Nonlinear Elastic Wave Spectroscopy (NEWS) Measurements of the Nonlinear Acoustic Parameter : Applications in Quenched Metallic Samples

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Introduction

The nonlinear acoustic parameter (β) is of great interest for material characterization for non-destructive testing in industrial applications such as aircraft company. Furthermore, Nonlinear Elastic Wave Spectroscopy (NEWS) comprise a new class of innovative ultrasonic techniques that provide extreme sensitivity in detecting damage in the form of microcracks, delamination or dislocation.

In this paper, we propose to evaluate the β of XC48 steel samples (previously quenched by immersion in water and oil) using one of the NEWS technique: an ultrasonic contact calibrated measurement set-up previously validated in solid plates[1].

Preparation of XC48 samples

The samples were prepared by heating them at 850 °C in order to reach the austenite domain (Fig.1). The Rockwell C hardness (HRC) was determined for each sample with a Wolpert hardness tester. One sample was rapidly oil quenched (HRC=64) where the martensite transformation has occurred, the other one was water quenched (HRC=33), and the third one is the non treated original sample. The longitudinal phase velocity c_0 was measured in each sample with a pulse-echo superposition technique and using a laser interferometer. Measurement reveals that the velocity and the attenuation during 1 cm of propagation is not sensitive to the hardness. Samples characteristics are listed in Table 1.

Table 1: Linear acoustic properties of the XC48 samples

|	%C	c_0 (m/s)	ρ_0 (kg/m³)	d(mm)
XC48	0.48	5940	7800	10

Experimental Set-up

The experimental set-up is described elsewhere[2] and resumed on Fig.2. An HF planar contact transducer (5 mm diameter) is driven by a 20 MHz toneburst of 37 periods, created by an HP 3314A waveform generator. The 2.25 MHz transducer (diameter $a = 25$ mm) is laid in contact with the sample (using a suitable coupling) and is excited by a pulse delivered by an HP 3314A generator and amplified by an ENI amplifier. The HF wave, so created, propagates in the 1 cm thick XC48 sample and is reflected by the sample /LF transducer interface. The two HP3314A are trigged by an HP 33120A waveform generator, so that the reflected HF acoustic wave interacts
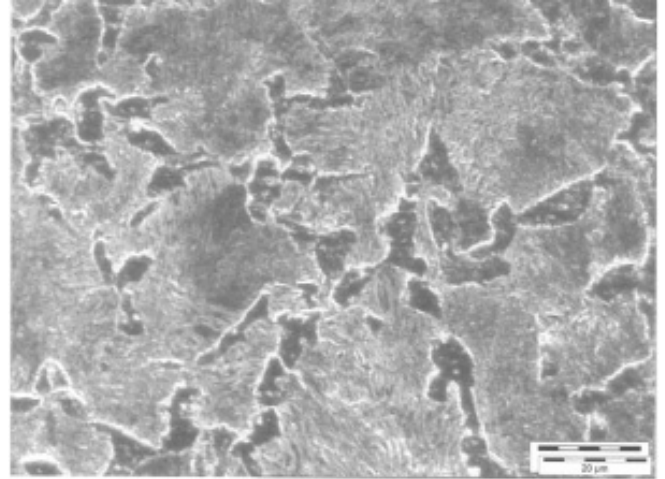
Figure 1: Image obtained with a platina microscope of the treated XC48 sample after the quenching treatment. Dimension : $100{\times}80$ μm. The quenching process change the crystallographic structure of the sample leading to a higher hardness.

collinearly with the LF pulse during its back propagation toward the HF transducer. The phase modulation of the HF received signal, produced by the collinear interaction, is measured with a phase demodulation algorithm programmed in Matlab.
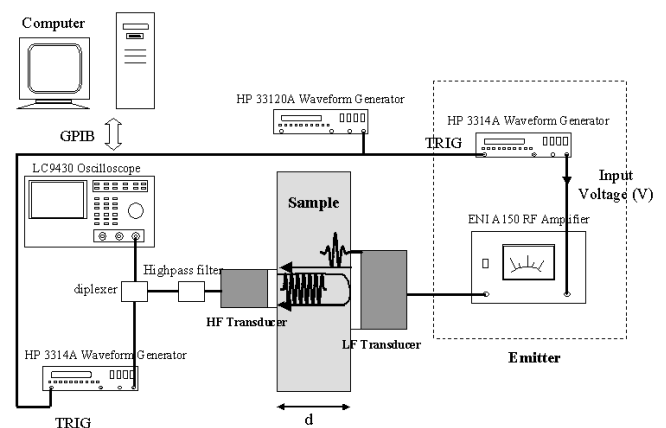
Figure 2: Contact self-reciprocity measurements of the LF transducer surface velocity versus the amplifier input voltage

Contact Phase Modulation Method

A contact phase modulation method[1], based on the interaction of a low frequency pulse and a high frequency acoustic toneburst, is used. When the two primary

waves have a high frequency ratio ($f_{HF} >> f_{LF}$), their collinear interaction results in a phase modulation of the HF wave given by

$$\Delta\Phi = \frac{\omega_{HF}d}{c_0^2}\beta v_{LF}, \tag{1}$$

where the nonlinear parameter β in solid is defined by

$$\beta = -\left(\frac{3}{2} + \frac{C_{111}}{2C_{11}}\right). \tag{2}$$

The elastic constants C_{11} and C_{111} are respectively a second and third order elastic modulus, and ω_{HF} is the angular frequency of the HF wave.

In order to determine the LF velocity emitted in the sample by the LF transducer, a self-reciprocity calibration is used. Thanks to the self reciprocity calibration of the LF transducer[3], the velocity v_{LF} is known, and the measurement of the modulation index allows to determine of the nonlinear parameter:

$$\beta = \frac{c_0^2}{\omega_{HF}d}\left(\frac{\Delta\Phi}{v_{LF}}\right). \tag{3}$$

Moreover, this method does not need any calibrating of HF amplitude waves.

Results

For each input voltage V, $\Delta\Phi$ is evaluated performing a numerical demodulation of the acquired signal and Δv_{LF} is calibrated versus the input voltage V as described previously : $\Delta v_{lf} = C_{sample}V$, where C_{sample} must be evaluated for each sample. The ratio is then given by

$$\frac{\Delta\Phi}{v_{LF}} = \frac{\Delta\Phi}{C_{sample}V} = \frac{\widetilde{\Delta\Phi}}{V} = \beta\frac{\omega_{HF}d}{c_0^2} \tag{4}$$

where $\widetilde{\Delta\Phi}$ is the calibrated modulation index (Fig.3).
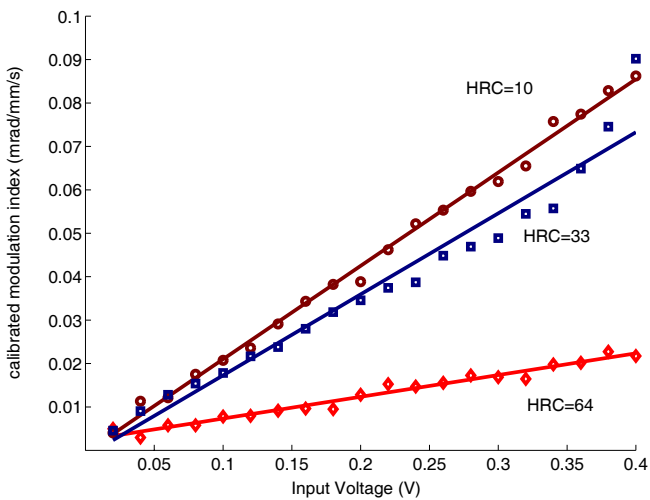
Figure 3: Calibrated modulation index $\widetilde{\Delta\Phi}$ versus the input voltage V for the XC48 sample used in the experiment. The nonlinear parameter β is dependant of the HRC hardness.

The ratio is then extracted from the linear fit of measurements made with various input voltages. Finally, using

Eq.(4), linear acoustic and geometrical properties of the sample reported in Tab.1, the nonlinear parameter β of samples is given in Tab.2.

Table 2: Ultrasonic results for the measurement of the non-linear parameter β for XC48 quenched samples versus the Rockwell C hardness (HRC). The decreasing of β versus the HRC hardness indicates a lower nonlinearity. A higher elasticity limit obtained after the quenching process and due to the modification of the grain size and distribution induce a lower density of dislocation which are well-known for generating nonlinearity

HRC	10	33	64
β	7.8	6.3	1.7
C_{111} (GPa)	−5100	−4300	−1780

Conclusion

Calibrated contact phase modulation method phase modulation method has been used to measure "in situ" the nonlinearity parameter of quenched steel sample, without any fluid coupling medium. Variation of HRC hardness induce a variation of the nonlinear parameter β. The decreasing of this nonlinearity may be attributed to the increase of the limit of elasticity obtained after the quenching process of the XC48 sample. The thermal treatment decrease the grain density in the sample, and consequently the dislocation density responsible of the nonlinearity. Measurements of hardness with the nonlinear parameter present the same sensitivity as measurements with the classical HRC method. It gives an interesting future trends for this kind of characterization, which is calibrated and non destructive, by opposition to the hardness testers.

Acknowledgments

References

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