research note

Quantitative measuring of pearlite in carbon steels using electromagnetic sensor

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Abstract

Non-destructive Eddy current (EC) technique has long been used to detect discontinuities in materials. Recently, its application has been extended to characterize materials microstructure. In order to identify different microstructures, four plain carbon steel bars with different chemical compositions (AISI 1015, 1035, 1045 and 1080) were used in annealed condition. The pearlite percentage, carbon content and estimated hardness were determined according to responses of the samples to eddy current. They include primary and secondary voltages and normalized impedance. These data were compared with those obtained from conventional metallographic method and hardness measurements. The results show the high precision of the non-destructive eddy current method in determining the pearlite percentage, hardness and carbon content of mild carbon steels.

Keywords: Eddy current method, Materials characterization, Pearlite percentage, Hardness

1. Introduction

Nowadays, application of non destructive methods is not limited to detect defects and cracks. Considering the advantages of these methods in quality control, in recent years several researches have been focused on non-destructive determination of the mechanical and physical properties of materials as a substitution for destructive methods. This new application for traditional eddy current techniques results in saving time and energy as well as providing 100% quality control in mass production line[1].

Among different methods, eddy current technique has individual advantages. Proper sensitivity to chemical composition, microstructure, mechanical properties and residual stress make it a reliable alternative to conventional destructive methods[2,3].

Recently, Konoplyuk managed to establish an appropriate relationship between the hardness of ductile cast iron and the primary and secondary voltages of eddy current signals[4]. Uchimoto and Check[5,6], found the same relationship for gray cast iron, and they managed to determine mechanical properties of cast ductile iron such as elongation and tensile strength using nondestructive eddy current method. Besides, decarburizing depth was also studied using harmonic analysis in martensite base

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microstructure of steel parts by Mercier et al[7]. Indeed using this nondestructive method, they have shown decarburizing depth can be measured after calibration of the Eddy Current system. Furthermore, on the basis of difference in magnetic properties of decarburized zone and the core of the mild carbon steel parts, the thickness of decarburized layer has been estimated using multifrequency electromagnetic sensor[8]. More recently, Rumiche et al. have investigated the effect of microstructure on magnetic behavior of carbon steels by electromagnetic sensors[9], and the effect of grain size on magnetic properties was investigated and proved by other researchers[10-12].

The potential to determine measurable microstructure characteristics of steel parts has not been explored nondestructively. Therefore, the goal of the present study is to determine pearlite percentage, carbon content, hardness, and nondestructively according to magnetic responses of plain carbon steels to eddy current.

2. Experimental

For the purpose of determining the pearlite percentage in steel, four sample rods with 22mm diameter and 150mm length were prepared from four different kinds of steels (AISI 1015, AISI 1035, AISI 1045 and AISI 1080). Chemical compositions of steels are presented in Table 1. All samples were austenitized in 900°C for 30 minutes. Subsequently, all samples were cooled to ambient temperature resulting in equilibrium microstructures of pearlite and ferrite.

Phase fraction percentage and the hardness of the samples were measured by metallographic method (using Microstructure Image Processing (MIP)

software) and hardness destructive measurement method to compare with the obtained nondestructive values.

Finally, Eddy Current tests were performed on the cylindrical samples at different frequencies. A schematic diagram of the used Eddy Current system is

Table 1. Chemical composition of studied steels

Steel	%C	%Si	%Mn	%P
AISI 1015	0.13	0.26	0.53	0.03
AISI 1035	0.34	0.20	0.55	0.02
AISI 1045	0.48	0.30	0.57	0.013
AISI 1080	0.77	0.18	0.17	0.02

shown in Fig. 1. Eddy Current testing was performed at 27°C with the fill factor of 0.98. A sinusoidal current was applied to the coil for all samples, primary and secondary voltages (V_x and V_y) and input currents (I) were measured, and the impedance (Z) of the coil was calculated using equation (1) [1].

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

Calculated impedances of samples were divided by the impedance of the empty coil (Z0) to make a new parameter called normalized impedance (Z/Z0)[3, 13].
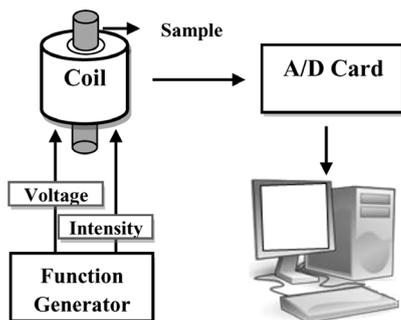

Fig. 1. General synopsis of the experimental apparatus.

3. Results and Discussion

Hughes [14] presents in detail the Eddy Current theory which can be summarized as follows. By passing an alternative current through a coil, fluctuating electromagnetic fields are created. When the sample is introduced into the coil, the electromagnetic fields induce eddy currents, which affect primary and secondary voltages of the coil. These induced variations depend on the Eddy Current magnitude, which in turn, is a function of electrical conductivity and magnetic permeability of the sample as well as test frequency and fill factor (distance between the coils and the sample).

The response of eddy current testing is affected by two major parameters. These two parameters are microstructure and residual stress[5, 6]. The residual stress was kept at a minimum and equal level using the same normalization heat treatment for all samples. Besides, since decarburization depth has an extreme effect on eddy current outputs, surface of all samples were machined to eliminate the decarburized layer. Thus,

the outputs are mainly affected by microstructure.

Fig. 2 shows microstructures of four different steels with different pearlite percentage after full annealing treatment. The percentage of pearlite and hardness of the samples are measured by optical observation (using MIP software) and hardness measurement respectively, which are presented in Table 2.
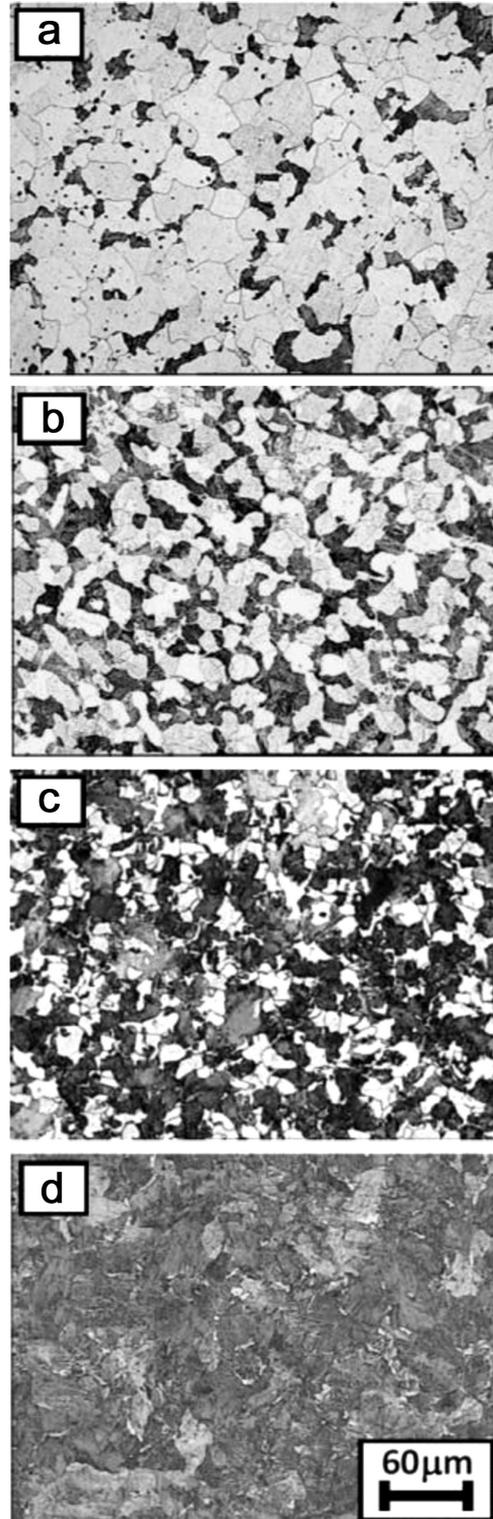

Fig. 2. Metallographic images of AISI a) 1015, b) 1035, c) 1045, d) 1080 steel after full annealing.

Table 2. The pearlite percentage and carbon content in the steel samples using MIP software and quantometery, respectively

steel	Percentage of carbon from analysis(%)	Percentage of pearlite by software(%)	Hardness (RB)
1015	0.13	20.23	65
1035	0.34	41.35	79
1045	0.48	64.97	85
1080	0.77	100	90

By means of regression analysis and by achieving correlation coefficient (R^2) for all tested frequencies, the frequency of 650 Hz was chosen as the optimum frequency.

The difference in eddy current response of dissimilar microstructures (caused by chemical composition or heat treatment) is as a result of difference in their magnetic properties.

In plain carbon steels, as the unequal carbon content is the main cause of difference in pearlite percentage (microstructure), direct relation between eddy current outputs and microstructure will lead to an indirect effect of chemical composition (carbon content) on eddy current outputs. Furthermore, micro-structural changes, or in other words changes in pearlite percentage have a direct effect on hardness of steel samples. As a result, there will be an indirect relation between hardness and eddy current response. Fig. 3 describes these relations.
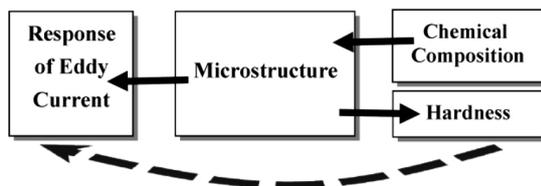

Fig. 3. Schematic relation between chemical composition, microstructure, hardness and eddy current response [15].

In Fig. 4, relations between eddy current outputs and pearlite percentage of steel are illustrated.

As can be seen, increase in pearlite percentage causes eddy current outputs (V_x, V_y, and $Z/Z0$) to decrease due to difference in their magnetic properties.

Regression analysis shows a high accuracy of these relations, particularly for normalized impedance. Thus, for pearlite percentage determination, normalized impedance is the optimum output because of the highest correlation coefficient of 0.99.
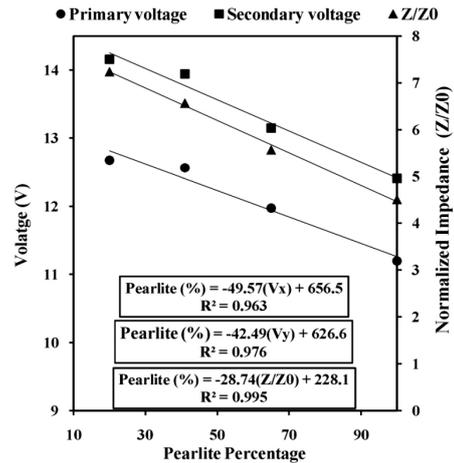

Fig 4. The relations between pearlite percentage and eddy current outputs at 650 Hz.

Besides, as is shown in Fig. 5, the same correlation between eddy current outputs and carbon content of the steels can be established. This is due to the direct relation between carbon content and pearlite percentage of steel samples. For these relations again normalized impedance is chosen as the optimum output because of the highest correlation coefficient ($R^2 = 0.98$) with respect to the other outputs.
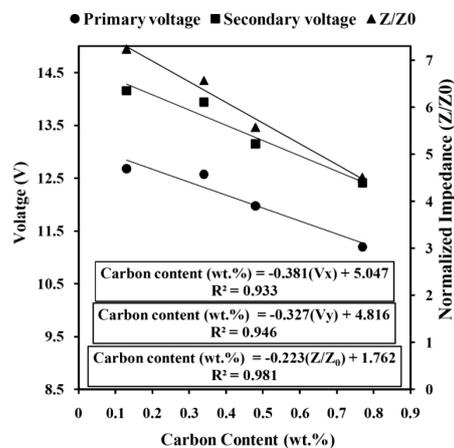

Fig 5. The relation between carbon content of steels and eddy current outputs at 650 Hz.

In the final stage of the current investigation, relations between hardness and the eddy current outputs are studied. These relations are shown in figure 6. As can be seen, the highest correlation coefficient of 0.87 for normalized impedance is a proof of the high ability of this nondestructive method to determine the hardness of steel samples. On the other hand, no suitable relation for primary and secondary voltages can be established. In summary, the results can be used to separate steels with different hardnesses due to different microstructures.
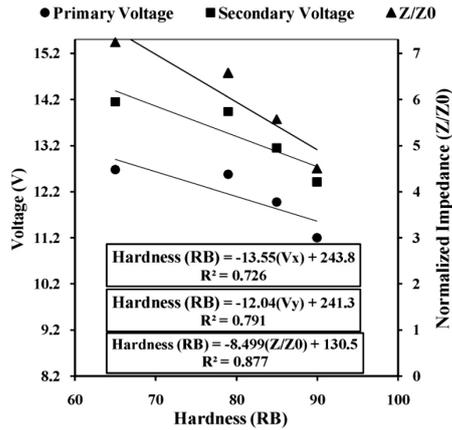
Fig 6. The relation between hardness of steels and eddy current outputs at 650 Hz.

Several researches have been performed to investigate the relationship between magnetic hysteresis curve parameters and microstructure of steels [9]. The results indicate that an increase in pearlite content of steel causes a coercivity (Hc) increase, and Saturated Magnetic Flux (Bs) decreases.

The main effect of increasing pearlite percentage in the microstructure is increasing in magnetic hysteresis loss because of: 1-increasing carbide layers and 2-increasing grain boundaries (due to barrier formation between ferrite and cementite in pearlite lamellar structure). Both of these parameters act as barrier locks and prevent magnetic domains aligning. Therefore, more magnetic field intensity (H) is required to overcome the obstacles against aligning the domains, and therefore more coercivity is needed. Indeed, in all samples, by increasing pearlite percentage and hardness, hysteresis loss will increase and magnetic permeability will decrease. So, considering equation (2), it can be concluded that a decrease in μ results in decrease in self-induction coefficient (L).

$$L = \mu N^2 A / l \qquad (2)$$

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

As a result, according to the following equations, by decreasing the magnetic permeability (μ), induction resistance (X_L) is decreased. Besides, since in ferromagnetic alloys such as steel, the effect of permeability or reactance is much stronger than that of resistance, impedance (Z) is also decreased.

$$XL = 2\pi fL \qquad (3)$$

$$Z = \sqrt{X_L^2 + R^2} = V / I \qquad (4)$$

According to equation (4), the impedance decreases with a increase in the pearlite percentage, hardness and carbon content. The reduction of impedance is a good reason for decreasing the voltage output of eddy current with an increase in the pearlite percentage, hardness and carbon content (Figs. 4, 5 and 6).

4. Conclusion

In the present study, eddy current method was used to determine the pearlite percentage, carbon content and the hardness of steel samples. It was shown that measured (primary and secondary voltages) and calculated (normalized impedance) parameters have good relationship with mentioned micro-structural characteristics. For all samples, the measured and calculated parameters decreased with increasing pearlite percentage, hardness and carbon content. The best relation between the micro-structural characteristics of the samples and eddy current response of the samples can be established using normalized impedance.

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