Quantification of Fatigue using Nonlinear Ultrasound Measurements

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Abstract. Conventional ultrasonic inspections techniques for fatigue characterization are based on linear elasticity. Studies have shown that NDE methods based upon sound velocity and attenuation are more sensitive and reliable after crack formation i.e. 100% fatigue. In recent years nonlinear acoustics/ ultrasonics has been suggested as a new approach for the effective evaluation of a wide range of material degradation. In this paper we present results from studies on Titanium samples to quantify LCF, using second harmonics generated during nonlinear ultrasound inspections. Samples were tested to failure and inspected with 5 MHz signals for harmonics. The nonlinearity parameter (β) is evaluated from the measurements of the fundamental and second harmonics. Over 80% change in the nonlinearity parameter is observed between the gage and the grip sections of the LCF sample, where a conventional ultrasound velocity measurement shows a negligible variation

1. Introduction

Titanium alloys offers very good material properties for applications in aircraft engines. These alloys are used in critical components like low and high-pressure compressor (HPC) disks, blades etc. These components at present are classified as Life Limited Parts (LLP) because they are retired for time and not for cause. Engine components accumulate fatigue as the engine increases service. Each cycle in this low cycle fatigue situation comprises of aircraft takes-off, cruise and landing. As the material accumulates fatigue, notable changes in microstructure are observed, producing substructures such as dislocation dipoles, persistent slip bands (PSBs) and veins. These substructures are the precursors to crack generation. As the material reaches its fatigue life, these microstructure constituents combine together to form micro cracks, which eventually lead to crack formation.

Conventional ultrasonic techniques are sensitive to microstructure variations only after a crack has been initiated and is restricted to the linear domain of the stress-strain relationship. Earlier studies by researchers have shown that conventional ultrasonic techniques on sound velocity and attenuation are insensitive to fatigue cycle accumulation. Hence, there is a need for developing a non-destructive technique that is sensitive to critical material properties like fatigue.

Acousto-elastic and harmonic generation techniques have been reported in literature to measure third order elastic constants for various materials [1,2]. When fatigue accumulates, plastic deformation takes place producing much larger nonlinear effects than the one caused due to third order elastic constants, which measures the intrinsic material nonlinearity. Recent studies have shown that increase in harmonic generation can be related to microstructural changes due fatigue and artificial aging in precipitation hardened Al 2024 alloys [4-6]. The effect of microstructure changes on the nonlinearity parameter of Al 2024 both during fatigue accumulation and during transition from the T4 temper (natural aging) to T6 temper (artificially aging) has been reported.

Also reported in literature are creep assisted microstructure variations in CrMoV rotor steels [7]. CrMoV steel samples were heat-treated and fracture appearance transition temperature (FATT) was determined as a function of aging time for calculating fracture toughness. The second harmonic measurements correlated with FATT data.

Hurley et al [8] have also reported the sensitivity of second harmonics with carbon content in martensitic steel. The measurements on nonlinearity parameter were acquired in as-quenched state to ensure that the carbon present is primarily as an interstitial in the martensite. The nonlinearity parameter was found to increase monotonically with carbon content and hardness over a range of 0.1 –0.4 mass %.

Researchers from University of Dayton research institute (UDRI) have studied Ti 64 alloy at different stages of fatigue life [9,10] on multiple samples using second harmonic technique. A substantial increase in the second harmonic amplitude (180% increase in nonlinear factor) was observed. This indicates that the second harmonic signal is very sensitive to the microstructural changes in the material caused by fatigue.

In our study, the goal was to do a feasibility study to ascertain the sensitivity of NLU with fatigue accumulation in Ti-17 alloys.

2. Nonlinear Ultrasound (NLU)

When sound propagates through fatigue accumulated material, nonlinear elastic wave behaviour manifests in two primary ways. Firstly, under continuous wave, or pulse-wave excitation, frequency-mixing and spectral components such as harmonics/ sidebands appear. Secondly, under resonance conditions, the resonance tone changes as the applied volume is increased.

These effects are enormous in material with accumulated fatigue and are the signatures of variations in microstructure. As a first approximation we could explain this phenomenon using the nonlinear version of Hooke’s law [10,11],

$$\sigma \quad = \quad E\varepsilon(1+\beta\varepsilon+\ldots) \tag{1}$$

Where $\boldsymbol{E}$ is Young’s modulus and $\boldsymbol{\beta}$ is a higher order nonlinear elastic coefficient.

Assuming negligible attenuation in the material over the propagation distance, the equation of state can be represented as,

$$\rho\frac{\partial^2 u}{\partial^2 t} \quad = \quad \frac{\partial\sigma}{\partial x} \tag{2}$$

Where $\boldsymbol{\rho}$ is the mass density of the solid in the unperturbed state, $\boldsymbol{x}$ is the propagation distance, $\boldsymbol{u}$ is the displacement, and $\boldsymbol{\sigma}$ is the stress.

By substituting for nonlinear stress-strain relationship in Eqn. 2, the wave equation in terms of displacement can be easily derived and the solution for which contains a combination of fundamental and harmonic components. When a pure sinusoidal longitudinal wave of magnitude A_1 propagates through the material, the second harmonic component A_2 is generated due to material nonlinearity. The magnitude of the second-harmonic component A_2 depends on $\boldsymbol{\beta}$, which represents the nonlinear characteristics of degraded material. The dimensionless acoustic nonlinearity parameter in materials $\boldsymbol{\beta}$ can be defined as [10],

$$\beta = \frac{8}{k^2 x} \frac{A_2}{A_1^2} \tag{3}$$

where $\boldsymbol{x}$ is the propagation distance and $\boldsymbol{k}$ is the wave vector, $2\pi/\lambda$. A_1 and A_2 are absolute amplitudes having units of length.

The contributions to the nonlinear terms in the material behaviour can arise both from deviation from Hookean elasticity and from dislocation motion. When dislocations are pinned between obstacles, they oscillate in response to the applied ultrasonic wave and thereby result in harmonics. The amplitude of the harmonics is directly related to the strain arising from this motion of dislocations. In addition the amplitude is proportional to the density of dislocations and the nature of their arrangement. Thus, fatigue, which is a direct function of dislocation accumulation, can be related to $\boldsymbol{\beta}$.

Recent measurements by Cantrell and Yost [3-6] on aluminium 2024-T4 and Stainless steel 410Cb illustrates that as material accumulates fatigue, notable changes in nonlinearity parameter $\boldsymbol{\beta}$ were observed. They have also explained the interaction of acoustic waves with dislocations and other substructures in fatigued materials using a quasi-isotropic model. The model predicts strong second harmonic generation, which is dependent on the dislocation arrangements in the substructures. Based on their model, the acoustic nonlinearity parameter, $\boldsymbol{\beta}$ for fatigued materials is represented as [3],

$$\beta = \beta_{lattice} + f_{dipole}\beta_{dipole} + f_{T-N}\beta_{T-N} + f_{pT-N}\beta_{pT-N} \tag{4}$$

Where $\boldsymbol{\beta}_{\mathbf{lattice}}$ is the anharmonicity of the crystal lattice represented by third order elastic constants, and $\boldsymbol{f}_{dipole}$, $\boldsymbol{f}_{T-N}$ and $\boldsymbol{f}_{pT-N}$, are volume fractions of material consisting of dislocation dipoles (for $\boldsymbol{\beta}_{dipole}$), Taylor-Nabarro dislocation lattice structure of density (for $\boldsymbol{\beta}_{\mathbf{T-N}}$) and polarized Taylor-Nabarro dislocation lattice structure of density (for $\boldsymbol{\beta}_{pT-N}$) respectively.

3. Experimental setup

The block diagram of a typical experimental setup for performing NLU measurements is shown in the figure 1. System consists of high power pulser with a superheterodyne receiver (RITEC RAM 5000). The experiments are configured (figure 1) for performing through transmission measurements, where a fatigued sample is insonified at a frequency 5 MHz and received at a frequency 10 MHz. The input excitation voltage is varied and the amplitudes A_1 (fundamental, 5MHz) and A_2 (harmonic, 10 MHz) are recorded on the receiver. The slope of A_2 Vs A_1^2 plot gives a measure on the nonlinearity parameter β, which is sensitive to fatigue microstructural changes.

3.1 LCF Samples

In an attempt to prove the concept of nonlinear ultrasound, three LCF samples of Ti 17 were used in the experiments (Figure 2). Table 1 illustrates the testing details for these samples. The experimental plan was to measure the nonlinearity parameter across the length of the sample, from the grip section to the fracture area. Since deformation accumulates to various levels between the grip and the fracture areas, the hypothesis was that, as explained earlier, these microstrucural events, related to dislocation accumulation, would cause changes in the nonlinearity parameter.

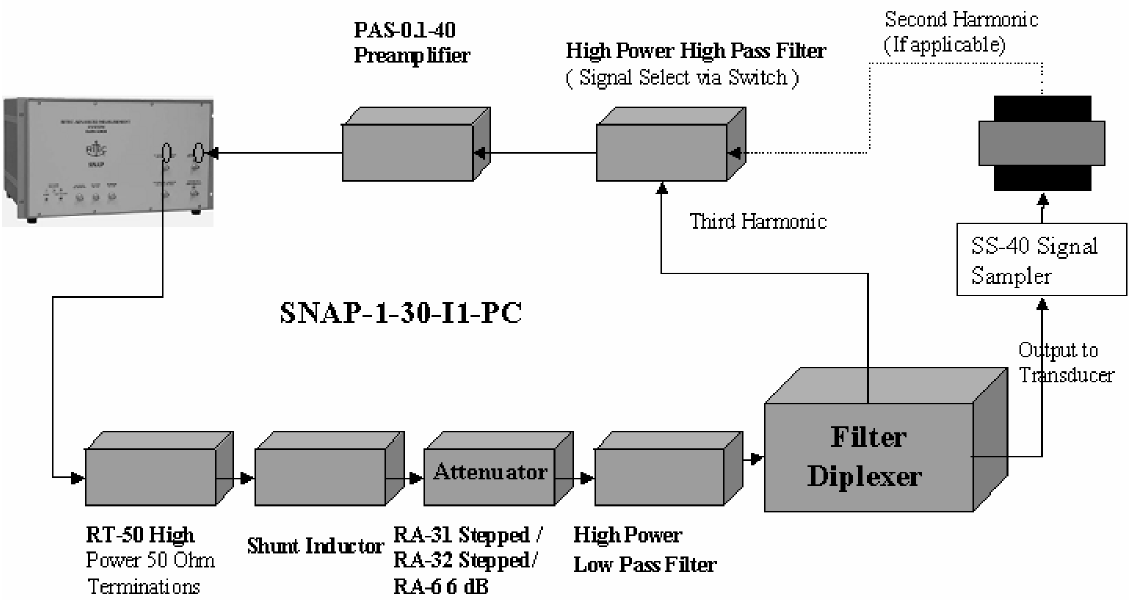

Figure 1: Block diagram for the experimental setup

Table 1: LCF sample details

Alloy	S/N	Cycles to failure	Max Strain %
Ti17	1	46,635	0.83
Ti17	2	56,704	0.83
Ti17	3	77,438	0.83

Figure 2: Ti-17 Fatigue samples

4. Experimental Results

Plots of A_2 Vs A_1^2 are shown for various sections along the length of the failed fatigue samples. It can be seen that the slopes of the plots increase as the transducer traverses the sample from the grip section to gage section [figure 3]. This is more evident from Fig. 4 where β is plotted as a function of distance along the bar. The increase in β was found to be more than 80 % between the grip and gage sections These results confirm that the nonlinearity parameter correlates with microstructural variations and can be used as a tool to track fatigue accumulation. Conventional ultrasonic data based on velocity and attenuation (figure 4) were also evaluated on these samples and found to show negligible change between the gage and grip sections of the sample.

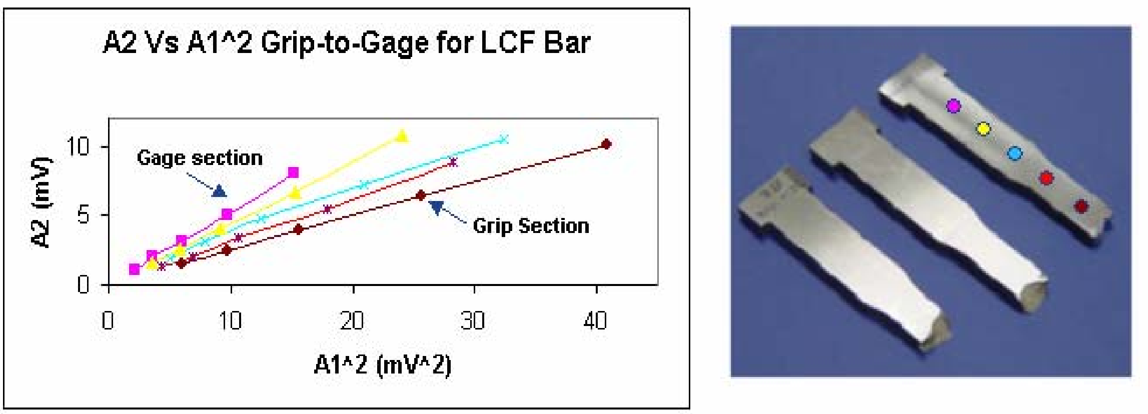

Figure 3: Variation in nonlinearity parameter β (slope) from grip section to the gage section. β sensitivity is indicated by the increase in slope from grip to gage section of the failed fatigue bar

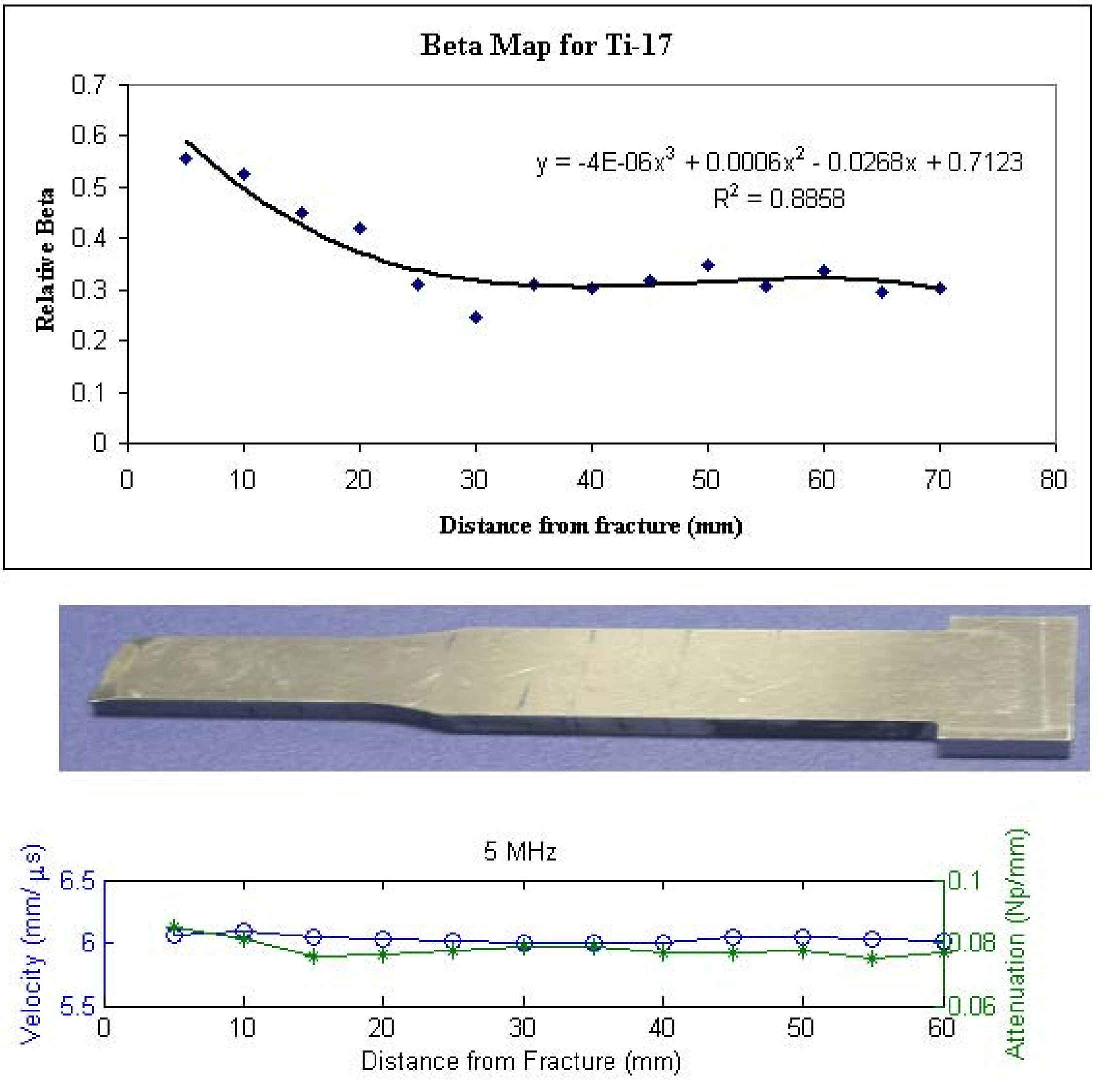

Figure 4: Sensitivity in relative β correlated with distance from fracture. Conventional ultrasound properties (Velocity, Attenuation) showing negligible change

4.1 Microstrutural origins of the β *parameter in fatigue:*

During normal monotonic deformation dislocations are generated and they accumulate in tangles as strain increases. These dislocations can give rise to harmonics by acting as vibrating strings. When a material is undergoing fatigue, the dislocations move back and forth giving rise to unique patterns whose size and shape depends on the number of cycles and magnitude of applied stress. These patterns can give rise to unique harmonics that are different from those arising from monotonic deformation. In addition, the microstructure of the material in terms of particles and precipitates can undergo changes caused by deformation and temperature. These changes can cause harmonics of their own. Microstrutural studies are underway to identify these differences and how they relate to the harmonics. Results from these studies are expected to help in developing a robust ultrasound based technique that differentiates between various kinds of microstructure variations and thereby serves as a life-assessment tool.

5. Summary

The measurements on β parameter on Ti-17 LCF samples show that NLU is sensitive to fatigue accumulation. Grip to gage variation in β is more than 80% in the case of NLU while in the case of conventional ultrasonic measurements; the variation is negligible. Further detailed analyses are underway to relate nonlinear ultrasound measurements to underlying microstructural sources.

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