Case Depth Profile Measurement of Hardened Components Using Ultrasonic Backscattering Method

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INTRODUCTION

A large number of moving mechanical components are surface hardened whilst their cores remain in the original structural condition. Surface hardness and case-depth measurements are the most important parameters for quality monitoring of surface hardened steel products. The current standard industrial technique for case-depth measurement is micro-indentation, which is destructive and time consuming, and therefore not suitable for on-line volume inspection.

There have been continuous efforts to search for new methods for evaluating case-depth in a non-contact and nondestructive fashion. Different nondestructive approaches have been considered including: use of the magnetic and magneto-electrical characteristics of the hardened layer, ultrasonic velocity measurement, and backscattering characteristics of ultrasonic waves.

Ultrasonic backscatter method is probably the most effective technique for measuring the case-depth of induction-hardened parts. Backscattered signals are accumulation of numerous ultrasonic scattered waves which occur because of surface roughness or part grain boundaries [1]. Backscattered echoes involve intense oscillations and these oscillations should be removed before any meaningful and reliable measurements could be accomplished.

In ultrasonic backscatter technique, the specimen and ultrasonic probe are both immersed in a tank filled with water. The probe is inclined at a certain angle from the specimen’s orthogonal cross sectional plane and shear waves are emitted into the specimen [2]. Ultrasonic backscatter takes place at the surface of the specimen due to surface roughness and results in the return of part of the energy to the probe (first echo). Ultrasonic energy also enters the hardened layer as a shear wave. The hardened surface layer is made of fine martensitic structure and thus no scatter of ultrasonic wave takes place in this region. However, when the shear wave reaches the transient zone (TZ), where martensitic structure is gradually converted to ferrite-pearlite structure which is of a larger grain size, once again, energy is scattered at grain boundaries. This transition zone backscatter forms the second echo. The difference in time-of-flight (ToF) of these two echoes is proportional to the case-depth of the specimen [3]. Figure 1 shows this process, and Fig. 2 shows a typical ultrasonic response from a hardened steel axle shaft. Two gates, designated by horizontal lines on the display, measure the distance between the two points at which the echoes cross a preset threshold value. In Fig. 2, the front surface gate is set at 50% and the TZ gate is set at 30% of full screen height.

In this paper the goal is to measure case depth profile of a hardened shaft in the form of a B-scan image. A special inspection system is designed and used for this purpose. This process includes measurement of case depth along of a straight line on the surface of a hardened shaft in small steps and processing each echo independently. The processed echoes are then put together to form the case depth profile. The accuracy of the measurements was verified by destructive and metallurgic tests on the shaft.
SIGNAL PROCESSING METHOD

In practice, many measured signals contain a rapidly-oscillating component. The amplitude of the oscillation varies slowly with time, and the profile of the slow time-variation is called the envelope. The envelope often contains important information about the signal. Using special techniques, the rapid oscillations can be removed from the signal to produce a direct representation of the envelope. One method of extracting the envelope of a signal is by using the Hilbert transform.

The Hilbert transform of a function \( f(x) \) is defined as [4]:

\[
F(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{f(x)}{t-x} \, dx \quad (1)
\]

Theoretically, the integral is evaluated as a Cauchy principal value. Computationally, one can write the Hilbert transform as the following convolution,

\[
F(t) = \frac{1}{\pi t} * f(t) \quad (2)
\]

where \(*\) is the convolution operator. By the convolution theorem of Fourier transforms, Eq. 2 may be evaluated as the product of the transform of \( f(x) \) with \(-j * sgn(x)\), where:

\[
sgn(x) = \begin{cases} 
-1 & x < 0 \\
0 & x = 0 \\
1 & x > 0 
\end{cases} \quad (3)
\]

The Hilbert transform can be considered as a filter which simply shifts phases of all frequency components of its input by \(-\pi/2\) radians.

An analytic (complex time) signal \( Y(t) \) can be constructed from a real-valued input signal \( f(t) \) by using the following equation,

\[
Y(t) = f(t) + jF(t) \quad (4)
\]

where \( Y(t) \) is the analytic signal, \( f(t) \) is the input signal, and \( F(t) \) is the Hilbert transform of the input signal. The real and imaginary parts can be expressed in polar coordinates as,

\[
Y(t) = A(t) \exp[j \psi(t)] \quad (5)
\]

where \( A(t) \) is the envelope or amplitude of the analytic signal, and \( \psi(t) \) is its phase (the derivative of \( \psi \) is called the “instantaneous frequency”). The magnitude of \( Y(t) \) is the envelope of the original time signal.
Moving Average
In the context of statistics, a moving average is a finite impulse response filter used for analyzing a set of data points by calculating the averages of different subsets of a whole data set [5]. A moving average is not a single number, but it is an array of numbers and each number in this array is the average of the corresponding subset of the larger set of data points.

A moving average is usually used with time domain data to smooth out short-term fluctuations and highlight long-term trends or cycles. Depending on the application, the threshold between short- and long-term may vary. For each specific application, the parameters of the moving average need to be chosen accordingly. Mathematically, a moving average can be considered as a convolution. It would also be similar to a low-pass filter which is defined as follows [5],

\[ y(n) = \frac{1}{N+1} \sum_{k=0}^{N} x(n-k) \]  

(6)

In computing a moving average by Eq. 6, only the past data are used. For certain applications, it is advantageous to avoid the shifting induced by using only the past data. Hence, a central moving average which uses both past and future data can be computed. In this case, the future data are not predictions, but they are the data obtained after the time at which the average is to be computed. For computing the central moving average, the following equation can be used,

\[ y(n) = \frac{1}{n_L + n_R + 1} \sum_{k=-n_L}^{N_R} x(n-k) \]  

(7)

Savitzky-Golay Smoothing Filter
Another filter that can be used for smoothing of ultrasonic backscatter signals is the Savitzky-Golay smoothing filter.

In this method, the digital filter is applied to a series of equally spaced data values \( f_i = f(t_i) \), where \( t_i = t_0 + i\Delta \) for some constant sample spacing \( \Delta \) and \( i = \cdots, -2, -1, 0, 1, 2, \ldots \) as,

\[ g_i = \sum_{n=-n_L}^{n_R} c_n f_{i+n} \]  

(8)

A non-recursive or finite impulse response filter replaces each data value \( f_i \) by a linear combination \( g_i \) of itself and some number of nearby neighbors. The purpose of Savitzky-Golay filter is finding filter coefficients \( c_n \) that preserve higher moments. Equivalently, the idea is to approximate the underlying function within the moving window by a polynomial not by a constant order. For each point \( f_i \), a polynomial is least-square fitted to all \( n_L + n_R + 1 \) points in the moving window. The \( g_i \) is then set to be the value of that polynomial at position \( i \).

In case the underlying function is constant, or changing linearly with time (increasing or decreasing), no bias is introduced into the result. A bias is introduced, when the underlying function has a nonzero second derivative. For instance, the moving window averaging always reduces the function value at a local minimum value. But by using Savitzky-Golay filters, higher moments are preserved and no bias is introduced in such cases [6].

These least-squares fits are mathematically complicated, but fortunately the process of least-squares fitting involves only a linear matrix inversion and the coefficients of a fitted polynomial are themselves linear in the values of the data. Therefore, the fitting can be performed in advance, for fictitious data consisting of all zeros except for a single one. The fits can then be done on the real data just by taking linear combinations. Hence, there are particular sets of filter coefficients \( c_n \) for which Eq. 8 automatically accomplishes the process of polynomial least-squares fitting inside a moving window [6].
Sample preparation
Alloy steel 4140 (composition: 0.42% C, 0.75%Mn, 0.2%Si, 1.0%Cr, 0.25%Mo) is widely used in various industrial sectors. This type of steel is suitable for induction hardening [7]. A shaft with diameter of 50 mm and length of 350 mm was made from alloy steel 4140. The shaft underwent of normalizing process in order to make sure that the structure is homogeneous. Then it was induction hardened in a special oven. In case hardening process, the gained case depth could be controlled using some key physical and electromagnetic parameters of oven. The oven used in this process is a special furnace that uses some coils to produce electromagnetic fields around the part. Electromagnetic field of coil produces heat only on the surface of the part. Depth of induced heat and subsequent case depth could be controlled using variations in voltage, current, rate of heating and cooling the process. Since we needed a case depth profile, the process of induction hardening of shaft was performed in a way that case depth would vary through the length of the shaft. Induction hardened shaft is shown in Fig. 3. Immersion probe sweeps a straight longitudinal line on the surface of shaft and ultrasonic data are collected subsequently. The positional ultrasonic data are being processed using specific signal processing technique in order to calculate positional case depth. Owing to the symmetrical physical nature of induction hardening process, case depth in any imaginary sectional cuts of the shaft are the same. This is because the shaft is being rotated by the case hardening system and induced electromagnetic heat from the coil remains the same around the periphery of the cross-section at each point. Therefore, measuring case depth on only a straight line would show the case depth of the whole shaft and there is no need to sweep and scan total lateral surface of the hardened shaft.

Positional Case depth measurement
A special inspection system was constructed and used for conducting the measurements. The system includes an ultrasonic immersion testing tank and a three axis control systems to manipulate the immersion probe. A special holder was included in the tank for holding the shaft. This system is shown in Fig. 4. A typical signal obtained from the experiment is shown in Fig. 5a. Echoes A and B represent the surface and transition zone echoes, respectively. In Fig. 5a, the surface echo is considerably stronger (approximately 3 volts) than the transition zone echo (0.12 volts). This is because of the relatively rough surface finish of the specimen. To amplify the weak echo, the gain of the ultrasonic receiver unit was set to 40 dB. Figure 5b shows the same signal with different scales so that the oscillations in the two echoes can be clearly identified. To extract the envelope profile of the signal, a Hilbert transform was applied to the signal as shown in Fig. 6.

It can be observed that this envelop contains numerous intense oscillations. To remove these high frequency oscillations, we can use a low-pass filter which combines the moving average and Savitzky-Golay filter.
One advantage of the moving average filter is its ability to remove random noise and high frequency oscillations from the signal. One drawback is that by using this filter, the sharpness of the edges is also reduced; a phenomenon that can reduce the accuracy of measurements. To overcome this deficiency, the Šavitzky-Golay smoothing filter is used. As mentioned earlier, this filter fits a polynomial to the data and then assumes the value of the smoothed data to be equal to the value of the polynomial at any specific position of the signal. One of the most significant advantages of this filter is its ability of preserving sharp points as well as limiting the widths of oscillations. These features contribute to the preservation of the resolution of the smoothed data. Despite these advantageous features, the smoothing ability of this filter is less than the moving averaging technique.

![Figure 5: (a) A typical signal of case depth hardness measurement, (b) magnification of the transition zone.](image)

In the case of signals obtained from case depth measurements, the measurement should be done on highly smoothed envelops having high resolution. Accordingly, in this case, both filters are applied consecutively to the signal in order to benefit from their advantages. The Šavitzky-Golay smoothing filter is applied first and followed by the moving average technique. Figures 6b and 6c show the results of applying these filters to the signal envelop shown in Fig. 5a.

As shown in Fig. 6c, this process not only smoothes the signal considerably, but also preserves the maximum amplitude values of the original signal.

One of the advantages of ultrasonic backscatter technique is that the filters can be applied to all measured signals regardless of the hardness depth or surface roughness. As reported in the literature [2], for parts with shallow hardness depths and slightly rough surfaces, selective video filtering (moving average filter) causes the surface and transition zone echoes to fall so close to one another that the detection of transition zone echo is almost impossible. Consequently, the smoothing techniques would have only been used when the two echoes were not too close. This means that in the case of shallow hardness depths and slightly rough surfaces, no smoothing filter could have been used.

**B-scan image of the case-depth**

The ultrasonic immersion system was used for linear scanning of the surface of the shaft. The ultrasonic immersion probe was swept on the surface of the shaft along the axis. Ultrasonic signals containing the backscattered echoes from the surface and the transition zone were collected at 1 mm intervals. The A-scan signals were then combined in order to prepare a B-scan image of the case-depth profile. A-scan signal envelopes were smoothed first by Savitzky-Golay filter and then by the moving average filter. Fig. 7 shows the smoothed envelopes of longitudinal positions 50, 85, 90, 130 and 195 mm along the shaft, respectively.

Due to the noisy nature of ultrasonic backscatter data, some data points on the shaft were not usable. When the hardening process is continuous and no sudden jumps appear in the case-depth profile, it is easier to construct the B-scan image of the case-depth profile.
Figure 6: (a) Envelop of the signal shown in Fig. 5 obtained by using the Hilbert transform, (b) envelop obtained by applying the Savitzky-Golay smoothing filter to the signal shown in 6a, (c) envelop of the signal obtained by applying the moving average filter to the envelope shown in 6b.

Verification
To verify the accuracy of measurements, the shaft was split into two semi-cylindrical parts on the scanning line which was already marked. Since traditional cutting techniques can increase the surface temperature and change the case-depth profile, the shaft was cut using water jet technique. The shaft surface was then micro-etched so that the case-depth profile could be seen. The case-depth could then be easily measured on the etched surface. The micro-etched surface of the shaft is shown in Figs. 9 and 10. The case-depth profile measured on the surface was in good agreement with ultrasonic measurements. Table 2. shows case depth data measured by destructive and nondestructive ultrasonic backscatter methods. Correlation coefficient between the two data sets is 0.997 which indicates excellent agreement between the two measurements.

Conclusion
Ultrasonic backscattering is being used as a newly developed method for measuring the case depth of hardened components. Ultrasonic backscattering results obtained from a surface are highly noisy and calculation of case depth needs proper signal processing techniques. By using a signal processing method described in this paper, quick and accurate calculation of case depth of steel AISI 4140 was accomplished.

To measure the case depth profile of an induction hardened AISI 4140 shaft, a special immersion inspection system was constructed. A B-scan image was produced from the case depth of the shaft by scanning it along its axis.

By using a destructive measurement method, the actual case depth profile of shaft was also measured. Comparison between the profile obtained by destructive and nondestructive methods showed good correlation between the two. The correlation coefficient between the two sets of results was 0.997.
Figure 7: Smoothed envelopes of signals received from testing of each sample; (a) sample no. 1, (b) sample no. 2, (c) sample no. 3, (d) sample no. 4, (e) sample no. 5. All envelopes are smoothed first by Savitzky-Golay filter and then by the moving average filter.

Table 1: measured Case depth of shaft obtained from ultrasonic backscattering method

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Figure 8: case depth profile of AISI 1440 hardened shaft measured using ultrasonic backscatter technique
Figure 9: shaft after cut out process by using water jet cutting method
Figure 10: sectioning surface after grinding, polish and Micro-etch process.

Table 2: actual Case depth of shaft obtained from destructive measurement

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