize these changes in attenuation corresponding to the changes in the microstructure of the sample.

## MATERIAL AND SPECIMEN PREPARATION

A low carbon version of INconel 738 super alloy is the turbine blade material used in most GE turbines and was selected as the candidate material for this study. This alloy is used in a heat treated condition which generates a bimodal distribution of precipitates known as $\gamma'$ in a matrix which is known as $\gamma$. The crystals of $\gamma$ are

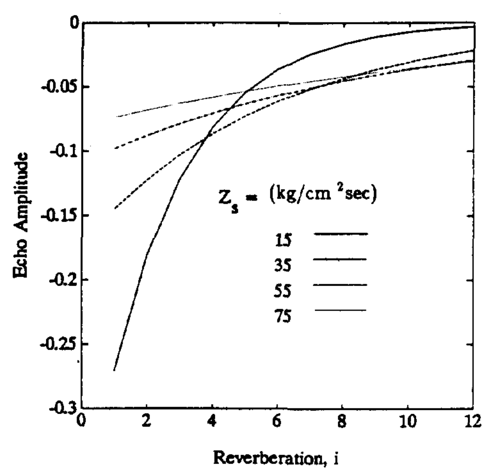



Figure 2. Simulated envelopes of reverberating echoes for various $Z_s$ ($\alpha=0.0$dB/cm).

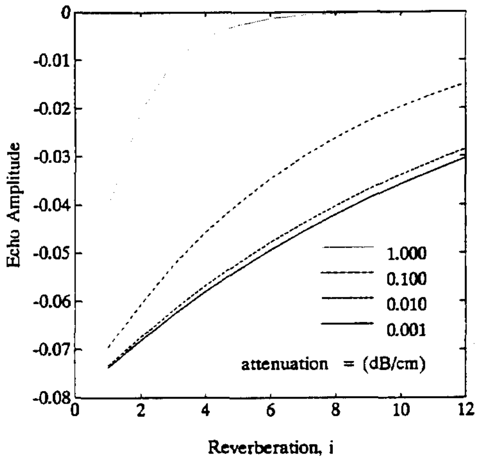



Figure 3. Simulated reverberant echoes envelope for a thin layer with acoustical impedance, $Z_s$=75 kg/cm$^2$sec, and various attenuation factors, $\alpha(f)$.

separated by grain boundaries containing carbides at some locations. Figure 4a shows a typical microstructure of this material. With degradation resulting from high temperature exposure and stress, the $\gamma'$ size and shape changes. This has been illustrated in Figure 4b. While coarsening of the precipitates is expected with exposures to higher temperatures, the directionality of the precipitates

(a) (b)

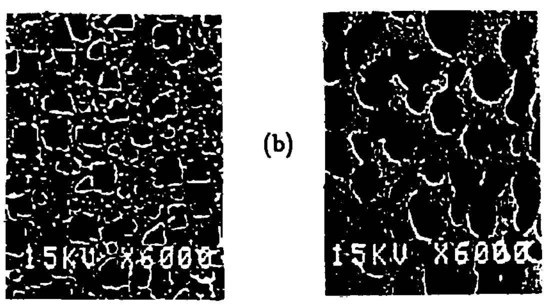



Figure 4. (a) Heat-treated microstructure (X6000) of the IN-738LC material observed using single stage replication technique. Both cuboid and spheroid $\gamma'$ particles are evenly distributed, observed at locations corresponding to the center of dendrites, (b) Microstructure (X6000) of the sample exposed to 1747° F under 15kpsi for 500 hours. The stress axis is perpendicular to the direction along which the $\gamma'$ precipitates are elongated.

develop with a simultaneous application of stress and temperature.

Creep is the time dependent deformation of materials under the simultaneous application of stress and temperature and is the dominant mode for degrading hot section turbine components. To generate degraded specimens for ultrasonic studies, the following scheme was chosen. From high temperature creep deformation studies it was realized that the material is expected to rupture in 1000 hrs if it is exposed to 1520° F under 40kpsi stress. The actual life span under these test conditions was found to be 1005.1 hours. To generate microstructures with progressive degradation, specimen were exposed for 500, 750, and 900 hours under the aforementioned conditions which would correspond to 50, 75, and 90 percent expenditure of their life span, respectively. The specimen thus generated have identifications presented in Table 1.

Table 1. IN738LC (Cast Material) SAMPLES

| Marking on Sample | Damage Treatment Time | Comments |
|---|---|---|
| Unmarked | None | Fresh Sample |
| RA | 500 hrs | Samples are exposed to a temperature of 1520° F under 40 kpsi stress. |
| NJ | 750 hrs | |
| F | 900 hrs | |

The specimens, which were machined flat (within a fraction of one thousandths of an inch), developed an expected but thin oxide layer during this treatment which was subsequently removed prior to NDE.

## EXPERIMENTAL RESULTS

Experimental results were conducted using the superalloy materials described above. The ultrasonic measurements were obtained using a pulse-echo immersion technique and data was acquired with a high speed digitizer. The transducer had a center frequency of 20MHz and a 3dB bandwidth of approximately 7 MHz which allows for high resolution echoes with a wavelength comparable to the grain size. Data was collected at a sampling rate of 100MHz with an 8-bit quantizer. The window length is about 20$\mu$sec. The four experimental measurements are shown in Figure 5, and the differences in the reverberant patterns are significant.

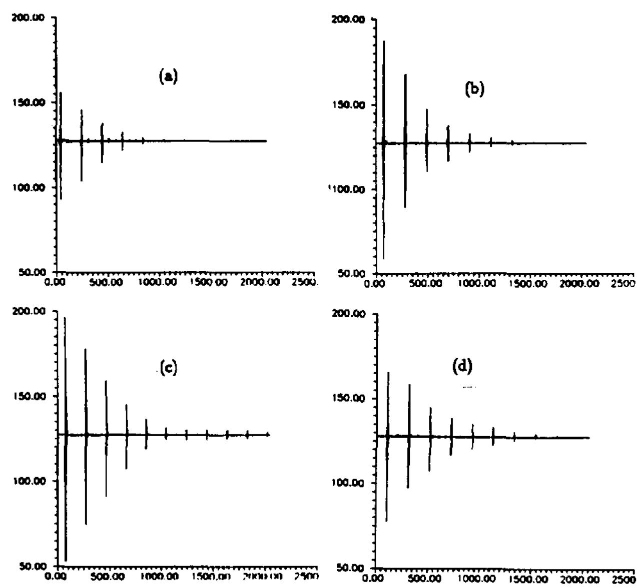
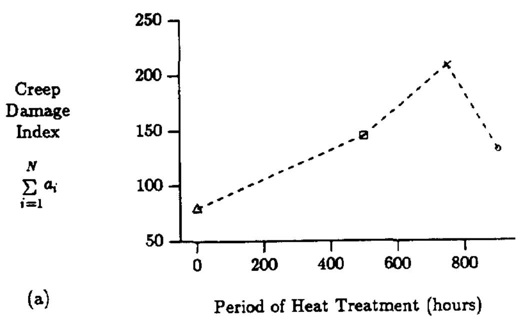



Figure 5. Experimental A-scans of samples: (a) reference, (b) RA, (c) NJ, and (d) F (see Table 1).

In order to characterize the creep-damage using attenuation estimates, a creep-damage index is defined as the sum of the amplitudes of $N$ experimental reverberant echoes, $\sum_{i=1}^{N} a_i$. The creep-damage index versus the treatment period is shown in Figure 6a. This figure indicates a definite increase in power for the treated samples in comparison with the untreated sample. However, there is not a clear relationship that can be seen from the treatment periods between 500 to 900 hrs. The decrease in power of the sample F (900hrs treated) with respect to sample NJ (750hrs treated) suggests either an insensitivity in this region or microstructure changes not consistent with the anticipated precipitation effect. Due to the limited samples available, this question is subject to further research.

Multiple velocity measurements are shown in Figure 6b, where great variability with respect to each sample is evident. Expected accuracies of velocity measurements are within 2 to 3 %. Velocity measurement variations can be due to changes in the material from region to region, limitations of the measurement system (transducer bandwidth, focal point, and sensitivity), or the geometry (size) of the sample. The results of these velocity estimates are inconclusive due to the large fluctuations (up to 10%) in the measurements of the reference sample (0 hrs treated) and sample RA (500 hrs treated). This suggests that a great degree of inhomogeneity exists in this type of material. Future recommendations would be to use larger sized samples. Larger samples would allow us to obtain more velocity estimates while testing the same sample through the progression of treatments to characterize the changes independent of variations that exist from sample to sample.



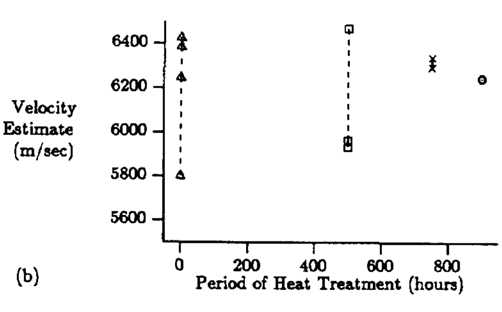




Figure 6. (a) Attenuation and (b) velocity measurements of experimental results.

## CONCLUSION

This study has presented the potential of ultrasound for characterizing creep damage in super alloy materials. Preliminary results using attenuation coefficients are very encouraging. A clear distinction between the fresh specimen and samples with creep damage can be recognized. Present velocity measurements lack quantitative value since significant variability exists in the sample prior to creep damage. An added advantage of ultrasonic testing can be the detection of cracks deep within the specimen. Recommended future research would be to conduct the study of a broad range of specimens with data being acquired and processed before and after heat treatment. In addition, better estimates of creep damage may be obtained by applying a broad range of ultrasonic frequencies. An important practical problem which deserves further investigation is the effect associated with improper focusing for specimens with certain geometries associated with turbine blades.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