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Advanced ultrasonic for remaining life assessment of industrial components

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Abstract *: Nonlinear ultrasonic is the new approach for the effective evaluation of material degradation in the area of non-destructive evaluation (NDE). Fatigue damage of a material produces a substantial distortion of ultrasonic waves propagating through the degraded material. The wave distortion is quantified by means of a material nonlinearity parameter ß that is defined as the ratio of the amplitude of the 2nd harmonic to the square of the amplitude of the fundamental. This nonlinear parameter changes when, for instance, a distribution of microcracks appears inside the material. This feature has recently been found as a new potential application in the characterization of fatigued and degraded materials. In this present paper, the potential of NLU technique to evaluate fatigue damage in structural steel and to assess the localized plastic deformation during high cycle fatigue to locate the position of crack initiation much before the failure along the gage length of hourglass type specimen in polycrystalline copper has been highlighted.*

Keywords : Nonlinear ultrasonic; Residual life estimation; Industrial component damage assessment; Fatigue testing.

INTRODUCTION

With increasing demands of integrity problems such as ageing of industrial components, development of higher strength materials, revolutionary changes in design, configuration and materials for aircraft or automotive industries pose great challenges for inspection methods used to evaluate their quality, efficacy and safety. It is required to develop new NDE solutions from process controls of raw materials to testing and fabrication of structural components to service damage assessments. Among various existing NDE techniques, ultrasonic is the most widely used inspection technique by the industries. In ultrasonic, the characterizing parameters are basically the velocity and attenuation of the wave. However, the conventional ultrasonic technique is sensitive to gross defects or opens crack, where there is an effective barrier of transmission, whereas it is less sensitive to evenly distributed micro-cracks or degradation. Hence an alternative technique to overcome the above limitation is essential for the detection and assessment of damage that occurs in components during service which play a key role for condition monitoring and residual life estimation (RLA) of in-service components/ structures. Non-linear ultrasonic (NLU) is one of such approaches. NLU is related to radiation and propagation of finite amplitude (especially high power) ultrasound and its interaction with discontinuities like cracks, interfaces, voids, etc. Since material failure or degradation is usually preceded by some kind of nonlinear mechanical behaviour before significant plastic deformation or material damage occurs, recently, considerable attention has been focused on the application of NLU for the non-destructive evaluation of materials degradation[1-4]. 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 dislocation which causes significant change in the material's non-linear elastic wave behaviour. This behaviour manifests itself in various manners such as non-linear attenuation, harmonic generation, resonant frequency shift etc. These effects are enormous in damaged material but nearly un-measurable in undamaged materials. Hence in the recent past considerable interest has been shown to apply NLU as a non-invasive tool to evaluate materials degradation. The effect of dislocation density on NLU parameter in quenched steels with different carbon contents has been reported. There have been limited attempts to relate these to fatigue damage[5, 6]. 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. Moreover detailed microstructural changes during fatigue and then correlation with suitable non-linear ultrasonic parameters are still required to be established. In this paper it has been attempted to show the potential of non-linear ultrasonic (i) to assess fatigue damage in structural steel and (ii) to detect the location of maximum localized plastic deformation in polycrystalline copper. The results of NLU have been correlated with the microstructures at different stages of fatigue.

EXPERIMENTAL

Fatigue testing

High cycle fatigue test was performed on an electromagnetic resonance fatigue test machine, model 100HFP5100, RK Amsler, Germany, at room temperature at a frequency of 72 Hz with a load ratio (R) = -1, where R= $\sigma_{min.}/\sigma_{max.}$, and σ_{min} and σ_{max} are the applied minimum and maximum stresses respectively. The applied constant stress amplitude was 150 MPa for structural steel (yield strength 230 MPa) and 93 MPa for copper. The hour-glass type test specimens have been machined from the same strip of steel. Prior to fatigue test, the steel specimens were annealed at 700°C for 30 minutes and copper at 200°C for 1 hour in an inert atmosphere. Different amounts of fatigue damage as % of the estimated fatigue life (20%, 40%, 60%, 80% etc.) were introduced to a number of specimens for NLU measurement. The damage was taken as no. of applied fatigue cycles as per the equation

$$\% \text{ of Damage} = \frac{N}{N_f} \times 100\% \quad \ldots (1)$$

where, N = number of fatigue cycles applied to the specimen at a given load, N_f = average number of fatigue cycles to failure at the same load.

Non-linear ultrasonic measurement

A high power ultrasonic signal analysis device, RAM 5000 (RITEC, USA) was used for the non-linear ultrasonic measurement. NLU measurements were made on before loading the sample for fatigue testing and then after an after an interval of 20,000 cycles till failure.

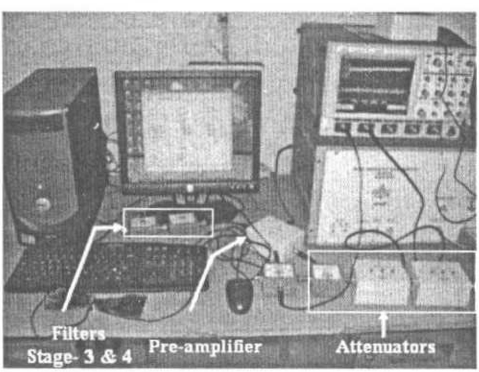

Fig. 1: Experimental setup for non-linear ultrasonic measurement

The experimental setup of the NLU measurement system is shown in Fig. 1. This system has high-power gated amplifiers for generating the finite-amplitude tone bursts and a super-heterodyne receiver. A 5 MHz longitudinal transducer was used as a transmitter and a longitudinal broadband transducer with a center frequency at 10 MHz was used as a receiver. The waveform of transmitting signal was a tone burst with 5 cycles. The received signal from the 10 MHz broadband sensor was filtered using a band pass filter and then amplified by a low-noise pre-amplifier. The amplitude of the transmitted signal (A_1) was measured by receiving the signal in pulse echo mode in one channel of the oscilloscope. The filtered and amplified received signal was fed to other channel of the oscilloscope to measure the amplitude of the 2nd harmonic (A_2). To reduce the signal to noise ratio, the received signal was further filtered through software designed filter in MATLAB and then the measurement parameter i.e relative ß was determined from the fast Fourier transformation of the windowed filtered signal

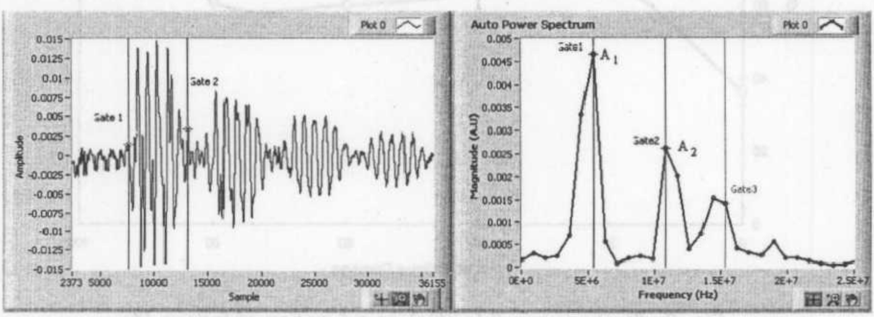

Fig. 2 : (a) A view of the Received Signal *(b) Power spectrum of the windowed signal*

to determine the value of A_1 and A_2. A view of the received signal and its power spectrum is shown in Fig. 2. The relative ß was determined using the relation, $\beta \propto A_2/A_1^2$, where A_1 and A_2 are the amplitudes of fundamental and 2nd harmonic. The detail derivation of the relation is described in reference[7].

RESULTS & DISCUSSION

In structural steel

Fig. 3 shows the plot of % change in β (Δ_b/β_0) as a function of % of fatigue life. Initially there is an increase in Δ_b/β_0 till 40% of fatigue damage w.r.t the total life. Thereafter till 80% of life there is no such change and increasing again till 95% of the fatigue life. Fig. 4 shows the TEM microstructures for various percentage of fatigue damaged specimen. At the initial stage of fatiguing till 40% of fatigue life, increase in dislocation density have been observed. Dislocations were rearranged and formed well defined cell structures at 60% of life (Fig. 4(c)).

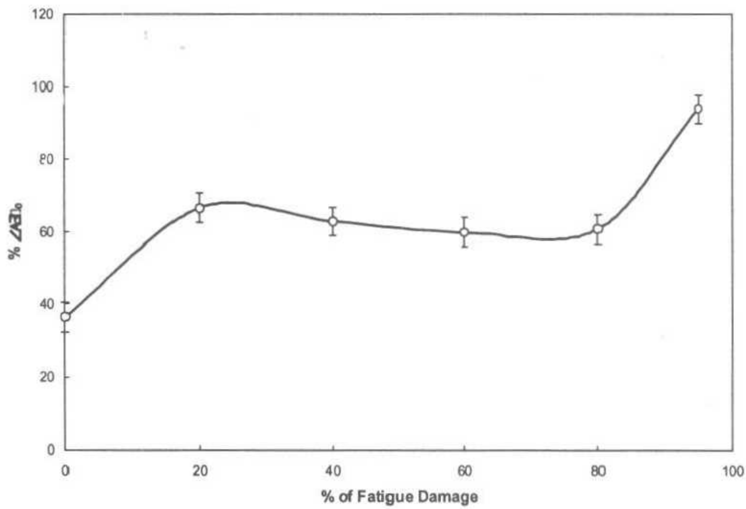

Fig. 3 : % change in β (Δβ/βo) as a function of fatigue life

With further fatiguing, formations of Persistant Slip Bands (PSBs) have been observed and the formations of slip bands have been confirmed by taking transmission electron micrographs in different specimens. Here only one TEM micrographs corresponding to 95% of fatigue damage have been presented to show the PSBs (Fig. 4(d).

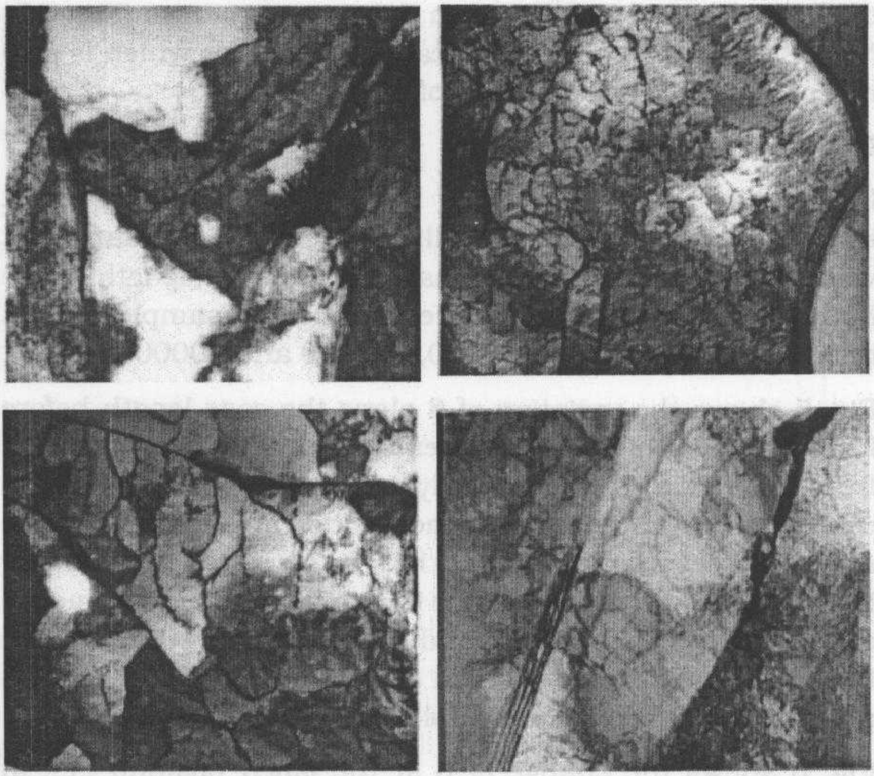

Fig. 4 : TEM micrograph and fatigued specimen

The increase in % Δ_b/β_0 at the initial stage of fatiguing, i.e. till 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. 4b) 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.4c). At this stage no such change has been observed in % of Δ_b/β_0. As the dislocations are piling up to form cells, availability of free dislocations inside the cells reduces, as a result amplitude of 2nd harmonic decreases. As we go on fatiguing, at 95% of damage, formation of PSBs have been observed in the microstructure (Fig. 4d). Near PSB, density of free dislocations increases which is also reflected in the variation of % of Δ_b/β_0.

In Polycrystalline Copper

In this work our aim was to locate the position of crack initiation much prior to the failure. Therefore, measurement was taken at different positions along the gage length of the hour glass type sample before loading the sample and at different fatigue cycles (100000, 300000 and 600000 cycles).

Fig. 5 shows the variation of ß along the gage length before loading the sample and at different cycles. It has been observed from the figure that ß sharply increased from position 8, reached a maximum value at the position approximately at 9, and then decreased at position 10. The sample is then further loaded and allowed to fail. It was found that the sample cracked at the position 9. This result indicates that the value of ß can be used to predict the position of appearance of crack much prior to the failure of the sample.

Fig. 6 shows the change of ß at the failed position i.e., at position 9 and at position anywhere away from the failed

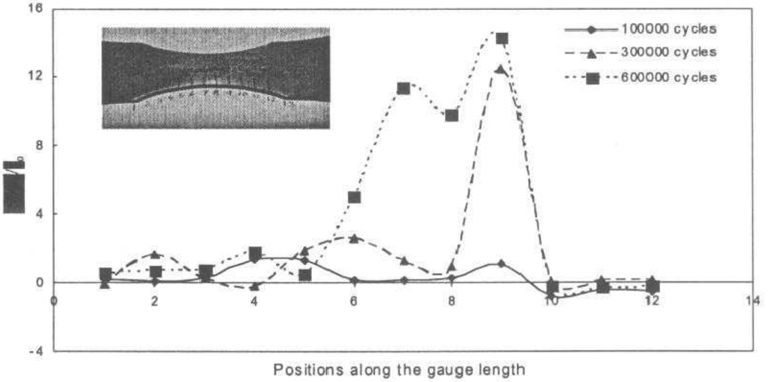

Fig. 5: Variation of ß before loading and after 8×10^4 cycles with positions (onset: view of cracked samples with marked positions)

position e.g. position 6. It is seen from this figure that at position 9 the change of ß exactly follows the same rule as followed by the dislocations arrangement during fatigue. At the early stage of the fatigue there is a fatigue hardening (bundles of dislocations formed with average spacing between the bundles is very less) followed by the fatigue-softening and then before failure increase in dislocation density occurs ($ß \propto N L^4 \sigma$). Whereas at position 6 there is still fatigue hardening when the sample has already failed from position 9.

It can be said that the origin of the increase in ß is probably associated with the growth and transformation of dislocation dipole substructures formed in the material during fatigue. The large variation of ß with measurement location in the material suggests that the relevant sub-structural changes are localized[3] and NLU can be a potential technique for localized damage detection. It is known that the microstructural feature which is predominantly altered during fatigue damage progression is dislocation. During high cycle fatigue in polycrystalline copper, microstructural evolution takes place in terms of dislocations multiplication, piling up of dislocations to form cell structures, formation of intrusions and extrusions which leads to micro-crack initiation[8-10]. As fatigue accumulated, dislocations move back and forth and give rise to harmonics of the transmitted sound waves. It has been suggested by the model of Suzuki et. al that the value of ß is proportional to the fourth power of the dislocation loop length. Hence it can be said that the origin of the increase in ß is probably associated with the growth and transformation of dislocation dipole substructures formed in the material during fatigue. The large variation of ß with measurement location in the material also suggests that the relevant sub-structural changes are localized[6] and NLU can be a potential technique for localized damage detection.

CONCLUSIONS

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 thorough microstructural evolution. To the best knowledge of the authors, this is the first time that such correlation between a nonlinear ultrasonic parameter and the dislocation structures has been done. It has been observed that the % Δ_β/β_0 is a very sensitive parameter to study the non-linear behaviour of materials during fatigue progression. The important observation of the present work is that the 2nd harmonic amplitude becomes comparable to the amplitude of the fundamental nearly at 95% of expended fatigue life, which could be the signature of fatigue crack initiation of in-service components.

This work also reveals that the nonlinear ultrasonic can be a potential technique for online monitoring of industrial components for the prediction of position of occurrence of failure. For industrial application, it is required to apply the technique from specimens to the components.

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REFERENCES

1. W. L. Morris, O. Buck and R. V. Inman, J. Appl. Phys., 1979, vol. 50(11), 6737-6741.

2. I. Y. Demin, T. Sato, Y. Mochida , K. Fujii, K. Y. Jhang , Proc. 13th ISNA, 1993, 344.

3. K. Y. Jhang, I.Y. Demin, T. Sato, J. KOSOMBE, 1993, vol. 14(1), 31.

4. G. P. Potriniche, M. F. Horstemeyer, B. Jelinek, G. J. Wagner, Int. J. Fatigue, 2005, vol. 27, 1179-1185.

5. H. Kawazoe, M. Niewczas, Philosophical Mag., 2004, vol. 84(3-5), 381-399.

6. M. Hirao, H. Ogi, N. Suzuki and T. Ohtani, Acta Mat., 2000, vol. 48, 517-524.

7. Jhang KY, Kim Kyung-Cho Ultrasonics 1999;37:39.

8. Cantrell JH, Yost WT, Int. J Fatigue 2001;23: S487.

9. Koehler JS, Imperfection in nearly perfect crystals, John Wiley & Sons, 1957:197.