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Hardness profile plotting using multi-frequency multi-output electromagnetic sensor

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ABSTRACT

Induction hardening technique was used to produce different case depths on nine AISI 1045 steel rods. Determining the optimum frequency for each depth below the surface, relations between eddy current outputs (primary and secondary voltages and normalized impedance) and hardness at each specific depth were investigated. Finally, the hardness values for each depth with the optimum eddy current output were determined and hardness profiles were plotted nondestructively. Comparisons were made with destructive hardness results.

1. Introduction

In industrial applications, induction hardening is a common process performed to improve wear and fatigue resistance of steel parts. In this surface hardening treatment, determination of the hardening depth by plotting the hardness profile is an important quality control factor.

There are two methods for measuring the thickness of the hardening depth. The first method is metallographic observation by use of an optical microscope in which the determination of the transition zone between the martensite layer and ferrite–pearlite zone is the main disadvantage. Besides, this method is destructively by nature cannot be used to determine effectively case depths. The second method consists of establishing a micro-hardness profile in a cross section of the sample and is also destructive. Comparing to the 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 the products in a mass production line by these methods.

Nowadays the use of nondestructive 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 examination is a nondestructive technique with a high sensitivity to chemical composition, microstructure and mechanical properties, which make it suitable for material characterization [1,2]. Indeed any changes in electromagnetic properties of materials such as electrical conductivity [3,4] and magnetic permeability [5] can be detected by this noncontact inspection method. There are advantages for eddy current sensors compared to the other inspection sensors such as capacitive or optical ones. Eddy current sensors are insensitive to dirt, dust, humidity, oil or dielectric material and can be employed in a wide range of temperatures. Therefore quality inspection can be shifted from off-line contact to on-line non-contact measurement using eddy current method [6]. The application of nondestructive methods for measuring the hardened layer thickness is important in the quality control process. Recently, several research projects have been performed to investigate electromagnetic properties of induction hardened steels. By determining magnetic hysteresis curve properties such as coercivity, remanence, hysteresis loss values and magnetic Barkhausen Noise effects [7–9] and also conductivity and permeability profiles in hardened steels [10], it was shown that there are differences between magnetic properties of hardened layer with other parts of the sample. In the above mentioned papers, the electromagnetic properties of induction hardened steel parts have been investigated, but the potential to plot hardness profile of the steels has not been explored nondestructively.

Moreover, using eddy current technique, Zergoug et al. [11] studied the relation between micro-hardness and changes in the impedance plane, and Hao et al. [5] investigated the micro-structural changes in decarburized steels using a multi-frequency electromagnetic sensor. Indeed the potential of plotting the hardness profile by the using an electromagnetic sensor in a multi-frequency approach and also the effect of hardness on the eddy current equipment

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outputs is understandable from their work. Thus in the present paper, hardness of different depths from the surface has been determined using a multi-frequency multi-output eddy current technique, which in turn could be used in determining the hardness profile of the samples nondestructively.

2. Experimental procedure

Nine AISI 1045 steel rods (0.45% C, 0.25% Si and 0.57% Mn) of 30 mm diameter and 150 mm length were prepared for the induction hardening process. For all samples the frequency and the power of induction hardening apparatus is fixed at 30 kHz and 50 kW, respectively. By changing the speed of the sample in the course of passing through the induction coil, different case depths were produced. Since the eddy current equipment outputs are affected by two important parameters including microstructure and residual stress [1–3], all samples were tempered at 250 °C for 2 h (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 25 N load to a depth of 6 mm. Then according to the International Standard ISO 3754, case depths were measured. Table 1 collects the effective and the total case depths obtained 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 30 to 3300 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. The impedance (Z) of the coil for all samples is given by [1]

$$Z = V/I \tag{1}$$

The calculated impedance (Z) for each sample was normalized to the impedance of the empty coil (Z_0) to obtain a new parameter. This parameter (Z/Z_0) is called normalized impedance [2,12].

3. Results and discussion

Microscopic and macroscopic images obtained from the sample induction hardened at speed 6.5 mm/s are illustrated in Fig. 2. As it is seen, the 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 structures is in the range of 625–640 and 230–235 HV, respectively. Therefore plotting hardness profile is a suitable destructive method to determine effective and total case depth of induction hardened samples but can be applied in a continuous production process only for statistical process control. Consequently there is a growing need for nondestructive inspection of induction hardened steels in mass production lines.

Applying the nondestructive eddy current method in order to determine hardness, the relations between hardness of a specified depth from the surface and eddy current equipment outputs were investigated. The induced eddy current penetration must be equal to the selected specified distance. So by using the well known equation for electromagnetic skin depth of a homogeneous magnetic field parallel to the surface as an approximation, the required frequencies for the evaluation of the penetration depths can be calculated. The results are presented in Table 2.

The depth at which the field drops to $1/e$ of the incident value is the skin depth (δ), which is given by

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{2}$$

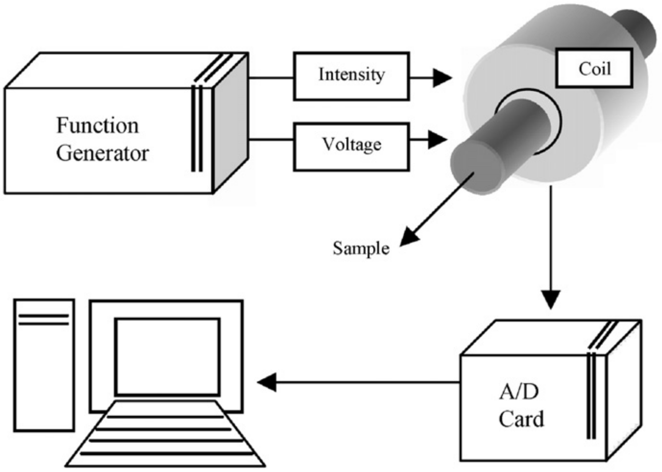

Fig. 1. General synopsis of the experimental apparatus.

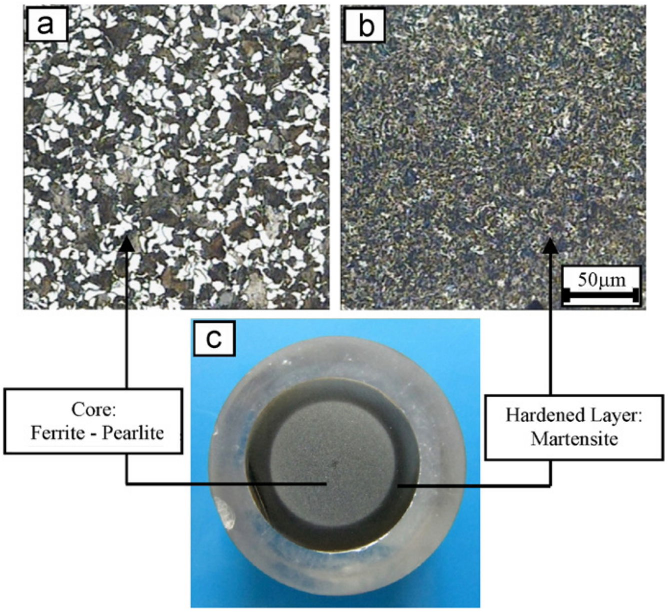

Fig. 2. (a) Microstructure of the core (ferrite–pearlite) (b) hardened layer (martensite) and (c) macro-etched image.

Table 1
Effective and total case depth estimated from hardness measurement.

Sample	1	2	3	4	5	6	7	8	9
Speed of passing through the induction coil (mm/s)	12	11	10.5	10	9	8	7.5	7	6.5
Effective case depth (mm)	0.7	1.9	2	2.25	2.3	3.2	3.3	3.5	4.1
Total case depth (mm)	1.65	2.2	2.4	2.6	3.2	4	4	4.6	5.6

Table 2
Required frequency for each specified distance.

Induced eddy current depth (mm)	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Calculated frequency (Hz)	3294	823	366	206	132	92	67	52	41	33

Table 3
Results of the regression analysis to relations between eddy current output voltages and hardness obtained from specified distances.

Depth	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
R^2 (Vx)	0.29	0.5	0.12	0.48	0.16	0.39	0.84	0.85	0.48	0.23
R^2 (Vy)	0.10	0.26	0.10	0.69	0.36	0.54	0.46	0.37	0.83	0.24
R^2 (Z/Z_0)	0.17	0.90	0.93	0.83	0.85	0.74	0.40	0.45	0.47	0.21

where δ is the eddy current penetration depth, f is the operating frequency, σ is the electrical conductivity, μ is the absolute magnetic permeability equal to $\mu_r\mu_0$ in which μ_0 is $4\pi\times10^{-7}$ Henry/m and μ_r is the relative magnetic permeability.

In this study, martensite electrical conductivity and relative magnetic permeability were considered $0.41\times10^7\,\Omega^{-1}\,\mathrm{m}^{-1}$ and 75, respectively [10].

The relations of primary and secondary voltages and normalized impedance with hardness of specified distances from the surface were investigated and the regression coefficients were calculated, which are mentioned in Table 3.

In each depth the output that has the highest correlation coefficient was considered as an optimum frequency.

As it can be seen, best of relations are obtained from normalized impedance for depths 1–3 mm, primary voltage for the depths 3.5–4 mm and secondary voltage for 4.5 mm depth. Fig. 3 illustrates the relation between hardness of specified distances and eddy current outputs at optimized outputs and frequencies. High regression coefficients obtained indicate the precision of the process.

The hardness directly depends on microstructure. As eddy current responses are also affected by microstructure [13], therefore, there is an indirect relation between eddy current outputs and hardness. Fig. 4 visualizes this relation.

Different hardness or better to say different microstructures (martensite, ferrite–pearlite and mix of them) and therefore different magnetic properties from surface to the core in induction hardened steel parts show the capability of the eddy current method to detect the hardness variation in each depth. In the surface layer, there is high density of dislocations caused by shear mechanism, which results from martensitic transformation. Presence of high density of dislocations in addition to distortion due to arrested interstitial atoms causes magnetic domain walls pinning [7,9]. Thus domain walls motion and aligning are restricted and this requires a higher reverse field to unpin domain walls and contributes to higher energy loss. As a result the coercivity and hysteresis loss increase while the permeability decreases [5,14]. These differences in magnetic properties are the main reason of different eddy current responses to the samples. As it is seen in Fig. 3, the hardness of each depth is proportional to the microstructure of that region.

As indicated in Eq. (2), change in the operating frequency has an inverse effect on the depth of the induced eddy current penetration (δ). Thus eddy current equipment outputs for each depth of the samples (in a fixed frequency) are affected by averaged electromagnetic properties of this layer (δ), which in turn is a function of the microstructure of the layer.

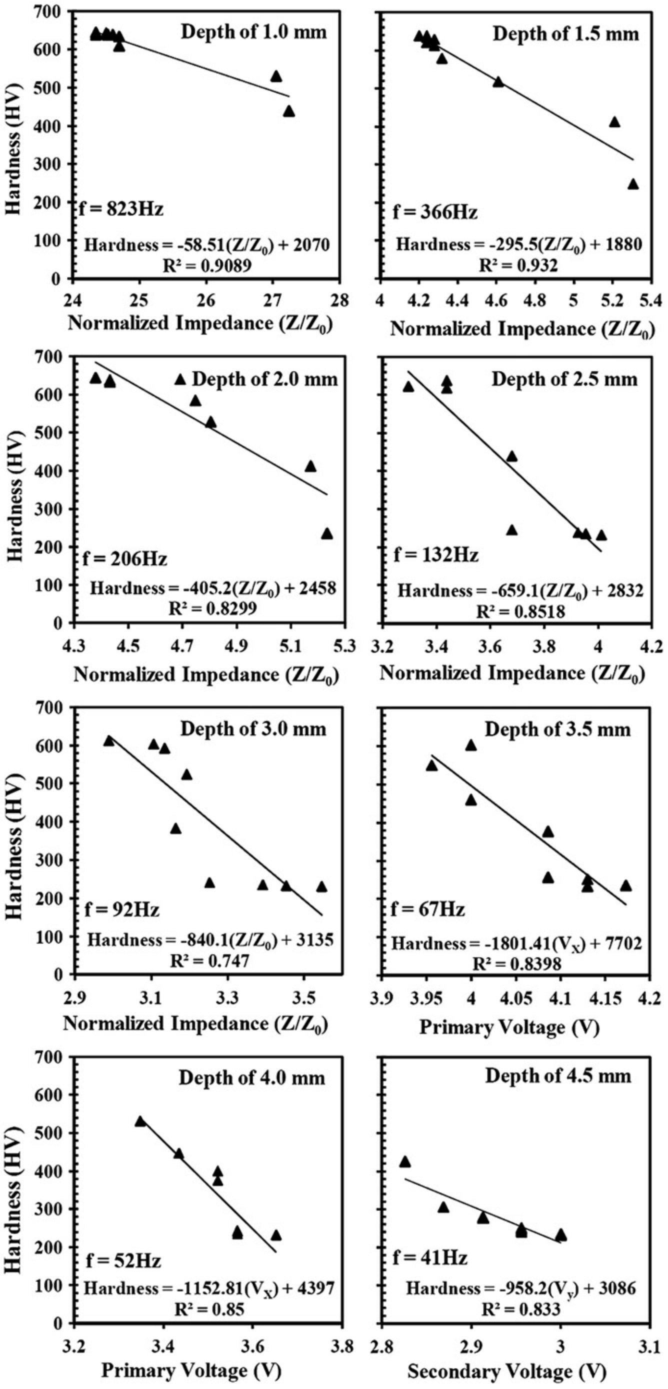

Fig. 3. Relation between the optimum eddy current outputs and the hardness of specified distances in the optimum frequencies.

In the case of the present study, the microstructure changes due to the increase in martensite content in a fixed penetration depth (δ), which results in a reduction in eddy current equipment output values (Vx, Vy and Z/Z_0) and, subsequently, an increase in the hardness.

For example hardness of a region with 3.5 mm distance from the surface is different for a specimen with total hardening depth

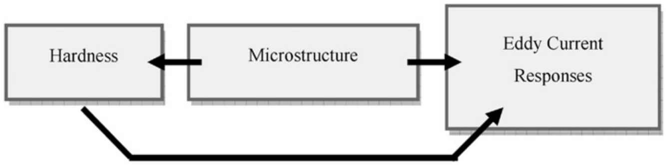

Fig. 4. Schematic diagram of effect of hardness and microstructure on eddy current responses.

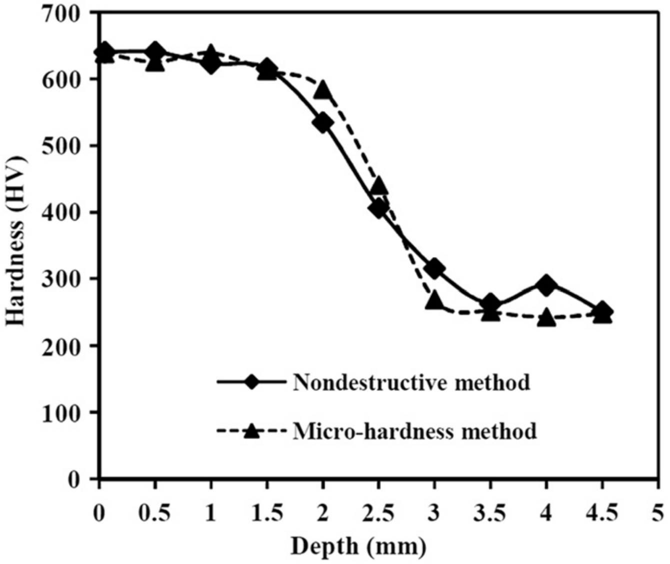

Fig. 5. Hardness profiles obtained by destructive and nondestructive methods.

of 3.2 mm (with ferrite–pearlite matrix) and a specimen with total hardening depth of 4 mm (with martensite matrix). Thus for those specimens of which the hardening depths increase, ferrite–pearlite microstructure changes to martensitic microstructure with lower magnetic permeability. Considering Eq. (3), it can be concluded that decrease in μ results in a decrease in self-induction coefficient (L).

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

where μ is the magnetic permeability, N is the number of turns round the coil, A is the cross section area and l is the coil length.

So, according to Eq. (4), by decreasing magnetic permeability (μ), induction resistance (X_l) is reduced and since in ferromagnetic alloys such as steel, the effect of permeability or reactance is stronger than the effect of resistance (R) [1,12], the impedance (Z) is decreased too (Eq. (5)).

$$X_l = 2\pi f L \tag{4}$$

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

According to Eq. (5), the impedance decreases with increase in hardening depth, which is a good reason to understand the decrease in the output voltage of eddy current equipment with the increase in the hardening depth (Fig. 3)

The next step is the hardness determination in different depths. To do this, using the obtained equation concerning the relation between the optimum eddy current equipment outputs and hardness values at the optimum frequency (equations in Fig. 3 for each depth), hardness can be determined subsequently. Finally, calculating the hardness of the samples in eight different depths (Fig. 3), the hardness profile can be plotted for all samples nondestructively. Fig. 5 comprises hardness profiles of sample 5, one obtained by micro-hardness testing and the other by nondestructive eddy current testing.

It is worth mentioning that in the present study hardness values related to depths less than 1 mm (martensite microstructure) and more than 4.5 mm (ferrite–pearlite microstructure at core) cannot be measured by eddy current testing .That is due to micro-structural similarities for all samples in these regions, which produce no differences in eddy current responses. Since the hardness values of these regions are nearly constant, the values obtained for 1 mm depth (full-matensite microstructure) are used as surface hardness of the sample.

4. Conclusion

By using the nondestructive eddy current method and according to the difference in the microstructures and hardness values of the samples with different hardening layer thicknesses, a linear relation between hardness values and eddy current equipment output voltages was obtained. Using an optimum frequency for each output voltage, hardness at specified distances from the surface was determined and the hardness profile was plotted. Good accordance between hardness profiles obtained by destructive and nondestructive methods confirms the preciosity of nondestructive method.

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References

[1] Bray Don E, Stanley Roderic K. Nondestructive evaluation: a tool design, manufacturing and service. Boca Raton, FL: CRC Press; 1997. p. 415.
[2] Hagemair Donald J. Fundamentals of eddy current testing. American Society for Nondestructive Testing; 1990.
[3] Abu-Nabah BA, Nagy PB. High-frequency eddy current conductivity spectroscopy for residual stress profiling in surface-treated nickel-base superalloys. NDT and E Int 2007;40(5):405–18.
[4] Morozov M, Tian GY, Withers PJ. Noncontact evaluation of the dependency of electrical conductivity on stress for various Al alloys as a function of plastic deformation and annealing. J Appl Phys 2010;108:024909.
[5] Hao XJ, Yin W, Strangwood M, Peyton AJ, Morris PF, Davis CL. Off-line measurement of decarburization of steels using a multifrequency electromagnetic sensor. Scr Mater 2008;58:1033–6.
[6] Tian GY, Zhao ZX, Baines RW. The research of inhomogeniety in eddy current sensors. Sens Actuators, A 1998;58:153–6.
[7] Zhang C, Bowler N, Lo C. Magnetic characterization of surface-hardened steel. J Magn Magn Mater 2009;321:3878–87.
[8] Zhu B, Johnson M, Jiles DC. Evaluation of wear-induced material loss in case-hardened steel using magnetic Barkhausen emission measurement. IEEE Trans Magn 2000;36:3602–4.
[9] Lo CCH, Kinser ER, Melikhov Y, Jiles DC. Magnetic nondestructive characterization of case depth in surface-hardened steel components. In: Thompson DO, Chimenti DE, editors. Review of progress in quantitative nondestructive evaluation 25B, AIP conference proceedings, vol. 820; 2006. p. 1253–60.
[10] Johnson M, Lo C, Hentscher S, Kinser E. Analysis of conductivity and permeability profiles in hardened steel. In: Udpa L, Bowler N, editors. Electromagnetic nondestructive evaluation (IX), IOS, Amsterdam; 2005. p. 135–42.
[11] Zergoug M, Lebaili S, Boudjellal H, Benchaala A. Relation between mechanical micro-hardness and impedance variations in eddy current testing. NDT&E Int 2004;37:65–72.
[12] Shull Peter J. Nondestructive evaluation: theory, techniques and applications. New York: Marcel Dekker, Inc;; 2002. p.279.
[13] Sheikhamiri M, Kashefi M. Application of eddy current nondestructive method for determination of surface carbon content in carburized steels. NDT and E Int 2009;42:618–21.
[14] Rumiche F, Indacochea JE, Wang ML. Assessment of the effect of microstructure on the magnetic behavior of structural carbon steels using an electromagnetic sensor. J Mater Eng Perform 2008;17:586–93.