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NON-LINEAR ULTRASONIC METHOD FOR MATERIAL CHARACTERISTICS

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Abstract

Non-linear ultrasonic methods are useful for characterisation of microstructures. Experiments have been carried out on heat treated carbon steel specimens in through transmission mode using 2 MHz narrow band transducer as a transmitter and 4 MHz broad band transducer as a receiver. The non-linear ultrasonic parameter called β parameter has been calculated using the measured fundamental and second harmonic signal amplitudes. A linear correlation has been observed between the β parameter and the hardness.

Keywords: Non-linear ultrasonics, carbon steel, microstructure, spectral analysis, hardness.

1.0 INTRODUCTION

The approximation that the stresses produced by an ultrasonic wave propagating through a solid medium is linear, no longer valid for larger amplitude waves. As a consequence of this, the propagation of a finite amplitude ultrasonic wave will result in non-linear stress-strain relation. This causes a progressive change in the wave shape as it propagates - the distortion takes the form of a gradual transfer of energy in the fundamental to higher harmonics, which are then attenuated due to the frequency dependence of the attenuation coefficient. Measurement of amplitude of these harmonics in through-transmission mode allows one to investigate microstructural features of material. There is a growing interest to correlate “non-linear parameter β” derived from the amplitude of fundamental and harmonics with ageing induced microstructural changes [1], precipitate hardening process [2], dislocation density [4], material degradation [3] etc. To give an example, a monotonic increase of β parameter with lattice strain reported in [6] has opened up new avenues to examine precipitation hardening. Similarly, measurement of the non-linear parameter in heat treatable alloys as a function of heat treatment time is expected to provide quantitative information about the kinetics of precipitate nucleation and growth. The non-linear parameter is found to correlate well with the mechanical properties such as adhesion of composites [5] and diffusion bond integrity in copper. Authors have recently carried out non-linear ultrasonic studies on heat treated carbon steel specimens. The theory of non-linear ultrasonic method, experimental setup used and the results obtained from the experiments are discussed in this paper.

2.0 NON-LINEAR ULTRASONICS - THEORY

Conventional ultrasonic methods involve the measurement of ultrasonic velocity along the principal directions of the crystal lattices and correlate the change in velocity with the microstructure of materials. In this process, it is assumed that the deformations caused by stressed ultrasonic waves are small and a linear relationship between stress (σ) and strain (ε) through the young's modulus of (E) is valid. Such a linear relationship when substituted in the equations of motions will result in the linear wave equation. But in actual practice, the stress-strain relationship is non-linear due to the anharmonicity of the crystal and the existence of dislocation displacements, which will distort an elastic wave when propagating through the medium. It has been reported that the distortion of an elastic wave due to the dislocation displacement contributes more to the non-linearity of the material than that of the anharmonicity of the crystal lattice [4]. Hence, a general stress-strain relationship is non-linear and can be expressed as a power series of strain as

$$\sigma = E\varepsilon\,(1+\beta\varepsilon+...) \tag{1}$$

Where E is the young's modulus and β is a constant called the higher order non-linear elastic coefficient and defined as

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

where A_1 is the fundamental amplitude, A_2 is the second harmonic amplitude, k is the propagation constant and *a* is the material thickness through which the ultrasonic beam passes.

3.0 SPECIMEN PREPARATION

Cylindrical specimens of 30 mm diameter and 40 mm length have been machined from 0.4% carbon steel. The machined specimens have been heated to 870^{o} C (50^{o} C above the upper critical temperature) and held for two hours. Then different cooling rates have been adopted to obtain specimens with different microstructures and hardness. Three types of cooling methods have been followed viz. furnace cooling (annealing), air cooling (normalising) and water quenching. After polishing the heat treated specimens, Rockwell (Macro) hardness has been measured. Metallographic studies have been carried out to observe the microstructural changes with heat treatment. The hardness values, cooling conditions and the dimensions of one set of specimens are given below:

Specimen size		Cooling condition	Rockwell Hardness
Length (mm)	Diameter (mm)		
40	30	Furnace cooled	67
40	30	Air cooled	80
40	30	Water quenched	98

4.0 EXPERIMENTAL

The experimental setup used for the non-linear ultrasonic studies is given in Fig. 1. It essentially consists of a tone burst (continuous wave) sinusoidal source, a pre-amplifier and a personal computer with software for data acquisition and analysis. A narrow band ultrasonic transducer of 2 MHz and a 4 MHz broad band transducer have been used as transmitter and receiver, respectively. The receiver output has been pre-amplified and its power spectrum has been acquired and stored for the measurement of second harmonic amplitude. TB1000 instrument (supplied by M/s. MATEC, USA) has been used for implementing the above steps using Labview software interface. The excitation frequency, number of cycles and the pulse repetition rate of the tone burst are controlled through the software. There exists a provision to activate high, low and band pass filters through software to eliminate any unwanted frequency components. For the specimens under consideration, we have used 15 cycles of 2 MHz tone burst with 1 second pulse repetition rate. The amplitudes of the fundamental and the second harmonics of the amplified received signal have been measured for different specimens and substituted in equation (2) to obtain the β parameter.

5.0 RESULTS AND DISCUSSION

Typical time domain signal and its Fourier power spectrum for the three types of specimens are shown in Fig. 2. A change in the second harmonic amplitude can be observed from the power spectrum and such a change can not be seen in the time domain signals. The normalised β parameter (with respect to the furnace cooled specimen) has been found from the power spectral density. Typical relation between the normalized β parameter and the hardness is shown in Fig. 3. As can be seen, a linear correlation is noticed with a correlation coefficient of 0.97. Typical microstructures of the three types of specimens are given in Fig. 4. As expected, martensitic structure is observed in the water quenched specimens and this is responsible for very high hardness. In the other two specimens, microstructures consisting of ferrite and pearlite with varying grain size and distribution are noticed contributing to lower hardness than the water quenched specimens. This confirms the fact that the microstructure dependant hardness and the β parameter are well correlated. The scatter in the measurements is attributed to variations in the couplant and the pressure holding the transducers on to the specimens. Suitable mechanical fixture is being designed to minimize these variations.

6.0 CONCLUSION

Non-linear ultrasonic experiments have been carried out on carbon steel specimens to calculate non-linear ultrasonic parameter β. A linear correlation has been obtained between the β parameter and the hardness of the specimens with different microstructures. Non-linear ultrasonic method is found to be promising for the microstructural characterization of materials. Further studies are planned for microstructural characterization of tempered carbon steel specimens, stainless steel and Cr-Mo ferritic steel subjected to cyclic loading with a view to evolve a reliable method for quantitative assessment of microstructural degradation and fatigue damage in operating components.

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REFERENCES

1. K.Y. Jhang, “Application of non-linear ultrasonics to the NDE of material degradation”, IEEE Tran. on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 47, No. 3, 2000.
2. J.H. Cantrell, W.T. Yost, “Non-linear acoustic assessment of precipitation induced coherency strains in Aluminum alloy 2024”, Rev. Prog. in QNDE, Vol. 15, pp-1361.
3. D.C. Hurley, D. Balzar, P.T. Purtscher, and K. W. Hollman, “Non-linear ultrasonic parameter in quenched martensitic steels”, Journal of Applied Physics, Vol. 83, May 1998.
4. A. Hikata, B.B. Chick and C. Elbaum, “Dislocation contribution to the second harmonic generation of ultrasonic waves”, Journal of Applied Physics, Vol. 36, No. 1 Jan 1963.
5. S. Pangraz and W. Arnold, “Measurement of adhesion strength using non-linear acoustic”, Review of Prog. in QNDE, Vol. 13, pp. 1995-2001.
6. J.H. Cantrell and W. T. Yost, “Effect of precipitate coherency strains on acoustic harmonic generation", Journal of Applied Physics, Vol. 81, 2957, 1997.
7. M.A. Breazeale and J. Philip, Physical Acoustics, edited by W.P. Mason and R.N. Thurston, Academic, New York, 1984, Vol. 17, Chapter. 1

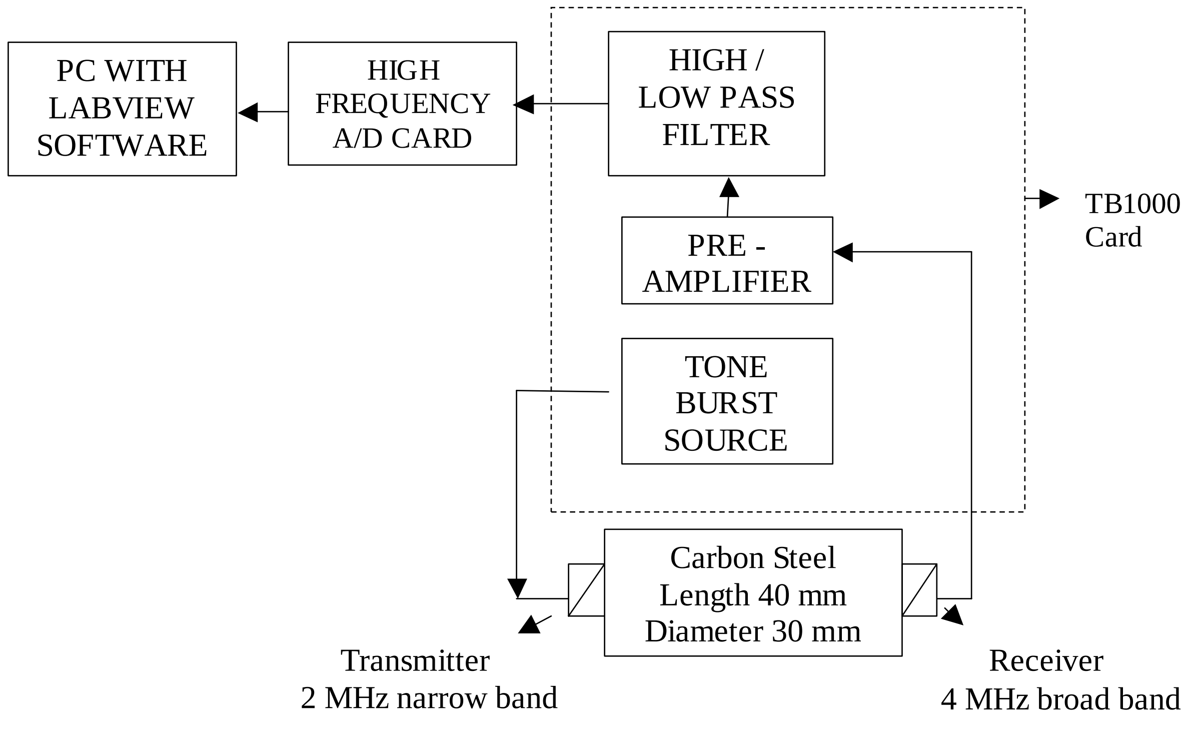
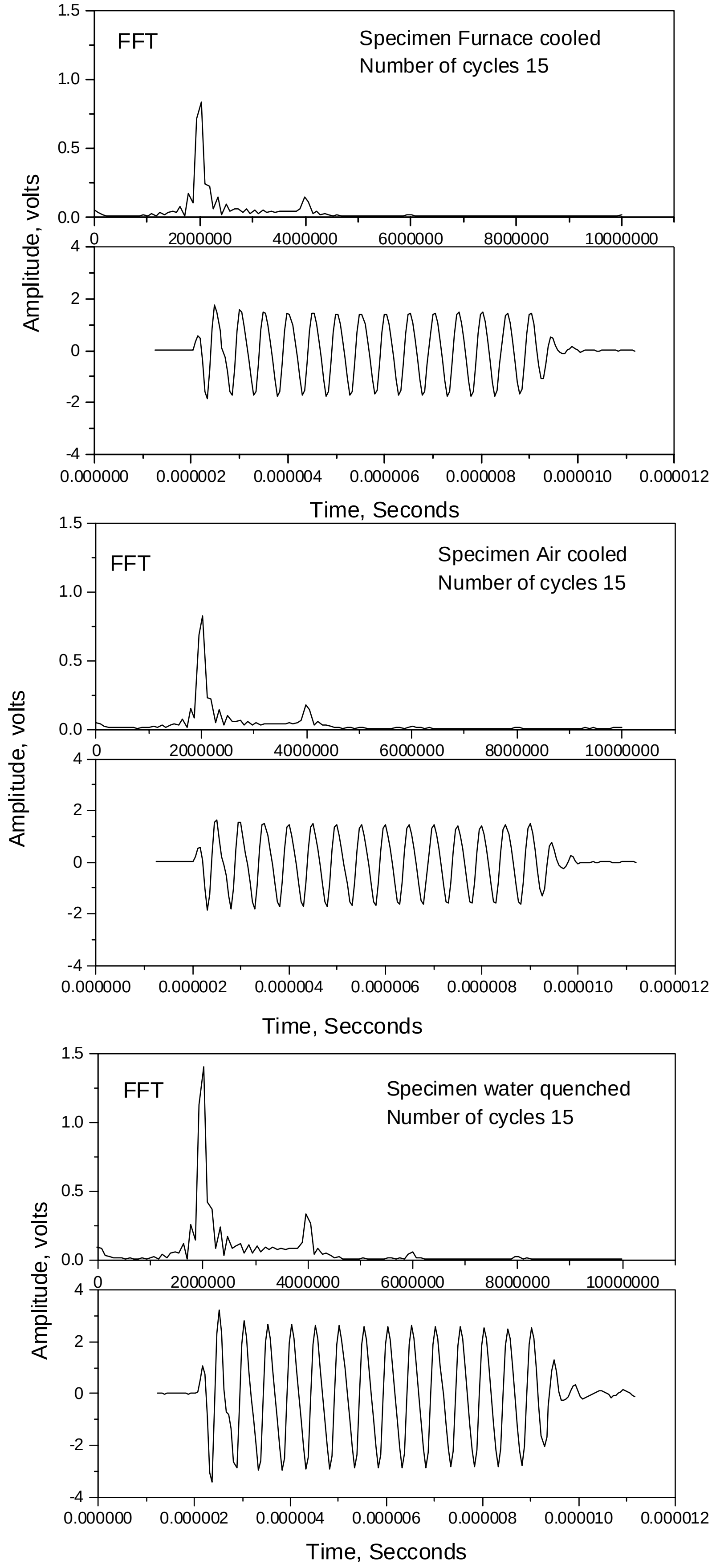


Fig.1 Schematic diagram of the experimental setup made for non-linear ultrasonic experiments.



a)

b)

c)

Fig. 2 Transmitted time domain waveform and the corresponding Fourier transform for a) furnace cooled b) air cooled and c) water quenched specimens

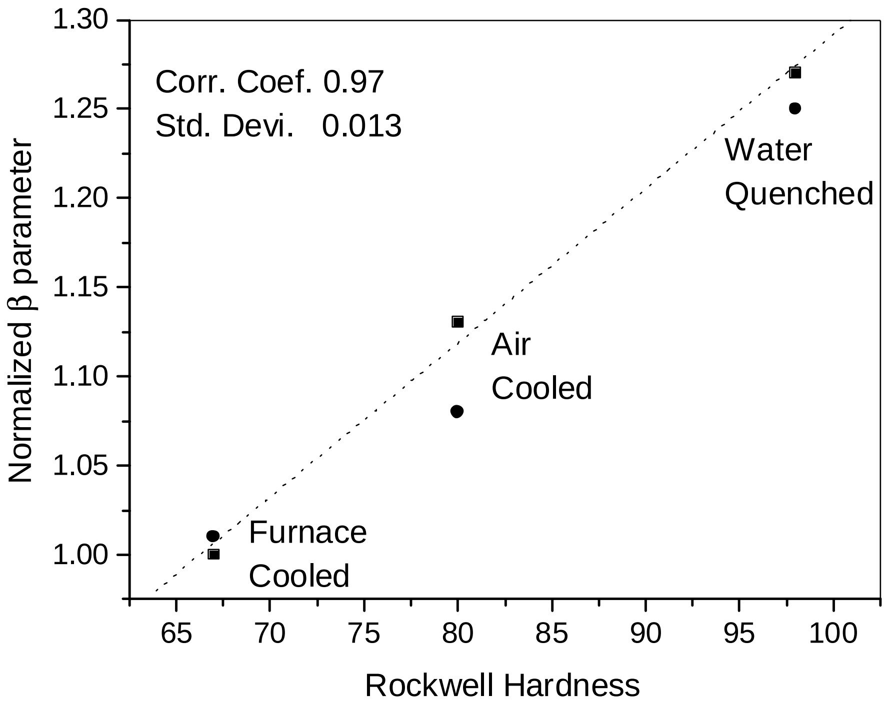
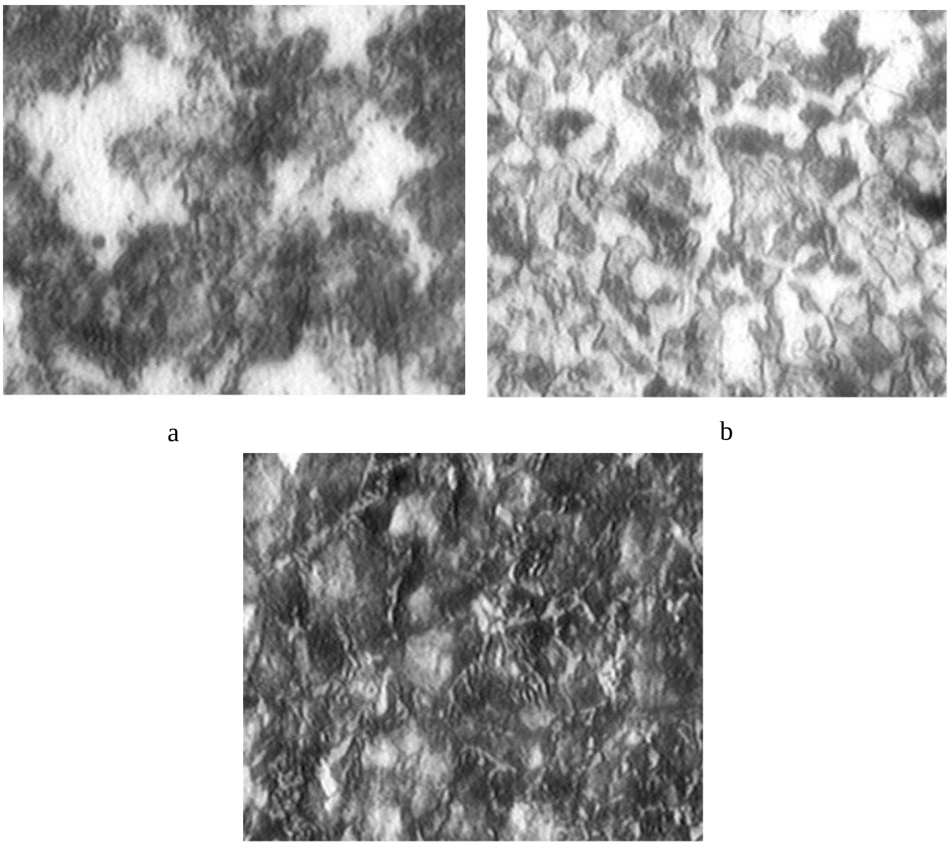


Fig. 3 Variation of non-linear β parameter with Rockwell hardness in heat treated carbon steel specimens.



a b

c

Fig. 4 Microstructure (500X) of heat treated carbon steel specimens a) furnace cooled, b) air cooled and c) water quenched.