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CAST IRON

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USE OF EDDY-CURRENT METHOD FOR DETERMINING THE THICKNESS OF INDUCTION-HARDENED LAYER IN CAST IRON

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Cast iron with globular graphite is studied after surface induction hardening. Hardness profiles of iron bars are plotted for determining the thickness of the hardened layer. Relations between the thickness of the hardened layer and the output voltage are obtained by the method of dual frequency (induced voltage and normalized impedance) for checking the applicability of the eddy current method. The correlation coefficient and the error of the evaluation of the thickness of the hardened layer are determined with the help of the relations obtained.

Key words: induction hardening, layer thickness, ductile cast iron, electromagnetic sensor.

INTRODUCTION

Induction hardening of parts from cast iron raises their wear resistance due to creation of a martensitic structure in the surface layer. The thickness of the hardened layer depends on the operating conditions of the parts, which makes determination of the thickness of the layer very important for control of the quality of ready products.

As a rule, the thickness of a hardened layer is determined by plotting hardness profiles of statistically selected parts. This is a time-consuming and expensive procedure applicable to only a limited number of test samples. This makes it necessary to create a reliable method of nondestructive control for efficient evaluation of the quality of any part subjected to surface hardening.

Nondestructive check methods (plotting of magnetic hysteresis curves, magnetic Barkhausen emission, ultrasonic and eddy-current methods) are used widely for analyzing changes in the microstructure of ferromagnetic alloys such as steel and cast iron. In the recent decade the eddy current (EC) technique has been used extensively in addition to detection of flaws. The EC method has many advantages such as a high sensitivity and rate of scanning, adaptability to various parts. For example, the authors of [1] have studied the variation of EC coil impedance in steel specimens subjected to various modes of heat treatment and determined the correlation between the impedance and the changes in the microstructure of the steels. In [2] the EC method is used for determining the content of pearlite in low- and high-carbon steels. In [3] a nondestructive EC check is used to control the quality of steel parts in large-scale production lines. These studies have shown that the mechanical characteristics and microstructure of steels and alloys can be evaluated without resorting to destructive testing.

In [4] an analysis of the microstructure of a core is followed by a study of the properties of hardened layer by nondestructive methods. The authors of [5] determine the relationships between magnetic properties and hardness profiles for a series of induction-hardened steel bars with different hardness of the layer. It is shown in these works that the changes in magnetic properties, such as the coercivity and the Barkhausen effect signal, agree well with the changes in the hardness. A multi-frequency variant of EC is used in [6] for determining the thickness of hardened layer in steels. The relationships between the hardness and the output eddy current signal are derived in this work by determining the optimum frequency and hardness for each layer thickness. Then a nondestructive technique is used to plot the hardness profiles.

Data on the relationships between eddy current parameters and mechanical properties are also available in the literature on cast iron. The authors of [7] give the relationship between the hardness of gray cast iron and the output eddy current signal. Work [8] presents the results of an EC technique evaluation of the hardness and mechanical properties of ma-

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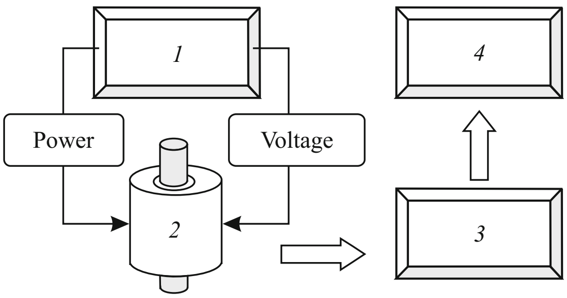

Fig. 1. Diagram of the experimental device: *1*) functional generator; *2*) coil with cylindrical specimen; *3*) memory map; *4*) computer.

terials tested for tensile properties. A good correlation is shown to exist between the output eddy current signal and the proportion of pearlite, the hardness and the strength.

The aim of the present work was to study the structure, hardness and magnetic characteristics of cast iron with globular graphite after induction hardening for determining the possibility of evaluation of the thickness of hardened layer with the help of the EC method.

METHODS OF STUDY

We subjected eight cylindrical specimens (35 mm in diameter and 150 mm long) of cast iron with globular graphite (3.6% C, 2.09% Si, 0.63% Mn) to induction hardening. In all the cases the induction hardening was performed at a frequency of 30 Hz and a power of 50 kW. Hardened layers with different thicknesses were obtained by varying the speed of the bars passed through the inductor (from 5.5 to 12.5 mm/sec). After the hardening, all the bars were tempered at 300°C for 2 h to eliminate residual stresses. Then the bars were cut to obtain specimens for a metallographic study and measurement of the hardness. The microhardness was measured using a Vickers indenter and a Bohler microhardness tester.

The diagram for measuring the eddy current signal is presented in Fig. 1. The eddy current tests were performed at 27°C with a fill factor of 0.98 and sinusoidal currents in the coil at a frequency of from 10 to 100 Hz. We measured the eddy current voltage (V) and the input current (I); the impedance (Z) of the coil was calculated from an equation [9, 10]

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

The calculated impedance Z of each bar was normalized for the impedance of an empty coil Z_0 to obtain a normalized impedance Z/Z_0 [11].

RESULTS AND DISCUSSION

Figure 2 presents the microstructure of cast iron after induction hardening at a speed of 5.5 mm/sec. The microstructure of the surface layer was represented by a mixture of martensite and graphite; that of the core was represented by a mixture of ferrite, pearlite and graphite. The profile of the microhardness was determined in a 8-mm-thick layer at a load of 9.8 N. The microhardness level for the martensite and ferrite-pearlite structures was 600 – 640 *HV* and 235 – 245 *HV*, respectively. The hardness profile was used to evaluate the effective and total thicknesses of the hardened layer.

In accordance with the ISO 2639 International Standard the effective thickness of a hardened layer (ETL) is the distance from the surface to the region with a microhardness of 550 *HV*, and the total thickness of the layer (TTL) is the distance from the surface to the point where the hardness corresponds to that of unhardened material. Figure 3 presents the hardness profile for a specimen passed through an induction coil at a speed of 8.5 mm/sec. The values of the ETL and TTL determined from the thickness profiles are presented in Table 1.

In the first stage of the study we computed optimum frequencies by two methods, i.e., (*1*) from the thickness of the electromagnetic skin layer and (*2*) with the help of regression analysis of the relationships between the ETL, TTL and the output eddy current signal.

In the first method the optimum frequency is determined approximately from the well-known equation for an electro-

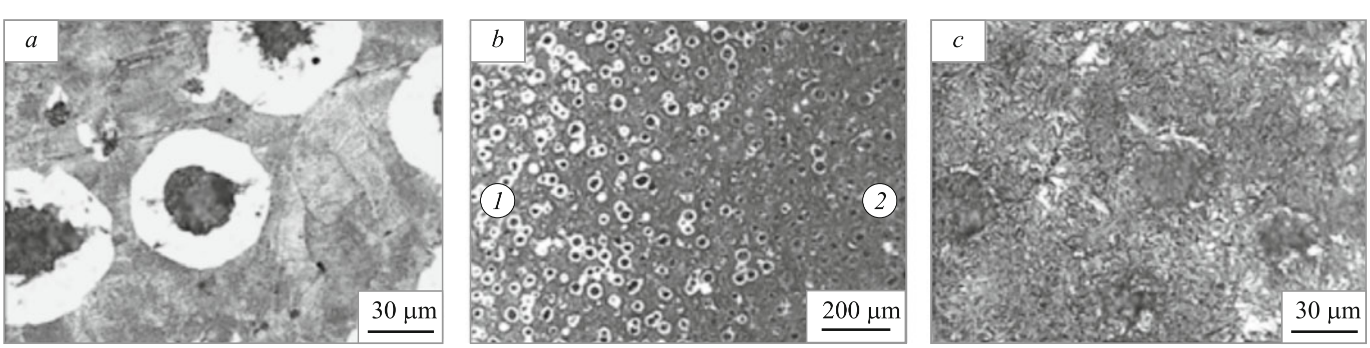

Fig. 2. Microstructure of cast iron after induction hardening at a speed of 5.5 mm/sec: *a*) core (ferrite, pearlite, graphite); *b*) transition layer between the core (*1*) and the hardened zone (*2*) near the surface; *c*) hardened layer (martensite and graphite).

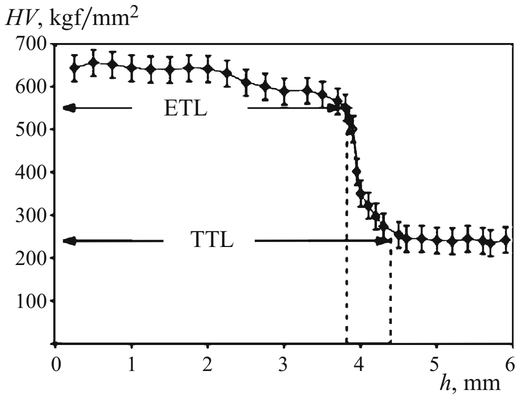

Fig. 3. Hardness profile (HV) of cast iron after induction hardening at a speed of 8.5 mm/sec (h is the distance from the surface): ETL) effective thickness of the layer; TTL) total thickness of the layer.

magnetic skin layer for the case of a homogeneous magnetic field directed in parallel to the surface, i.e.,

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

where δ is the depth of penetration of the eddy current, f is the operating frequency, σ is the electrical conductivity, and $\mu = \mu_r/\mu_0$ is the absolute magnetic permeability ($\mu_0 = 4\pi \times 10^{-7}$ V · sec/(A · m) and μ_r is the relative magnetic permeability).

At very low frequencies (when the thickness of the skin layer is much greater than the thickness of the hardened layer) the contribution of the hardened (martensite) layer into the value of the eddy current signal is very low as compared to the contribution of the core with ferrite-pearlite structure. On the other hand, if the thickness of the skin layer is little with respect to the thickness of the hardened layer (at high frequencies), the variation of the thickness of the hardened layer cannot be evaluated, because the signal corresponds to only a part of the hardened layer.

In our work we determined the following maximum values of layer thickness: ETL = 5.8 mm and TTL = 6.75 mm,

TABLE 1. Effective (ETL) and Total (TTL) Thicknesses of Hardened Layer According to the Measured Hardness Data

v,* mm/sec	ETL	TTL, mm
12.0	2.10	2.90
11.5	2.45	3.50
10.5	2.70	3.50
9.5	2.85	3.65
8.5	3.80	4.40
7.5	5.20	6.10
6.5	5.00	6.00
5.5	5.80	6.75

* Speed of passing through the induction coil.

i.e., the depth at which the current is induced in the sensor should be on the order of these values. Therefore, the changes in the hardness (in the microstructure) may be determined to this depth. Assuming that the layer has a relative magnetic permeability of 75 $\Omega^{-1} \cdot m^{-1}$ and a conductivity of $0.41 \times 10^7\ \Omega^{-1} \cdot m^{-1}$ we obtain a thickness of 5.8 mm for the skin layer at 24.49 Hz and 6.75 mm at 18.08 Hz, respectively. Such a thickness of the skin layer implies that the sensor current corresponds to the thicknesses of the ETL and TTL. Therefore, for all the tested specimens with ETL < 5.8 mm and TTL < 6.75 mm the induced current can be used for evaluating the thicknesses of the hardened layer.

We used the second method to determine the relationships between the ETL, TTL and the output eddy current signal (in the range from 10 to 100 Hz) individually for each specimen. The maximum values of the correlation coefficient were obtained at 25 Hz for the ETL and at 20 Hz for the TTL. Consequently, the frequencies of 25 and 20 Hz are optimum ones for determining the ETL and TTL by the method of dual frequency. The relationships between the output eddy current signal and the ETL and TTL at the optimum frequencies are presented in Fig. 4.

The maximum correlation coefficients for ETL and TTL and the output eddy current signal were $R^2 = 0.93$ and 0.91. Using the relationships obtained (Fig. 4) we determined the ETL and TTL for the optimum dual frequency. Figure 5 presents the values of ETL and TTL determined by the eddy current method and from the measured microhardness profiles for different speeds of motion of the specimens with respect to the inductor. It can be seen that the results obtained by the destructive and nondestructive methods agree well.

A martensitic structure is characterized by a high dislocation density and distortions caused by interstitial atoms, which is responsible for fixation of domain boundaries. Therefore, the mobility of domain walls in a martensite structure is lower than in a ferrite-pearlite structure [4, 5]. For this reason a higher magnetic field intensity is required for overcoming obstacles to the motion of domain boundaries in martensite. In its turn, this results in lowering of the magnetic permeability.

In all the specimens growth in the depth of hardening, i.e., in the thickness of the layer with a martensite structure, was accompanied by decrease in the permeability. This is the main cause of different eddy current signals from specimens with different depths of hardening.

Considering Eqs. (3) and (4) below we may conclude that decrease in magnetic permeability results in lowering of the coefficient of self-induction (L) and of the induction resistance (X_L), i.e.,

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

$$X_L = 2\pi f L, \tag{4}$$

where μ is the magnetic permeability, N is the number of turns in the coil, A is the cross sectional area of the coil, and l is the length of the coil. Since in ferromagnetic materials

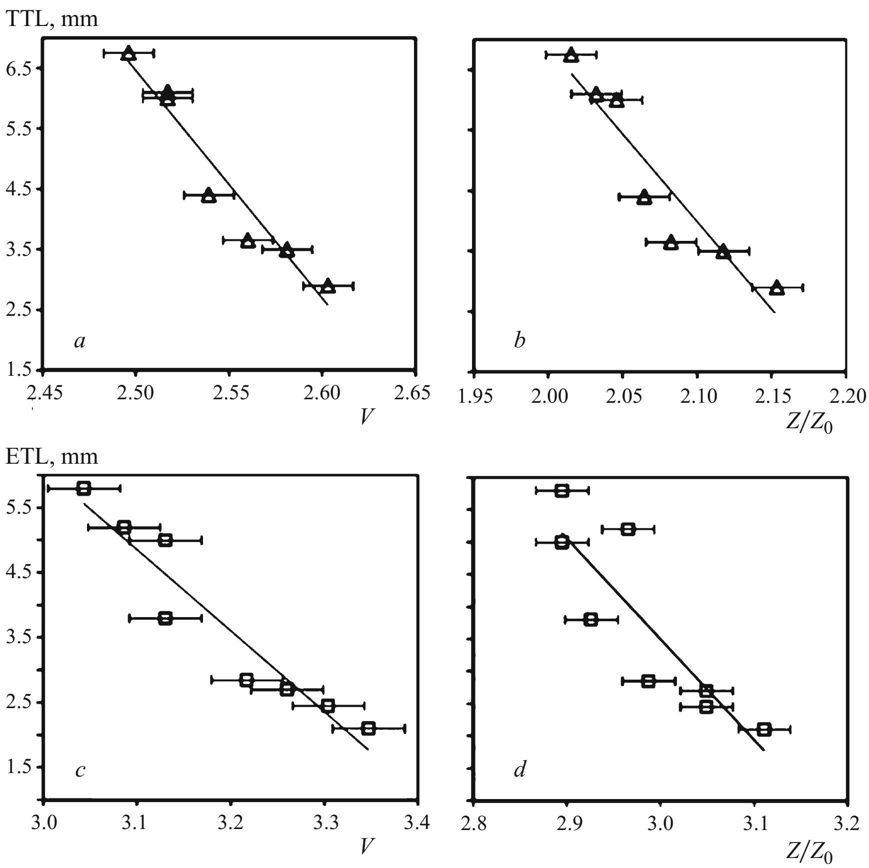

Fig. 4. Relationships between the eddy current signal *V*, the normalized impedance (Z/Z_0), and the effective (ETL) and total (TTL) thicknesses of hardened layer in cast iron: *a*) ETL = – 0.0371*V* + 99.121 (mm), $R^2 = 0.9308$, *f* = 20 Hz; *b*) TTL = – 28.88(Z/Z_0) + 64.628 (mm), $R^2 =$ 0.8893, *f* = 20 Hz; *c*) ETL = – 0.0125*V* + 43.57 (mm), $R^2 = 0.9108$, *f* = 25 Hz; *d*) RTL = – 15.6(Z/Z_0) + 50.287, $R^2 = 0.7582$, *f* = 25 Hz.

the effect of permeability or reactance is stronger than that of resistance (R), the impedance (Z) decreases too, i.e.,

$$Z = \sqrt{X_L^2 + R^2} = V/I. \quad (5)$$

The decrease in the impedance upon growth in the thickness of the hardened layer indicates decrease in the output eddy current signal (Fig. 5).

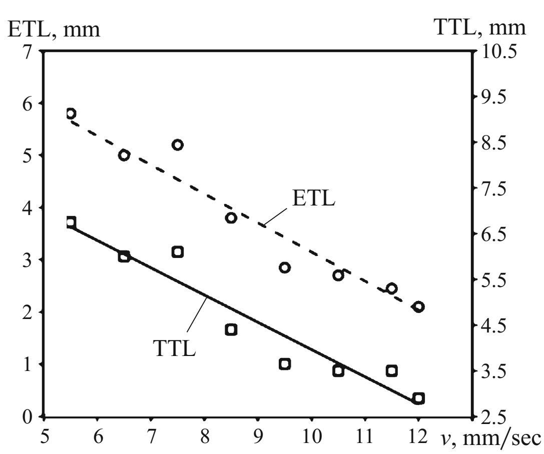

Fig. 5. Effective (ETL) and total (TTL) thicknesses of hardened layer in cast iron as a function of speed of motion of the specimen with respect to the inductor: symbols) experimental results; lines) design value.

CONCLUSIONS

1. The effective and total thicknesses of hardened layer of cast iron with globular graphite can be determined by the eddy current method due to the difference in the magnetic properties of the hardened martensite layer and of the ferrite-pearlite core.

2. Two optimum frequencies for eddy current control of the effective and total thicknesses of hardened layer in cast iron have been determined, i.e., 25 and 20 Hz respectively.

3. High values of correlation coefficients have been obtained for the output eddy current signal and the effective and total thicknesses of the hardened layer ($R^2 = 0.93$ and 0.91 respectively).

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