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Scripta Materialia 55 (2006) 199–202

Scripta MATERIALIA

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Non-linear ultrasonic technique to assess fatigue damage in structural steel

S. Palit Sagar,[a,*] S. Das,[a] N. Parida[a] and D.K. Bhattacharya[b]

[a] *National Metallurgical Laboratory, Materials Science and Technology, Burmamines, Jamshedpur, Jharkhand 831 007, India*
[b] *Central Glass and Ceramic Research Institute, Kolkata 700 032, India*

Received 12 January 2006; revised 6 March 2006; accepted 16 March 2006
Available online 27 April 2006

A non-linear ultrasonic technique has been used to assess the fatigue damage in low carbon structural steel. The percentage of total harmonic distortion, which is the ratio of the amplitude of 2nd harmonic and the fundamental, has been introduced as the measurement parameter in this paper. It has also been observed that before crack initiation the 2nd harmonic amplitude is comparable to the fundamental. The results have been analysed in light of the dislocation theory for harmonic generation during material degradation.

Keywords: Non-linear ultrasonic; Dislocations; Fatigue; Total harmonic distortion; Harmonics

The detection and assessment of the damage that occurs in components during service play a key role for condition monitoring and residual life estimation of in-service components/structures. One of the most common material degradation mechanisms in industry is fatigue. The fatigue life of a component may be divided into three broad stages: microstructural changes leading to crack initiation, growth of micro-cracks beyond the critical length, followed by rapid fracture and failure. Particularly in the case of high cycle fatigue (HCF), where the stress level is much below the yield strength, the duration of the first stage is often more than 90% of the total life [1–3]. In other words, the life of the component is crack initiation controlled. In the case of low cycle fatigue, although the damage processes and the sequences are broadly similar to those in HCF, the crack growth stage is often more important than the crack initiation stage. Because of the importance of the failure mode and because of the predominating role that the crack initiation stage plays in HCF failures, it is important to have a suitable nondestructive testing (NDT) technique to characterize the progression of the damage until cracks are initiated. The classical approaches of prediction of the residual life of cyclically loaded materials and structures are based on the use of the fatigue life curves of the material measured on small laboratory specimens. But this can only predict the number of cycles necessary for the appearance of the cracks whose dimensions are comparable with the laboratory specimen and in a number of cases this approximation results in appreciable errors in life estimation. Hence the importance of evaluation of fatigue damage in metallic components in a nondestructive way is growing if catastrophic failures are to be avoided [4–9].

There exist several NDT techniques such as ultrasonics, magnetic and acoustic emission for fatigue damage assessment in materials. Of these, the most powerful way of evaluating material degradation is the ultrasonic method since the characteristics of ultrasonic wave propagation are directly related to the properties of the material. In ultrasonics, the characterizing parameters are the velocity and attenuation of the wave. However, the conventional ultrasonic technique is sensitive to gross defects or open cracks, where there is an effective barrier to transmission, whereas it is less sensitive to evenly distributed micro-cracks or degradation. An alternative technique to overcome the above limitation is non-linear ultrasonics (NLU). This is related to the radiation and propagation of finite amplitude (especially high power) ultrasound and its interaction with discontinuities, such as cracks, interfaces and voids. Since material failure or degradation is usually preceded by some kind of non-linear mechanical behavior before significant plastic deformation or material damage occurs,

* Corresponding author. Tel.: +91 657 2433626; fax: +91 657 2270527; e-mail addresses: sarmi@nmlindia.org; sarmi2k@yahoo.com

1359-6462/$ - see front matter
doi:10.1016/j.scriptamat.2006.03.037

considerable attention has recently been focused on the application of NLU [10–13]. When a purely sinusoidal ultrasonic wave propagates through a solid medium, it distorts and generates higher harmonics of the fundamental waveform as a result of the non-linearity of the propagation medium. It is known that the microstructural feature which is predominantly altered during fatigue damage progression is the distribution of dislocations which causes significant change in the material's non-linear elastic wave behavior. This behavior manifests itself in various ways such as by non-linear attenuation, harmonic generation, or resonant frequency shift. These effects are enormous in damaged material but nearly un-measurable in undamaged materials, hence the interest in applying NLU. The effect of dislocation density on the NLU parameter in quenched steels with different carbon contents has been reported. There have been limited attempts to relate these to fatigue damage [14–16]. While these works dealt with the calculation of the effect of dislocations on the NLU parameter, the actual changes in the dislocation structures were not shown. Also, they did not cover the total fatigue life, which is an important industrial requirement. The present work aimed to show the correlation between a non-linear ultrasonic parameter and progression of fatigue damage manifested by the changes in dislocation structures from the virgin state to almost the end of life.

The steel used in the study had the following composition (in wt.%): C–0.16; Mn–0.6; P–035; S–0.035; Al–0.07; Fe-balance. In the annealed starting condition, the average grain size was 16 μm and the yield strength 230 MPa. The fatigue test was carried out in a high cycle fatigue test machine (model 100HFP5100, RK Amsler, Germany) at room temperature with load ratio of $R = -1$ and at a frequency of 84 Hz. The applied constant stress amplitude was 150 MPa. The test specimens have been machined from the same strip of steel. The average fatigue life of the material was determined after carrying out high cycle fatigue experiments in five specimens and then taking that average life as 100% damage; a different % of damage (20%, 40%, 60%, 80%, 95%, etc.) was introduced in different specimens. Three sets of specimen were prepared accordingly.

The experimental setup used for the non-linear ultrasonic study is shown in Figure 1. A pure sinusoidal wave of frequency 150 kHz has been transmitted through a piezoelectric transducer and a broadband transducer having frequency response up to 1 MHz was used to receive the signal. The received signal was then amplified and fed to the data acquisition card of sampling rate 1.2 MHz. The acquired signal was analysed in both time and frequency domains. The measurement parameter chosen was the total harmonic distortion (THD), which is given by

$$\%\mathrm{THD} = \frac{(A_2^2 + A_3^2 + \cdots + A_N^2)^{1/2}}{A_1} \times 100\% \tag{1}$$

where A_1 is the amplitude of the fundamental and $A_2, A_3, \ldots, A_N$ are the amplitudes of 2nd, 3rd, …, Nth harmonics, respectively. Here we consider only up to the 2nd harmonic since the higher harmonic amplitudes are negligibly small. Hence the THD is defined only by the ratio of the amplitude of the 2nd harmonic to the amplitude of the fundamental (A_2/A_1).

For microstructural characterization, transmission electron microscopy (TEM) was performed in annealed and fatigued specimens using a Philips CM200 at 200 kV. The specimens for TEM were prepared from pieces of 0.4 mm thickness cut by EDM from the gauge length region. Mechanical polishing was carried out from one major surface down across the cross section. When the thickness was about 0.1 mm, further thinning has carried out by 'twin jet' electro-polishing. In this way, it was ensured (as much as practically possible) that the examination layer for TEM pertained to the surface layer of the specimens.

Figure 2 shows the transmitted signal of frequency 150 kHz (Fig. 2(a)) and its power spectrum (Fig. 2(b)). The power spectrum of the received signals during various stages of fatigue damage is shown in Figure 3. It was found that even in the virgin state, the power spectrum contained a second harmonic with a small peak height along with the fundamental. This is not surprising because it is difficult to get an ideal linear mate-

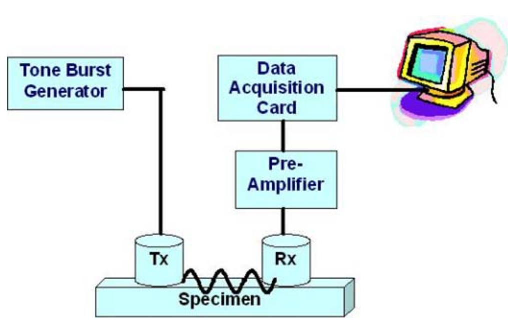

Figure 1. Experimental setup for non-linear ultrasonic study.

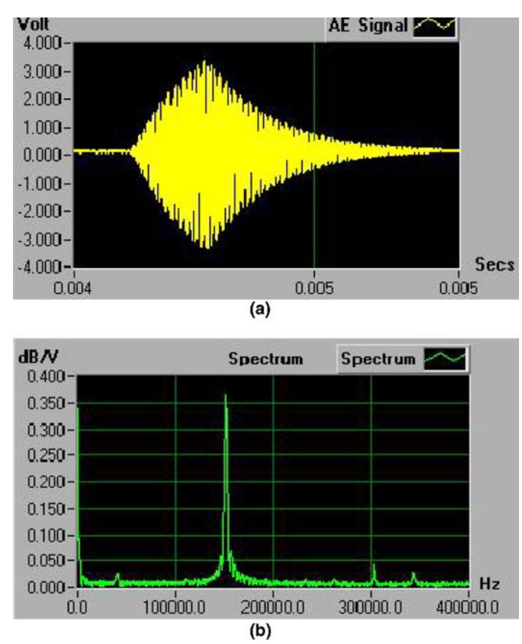

Figure 2. (a) 150 kHz transmitted signal, (b) Power spectrum of transmitted signal.

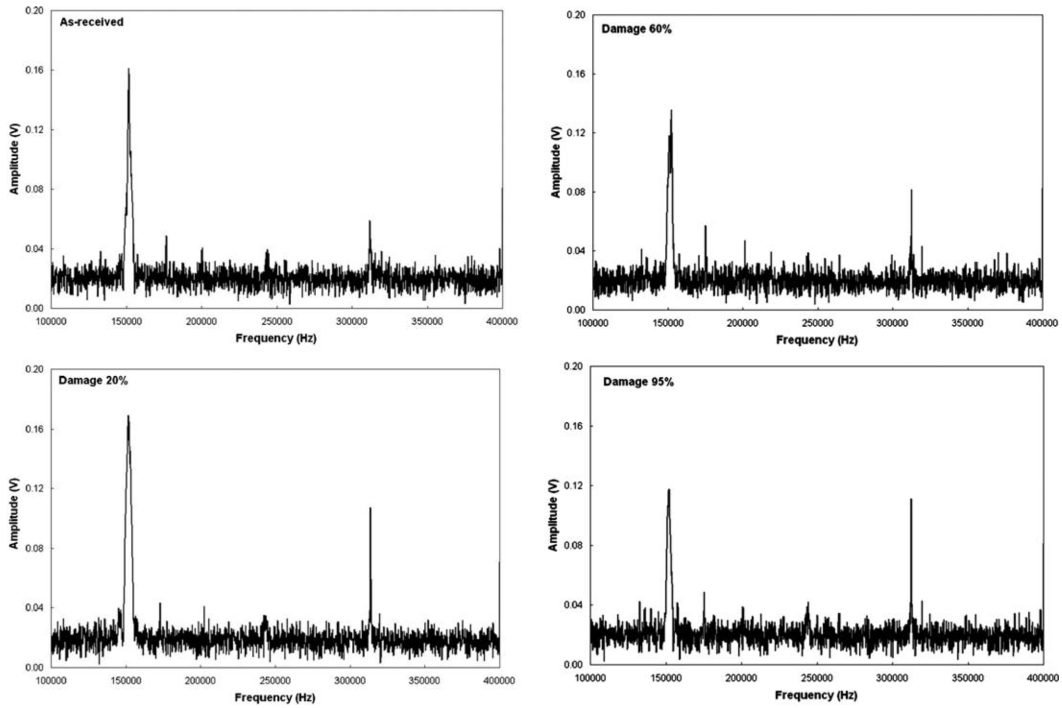

Figure 3. Power spectrum of received signals during various stages of fatigue damage.

rial. With the progression of the fatigue damage the height of the second harmonic peak increased. As shown in Figure 3, the amplitude of the 2nd harmonic increased with the progression of damage until 40% of fatigue life, thereafter until 80% of life there was no such change and it then increased again until 95% of the fatigue life. At this stage, the amplitude of 2nd harmonic peak became comparable to the amplitude of the fundamental, indicating that the non-linearity in material was enhanced enormously before failure. Figure 4 shows the plot of %THD as a function of % of fatigue life. Figure 5 shows the TEM microstructures for various percentages of fatigue damage of specimens. At the initial stage of fatiguing an increase in dislocation density was observed. Dislocations were rearranged and formed well defined cell structures at 60% of life (Fig. 5(c)). With further fatiguing, formation of persistent slip bands (PSBs) was observed and the formation of slip bands was confirmed by taking transmission electron micrographs of different specimens. Here only two TEM micrographs

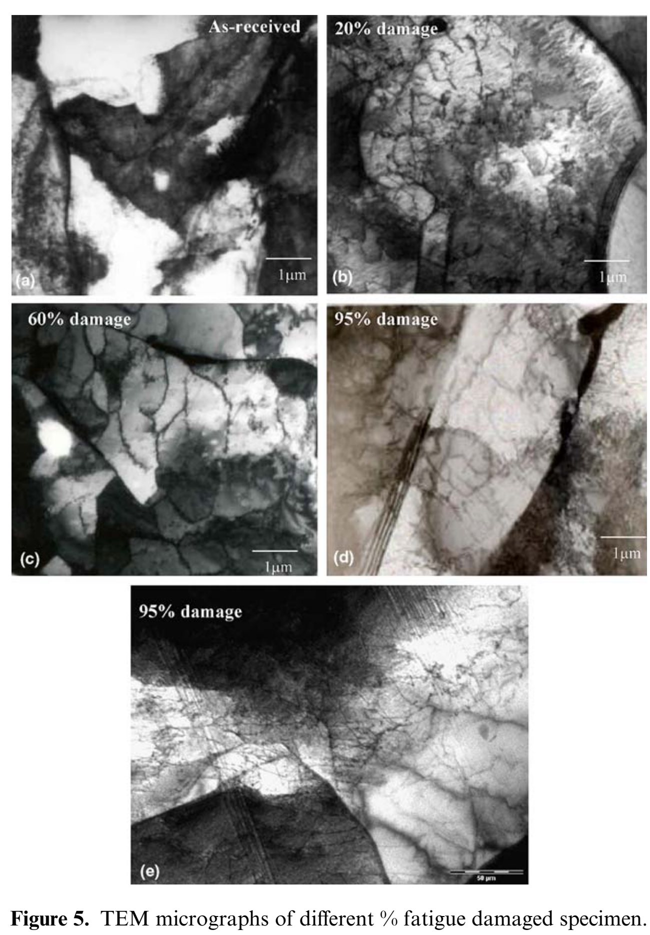

Figure 5. TEM micrographs of different % fatigue damaged specimen.

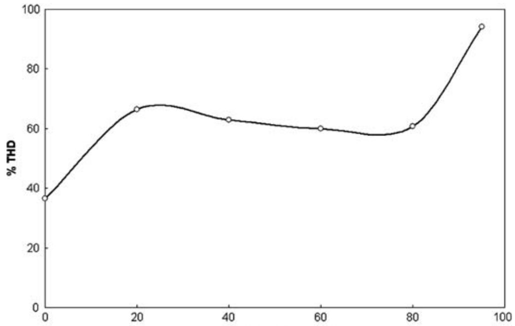

Figure 4. Variation of % of Total Harmonic Distortion (THD) with % of fatigue damage.

corresponding to 95% of fatigue damage are presented to show the PSBs (Fig. 5(d) and (e)).

A dislocation line is treated as a vibrating string as proposed by Koehler [17]. The equation of motion of a damped vibrating dislocation line can be written as

$$A\mathrm{d}^2\xi/\mathrm{d}t^2 + B\mathrm{d}\xi/\mathrm{d}t - C\mathrm{d}^2\xi/\mathrm{d}y^2 = b\sigma \quad (2)$$

where $\xi(x, y, t)$ is the displacement of an element of dislocation from its equilibrium position, y is the co-ordinate along the dislocation line, x is the co-ordinate along which the stress wave propagates, t is time, A is the effective mass per unit length of the dislocation, B is the damping force per unit length and $C = Gb^2/2\pi(1 - \nu)$, G is shear modulus, b is the Burgers vector and ν is the Poisson's ratio.

The applied alternating stress is $\sigma = \sigma_0 \sin \omega t$. The motion of dislocation segments under the applied stress results in an additional dislocation strain along with the elastic strain, which in turn causes an anelastic strain. Under this condition Hooke's law can be written as

$$\sigma = E\varepsilon(1 + \beta\varepsilon + \cdots) \quad (3)$$

where E is the Young's modulus and β is the higher order non-linear elastic constant. The higher order strain terms in Hooke's law are the cause of the generation of higher harmonics of a pure sinusoidal stress wave as it passes through the degraded material.

Our results can be analysed in the light of dislocation theory for the generation of higher harmonics. The increase in % of THD at the initial stage of fatiguing, i.e. until 40% of damage compared to the total life is because of the increase in dislocation density in the material as observed by TEM study. TEM microstructures for 20% damaged specimen (Fig. 5(b)) shows dislocations at that stage. Whereas with further fatiguing, dislocation rearrangements have taken place to form well defined cells, which is clearly visible in the microstructure of 60% damaged specimen (Fig. 5(c)). At this stage no such change has been observed in the % of THD. As the dislocations pile up to form cells, the availability of free dislocations inside the cells reduces, and as a result the amplitude of the 2nd harmonic decreases (Fig. 3(c)). As we go on fatiguing, at 95% of damage, the formation of PSBs has been observed in the microstructure (Fig. 5(d) and (e). Near PSB, the density of free dislocations increases, which is also reflected in the variation of % of THD.

Non-linear ultrasonic technique has been utilized to evaluate various stages of fatigue during high cycle fatiguing and the results have been correlated with the existing dislocation theory through microstructural evolution. To the best knowledge of the authors, this is the first time that such a correlation between a non-linear ultrasonic parameter and dislocation structures has been carried out. It has been observed that the %THD is a very sensitive parameter for studying the non-linear behavior of materials during fatigue progression. An important observation of the present work is that the 2nd harmonic amplitude becomes comparable to the amplitude of the fundamental at nearly 95% of expended fatigue life, which could be the signature of fatigue crack initiation of in-service components. To understand whether a similar trend is present in other steels and alloys, it will be necessary to extend the present work. It is also planned to characterize the dislocation structure mode by using X-ray line profile analysis.

The authors would like to express their thanks to Prof. S.P. Mehrotra, Director, National Metallurgical Laboratory, Jamshedpur for his permission to publish this work.

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