Workshop of the Consultative Committee for Acoustics, Ultrasound and Vibration

Quantification of hardened layer thickness in carbon steel using ultrasound metrology

Centro Nacional de Metrología

Dirección de Vibraciones y Acústica

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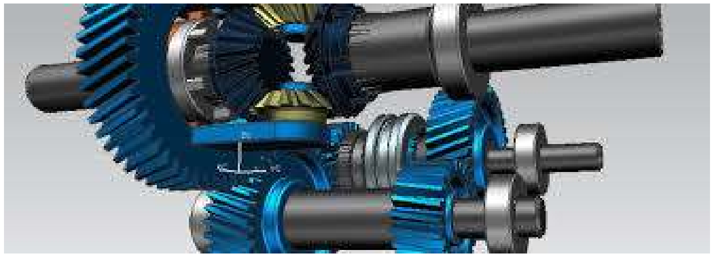
Motivation

The surface of industrial components which are subject to high wear is usually heat treated to hardened its surface whilst its core maintain its original structure condition.

In general, destructive tests are performed to quantify the hardened layer thickness that may require too much time to carry them out in order to ensure that a production line indeed manufactures components with the hardness depth profile required.

A viable ultrasound alternative has been studied and implemented at laboratory level at the National Metrology Center (CENAM) in Mexico. Basically, a non-destructive ultrasonic method was developed to measure hardening depth in steels after being heat treated by induction.



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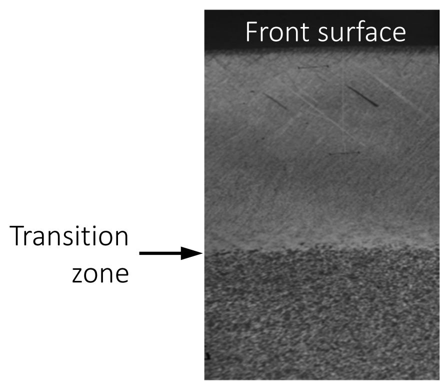
Methodology

The ultrasonic method developed uses a high frequency ultrasonic transducer in an immersion setup, at a fix angular orientation to propagate ultrasonic shear waves inside the hardened steel specimen.

The interaction of ultrasonic waves in the transition zone (interface of hard layer and soft steel core) generates ultrasonic indications, backscattering, that are used to quantify the depth of hardened layer through the measurement of time-of-flight.



Methodology

The depth of hardened layer (h_m) in a heat treated specimen can be quantified by measuring the time-of-flight between the reflection at the interface water-steel (front surface reflection of the steel specimen) and the backscattering reflections, the wave propagation velocity (c), and the refraction angle (θ) of the ultrasonic shear waves in the material.

$$h_m = c\,\frac{t_m}{2}\cos\theta$$

Another specimen of the same material and heat treated, with a known depth of hardened layer (h_p), that will be used as a reference, will fulfill the same equation,

$$h_p = c\,\frac{t_p}{2}\cos\theta$$

where h_p can be previoulsy determined using a destructive technique such as metallography or a hardness profile.

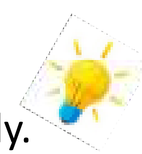
Methodology

The measurement error (e) in the depth of hardened layer between an unknown component (h_m) and a reference specimen (h_p), will be given by:

$$e = h_m - h_p = \frac{c}{2}(t_m - t_p)\cos\theta$$

From this equation, the depth of hardened layer (h_m), can be determined by,

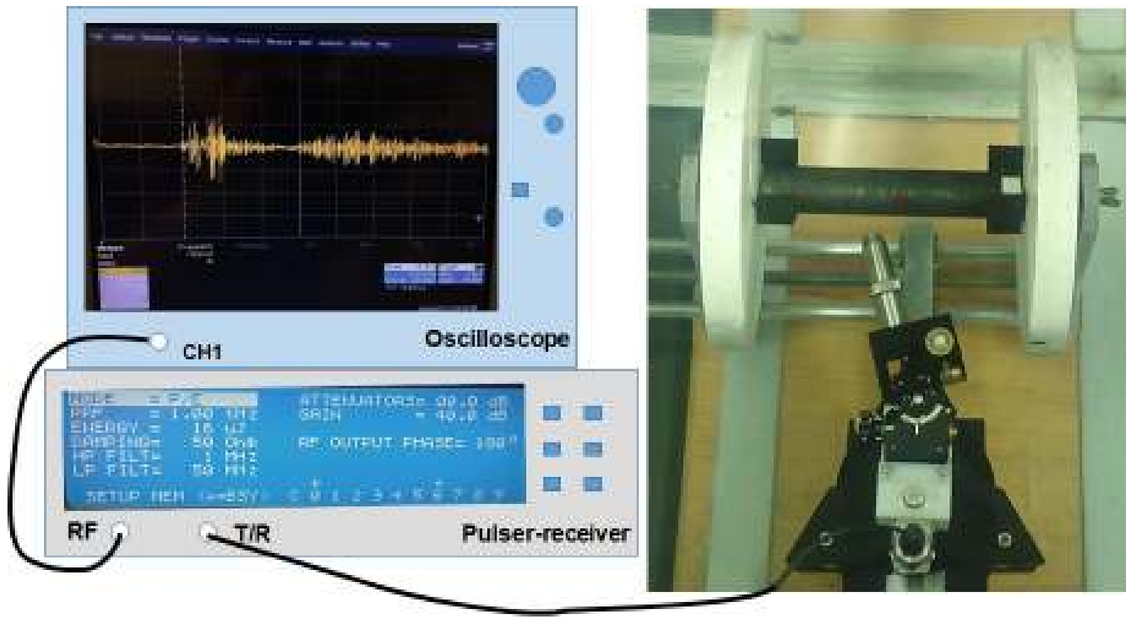
$$\boxed{h_m = h_p + \frac{c}{2}(t_m - t_p)\cos\theta}$$

where both times-of-flight t_m and t_p are determined experimentally. 

Experimental setup

The measurement system used includes:

1) an ultrasonid immersion transducer of 20 MHz,
2) pulser/receiver to excite the transducer,
3) digital oscilloscope with a 500 MHz bandwith,
4) immersion tank,
5) positioning system for the ultrasonic transducer and a mounting system for the piece under measurement.



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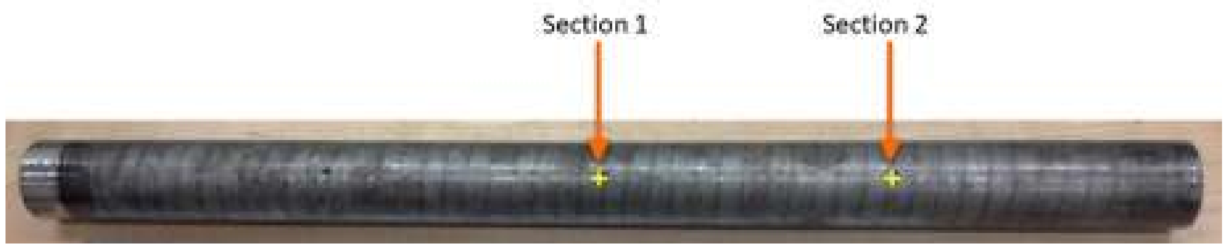
Experimental setup

Specimens of carbon steel, heat treated by induction furnace were measured in two sections, and in each section a four measurements were made 90° apart by rotating the specimen.



$c = 3\ 216.3\ \mathrm{m/s}$ propagation velocity for shear waves in carbón steel obtained experimentally

Angle of incidence: $\alpha_i = 16.43°$ → $\theta = 37.9°$ Angle of refraction of shear waves in carbon steel

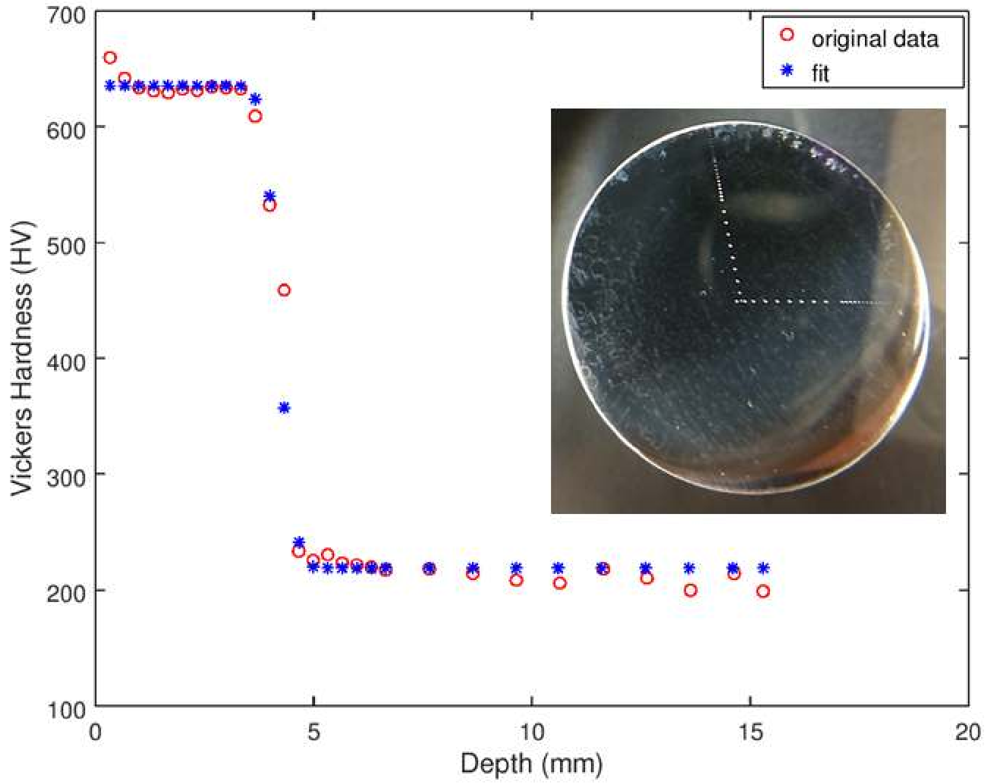
The angle of incidence was chosen to have an approximately a maximum refraction coefficient for shear waves in the material.

Depth of hardened layer in a reference specimen

The depth of hardened layer, h_p, in a specimen used as a reference was obtained from a microhardness profile of a cross section a specimen.

The value of h_p, is quantified as the distance from the surface of the specimen to a point where the hardness corresponds to the maximum value of the derivative of the fitting curve of the original hardness data to an error function, erfc.

$$y = 208.31 \cdot erfc\left(\frac{x - 4200}{400}\right) + 218.92$$



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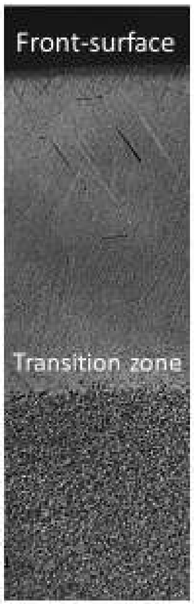
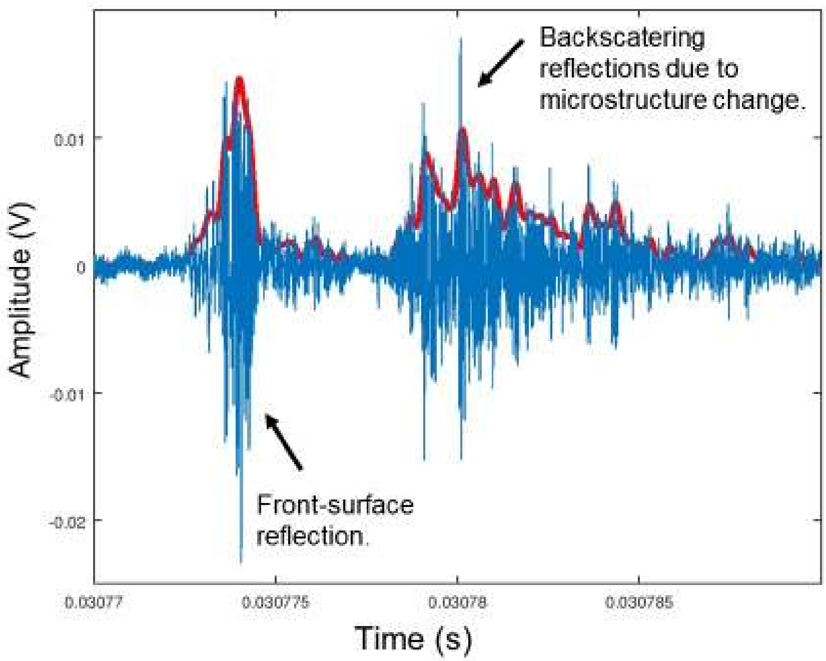
Signal acquisition and postprocessing



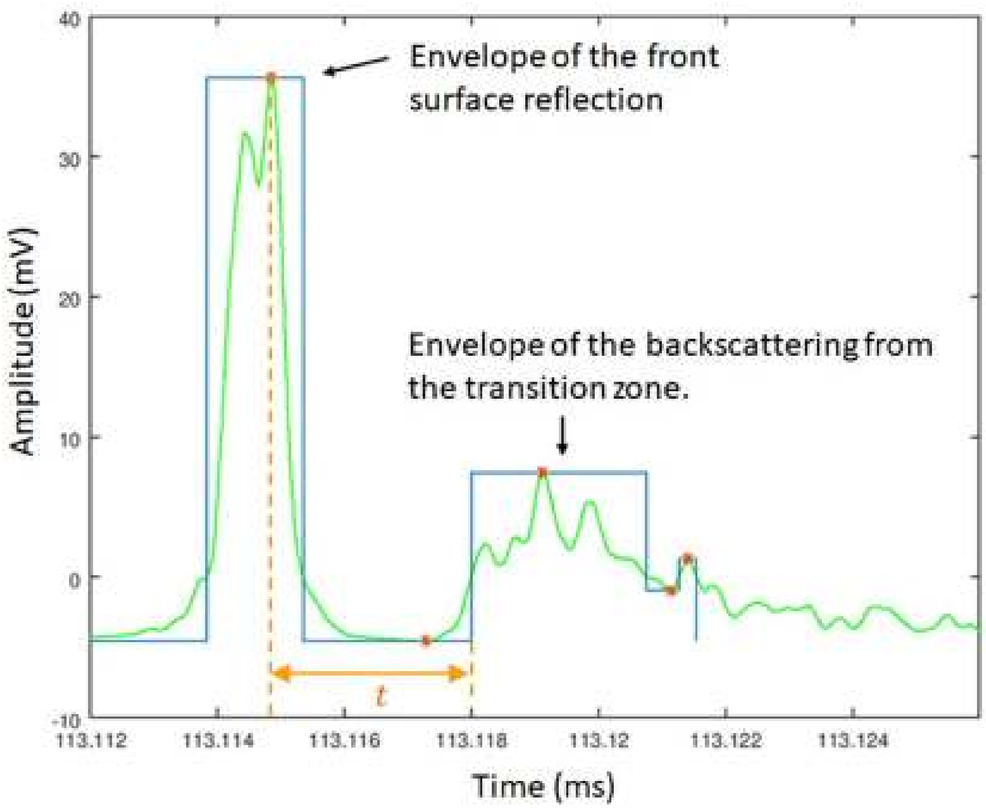


The time-of-flight is measured between the indication of the front surface of the specimen under test and the indications of the transition zone, using the digitally processed ultrasonic signal applying secuentially:

1) multiresolution based discrete wavelet transform,
2) Hilbert transform to obtain the envelope of the singal,
3) Savey-Golevsky filtering,
4) moving averaging to smooth abrupt changes;

the result of these processing is the envelope curve in red color.

Signal acquisition and postprocessing



The time-of-flight is quantified by determining the zero-crossing point of the smoothed envelop of the ultrasonic signal.

More precisely, the time-of-flight is determined as the difference between the time of the maximum amplitude of the front surface reflection and the time of the first zero-crossing point of the backscattering envelope.

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Results

Data of the specimen used as reference.

Reference specimen – 03A	Value
Time-of-flight, t_p	3.26 µs
Hardened layer thickness – from microhardness profile, h_p	3.99 mm

Comparison of the results obtained for three specimens using ultrasound and micro hardness.

Measurement method	Hardened layer thickness (mm)		
	01A	**09A**	**14A**
Ultrasound	2.52	2.96	5.48
Microhardness	2.66	2.99	5.32
Measurement error	-0.14	-0.03	0.16

The measurement error obtained in the three specimens measured are below 0.2 mm with an expanded uncertainty (k=2) < 0.3 mm.

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Conclusions

The methodology developed has proved to be successful at laboratory level; results obtained show measurement errors < 0.2 mm compared to micro-hardness methods, but being much faster and feasible for an on-line implementation in production lines.

The measurement methodology described can be applied by manufacturing companies with production activities in the production chains of the automotive, aeronautics, and metalworking industries; that use induction hardening as part of their production processes.

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References

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Thank you for your attention!

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