ULTRASONIC INVESTIGATION OF PHYSICAL MECHANICAL PROPERTIES OF STEELS

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ABSTRACT

Ultrasonic techniques are primarily used in engineering for the purpose of flaw detection in materials and components. Such techniques can also be used for measuring the ultrasonic parameters such as wave velocity and wave attenuation in a material. These parameters are predominantly affected by the structure of the material through which the ultrasonic wave passes. Structure, in turn, affects the properties of the material. The aim of this research is to investigate such effects and to determine any correlation between the ultrasonic parameters mentioned, and the mechanical properties of metals.

Usually material properties such as elastic modulus, strength, hardness, fracture toughness, grain size etc. are determined by destructive tests. Such tests not only result in the destruction of materials, but also have other disadvantages such as, increased cost and inability to give reproducible results. On the other hand non-destructive techniques such as ultrasonic inspection can be used for the determination of properties even after the manufacture of the product/component as well as in service, if a successful method is developed.

This research concentrates on steels subjected to different heat treatment processes. The initial work was carried out on 0.36 percent carbon steel (AISI designation 4340). The results obtained and the correlation found, between ultrasonic measurements and destructive tests are presented.

INTRODUCTION

Determination of mechanical properties is conventionally done by destructive tests at the expense of material and manufacturing costs. On the other hand the potential benefits of in process and continuous monitoring of mechanical properties, are strong incentives for research on the use of nondestructive methods for materials characterization.

Ultrasonic parameters such as wave velocity and attenuation are taken into consideration in this research work. Wave velocities are directly related to material moduli because moduli are in turn related to inter-atomic forces. In polycrystalline materials microstructure plays an important role in determining mechanical properties such as strength and toughness. Wave attenuation, which is defined as the loss of sound energy through a medium, is highly sensitive to microstructural features in a material. Hence attempts are made in this research to establish correlations between attenuation coefficient (attenuation per unit distance) and mechanical properties. This requires precise ultrasonic measurements based on pulse echo techniques. An ultrasonic flaw

detector is used for this purpose. The emphasis on attenuation does not preclude velocity measurements at all.

LITERATURE SURVEY

Ultrasonic testing

Ultrasonic testing is a nondestructive testing method in which high frequency sound waves are introduced into the material being inspected and the sound emerging out of the test specimen is detected and analyzed. Ultrasonic waves propagate through mechanical vibrations of the particles of the medium in which they travel. Most commonly ultrasonic testing of materials is done at a frequency range of 0.5MHz to 25MHz. (Frequency range of human hearing is 20Hz to 20kHz.) The waves are represented by amplitude, frequency and velocity. Ultrasonic waves are reflected, refracted, scattered and absorbed in the media they travel through. Ultrasonic waves are usually generated utilizing the piezoelectric effect. Piezoelectricity is the property of converting mechanical energy into electrical energy and vice versa. Sound velocity is different in different materials. Also different materials offer varying degrees of resistance to the passage of sound through them. This resistance is referred to as the acoustic impedance of the medium.

General procedure of ultrasonic testing involves the following steps:

I. Generating and sending ultrasonic pulses into the material using a piezoelectric crystal transducer. A coupling medium is used in between the transducer and the specimen, since the acoustic impedance of air is very high.
II. Detecting the ultrasound either after the transmission through the test specimen (known as the *through transmission technique*) or after reflection from interfaces and boundaries within the specimen (known as *pulse echo technique*).
III. Analyzing and interpreting the received signals in terms of internal condition and other properties of the tested specimen.

The list below gives the most frequently used quantities, their symbols and the units as used in this paper.

f	frequency	Hz (/s)
λ	Wave length	m
V	velocity of sound	m/s
ν	Poisson's ratio	
a	wave amplitude	m
ρ	Density of materials	kg/m^3
Z	acoustic impedance	Ns/m^3 or kg/m^2s

The ultrasonic beam

The region in which ultrasonic waves are propagated from an ultrasonic transducer is known as the ultrasonic beam. Simplified shape of an ultrasonic beam for a circular transducer is shown in Figure 1a. Two distinct regions of the beam exist and they are named as near field [Freznel zone] and far field [Fraunhofer zone]. Near field length is usually denoted as N. The region from N to 3N is referred to as transition zone and beyond 3N as far field. The intensity variation along the distance is shown in Figure 1b.

The intensity passes through a number of maxima and minima. The last minimum occurs at N/2 while the last maximum occurs at N distance. After one near field length the intensity decreases continuously.
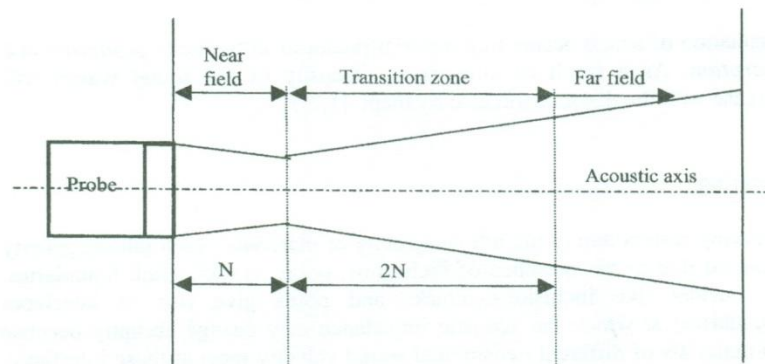

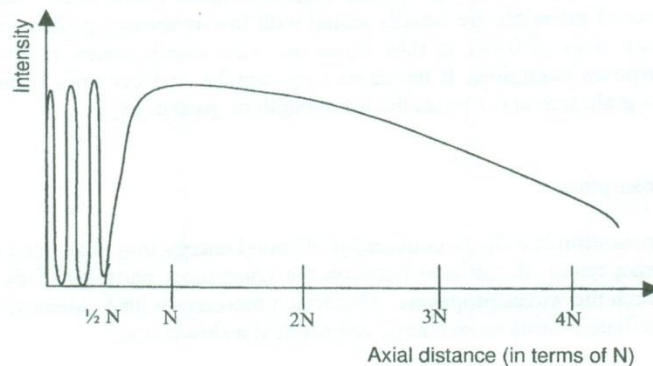**Figure 1a Sound beam from a circular crystal normal probe**

Figure 1b Intensity variation along the beam

Flaws appearing in the near field must be clearly interpreted because a flaw occurring in the near field region can produce multiple indications and the amplitude of the reflected signal can vary considerably with the location. The near field length N [for steel] will be given by

$$N = \frac{D^2}{4\lambda} = \frac{D^2 f}{4V}$$ [1]

D – diameter of the transducer crystal (2)

Attenuation of sound

Cause and effect

Attenuation of sound occurs in a material predominantly due to *scattering* and *absorption*. As a result of attenuation, intensity of the sound waves will decrease with the distance traveled by them. [1,2,5]

Scattering

Scattering results due to the inhomogeneity of materials. Such inhomogeneity is caused due to the presence of inclusions, pores, cracks, grain boundaries, etc. Factors like inclusions, cracks and pores give rise to interfaces (boundaries) at which the acoustic impedance may change abruptly because two materials of different density and sound velocity meet at these interfaces. As a result scattering occurs at these interfaces. When the grains are large compared to the wavelength scattering occurs geometrically on the grains. In other words scattering will be high at higher frequencies. Hence, coarse-grained materials are usually tested with low-frequency probes. In the case of grain sizes of 0.001 to 0.01 times the wavelength, scatter is for all practical purposes negligible. It increases very rapidly, and becomes significant when the grain size is 0.1 times the wavelength or greater. [5]

Absorption

Absorption is a direct conversion of sound energy into heat. This conversion a direct result of collision between the constituent particles of the material in which the waves propagate. Absorption increases with frequency, since a rapid oscillation loses more energy as heat than a slower one.

Measurement of attenuation

The sound pressure, which decreases as a result of attenuation by scattering and absorption, can be written in the form of an exponential function as shown.

$$p = p_0 \exp[-\alpha d] \qquad [2]$$

Where p_0 – acoustic pressure at a given point

p – acoustic pressure at a distance 'd' from the given point

α -- attenuation coefficient dB/m

The natural logarithm of this equation gives,

$$\alpha d = \ln[p_0/p] \qquad [3]$$

$$\therefore \alpha d = 20 \log[p_0/p]dB \qquad [4]$$

$$\alpha = \frac{20}{d} \log[p_0/p]dB/mm \qquad [5]$$

Since the acoustic pressure p is proportional to echo height h,

$$\alpha = \frac{20}{d} \log[h_0/h]dB/mm \qquad [6]$$

Attenuation coefficient α can be measured using pulse echo technique by placing a normal probe on a parallel-sided specimen and observing the envelope of successive back wall echoes. See figure 2.
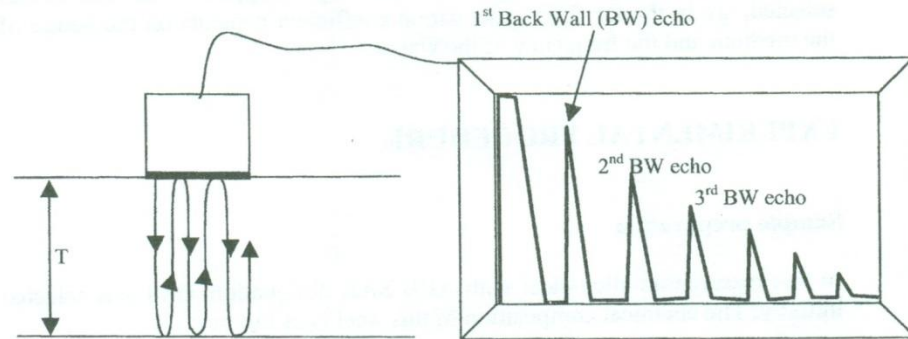

Figure 2. Multiple echoes from a parallel-sided specimen

Multiple echoes shown in figure 2 are due to the repeated reflections of the ultrasonic waves on a parallel-sided specimen. The distance traversed by the wave between two adjacent echoes will be equal to twice the thickness (2T) of the specimen.

The progressive reduction in echo heights is caused due to attenuation (by scattering and absorption) and beam spread. Echo height difference between two such echoes (Δh) can be given as in equation 7.

$$\Delta h = \Delta h_S + \Delta h_{BS} \qquad [7]$$

Δh_S – echo height drop due to attenuation (scattering and absorption)
Δh_{BS} – echo height drop due to beam spread.

By definition, echo height difference between two echoes caused by attenuation (Δh_S) divided by the total distance traveled by the beam (d), will give the attenuation coefficient α.

$$\alpha = \frac{\Delta h_S}{d} = \frac{\Delta h - \Delta h_{BS}}{d} \, dB/mm \qquad [8]$$

In equation 8, d will be equal to twice the thickness of the specimen (2T) for two adjacent echoes.

When the distance d is at least three near field lengths i.e. in the far field, beam spread law for large reflectors (i.e. $I \propto 1/d$) can be used to find Δh_{BS}, since the back wall can be considered as a large reflector. Accordingly, when the distance is doubled echo height will be halved i.e. 6dB drop. Thus, when considering nth and 2nth echoes the above equation can be rewritten as

$$\alpha = \frac{\Delta h - 6}{2nT} \, dB/mm \qquad [9]$$

Δh – echo height difference between nth and 2nth echoes measured in dB
T – material thickness in mm

It is important to note that equation 9 can only be applied when the echoes selected, are in the far field. Attenuation coefficient depends on the nature of the medium and the frequency of the waves.

EXPERIMENTAL PROCEDURE

Sample preparation

In this research an alloy-steel with **AISI-SAE** designation 4340 was selected initially. The chemical composition of this steel is as follows:

$$Fe + 0.36\% \, C + 0.25\% \, Si + 0.70\% \, Mn + 1.40\% \, Cr + 1.40\% \, Ni + 0.20\% \, Mo$$

Other equivalent standards for this steel are **BS** 817M40(EN24), **JIS**-SNCMB and **DIN**-34CrNiMo6.

The material is obtained in rod form with a diameter of 46mm. There were ten 50mm length specimens cut from this rod. All these specimens (as received) were then subject to different heat treatment processes as given in Table 1.

Table 1-Heat Treatments Performed on AISI-SAE 4340 Specimens

SAMPLE	TREATMENT	REMARKS
4340-A	Annealed	
4340-B	Normalized	
4340-C	Quenched in oil	
4340-D	Quenched in water	
4340-E	Quenched in oil (for tempering)	Specimen cracked after quenching
4340-F	Quenched in oil and tempered at 300^0C for 2hours	
4340-G	Quenched in oil and tempered at 500^0C for 2hours	
4340-H	Quenched in oil and tempered at 500^0C for 4hours	
4340-J	Quenched in oil and tempered at 300^0C for 6hours	
4340-K	Quenched in oil and tempered at 700^0C for 2hours	

NB: All samples are austenitized at 850^0C.

Measurement of attenuation coefficient α

Attenuation coefficient values for the above samples were obtained using pulse echo technique with normal probes. The attenuation of longitudinal waves in a specimen is measured in the following manner:

I.   Near field length N for the selected probes were determined.
II.   Three near field lengths 3N was calculated for each probe.
III. Multiple back wall echoes were obtained on the CRT screen of the ultrasonic flaw detector by positioning the probe on the steel specimens as shown in Figure 2.
IV.   The echo height of the second back wall echo is adjusted to 75% of the full screen height of the CRT screen of the ultrasonic flaw detector and the gain setting was noted down in decibels (dB).
V.   The echo height of the fourth back wall echo is then adjusted to the same height and the gain setting was noted down again.
VI.   The echo height difference gives the attenuation in dB, and the attenuation coefficient is determined using equation 9.
VII. The same procedure was repeated for the other specimens as well.

Measurement of ultrasonic velocity

The ultrasonic velocity in these specimens was determined by measuring the transit time of the waves through the length of the specimen.

Measurement of hardness

Surface hardness of each of the nine specimens was measured in Vickers units by applying 20kg load.

RESULTS

The results obtained from the above tests are shown in Table 2 below.

Table 2 Results obtained for AISI-SAE 4340 Steel

SAMPLE	ATTENUATION COEFFICIENT α (dB/m)	HARDNESS (HV-20kg)
4340-A	60	I85
4340-B	60	296
4340-C	50	340
4340-D	20	416
4340-E	----	------
4340-F	10	509
4340-G	10	391
4340-H	40	415
4340-J	40	376
4340-K	20	429

HARDNESS vs ATTENUATION FOR AISI 4340 SPECIMENS
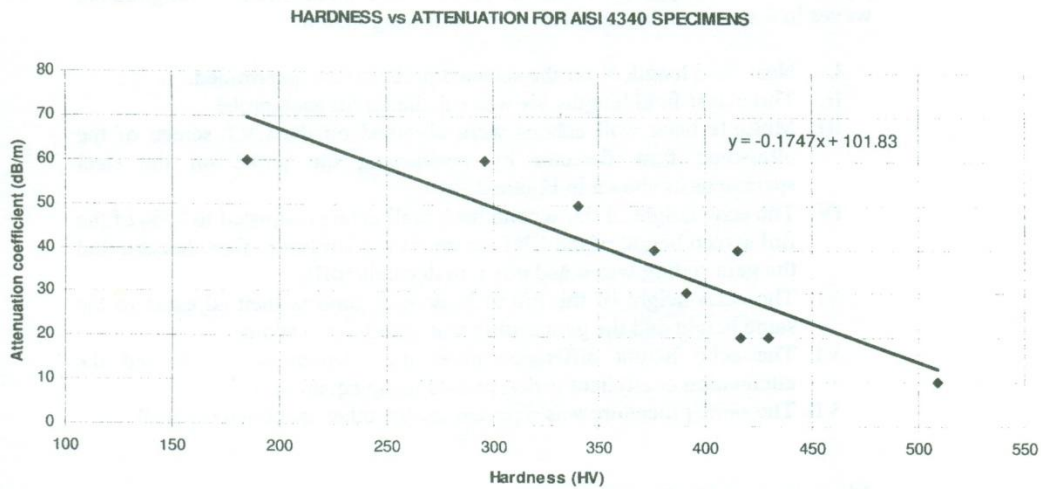

$y = -0.1747x + 101.83$

Figure 3 HARDNESS vs. ATTENUATION FOR AISI 4340 SPECIMENS

*The longitudinal wave velocity in all the specimens was the same. The value is determined as 5950m/s.

DISCUSSION

The hardness values and the attenuation coefficient values obtained for the specimens showed significant changes. Accordingly the change in attenuation with the change in material hardness (for AISI 4340 steel) is given in Figure 3. The results obtained show that the wave attenuation due to scattering and absorption decreases as the material hardness is increased. Since tensile strength and yield strength are related to hardness in polycrystalline materials similar relationships could be expected to these properties as well. However this has to be verified by performing tensile tests for these specimens. Usually the three properties considered here, increases as the grain size is reduced. On the other hand attenuation due to scattering decreases as the grain size is reduced. This could be one reason for the results obtained. Here again, microstructure observation and measurement of grain size need to be performed before any conclusion is made.

The linear relationship suggested here (for hardness vs. attenuation) has to be confirmed by repeating the whole procedure for another set of samples from the same alloy. On confirmation, the work has to be expanded to other types of steels as well to arrive in at any conclusions.

The observation that the wave velocity remained unchanged in all the specimens indicates that the structural changes achieved by the heat treatment processes have not affected the velocity. The result obtained here suggests that the hardness of the material does not affect the wave velocity in it. However, it should be mentioned that measurement of ultrasonic wave velocity using an ultrasonic flaw detector would not be precise enough to make a conclusion as such.

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