# Application of signal processing techniques to case depth measurements by ultrasonic method

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## Abstract

The surface hardness of industrial parts which are subject to high wear is usually treated by surface hardening processes. For hardened surfaces, it is desirable to know both the surface hardness value and the depth of the hardened layer. Ultrasonic testing has been used to nondestructively measure the depth of the hardened surface layer. The technique is based on the detection of the transition between different polycrystalline structures due to their variation in backscattering characteristics. Increase of the grain size increases the backscattering of ultrasonic waves. The hardened top layer of the part has small grains while the base material has larger grains. Accordingly, the hardened top layer structure is transparent to ultrasonic waves while the coarse-grained base material structure exhibits considerable ultrasonic backscattering, which results in signal amplitudes suitable for display. However, if the depth of the hardened layer is very small, the discrimination of the backscattered echoes becomes very difficult. Special signal processing techniques including Wiener filtering and autoregressive spectral extrapolation have been used to overcome this problem. Using an immersion ultrasonic system, the depth of the hardened layer has been measured on a number of induction-hardened specimens. These specimens are then subjected to destructive tests. Comparison of the results indicates that the application of signal processing techniques have significantly improved the capability of ultrasonic measurements.

***Keywords***: surface hardening, ultrasonic testing, signal processing, Wiener filter

## Introduction

Surface hardening may be defined as a process by which a ferrous material is hardened so that the surface layer, known as the case, becomes substantially harder than the remaining material known as the core. The main purpose of surface hardening is to produce a surface which is resistant to wear while maintaining the overall toughness and strength of the steel core. Surface hardening improves not only the wear resistance but also the fatigue strength of parts under dynamic and/or thermal stresses. The characteristics of surface hardening are primarily determined by surface hardness and the effective hardness depth. Surface hardening processes include carburizing, nitriding, carbonitriding, cyaniding, induction and flame hardening [1]. All these methods increase the surface hardness of ferrous materials.

Case hardening is usually carried out by packing the steel with carbonaceous materials and raising the temperature to around 920 °C. The time required for the process depends on the desired case depth. This is followed by quenching and annealing. The initial treatment temperature is above the point at which carbon steel undergoes a phase transition from ferrite (body-centered-cubic structure) to austenite (face-centered-cubic structure). In the austenite phase, steel absorbs more carbon so that after quenching the surface turns into a supersaturated steel. A martensitic structure is also formed near the surface due to thermal stresses when the steel is returned back to room temperature. After quenching, the case hardened steel is usually too brittle to be used and therefore by annealing some of the carbon is extracted from the solution and toughness is improved [1,2].

Case depth - or the thickness of the hardened layer - is an essential quality parameter of the case hardening process. The methods employed for measuring the case depth are chemical, mechanical, visual (with an acid etch) and nondestructive techniques [2]. The mechanical method is the most widely used technique for case depth measurement which is by random sampling and destructive testing. Each method has its own area of application, and no single method can be recommended for all purposes.

In order to evaluate the characteristics of the hardened surface, it is advantageous to use a nondestructive method for measuring the case depth. Different solutions have therefore been suggested:

1. Using the magnetic and magnetic-electrical characteristics of this layer [3],
2. Using the sound velocity of ultrasonic waves [4], and
3. Using the backscatter of ultrasonic waves [5].

In this paper we use the ultrasonic technique for measuring the depth of a hardened surface layer. The method that is proposed incorporates a special signal processing scheme which makes the measurement of the thin layer of the hardened surface possible.

**Ultrasonic Testing**

In an ultrasonic test, sound waves of high frequency are sent into the material. Interaction of the emitted wave with the material borders or discontinuities can be sensed either by the same transmitting transducer or by another transducer. An ultrasonic technique which has already been used for measuring the case depth of circular components is based on the backscattering of the wave from the interface of the hard layer and soft steel core [5]. It uses high frequency ultrasonic waves (10 MHz to 25 MHz) to measure the case depth. To carry out the measurements, the test piece is placed in a water tank. A tilted ultrasonic probe directs sound waves at the submerged part at a known angle. The transmitted wave first passes through the fine grained surface layer and then hits the softer underlying microstructure which has larger grains. There exists an interface called the “transition zone” between the hard surface and soft core. The depth of the hardened layer is measured by measuring the time delay or “Time-of-Flight” (TOF) between the front surface reflection and the reflection at the transition zone. In figure (1) a typical ultrasonic response showing the front surface reflection (left echo), and the transition zone reflection (center echo) is shown. Two gates, represented as horizontal lines on the display, measure the distance between the two points at which the echoes cross a preset threshold value. One limitation of this technique is that the thinner the hardened layer is, the less accurate the depth of the measurement would be.

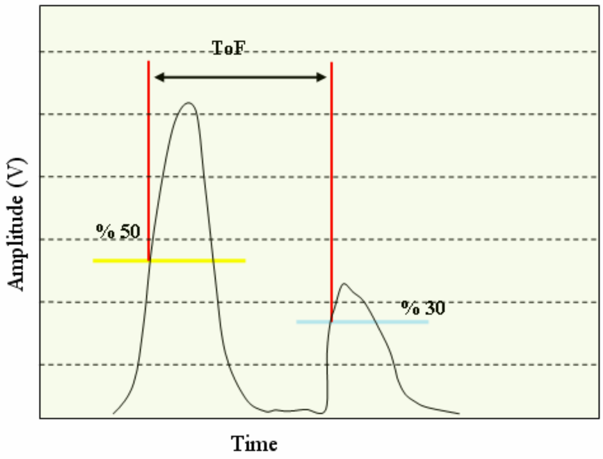


**Figure 1: A typical ultrasonic response from a hardened shaft**

In the method used in this paper, the specimen is immersed in a water tank and ultrasonic waves are sent into the specimen by a high frequency (15 MHz) spherically focused probe, see figure (2). The probe direction is normal to the specimen surface. Therefore, it can be said that it is more of a pulse-echo test rather than backscattering. When the wave strikes the top surface of the specimen, part of it is reflected back and the rest enters into the specimen. Inside the material, reflection (or backscattering) of waves occur both from the transition zone and the back surface. However, because the thickness of the hardened layer is small with respect to the wavelength, the echoes returning from the top surface and the transition zone merge together and it is very difficult to discriminate them from each other. A special signal processing technique which incorporates deconvolution by Wiener filtering followed by autoregressive spectral extrapolation is used to overcome this problem. The principles of this signal processing technique is described in the following sections.

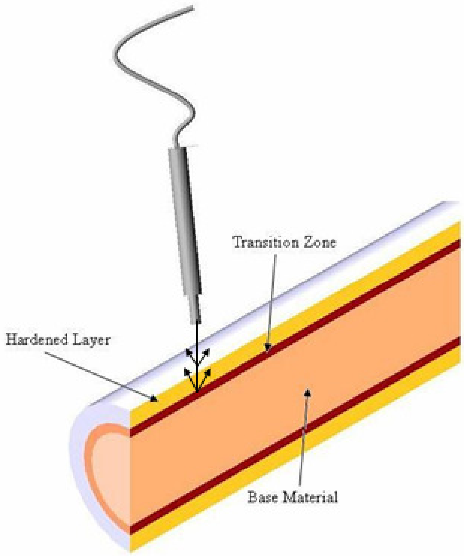


**Figure 2: Ultrasonic testing of a hardened shaft**

## Signal Processing

The signal processing technique which is incorporated for improving the ultrasonic signals obtained form case depth measurement incorporates a deconvolution technique called Wiener filtering. A measured ultrasonic signal, *y(t)*, can be expressed as the convolution of the measurement system impulse response, *h(t)*, with the test specimen impulse response, *x(t)*, plus noise, *n(t)*,

$$y(t) = h(t) * x(t) + n(t) \qquad \text{(Eq. 1)}$$

In Eq. (1), $*$ denotes the linear convolution operator. If Eq. (1) is transformed into frequency domain, Eq. 1 becomes,

$$Y(\omega) = H(\omega)X(\omega) + N(\omega) \qquad \text{(Eq. 2)}$$

where *Y(ω), H(ω),* , and *N(ω)* are the Fourier transforms of *y(t), h(t), x(t),* and *n(t),* respectively. The convolution process turns into simple multiplication in frequency domain. In Eq. (1) *y(t)* is known, and *h(t)* and the characteristics of *n(t)* can be measured, one has to find *x(t)* by applying the following equation which is called the Wiener filter [6],

$$X(\omega) = \frac{Y(\omega)H^*(\omega)}{\left|H(\omega)\right|^2 + Q^2} \qquad \text{(Eq. 3)}$$

In Eq. (3), $H^*(\omega)$ is the complex conjugate of *H(ω)* and,

$$Q^2 = 10^{-2}\left|H(\omega)\right|^2_{\max} \qquad \text{(Eq. 4)}$$

The deconvolved signal obtained by applying the Wiener filter to the signal can be further improved by autoregressive (AR) spectral extrapolation. To apply the AR spectral extrapolation, first *X(ω)* is obtained by a Wiener deconvolution process. A certain bandwidth of *X(ω)* which has a high signal-to-noise ratio is selected. The AR model which extrapolates the rest of the signal based on the selected region is then applied to this frequency window. The extrapolation is performed based on the following equations,

$$\begin{aligned} \hat{X}_p &= -\sum_{i=1}^{K} a_i^* X_{p+i} \qquad p = 1,2,\ldots m-1 \\ \hat{X}_q &= -\sum_{i=1}^{K} a_i X_{q-i} \qquad q = n+1,\ldots, N \end{aligned} \qquad \text{(Eq. 5)}$$

where $a_i$ values are the AR coefficients and $K$ is the AR order; $N$ is the number of data samples, and $^*$ denotes complex conjugate. Eq. (5) corresponds to forward and backward linear prediction which causes that the band-limited ultrasonic data to be extrapolated to a wideband data.

The aforementioned signal processing techniques are applied to the ultrasonic data following the procedure explained in Ref. 6.

## Experiments

Figure (3) shows the configuration of the experimental test system used for measuring the case depth of hardened specimens. The system consists of a water tank, an ultrasonic pulser/receiver, a 100 MHz A/D converter, and a desktop computer. The ultrasonic probe is spherically focused and has nominal frequency of 15 MHz and diameter of 0.25 in.

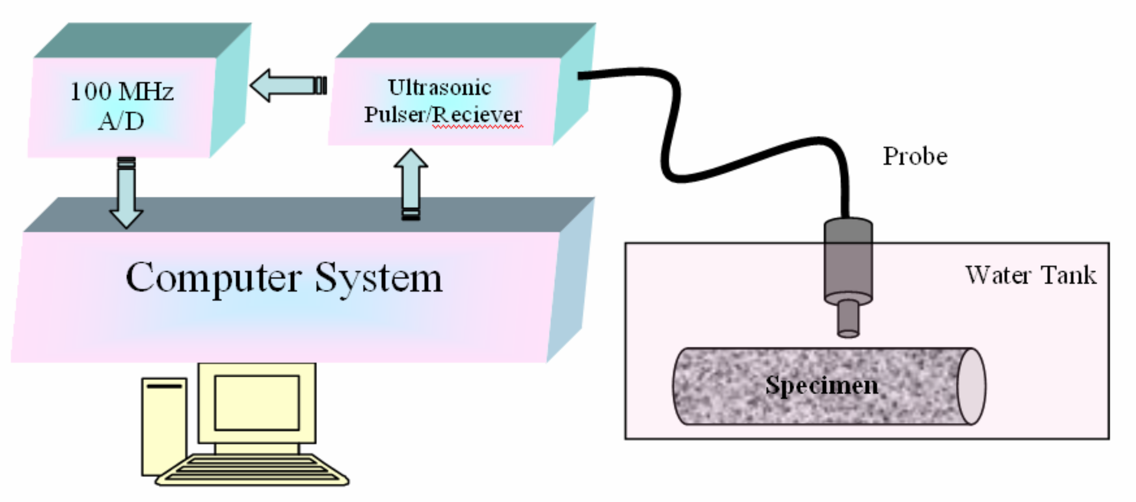


**Figure 3: Block diagram of experiment setup**

The test piece is submerged in the water tank and the probe is positioned such that the ultrasonic beam is perpendicular to the top surface of the test piece. Two cylindrical test samples (sample 1 and sample 2) made from carbon steel were used. The surfaces of samples 1 and 2 were respectively hardened by induction hardening to 2.1 mm and 1.4 mm depths, see figure (4).

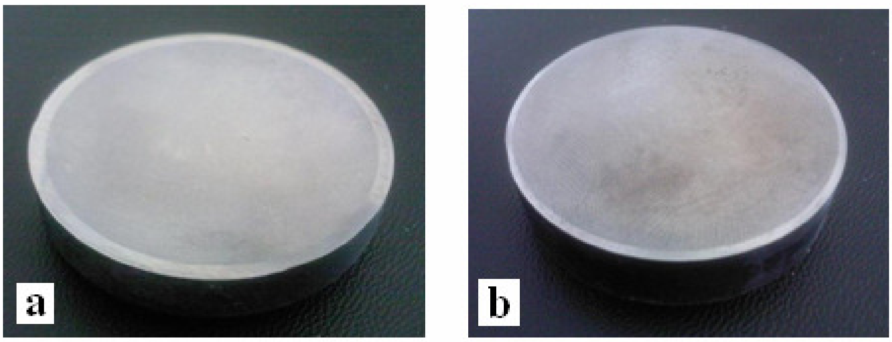


**Figure 4: a) Sample 1 with case depth of 2.1 mm, b) Sample 2 with case depth of 1.4 mm**

During the measurement of the reflected signal from these samples, the focal point of the ultrasonic probe was positioned on the top surface of the specimen. The ultrasonic signals obtained from these two samples are shown in figure (5). From the ultrasonic signals shown in figure (5), it is not possible to see the echoes returning from the transition zone. We process these signals in order to extract the required information from them.

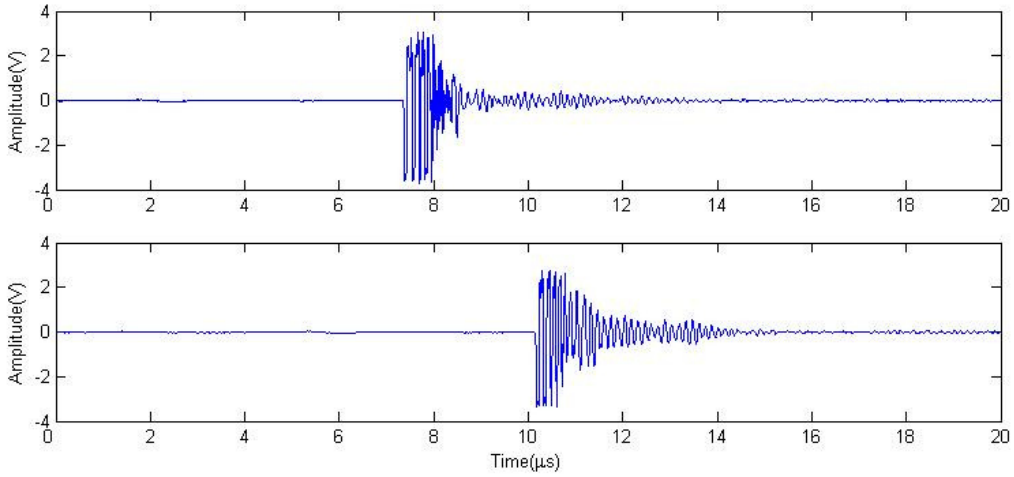


**Figure 5: Ultrasonic signals obtained from sample 1 (top) and sample (2).**

For processing of these signals, the backwall echo is used as the reference wavelet in the deconvolution process. The two signals were processed by Wiener filtering and autoregressive spectral extrapolation. The processed signals are shown in figures (6a) and (6c). These signals are then rectified and filtered as shown in figures (6b) and (6d). It can be observed that in the signals obtained from the two specimens, the echo returning from the transition zone can be clearly identified in figures (6b) and (6d). The time-of-flight between this echo and the echo returning from the top surface is a measure of the case depth. The experiments reported in this paper are only qualitative for the purpose of showing that the technique is capable of measuring the depth of the hardened layer. Quantitative methods for exact measurement of the case depth are currently being pursued.

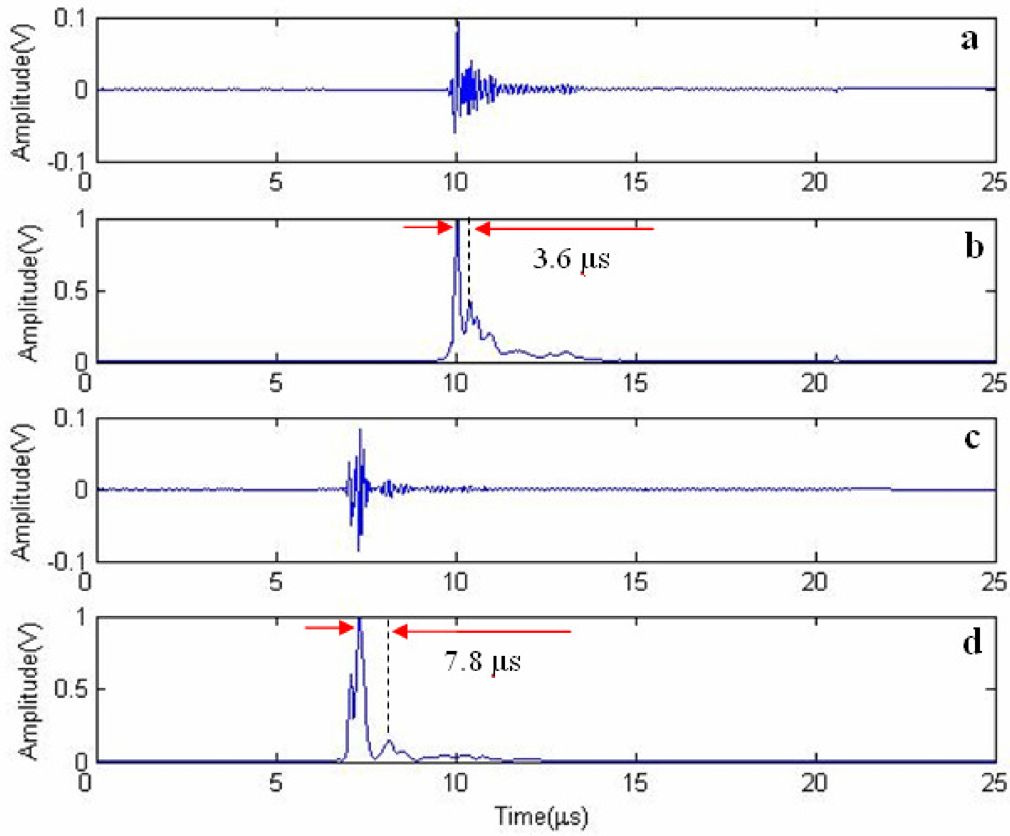


**Figure 6: a) and b) Processed signals of sample 1, c) and d) processed signals of sample 2**

## Conclusions

The depth of the hardened surface in steel samples was measured by ultrasonic technique. A signal processing scheme was used to make the separation of echoes coming from the top surface of the specimen and the transition zone between the hard surface layer and the soft core possible. Qualitative experimental measurements on carbon steel specimens with different case depths show that the technique is quite promising. Quantitative measurements are currently underway.

## References


1- ASTM Standard A919-84(1993)e1, "Terminology Relating to Heat Treatment of Metals," ASTM International, www.astm.org.

2- SAE Standard J423(1998), "Methods of Measuring Case Depth," SAE International, www.sae.org.

3- W. Morganer, F. Michel, "Some New Results in the Field of Non-Destructive Case Depth Measurement", 9th European NDT Conference (ECNDT2006), Berlin, Germany, September, 25-29, 2006.

4- S. Singh, R. Fuquen, D. R. Leeper, "Process for measuring the case depth of case-carburized steel**,"** United States Patent 5648611, 1997.

5- W. Theiner, R. Kern, M. Stroh, "Process Integrated Nondestructive Testing of Ground and Case Depth Hardened Parts", European Conference on Non-Destructive Testing (ECNDT2002), Barcelona, Spain, June, 17-21, 2002.

6- F. Honarvar, H. Sheikhzadeh, M. Moles, A. N. Sinclair, "Improving the time resolution and signal-to-noise- ratio of ultrasonic NDE signals," Ultrasonics, Vol. 41, pp.755-763, 2004.