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Quantitative analysis by the ultrasonic method of the effect of fluid of quenching on elastic and acoustical properties of hardened steel

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We have studied by an ultrasonic non destructive testing system the effect of fluid of quenching on acoustical and elastic properties of hardened steel, the measurements are performed by an ultrasonic transducer with 5 MHz in the center frequency, working simultaneously as a transmitter and receiver. The measurements are made for three samples of steel, each of these specimens are hardened according to different conditions of tempering (different durations and fluids of quenching). From the signals backscattered by these samples, we have determined the ultrasonic velocities and attenuations of ultrasonic wave propagating in these specimens. In this study the results show that the tempering is more efficient for the sample which is quenching more times in water and then the acoustical and elastic properties are best than those tempered in air. Then in this work we have able to follow by an ultrasonic system the influence of the fluid of quenching on acoustical and elastic properties of hardened steel.

1 Introduction

The non destructive testing of products is very important in industry; it allows improving the security, reliability or quality of product without to affect its structure. In some cases the samples to be investigated are complex. A material subjects to permanent solicitation (mechanical strain, heat shock, chemical aggressions…) sees his behaviour changed; this evolution can be harmful and can lead to a weakening of the structure. Ultrasonic characterization is one of the means that allows assessing the risks related to the change of mechanical properties of materials; this technique provides access non-destructively to the properties of the materials. The main objective of non-destructive methods applied to materials is to provide correct information about their state of health. Non destructive testing by ultrasound in the field of metallurgy has an important place, because of its ease of use and reasonable cost [1].

The thermo chemical diffusion processes such as carburizing and nitriding is very important in modern industrial technologies. During this processes, alloying elements such as carbon or nitrogen are diffused into the iron surface in order to improve the mechanical and elastic properties near to the surface of treated material [2]. The knowledge of the main physical parameters that influence on the hardenability and its quality is necessary to ensure an efficient quenching process. Several metallurgical studies show that the thermal properties of quenching fluids contribute to the reconstruction of a new microstructure more efficient than that existing before hardening [3]. The object of this article is to show the important place of quenching fluids during tempering process.

2 Experimental setup

The experimental assembly used consists of tow ultrasonic transducers of 1.40cm in the diameter and the both have a center frequency of 5 MHz, these transducers were attached to a cubic tank filled with water (the coupled fluid used). One of the transducer is a transmitter and the other is used as a receiver. The samples to be studied are placed in the middle of the tank and their surfaces are perpendicular to the transducers axis.

A pulse generator of the type Sofranel 5073PR excites electrically the transmitting transducer that sends the ultrasonic waves to the sample investigated, the waves transmitted the specimen are captured by the second transducer (receiver) which is connected with a digital oscilloscope LeCroy 9310M, the signals are acquired from the oscilloscope by using an electronic system formed by a captured card and a personal computer. The three samples which were instigated in this work are quenching according to different conditions of quenching.

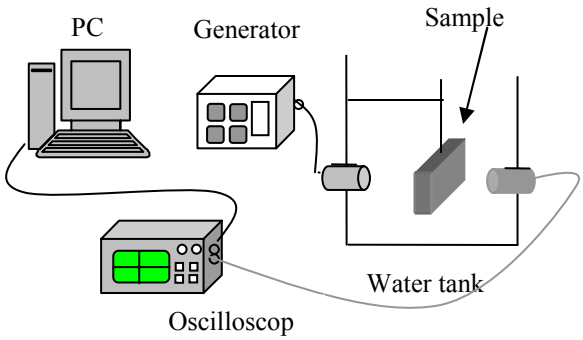

Figure 1: Experimental setup.

3 Experimental signals obtained

3.1 Steel sample quenching in water

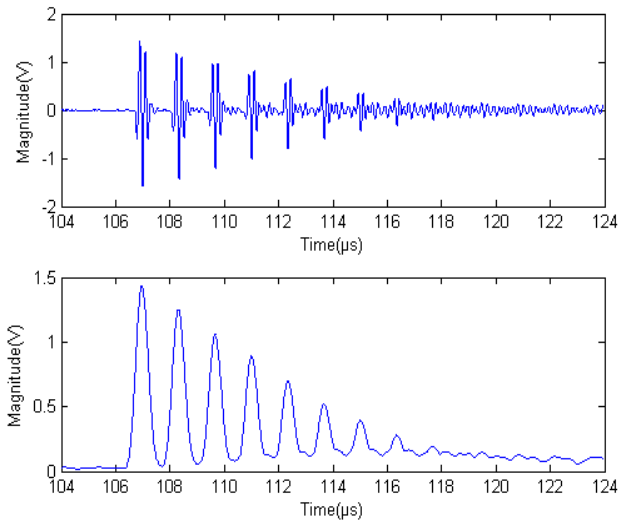

Figure 2: Experimental setup.

The curves in the figure 2. Present the signal in time domain and its normalized envelope of the sample of steel tempered 1 and 5 minutes in water. The temporal signal is obtained after many transmissions of ultrasonic wave of the surface of the specimen. The envelope of temporal signal is obtained by application of short time Fourier transform on the signal in time domain; we have presented only the positive part of the temporal signal.

The envelope of the temporal signal can help us to determine the time of flight with better resolution and also

when the pulse echoes are overlapped. The time of flight is then determined from tow successive maxima of the envelope of temporal signal.

The method of short time Fourier transform consists to drag a weighting window on the signal in time domain and to applied FFT to the result function and the results is a matrix M n×m [4], this matrix is determined by the following formula :

$$M(\tau,\omega)=\int_{-\infty}^{+\infty} W(t-\tau)x(t)\exp(-j\omega t)dt \qquad (1)$$

With W and x(t) are respectively the Haning window applied and the temporal signal.

The envelopes of temporal signals presented in this article are determined by the relation 2:

$$E_j=\sum_{i=1}^{n} M_{ij} \quad j=1,...,m \qquad (2)$$

E is the envelope of each temporal signal x(t), n and m are respectively the number of lines (frequencies) and columns (times) of the matrix M.

3.2 Sample tempered 5 minutes in water

The figure above represents the temporal signal and its envelope for a sample of steel quenching five minutes in water.

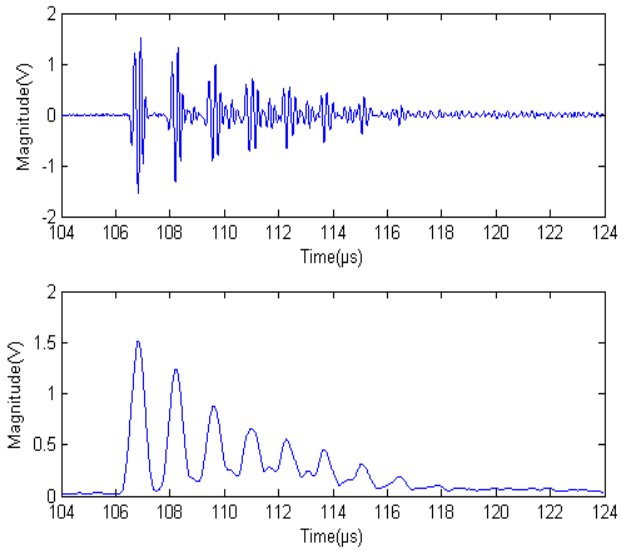

Figure 3: Experimental setup.

The temporal signal below is captured by the second transducer after many reflections and transmissions by the structure of steel sample quenching five minutes in water (fluid of quenching).

The first echo in the curve in figure 3 (figure 2 also) is related to the first transmission of ultrasonic energy by the other surface of steel sample and the second echo corresponds to the ultrasonic energy transmitted by the second surface after the tow reflections respectively at the the first and the second surface and so on until the total attenuation of the energy and thus the disappearance of ultrasonic echoes, this attenuation is due to phenomena absorption and scattering of ultrasonic energy by the microstructures (present of different phases) of the investigated sample.

3.3 sample quenching 5 minutes in air

The curves above show the temporal signal and its envelope for a specimen of steel quenching five minutes in air (figure 4)

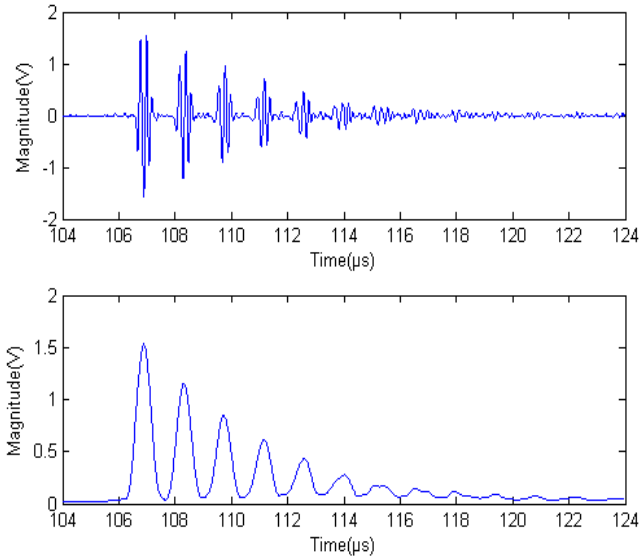

Figure 4: Experimental setup.

The signal in figure 4. Is similar to those plotted in figures 2 and 3 the main difference consists in time of flight of ultrasonic wave in each sample.

4 Time of flight and velocities

From the envelopes of signals we can determine the time of flight of ultrasonic wave in the volume of treated samples, (the table 1). All specimens have the same thickness e=4.10mm.

The longitudinal velocities of ultrasonic wave can be determined by Eq. (3). [5].

$$V_L=\frac{2e}{\Delta t} \qquad (3)$$

Table 1: Time of flight

Samples	Sample 1	Sample 2	Sample 3
$\Delta t(\mu s)$	1.360	1.430	1.545
$e(mm)$	4.10	4.10	4.10
$V_L(m.s^{-1})$	6029.40	5734.30	5307.40
$V_T(m.s^{-1})$	3014.70	2867.20	2653.70

The samples 1 and 2 and 3 are quenched respectively one and five minutes in water and five minutes in water and five minutes in air. From the results in the table 1. We can

see the influence of fluids of quenching in acoustic parameters of treated specimens.

4.1 FFT analysis of pulse echoes

The figures below show the first tow echo and their FFT, to isolate each echo we have applied the Hanning window on each temporal signal.

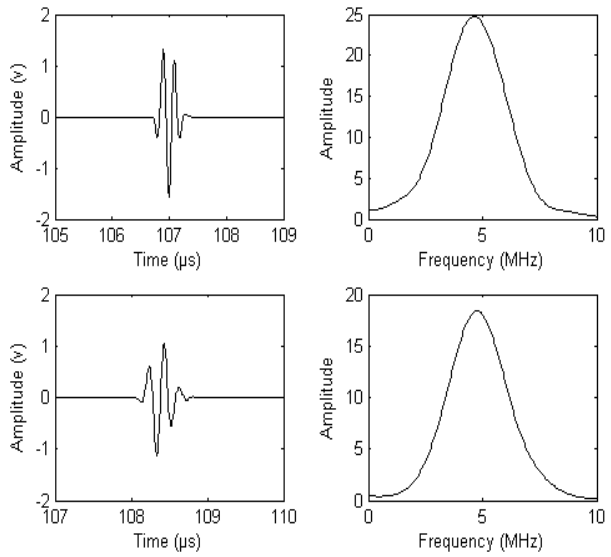

Figure 5: Experimental setup.

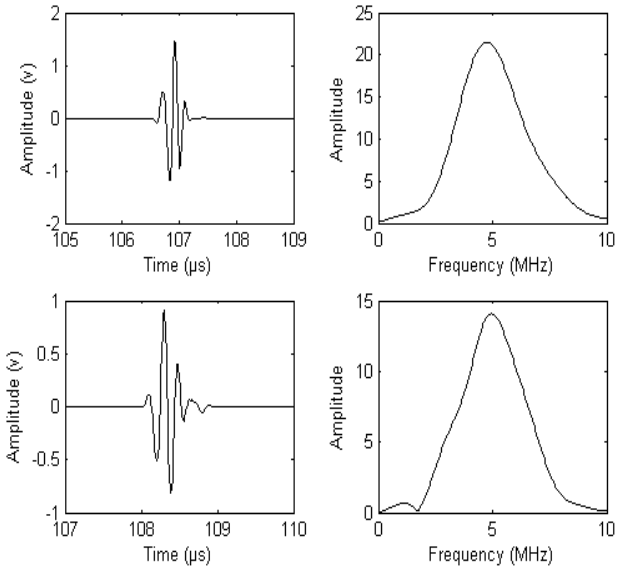

Figure 6: Experimental setup.

The curves above are related to specimen quenching 1 and 5 minutes in water (figure 5.) and the specimen quenching 5 minutes in water (figure 6.), the both specimens are quenched in the same fluid of quenching (water) but they differ by the times of quenching (once or twice times in water). The tow first pulse echoes of each temporal signal are plotted and thus their FFT.

The curves in figure 7. Are similar to those mentioned in figures 5 and 6, it concerns the steel sample which quenched 5 minutes in air. From all these curves we can see the influence of the fluid of quenching on the sample structures studied.

The figure 9. Shows the coefficient of ultrasonic attenuations in the steel specimens controlled.

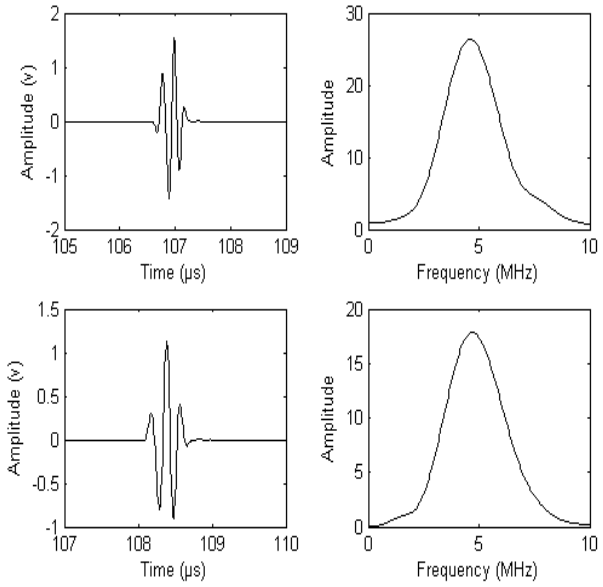

Figure 7: Experimental setup.

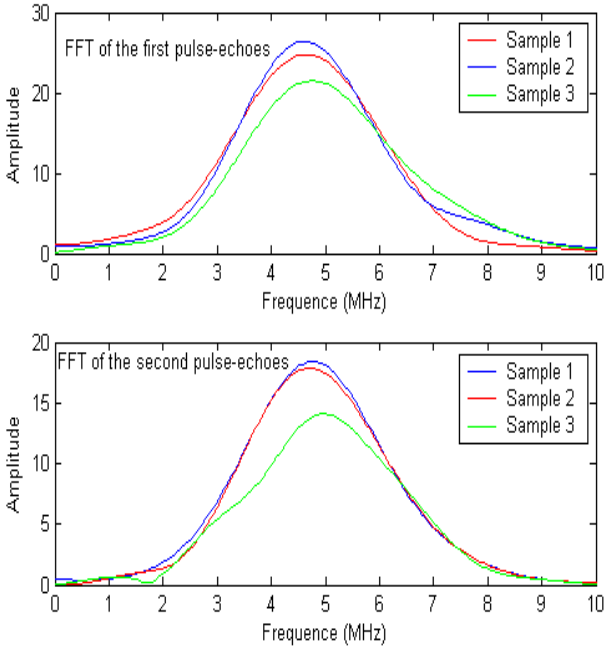

Figure 8: Experimental setup.

In the figure 8. We have compared the amplitude of the FFT of the tow first and second ultrasonic pulse echoes transmitted by the three samples and we can see the difference in amplitude of signals above (figure 8.), for more illustration we have plotted the coefficient of attenuation versus frequency in the figure 9.

For measuring the attenuation we have adopted the immersion method (see figure 1.), the transducers and sample to investigate are emerged in water (coupling liquid), this method is widely used because of its better accuracy and also for its simplicity of implementation. The principle of measuring the attenuation consists to acquire the successive pulse echoes and to applied to each of them

the FFT analysis, and so the attenuation can be calculated in the frequency domain, the following equation can be determined the attenuation coefficient:

$$\alpha_L(f) = \frac{1}{2d} Ln\left(\frac{S_1(f)}{S_2(f)}\right) \quad (4)$$

With d is the tackiness of the specimens and S_1 and S_2 are respectively the specter of the first and the second pulse echoes. In this method we have neglected the attenuation in the coupling liquid

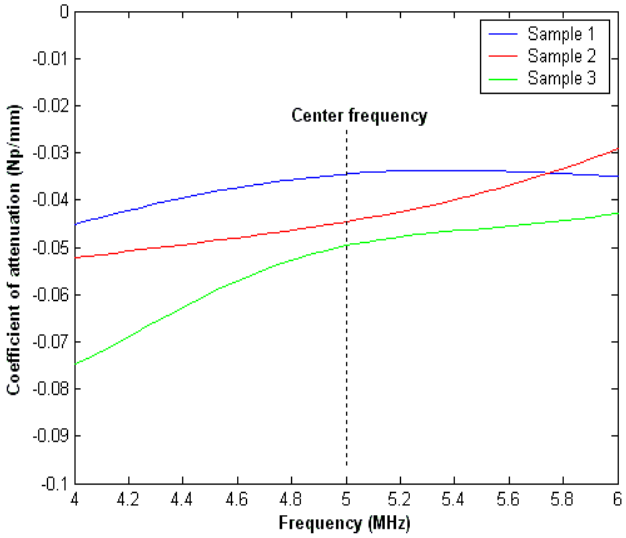

Figure 9: coefficient of attenuation

The amplitude of ultrasonic wave's decreases according to distance traveled, it results the attenuation of waves in the medium traversed. The intensity of ultrasonic wave in each point z of medium is given by the following low:

$$I = I_0 \exp(\alpha z) \quad (5)$$

With I_0 is the initial intensity and α the attenuation's coefficient, where α is negative in some articles the attenuation's coefficient is adopted positive and then the Eq. (5). According to this convention, becomes:

$$I = I_0 \exp(-\alpha z) \quad (6)$$

In figure 9. We can see the variation of attenuation versus the frequency for the three steel samples. For the centre frequency of 5MHz the value of attenuation's coefficient are grouped in the table 2.

Table 2: Coefficient of attenuation at 5MHz

Samples	Sample 1	Sample 2	Sample 3
α(Ln/mm)	-0.035	-0.048	-0.052

The three steel specimens have different coefficient of attenuation, the ultrasonic wave is more attenuate in the sample 3 (steel quenching 5 minutes in air) and less attenuate in the sample 1 (sample quenched 1 and 5 minutes in water), this variation in attenuation can be related to the structure of each steel sample.

4.2 Elastic and mechanical parameters

Once the ultrasonic velocities are determined, we can then easily deduce the elastic constants of samples by using the relationships derived from the laws of linear elasticity [6]:

$$E = \rho V_T^2 \frac{3V_L^2 - 4V_T^2}{V_L^2 - V_T^2}$$

$$\mu = \rho V_T^2$$

$$\nu = 0.5 \frac{V_L^2 - 2V_T^2}{V_L^2 - V_T^2}$$

Where E, μ, ν and ρ are respectively the Young's modulus, shear modulus, Poisson's ratio and bulk density of steel specimens.

Table 3: elastic properties of steel samples

	Sample 1	Sample 2	Sample 3
$\rho\,(kgm^{-3})$	7450	7250	7100
$E\,(GPa)$	196	173	145
$\mu\,(GPa)$	75	66	55
ν	0.3	0.3	0.3

From the results in the table 3. We can see that the elastic constants increase with quenching and its conditions, except the Poisson's ratio which remains insensitive to the conditions of quenching.

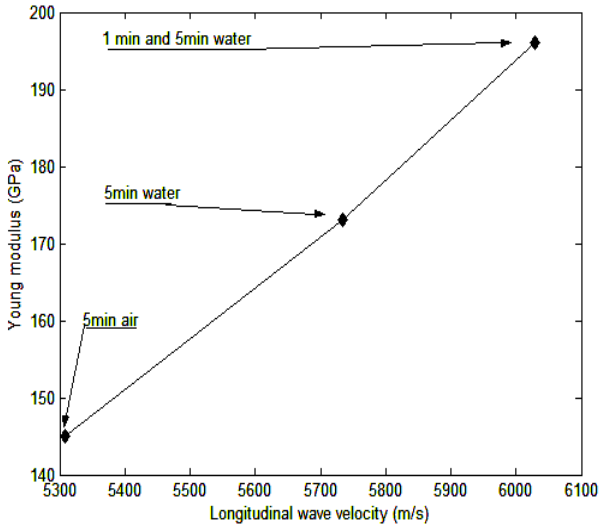

Figure 10: Evolution of Young modulus with velocity.

The figure above shows the evolution of Young modulus as a function of longitudinal wave velocity which is also

depend to the conditions of quenching such as fluid of quenching and its duration.

5 Conclusion and interpretation

Quenching is on of the stages of heat treatment of steels, it consists to cool brutally a given sample to freeze its structure obtained during the dissolution. The processing treatment of steels is as follows:

- The dissolution.
- Heating the sample up to the austenitizing Temperature.
- Maintain the structure at the austenitizing temperature for homogenization and put in a solid solution of alloying elements.
- Tempering.

The thermal properties of the quenching fluid are very important parameters during quenching, so these are some parameters to be monitored for making a good temper and therefore to have the best mechanical properties of tempering samples.

The fluids used in quenching, by decreasing order of the cooling rate, are [7]:

- Salt water.
- Water.
- Water with additives.
- Oil.
- Water mist.
- Gases (air, argon, nitrogen…).

The cooling rate is determined by three factors:

- Heat transfer in the quenching fluid.
- Heat transfer at the interface metal-quenching fluid.
- Heat transfer in the metal.

For explaining the results in table 3. We have compared the thermal properties of the tow quenching fluids used (water and air) during temper, especially the thermal conductivity. As the figure above shows, the thermal conductivity of air at room temperature is 0.0278 W/m.K and that of water is very higher [7] (0.58 W/m.k) so the variation of elastic constants in table 3. Can be due to the effect of the thermal properties of quenching fluids.

For the quenching in air, the cooling is slow and the carbides have sufficient time to precipitate before reaching the stage of hardening, by cons if cooling occurs at a rate fast enough, the carbon atoms do not have time to disseminate and then the precipitaion is prevented.

The ultrasonic technique allows monitoring the quality of tempering of steel, this method can be employed to determine the effect of temper conditions (fluid and duration of quenching) on the quality of structure of the tempering steel and so allows choosing the best of these conditions to improve the quality of elastic constants of samples.

6 Reference

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