RILEM Bookseries

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Nondestructive Testing of Materials and Structures

Proceedings of NDTMS-2011, Istanbul, Turkey, May 15–18, 2011

Part I

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Springer

Investigating Eddy Current Response to Microstructural Changes to Determine Case Depth of Induction Hardened Parts

S. Kahrobaee and M. Kashefi Torbati

Abstract The ability to characterize hardness profile in induction hardened steel part is important from quality inspection point of view. Traditional destructive methods such as plotting hardness profile are generally time-consuming. Besides, the tests can not provide 100% quality control in a mass production line. Eddy current response of steel is sensitive to changes in microstructure of the material under investigation. So, the non-destructive method can be used in determining the depth of the hardened layer in steel parts due to the change in the microstructure from the surface to the core of the hardened part. In the present study, induction hardening technique was used to produce different case hardened depths in identical rods of CK45 carbon steel. Plotting hardness profile, effective and total case depths were determined. In order to investigate the applicability of the eddy current technique, relation between effective and total case depth and eddy current outputs (such as primary and secondary voltages and normalized impedance) were studied. High correlation coefficients of these relations indicate an acceptable level of accuracy in comparison with destructive method.

Keywords Case depth • Eddy current • Hardness profile • Induction hardening • Magnetic properties

Introduction

The Standard methods for determining case depth of induction hardened parts can be devided into following methods. The first one consists of an optical observation of the microstructure in a cross section of a sample. The difference in core microstructure (ferrite-pearlitic) from the martensitic structure at the surface can be

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used to determine case depth. The second method consists in establishing a microhardness profile in a cross section of the sample after polishing. The two methods are destructive and need considerable preparation and so are time-consuming and costly. Considering the advantages of non destructive methods in industrial quality control, research are focused on Non-Destructive Evaluation (NDE) of the mechanical and physical properties of materials as a substitute to destructive method which, in return, provides 100% quality control in mass production lines. Among all nondestructive methods, Eddy Current is a technique which its high sensitivity to chemical composition, microstructure and mechanical properties makes is suitable for materials characterization [1, 2].

Recently, several research have been performed to investigate electromagnetic properties of induction hardened steels. By determining magnetic hysteresis loss values, magnetic Barkhausen Noise effects [3-5] and also electrical resistivity as well as magnetic permeability [6], it was concluded that there is a difference between magnetic properties of hardened layer with the other parts of the sample. This difference is a potential of eddy current method for case depth characterization of induction hardened steel parts. In the present study relations between the eddy current equipment outputs (include primary and secondary voltages and normalized impedance) and effective and total case depths have been investigated.

Experimental Process

Nine cylindrical AISI 1045 steel rods 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 througth the induction coil, different case depths were produced. In order to eliminate residual stresses resulting from induction hardening treatment, all samples were put in 250°C for two hours. 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 Figure 1. A sinusoidal current with a frequency ranging from 10 to 100Hz was applied to the coil for all

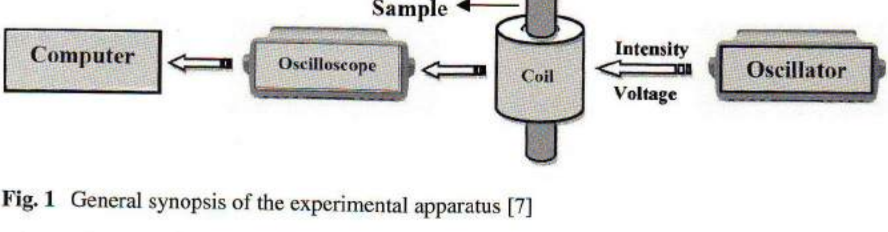

Fig. 1 General synopsis of the experimental apparatus [7]

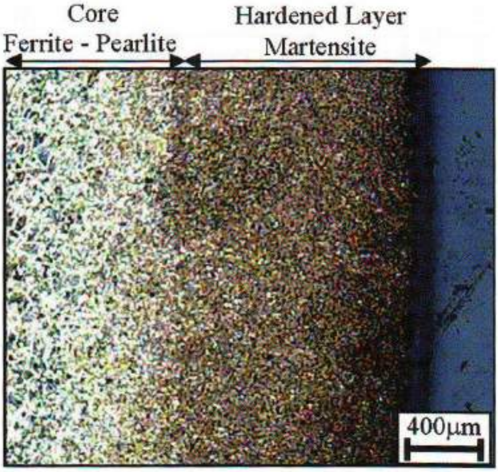

Fig. 2 Optical microscopic image of a microstructure in a cross section of an induction hardened sample at speed of 12mm/s passing through the induction coil

Table 1 Effective and Total Case Depth estimated from hardness measurment

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

samples. Primary and secondary voltages and input currents were measured and the impedance of the coil was calculated.

Figure 2 indicates optical microscopic image in a cross section of an induction hardened sample at the speed of 12mm/s passing through the induction coil. As it is shown, the hardened zone with a martensitic structure at the surface is mainly darker than ferrite-pearlitic structure of the core that is not affected by the heat treatment. Effective Case Depth (ECD) and Total Case Depth (TCD) values were measured according to the International Standard ISO 3754 (Table 1).

Results and discussion

The first step for evaluation of effective and total case depth (ECD and TCD) is determination of optimum frequency. In the present study, optimum frequency has been chosen by applied regression analysis between ECD/TCD and eddy current outputs [1,2] and relations between eddy current outputs and ECD/TCD in the range of 10 to 100Hz were investigated, separately. The best correlation coefficient between these parameters was obtained at 50Hz for ECD and 25Hz for TCD, respectively. As a result, 50 and 25Hz frequencies have been used to evaluate effective and total case depth using eddy current method.

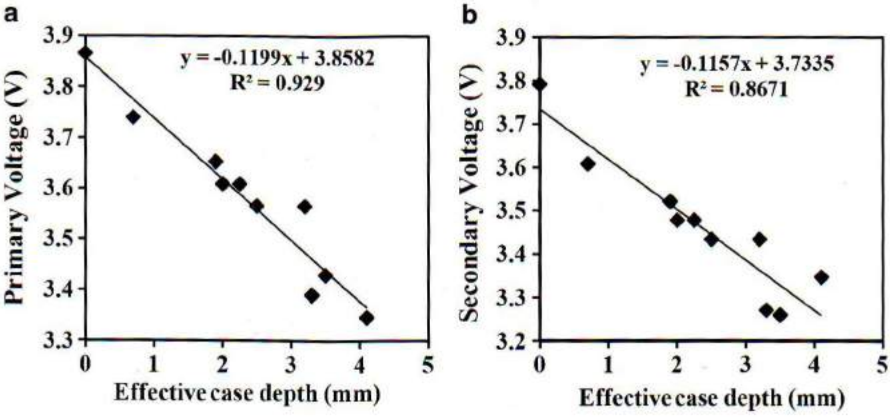

Fig. 3 Relation between ECD and **a**)Vx, **b**)Vy at 50Hz

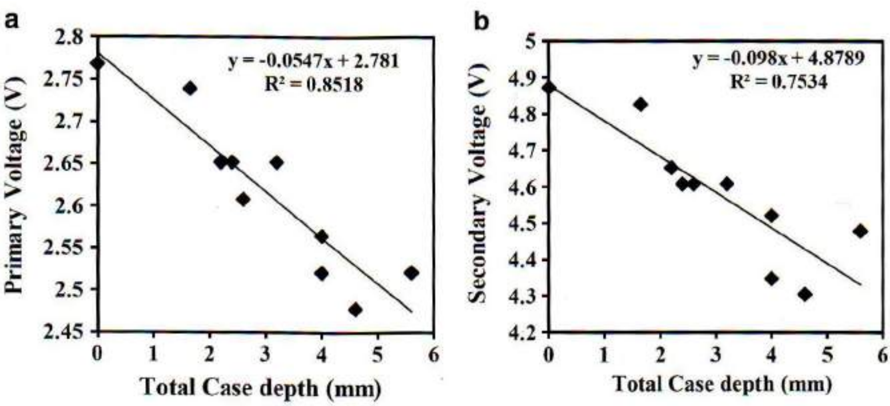

Fig. 4 Relation between TCD and **a**)Vx, **b**)Vy at 25Hz

The next step would be establish relations between effective/total case depths and eddy current equipment outputs. Figures 3 and 4 show the relationship between primary (Vx) and secondary voltage (Vy) with ECD and TCD at 50 and 25Hz frequencies. As can be seen, the maximum correlation cofficients that express the linear relationship were obtained for primary voltage. The R^2 for ECD and TCD were obtained to be 0.92 and 0.85 respectively. On the other hand, low obtained regression for secondary voltage demonstrate unreliable relationships in comparison with the primary voltage.

To find a better relationship, voltage (V) and intensity (I) of the coil were used to calculate the impedance (Z) of the coil for all samples using Eqn. (1) [1].

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

The calculated impedance (Z) for each sample was divided by the impedance of the empty coil (Z_0) to make a new parameter. This parameter (Z/Z_0) is called normalized impedance [1, 2, 8].

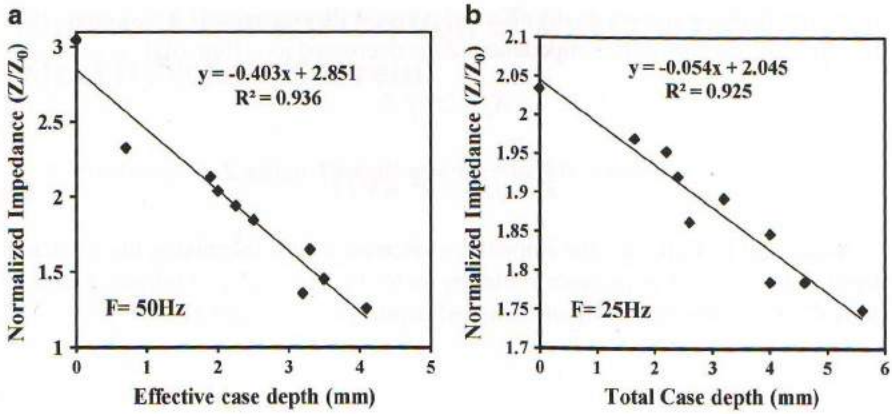

Fig. 5 Relation between normalized impedance(Z/Z_0) and **a**) ECD at 50 Hz, **b**) TCD at 25Hz

The relationship between ECD and TCD and normalized impedance (Z/Z_0)) is shown in Fig. 5. As it is seen, for determination of TCD, the best correlation coefficient was obtained for the normalized impedance ($R^2 = 0.92$) and for determination of ECD, maximum correlation coefficients were obtained for both the normalized impedance ($R^2 = 0.93$) and the primary voltage ($R^2 = 0.92$).

In the hardened layer, as a result of formation of martensitic microstructure, high dislocation density is produced due to the shear deformation of martensitic transition. This high dislocation density as well as high distortion due to the interstitial atoms embedding in crystal structure of martensite causes pinning of magnetic domain walls. As a result, less mobility of domain walls can be expected in comparison with ferrite-pearlite structure with lower dislocation density [3,5]. That is the reason that the demagnetization of martensite structure is more difficult than ferrite-pearlite one [9]. Thus, more magnetic field intensity (H) is required to overcome the obstacles against aligning the domains, and in return, more coercivity is needed. Therefore in all samples, by increasing the case depth, or in the other word martensite structure, coercivity and hysteresis loss increase and magnetic permeability (μ) decreases. These differences in magnetic properties are the main reasons for the difference in obtained responses of eddy current for samples with different case depths.

Considering Eqn. (2), it can be concluded that decreasing in μ results in decreasing of self-induction coefficient (L).

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

Where μ is magnetic permeability; N, number of turns round the coil; A, cross section area and l, the coil length. Finally, according to the Eqn. (3), by decreasing in magnetic permeability (μ), induction resistance (X_l) is decreased. 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 (Eqn. (4)).

$$X_l = 2\pi \ f L \tag{3}$$

$$Z = \sqrt{X_l^2 + R^2} = V / I \tag{4}$$

According to Eqn. (4), the impedance decreases with increasing the hardened depth. Decreasing of impedance is the key factor for decreasing of output voltage of Eddy Current with increasing of hardened depth (Figs. 3, 4 and 5).

Conclusion

Based on magnetic property differences between martensitic microstructure (hardened layer) and ferrite-pearlitic microstructure (core of the sample) the eddy current method is capable of measuring effective and total case depth of induction hardened steel rods. In order to determine ECD and TCD, relations between case depth and eddy current outputs were investigated. High correlation coefficient between these relations show high success of nondestructive Eddy Current technique in determining ECD and TCD of induction hardened steel parts.

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