Nondestructive characterization of induction hardened cast iron parts

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Abstract :

Surface hardening is commonly applied to improve wear and fatigue properties of industrial parts. From practical point of view, determining the depth of hardened layer is important in quality control process which is traditionally performed by the time-consuming and costly destructive method of micro-hardness testing. Eddy current test is a non-destructive technique which can be performed rapidly. Since the electromagnetic responses are sensitive to chemical composition and the microstructure of the materials under investigation, it can be used to determine the depth of the hardened layer in steels and cast iron parts due to the difference in magnetic properties of the hardened layer in comparison with the core of the specimens. In the present study, identical rods of ductile cast iron were case hardened using induction hardening technique and by plotting hardness profile, case depths were determined. In order to investigate the applicability of the eddy current technique, relation between case depth and eddy current outputs (primary and secondary voltages as well as normalized impedance) were studied. High correlation coefficients of these relations indicate an acceptable level of accuracy in comparison with the destructive method.

Keywords :

Ductile cast iron, Induction hardening treatment, Case depth, Nondestructive evaluation

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ABSTRACT

In induction hardening treatment, determining the depth of hardened layer is important in quality control process which is traditionally performed by destructive micro-hardness testing. Since the electromagnetic properties of ferromagnetic metals are sensitive to chemical composition and microstructure, eddy current testing can be used to determine the depth of the hardened layer in steels and cast iron parts due to the difference in magnetic properties of the hardened layer in comparison with the core of the specimens. In the present study, identical rods of ductile cast iron were case hardened using induction hardening technique and by plotting hardness profile, case depths were determined. In order to investigate the applicability of the eddy current technique, relation between case depth and eddy current outputs (primary and secondary voltages as well as normalized impedance) were studied. High correlation coefficients of these relations indicate an acceptable level of accuracy in comparison with the destructive method.

KEYWORDS:

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1. Introduction

Induction hardening of cast iron steel parts improves the resistance to wear by changing the microstructure of the surface region. The required depth of the case hardened layer varies depending on the purpose for which the component is needed.

Monitoring case depth in cast iron induction hardened parts is critical for quality inspection of both new and remanufactured products.

Usually, case depth is determined by measuring micro hardness profile in randomly selected parts. Sample preparation includes cutting and polishing in the areas of measurements.

This method is time consuming and expensive. As a result it can be used on a small fraction of samples.

So a reliable non-destructive method is desired to improve efficiency of the measurements and monitor all the parts ran through the case hardening process.

Eddy current testing is a non-destructive method applied to electrically conductive materials. There are numerous advantages of this technique e.g. high sensitivity; rapid scanning, contact-less inspection, and its versatility contribute to its widespread utilizations. This technique can also be utilized for the evaluation of metallurgical variations in addition to defect detection [1].

This method works on the principle of Faraday's law. It measures changes in coil impedance in the same exciter coil or induced voltage in a separate coil. The excitation frequency is selected according to the inspection of the material. The coil impedance or induced voltage in the receiver coil changes when exciter coil is placed on different materials due to change in electrical resistivity and magnetic permeability of the material over which the coil is placed. The loci of induced voltage move downward when electrical resistivity of the material decreases and, on the contrary, these move upward when the permeability of the material increases [1].

Many researchers have investigated cast iron parts for characterization of microstructure.

For example, Konoplyuk could establish an appropriate relation between the hardness of ductile cast iron and the primary and secondary voltages of eddy current signals [2]. Uchimoto and Check [3, 4], found the same relation for gray cast iron and they could determine mechanical properties of cast ductile iron such as elongation and tensile strength using nondestructive eddy current method. Besides, different nondestructive methods have been investigated to measure hardness and case depth of steel parts, such as ultrasonic wave [5], Barkhausen noise measurement [6] magnetic hysteresis parameters [7] and eddy current [8]. But the potential of these nondestructive methods has not been explored for cast iron induction hardened parts. In this paper a relationship between the case depths of induction hardened cast iron parts and eddy current outputs (primary and secondary voltages, as well as normalized impedance) will be studied. Consequently we will examine the possibility to use eddy currents to measure precisely effective and total case depths after calibration.

2- MATERIALS AND METHODS

The present research was conducted on ten cylindrical samples of ductile cast iron (3.6%C, 2.09%Si, 0.63%Mn and 0.01%P) with the 35 mm diameter and 150 mm length.
Cast iron parts were prepared for the induction hardening process. For all samples the frequency and the power of induction hardening apparatus was fixed at 30 kHz and 50kw respectively. By changing the speed of the sample in the course of passing through the induction coil (5.5 to 11.5 mm/second) different case depths were produced. Since eddy current outputs are affected by two important parameters including microstructure and residual stress, all samples were tempered at 300°C for two hours (in order to eliminate produced residual stresses) after induction hardening treatment. Then specimens were cut from bars for initial metallographic and hardness measurement. The micro-hardness profile was measured with Vickers indenter on a Bohler micro-hardness tester. For each induction hardened sample, five indentations were performed using 25N load to a depth of 6 mm. Then according to the International Standard ISO 2639, case depths were measured. Table 1 collects the Effective Case Depth (ECD) and the Total Case Depth (TCD) obtained values for each of induction hardening treatment.
Finally Eddy Current tests were performed on the cylindrical samples. A schematic diagram of the Eddy Current system is shown in Fig. 1. The Eddy Current testing was performed at 27˚C with the fill factor of 0.98. Sinusoidal currents with frequencies from 10 to 100 Hz were applied to the coil for all samples. Primary and secondary voltages (Vx and Vy) and input currents were measured and the impedance of the coil was calculated. In order to obtain calculated parameter, voltage (V) and intensity (I) of the coil were used to calculate the impedance (Z) of the coil for all samples using equation (1) [9].

$$Z = V / I \qquad (1)$$

The calculated impedance (Z) for each sample was divided by the impedance of the empty coil (Z0) to make a new parameter. This parameter (Z/Z0) is called normalized impedance [10,11].

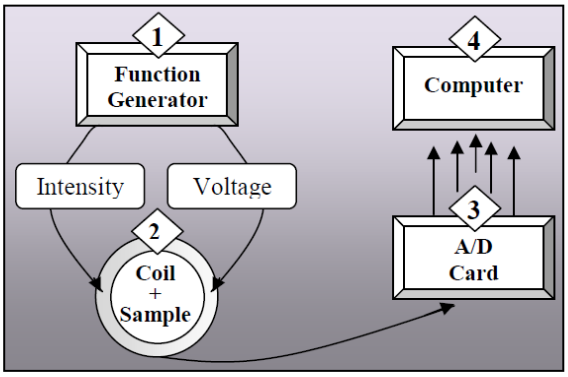

Fig. 1.General synopsis of the experimental apparatus.

TABLE 1. EFFECTIVE AND TOTAL CASE DEPTHS ESTIMATED FROM HARDNESS MEASUREMENT.

Sample number	1	2	3	4	5	6	7	8	9	10
ECD(mm)	2.10	2.450	2.70	2.85	3.30	3.50	3.80	5.20	5.00	5.8
TCD(mm)	2.90	3.50	3.50	3.65	4.60	4.30	4.40	6.10	6.00	6.75

3- RESULTS AND DISUSSION

Microscopic and macroscopic images obtained from the sample induction hardened at speed 5.5 mm/s are illustrated in Fig 2. As it is seen, surface layer (hardened area) microstructure is martensite which is distinct from ferrite-pearlite matrix at the core of the sample. In this study, hardness in the martensitic and ferrite-pearlitic structure is in the range of 620-670 HV and 235-265HV respectively. By plotting hardness, effective and total case depth of samples can be determined. But this method is considered destructive as well as time consuming and therefore cannot be carried out in mass production lines. Consequently there is a growing need for nondestructive inspection of induction hardened parts.

3-1- Eddy Current Technique

In order to measure the effective and total case depths (ECD and TCD) by eddy current method, we need the relation of experimentally obtained data with the optimum eddy current output at the optimum frequency.

In the present paper, optimum frequency [10, 11] has been chosen according to regression analysis performed on the relations between ECD/TCD values and eddy current outputs at frequencies in the range of 10 to 100Hz. Best of correlation coefficients are obtained at 25Hz, so it has been used as the optimum frequency in this study.

Figure 3 shows the relationships of eddy current outputs (primary and secondary voltages and normalized impedance) with ECD at 25Hz.

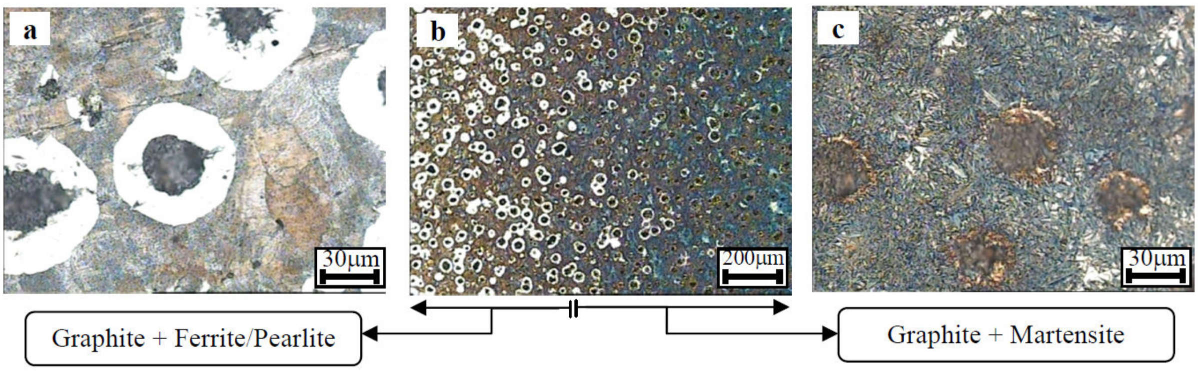

Figure 2: a) Microstructure of the core (ferrite-pearlite and graphite), b) The boundary between the hardened zone near the surface and the core of the material, c) Hardened layer (mirtensite and graphite).

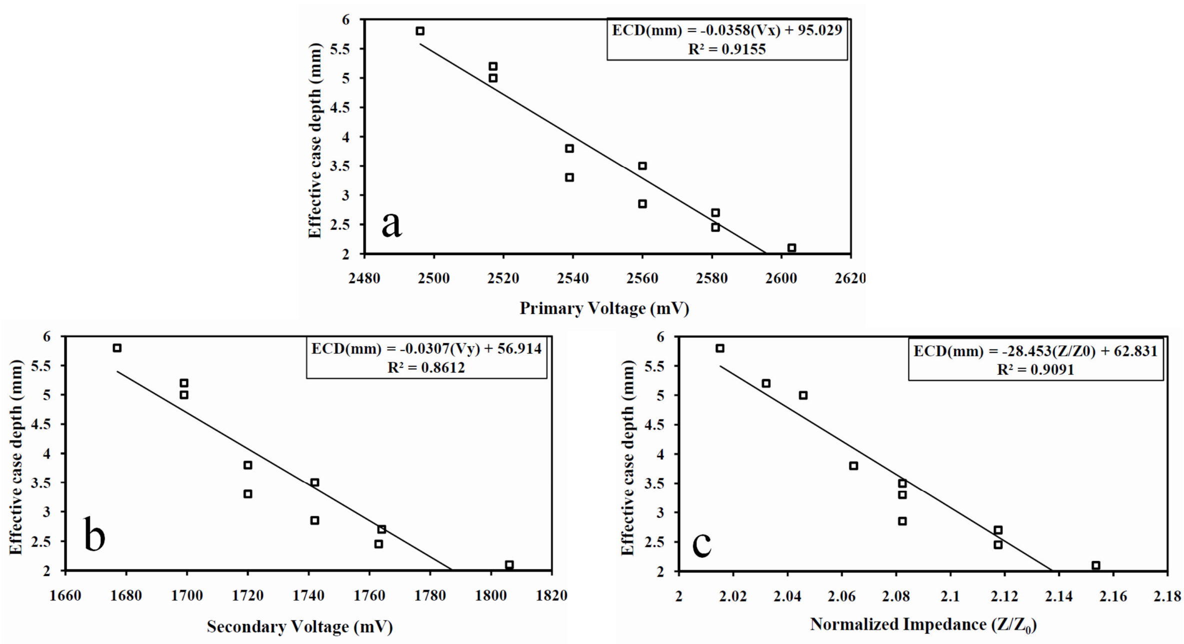

Figure 3: Relations between eddy current outputs and effective case depth of the samples.

As it is seen, the maximum correlation coefficients (R^2=0.91 and 0.90) are obtained for primary voltage and normalized impedance respectively. Therefore both primary voltage and normalized impedance were chosen as an optimum output with high accuracy.
In order to determine TCD, the relations between eddy current outputs and obtained values have been investigated. As it is shown in Fig. 4, the best correlation coefficient (R^2=0.93) is obtained for primary voltage.

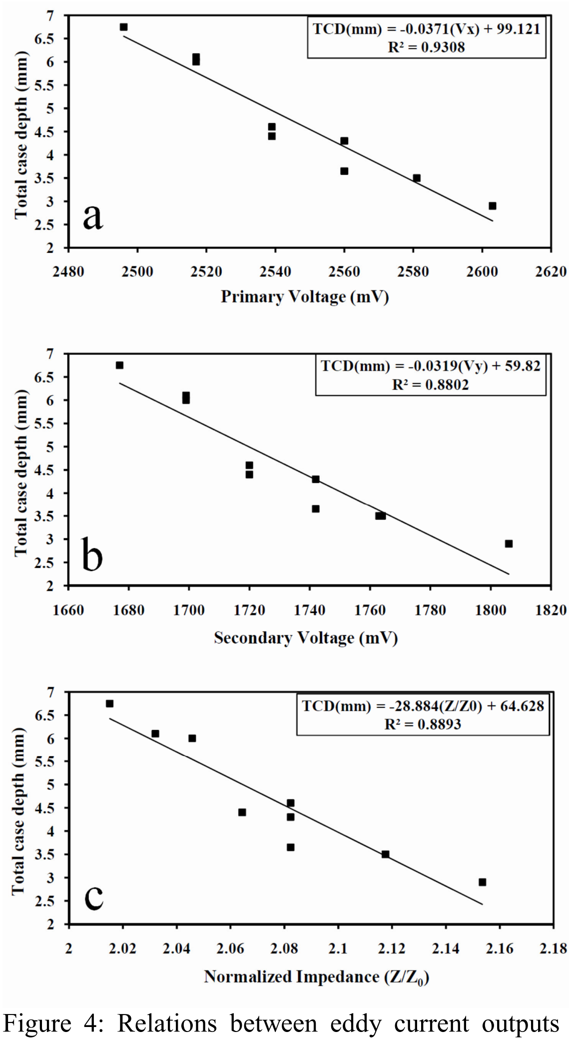

Figure 4: Relations between eddy current outputs and total case depth of the samples.

3-2- Microstructures and magnetic properties

As a result of martensitic formation in the hardened layer, high dislocation density due to the shear deformation of martensitic transition is produced. The microstructure have a high dislocation density plus high distortion due to the interstitial atoms embedding in crystallographic structure of martensite causes pinning of magnetic domain walls. This leads to less mobility of magnetic domain walls in martensite in comparison with ferrite-pearlite microstructure with lower dislocation density [7, 12]. So more magnetic field intensity (H) is required to overcome the obstacles against aligning the domains and thus according to (2), magnetic permeability (μ) decreases.

$$B=\mu.H \tag{2}$$

Therefore in all samples, by increasing the case depth and martensitic microstructure, μ decreases. This is the main reason for different eddy current responses of samples with various case depths.
Considering (3) and (4), it can be concluded that decreasing in μ results in decreasing of self-induction coefficient (L) and induction resistance (X_L)

$$L=\mu N^2 A/l \tag{3}$$

$$X_l=2\pi fL \tag{4}$$

Where μ is magnetic permeability; N, number of turns round the coil; A, cross section area and l, the coil length.
Since in ferromagnetic alloys (such as steel) the effect of permeability or reactance is stronger than the effect of resistance (R), impedance (Z) is decreased too (4).

$$Z=\sqrt{X_l^2 \quad R^2}=V/I \tag{5}$$

According to (5), the impedance decreases with increasing the hardened depth which indicates decreasing of output voltage of Eddy Current with increasing of hardened depth (Figures 3 and 4)

4- CONCLUSION

On the base of magnetic properties differences between martensitic (hardened layer) and ferrite-pearlitic microstructure (samples core), the eddy current method is capable to measure the effective and total case depth of induction hardened steel rods. In order to determine case depth, relations of obtained ECD/TCD values with eddy current outputs are investigated. High correlation coefficients of these relations show high accuracy of this method to determine ECD and TCD of induction hardened parts non-destructively.

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