# Application of harmonic analysis for determination of hardened depth in surface heat treated parts

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## Abstract :

Frequency domain evaluation of eddy current signals (harmonic analysis) in ferro-magnetic materials has been introduced in the last years as an industrial tool for materials characterization and proved to be a reliable and cost effective alternative to traditional techniques of quality control (metalography, mechanical tests, etc.). In the present study, identical rods of AISI 1045 mild carbon steel, case hardened using induction hardening method. Plotting hardness profile, effective and total case depths were also determined. In order to investigate the applicability of this nondestructive method, relations between case depths and calculated quantities of harmonic analysis on eddy current signals were studied. High correlation coefficients of these relations indicate an acceptable level of accuracy in comparison with destructive method.

## Keywords :

Harmonic analysis, case depth, induction hardening, mass production

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## ABSTRACT
**Frequency domain evaluation of eddy current signals (harmonic analysis) in ferro-magnetic materials has been introduced in the last years as an industrial tool for materials characterization and proved to be a reliable and cost effective alternative to traditional techniques of quality control (metalography, mechanical tests, etc.). In the present study, identical rods of AISI 1045 mild carbon steel, case hardened using induction hardening method. Plotting hardness profile, effective and total case depths were also determined. In order to investigate the applicability of this nondestructive method, relations between case depths and calculated quantities of harmonic analysis on eddy current signals were studied. High correlation coefficients of these relations indicate an acceptable level of accuracy in comparison with destructive method.**

## KEYWORDS:
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## 1. Introduction
In industrial applications, induction hardening is a common process which performed to improve wear and fatigue resistance of steel parts. In this surface hardening treatment, determination of hardened depth by plotting hardness profile is an important quality control factor.
There are two methods for measuring the thickness of hardened depth. First method is metallographic observation by optical microscope in which limited optical differentiation between martensite layer and ferrite-pearlite zone is the main disadvantage. Besides, this method cannot be used to determine effective case depths. The second method consists of establishing a micro-hardness profile in a cross section of the sample. Comparing to optical observation method, micro-hardness measurements are more accurate for the determination of effective and total case depths. Both of these methods are considered destructive, expensive and also time consuming. Furthermore, there is no chance to control all of the products in a mass production line by these methods.
Nowadays, using non destructive methods is not limited to detect cracks and defects and its application is extended to determine mechanical and metallurgical properties of materials in a fast and more economical manner. Eddy current is a non destructive technique which its high sensitivity to chemical composition, microstructure and mechanical properties makes is suitable for material characterization [1, 2].
Application of non destructive methods for measuring the hardened layer is important in quality control process. Recently, several research have been performed to investigate electromagnetic properties of induction hardened steels. By determining magnetic hysteresis parameters such as coercivity, remanence, hysteresis loss values and magnetic Barkhausen Noise effects [3-5] and also conductivity and permeability profiles in hardened steels [6], it was shown that there are differences between magnetic properties of hardened layer with the other parts of the

sample. Moreover, using eddy current technique, Zergoug et al have studied the relation between micro-hardness and changes in impedance plane [7].

In the above mentioned papers, the electromagnetic properties of induction hardened steel parts have been investigated, but the potential to determine case depth of these parts has not been explored nondestructively.

Another nondestructive evaluation method is Harmonic Analysis in ferro-magnetic materials. The method has recently been introduced as an industrial tool for materials characterization and proved to be a reliable and cost effective alternative to traditional techniques of quality control [8, 9].

The goal of the present study is to measure effective and total case depth of induction hardened steel parts using harmonic analysis on eddy current signals.

## 2- MATERIALS AND METHODS

Nine AISI 1045 steel rods (which chemical composition is given in table1) of 30mm diameter and 150mm length were prepared for the induction hardening process. For all samples the frequency and the power of induction hardening apparatus are fixed at 30kHz and 50kw, respectively. By changing the speed of the sample in the course of passing the induction coil, different case depths were produced. Eddy current outputs are affected by two important parameters: microstructure and residual stress. In order to eliminate produced residual stresses, after induction hardening treatment, all samples were heated in 250°C for two hours. Then, the case depths were determined using the hardness measurement method. Finally, the Eddy Current tests were performed on the cylindrical samples. A schematic diagram of the used Eddy Current system is shown in Fig. 1. The Eddy Current testing was performed at 27˚C with the fill factor of 0.98. The experimental eddy current apparatus provides a sinusoidal current with a frequency ranging from 10 to 100Hz. The output tension (voltage output) is recorded for these frequencies and then submitted to the Fast Fourier Transformation (FFT). The relations of calculated quantities of harmonic analysis and effective and total case depths have been investigated.

TABLE.1 CHEMICAL COMPOSITION OF STEEL

| | Element, wt.% | | | | |
|---|---|---|---|---|---|
| AISI | %C | %Si | %Mn | %P | %S |
| 1045 | 0.44 | 0.25 | 0.57 | 0.004 | 0.030 |

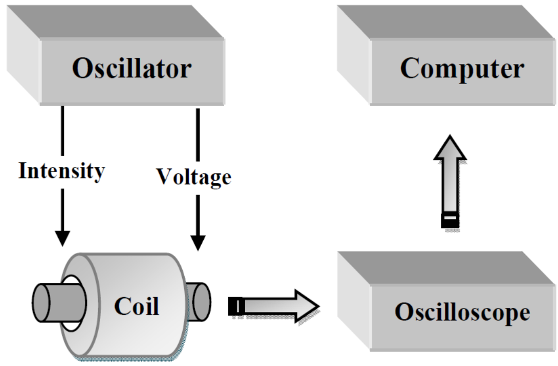


Figure 1: General synopsis of the experimental apparatus [10].

## 3- RESULTS AND DISUSSION

### 3-1- Hardness measurement for determination of case depth

Fig. 2 indicates optical microscopic image of a microstructure in a cross section of an induction hardened sample at the speed of 12mm/s passing through the coil. As it is shown, the hardened zone with a martensitic structure close to the surface is mainly darker than ferrite-pearlitic structure of the core that is not affected by heat treatment.

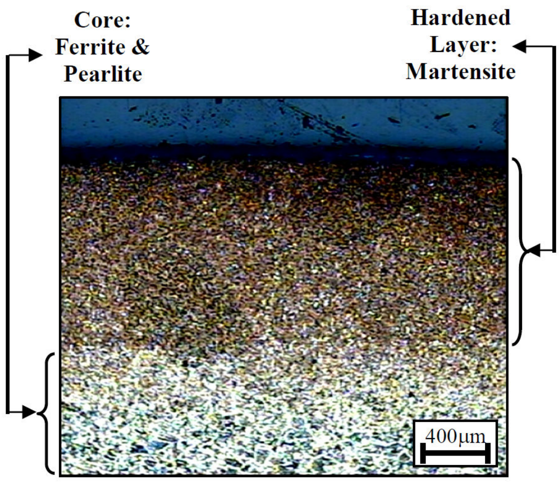


Figure 2: Optical microscopic image of a microstructure in a cross section of an induction hardened sample at speed of 12mm/s passing through the coil.

In this investigation, hardness in the martensitic and ferrite-pearlitic structure are in the range of 625-640 HV and 230-235HV, respectively. Therefore plotting hardness changes as a function of depth is a suitable destructive method to determine effective and total case depth of induction hardened samples. According to the International Standard ISO 3754, Effective Case Depth (ECD) definition is: the distance between the surface of the product and the layer where the Vickers hardness (HV) under a load of 9.8 N (1kgf) is equal to the value specified by the term "hardness limit". It is a function of the minimum surface hardness required for the part, given by the equation (1).

Hardness limit (HV) = 0.8 × minimum surface hardness (HV) (1)

Since in this study minimum surface hardness of all samples is about 625HV, so effective case depth is considered as perpendicular distance between the surface and the layer having a hardness of 500HV. On the other hand, the Total Case Depth (TCD) is defined as the distance from the surface to the limit beyond which the hardness of the unaffected zone of steel is reached.

In fig. 3, hardness profile of a part with maximum case depth which has been passed through the induction coil at the speed of 6.5mm/s, is shown. Effective and total case depths values of samples that are measured by plotting hardness profile are shown in table 2.

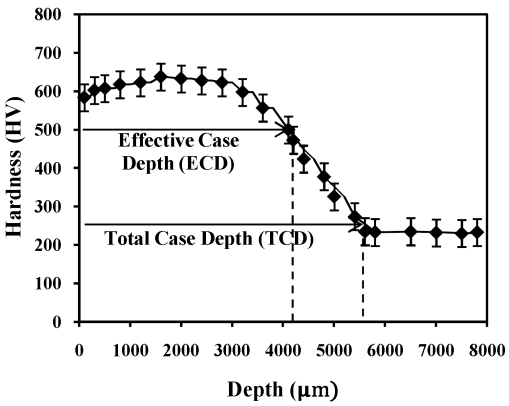


Figure 3: Hardness profile of two parts with maximum and minimum case depths.

## 3-2- Investigation of Harmonic analysis for different case depth hardened samples

In the present study, the harmonic analysis (Fast Fourier Transformation) is applied to induction hardened samples characterization to evaluate the technique performance in determining their microstructure changes from surface to the core. This analysis implies a magnetic-inductive method which determines electro-magnetic measurable values of decarburized steel which are closely connected to the micro structural characteristics of the material. The harmonic analysis of eddy current signals is based on the fact that a primary electro-magnetic field caused by a sending coil is influenced by a secondary electro-magnetic field in opposite direction. This phenomena result from the induction of eddy currents inside of the material and the magnetic behavior of the material. The variations in the magnetic properties influence the magnitude of the output signals.

The harmonic analysis of eddy current signals could be employed efficiently for the determination of case depth of steel parts due to different magnetic properties of hardened layer (martensite structure) and core of the sample (ferrite-pearlite structure).

To study the application of this nondestructive method for determining of case depth, harmonic analysis was applied on the eddy current output (voltage) and its obtained signals at the frequency of 25Hz. After calculating of real (Re) and imaginary (Im) parts of each harmonic, the relationships between these values of harmonics and ECD/TCD were investigated individually.

In the present research, only harmonics 3, 5 and 7 will be used to characterize the case depth. The values of imaginary and real parts are presented in table 3. The values of the imaginary and the real parts are plotted versus the effective and total case depth (Fig. 4).

TABLE.2 EFFECTIVE AND TOTAL CASE DEPTH ESTIMATED FROM HARDNESS MEASURMENT

| Sample | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| The speed of the sample in the course of passing the induction coil (mm/s) | 12 | 11 | 10.5 | 10 | 9 | 8 | 7.5 | 7 | 6.5 |
| ECD(mm) | 0.7 | 1.9 | 2 | 2.25 | 2.3 | 3.2 | 3.3 | 3.5 | 4.1 |
| TCD(mm) | 1.65 | 2.2 | 2.4 | 2.6 | 3.2 | 4 | 4 | 4.6 | 5.6 |

TABLE. 3 REAL AND IMAGINARY PARTS OF HARMONIC ANALYSIS ON EDDY CURRENT SIGNALS

| Sample | | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|---|
| Imaginary Part of the harmonic (in rad modulo 2π) | 3 | 4.29 | 3.6 | 3.03 | 6.03 | 7.51 | 8.57 | 9.3 | 9.99 | 9.62 |
| | 5 | 6.92 | 7.42 | 10.4 | 19.3 | 11.1 | 16.2 | 19.6 | 20 | 22.4 |
| | 7 | 9.78 | 13.4 | 16.7 | 21.7 | 18.7 | 28.4 | 31.2 | 28.8 | 35.5 |
| Real part of the harmonic (dB) | 3 | -3.51 | -3.2 | -4.77 | -12.8 | -7.37 | -21.1 | -31.3 | -27.3 | -41.2 |
| | 5 | -1.75 | -3.04 | -4.11 | -12.2 | -7.04 | -24 | -33.1 | -30.8 | -45.6 |
| | 7 | -0.29 | -2.77 | -5.72 | -12.3 | -7.46 | -23 | -34 | -30.8 | -45.4 |

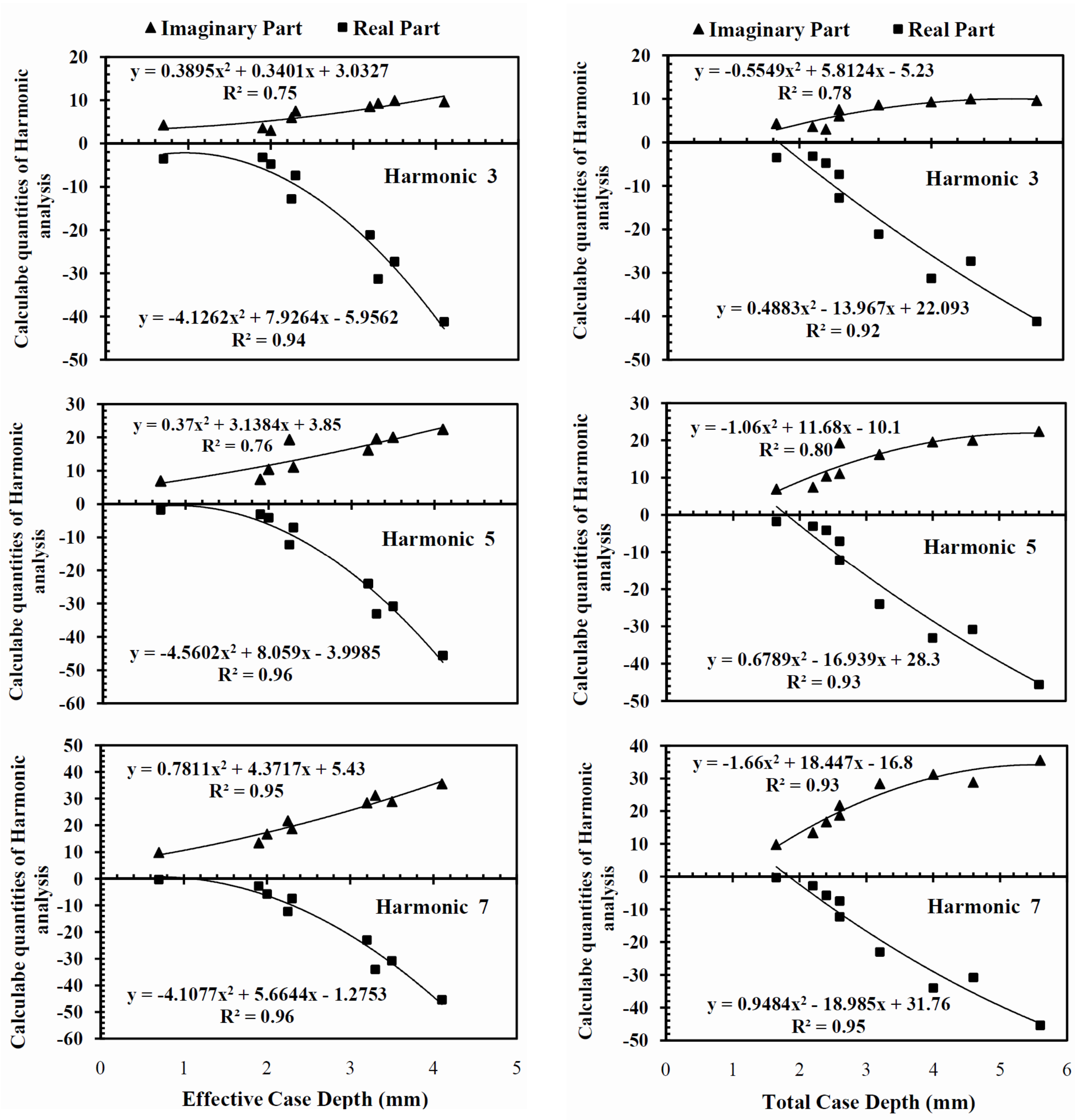


Figure 4: Relations between the real and imaginary parts of harmonic with the effective and total case depths.

As it is shown, the amplitude of the signals for imaginary parts increases with extent of the case depth while decreases for real parts of the harmonics.

Fig. 4 clearly shows correlation coefficients for relations of real parts and case depths are better than the results for imaginary parts.

We will study the possibility to obtain more information by using the values of the vector modulus (according to equation (2)) of the three harmonics separately.

TABLE. 4 VECTOR MODULUS OF HARMONIC ANALYSIS ON EDDY CURRENT SIGNALS

| Sample | | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|---|
| Vector modulus = Π | 3 | 5.55 | 4.82 | 5.66 | 14.1 | 10.5 | 22.8 | 32.7 | 29.1 | 42.3 |
| | 5 | 7.13 | 8.02 | 11.1 | 22.8 | 13.2 | 29 | 38.5 | 36.7 | 50.8 |
| | 7 | 9.78 | 13.7 | 17.6 | 25 | 20.1 | 36.6 | 46.2 | 42.2 | 57.6 |

$$\Pi = \sqrt{(\mathrm{Re})^2 + (\mathrm{Im})^2} \quad (2)$$

The values of the vector modulus are presented in table 4.

Fig. 5 shows this calculable parameter of the harmonics as a function of the effective and total case depths. The value of the vector modulus, which corresponds to the signal phase, is often used to verify the homogeneity of the experimental data. Besides, real and imaginary parts of the harmonics can be used to characterize the extent of case depth.

As it can be seen, the magnitude of the signals for the harmonic modulus increases with the extent of case depth. High correlation coefficients of these relations ($0.92< R^2 <0.96$) indicate high accuracy of this nondestructive method in determination of case depths.

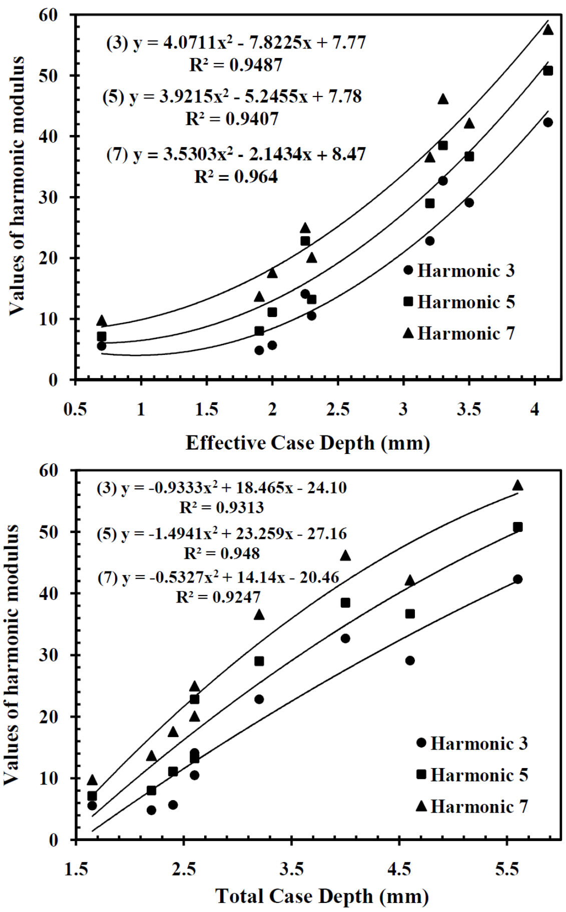


Figure 5: relations between values of the vector modulus with the effective and total case depths.

One important advantage of the automatic calibration method applied to the harmonic analysis of eddy current signals is the high calibration velocity which amounts to 1 minute. Another advantage of the system is the short measuring time using harmonic analysis for non-destructive testing. The determination of one characteristic value for material properties can be realized in less than 2 seconds. Therefore the presented measuring system is suitable for the employment in on-line inspection systems.

## 4- CONCLUSION

In the present paper on the base of magnetic property changes (due to the microstructure changes) eddy current signals can be used to detect this micro -structural variations.

Applying harmonic analysis on eddy current signals, the relations of harmonic parameters and effective and total case depth were investigated.

The harmonic analysis parameters measured in the sample were found to have a very good correlation with the destructive measurements of hardened depth in the same samples, showing reliable industrial applicability of the technique.

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