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On the Relationship of Magnetic Response to Microstructure in Cast Iron and Steel Parts

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Nondestructive eddy current technique has long been used to detect discontinuities in materials. However, recently, its application has been extended to characterize materials' microstructure and properties. In the present article, four mild carbon steel bars with different chemical compositions (AISI 1015, 1035, 1045, and 1080) were obtained in annealed condition. Besides, to determine the effect of microstructure, six ductile cast iron bars with the same chemical composition and different pearlite contents were prepared. The pearlite percentage and estimated hardness values were determined by eddy current nondestructive technique, and the results were compared with the data obtained from conventional metallographic and hardness testing methods. The results indicate that the eddy current is a sensitive comparative technique to detect the microstructure (directly) as well as the mechanical (indirectly) changes of mild carbon steel and ductile cast iron parts.

Keywords ductile cast iron, eddy current method, microstructure evaluation, mild carbon steel, normalized impedance

1. Introduction

Nowadays, application of nondestructive methods is not limited to detect defects and cracks.

Considering the advantages of nondestructive testing (NDT) methods in industrial quality control, in recent years, several studies have explored the use of NDT techniques to determine the mechanical and physical properties of materials as a means to save time and energy while providing full-scale quality control in production.

Among different NDT methods, the eddy current technique has advantages, such as high sensitivity to chemical composition, microstructure, mechanical properties, and residual stresses, thus making it a reliable alternative to conventional destructive methods (Ref 1, 2).

Sheikh Amiri (Ref 3) has studied the effect of surface carbon content of carburized steel on location of impedance point on Impedance Plane using eddy current method. Rumiche et al. (Ref 4) have investigated the effect of microstructure on the magnetic behavior of carbon steels by electromagnetic sensors, and the effect of grain size on magnetic properties has been investigated and proved by other researchers (Ref 5-7).

Recently, Konoplyuk et al. (Ref 8) have studied relation between the hardness of ductile cast iron and the output voltage of eddy current device. Uchimoto and Čech (Ref 9, 10), have found the same relation for gray cast iron. The depth of decarburized layer has been studied using harmonic analysis (Ref 11) and on the basis of differences in magnetic properties (magnetic relative permeability) of ferrite and pearlite (Ref 12).

The aim of the present study is to demonstrate a methodology to nondestructively determine percentages of pearlite and carbon, and hardness of steel and cast iron samples from an analysis of their magnetic response.

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2. Experimental Procedure

To determine the pearlite percentage, four cylindrical samples with 22-mm diameter and 150-mm length were prepared from four different steels (AISI 1015, 1035, 1045, and 1080). The chemical compositions of the samples are presented in Table 1. All the samples were austenitized at 900 °C for 30 min followed by subsequent cooling to ambient temperature, which yielded equilibrium ferrite-pearlite microstructures. Figure 1 shows the microstructures of the steel samples.

In addition to these samples, six cylindrical samples of ductile cast iron were also prepared. These samples had a diameter of 35 mm and were 150 mm long. The chemical compositions of the samples (presented in Table 1) were kept constant. All the cast iron samples were austenitized at 900 °C for 80 min and then cooled rapidly to 670 °C with a cooling rate of 55 °C min^{-1}, which resulted in a fully pearlitic microstructure. Subsequently, in order to obtain different ferrite-pearlite fractions in the ferritization process, the samples were heated up to 730 °C and kept at the temperature for different time periods. The pearlite fractions of all the samples were measured using optical microscopy as well as Microstructure Image Processing (MIP) software. By using the lever rule, the measured pearlite fractions of the steel samples were compared with the values predicted by the phase diagram (Ref 13) and are displayed in Table 2. The microstructure of the heat-treated ductile cast iron samples, and their estimated pearlite percentages are depicted in Fig. 2. After the heat-treatment processes, the surfaces of the samples were machined to eliminate the decarburized layer.

The hardness values of the cast iron and steel samples were measured using conventional methods (Brinell and Rockwell B, respectively) to compare with values obtained from the NDT method.

Finally, the eddy current tests were carried out at different frequencies with the eddy current system shown in Fig. 3. The primary and secondary voltages (*V*) and input electrical current (*I*) were measured and the impedance of the coil (*Z*) was calculated using Eq 1 (Ref 1).

$$Z = V/I \quad \text{(Eq 1)}$$

Table 1 Chemical composition of studied steels and ductile cast iron

Sample	%C	%Si	%Mn	%P
Steel AISI 1015	0.13	0.26	0.53	0.03
Steel AISI 1035	0.34	0.2	0.55	0.02
Steel AISI 1045	0.48	0.3	0.57	0.013
Steel AISI 1080	0.77	0.18	0.17	0.02
Ductile cast iron	3.6	2.09	0.63	0.01

The calculated impedance for each sample was divided by the impedance of the empty coil (Z_0) to obtain a ratio denoted as normalized impedance (Z/Z_0) (Ref 2, 14).

The magnetic field strength (*H*) can be calculated using the well-known equation:

$$H = NI/l \quad \text{(Eq 2)}$$

where N is the number of loops in the coil, l is the coil length, and I is the input electrical current in ampere. In the present article, N, l, and the maximum value of the current for I are 500, 0.12 m, and 0.21 A, respectively. As a result, the maximum magnetic field strength can be calculated as 875 A m^{-1}.

Table 2 The calculated and measured pearlite percentages in steel samples using lever law and MIP software, respectively

	Percentage of pearlite	
Steel	Lever law	MIP software
1015	16.9	20.23
1035	44.6	41.35
1045	63.06	64.97
1080	100	98

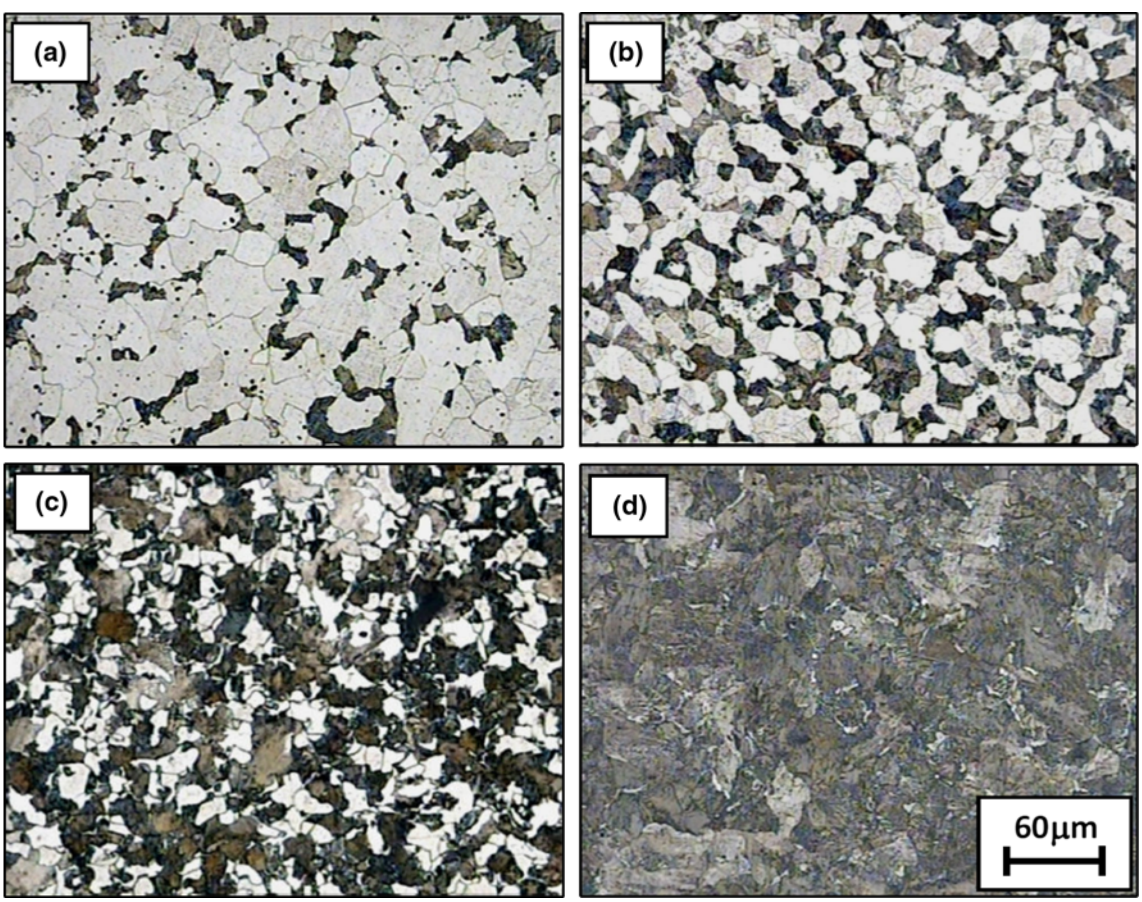

Fig. 1 Metallographic images of AISI: (a) 1015, (b) 1035, (c) 1045, and (d) 1080 steel after full annealing

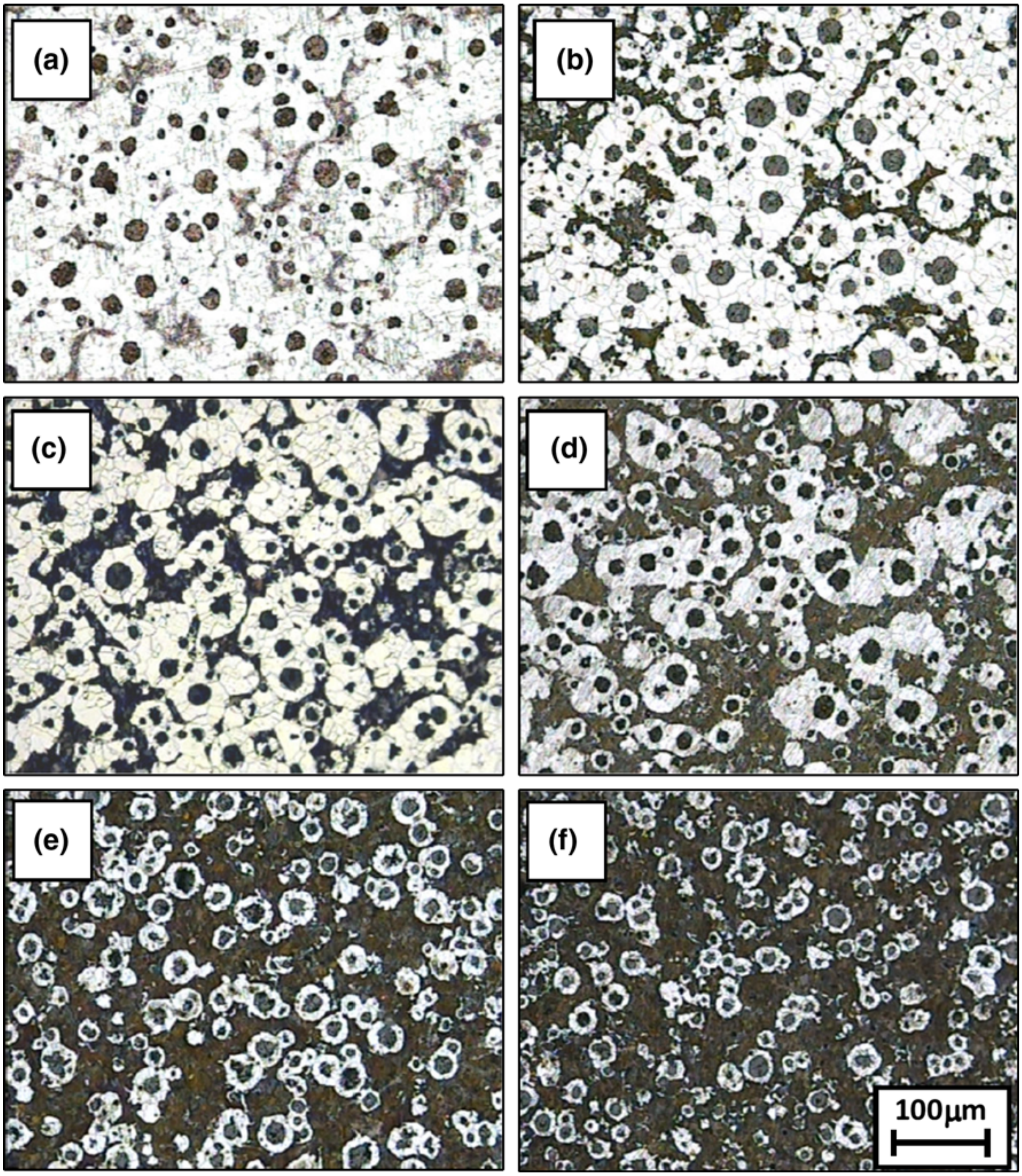

Fig. 2 Microstructures of heat-treated ductile cast irons containing (a) 6%, (b) 22.5%, (c) 30.4%, (d) 37.8%, (e) 67.3%, and (f) 71.4% pearlite (which were estimated by MIP software)

3. Results

With the aid of regression analysis and by maximizing the correlation coefficient (R^2) for all the tested frequencies, the optimum frequencies were identified as 650 Hz and 50 Hz for steel and ductile cast iron samples, respectively.

Figure 4 shows the correlation between the eddy current parameters and the fractions of pearlite in the steel and cast iron samples. The carbon contents of the steel samples are also presented in Fig. 5. As can be seen, an increase in the pearlite and carbon content will change the magnetic properties, and hence, cause a reduction in the eddy current outputs (primary and secondary voltages and Z/Z_0). The highest R^2 values were obtained for the normalized impedance (0.95 and 0.99 for pearlite percentage of cast iron and steel samples, respectively and 0.98 for carbon content of the steel samples). For this reason, the normalized impedance was considered as the optimum output for determining the pearlite percentages and carbon contents of the samples.

The changes in hardness values of the steel and cast iron samples versus the eddy current parameters are shown in Fig. 6. In the similar way as before, the highest correlation coefficients correspond to the normalized impedances, namely, 0.97 and 0.92 for cast iron and steel samples, respectively. This high accuracy proves that the eddy current method has the ability to nondestructively determine the hardness values

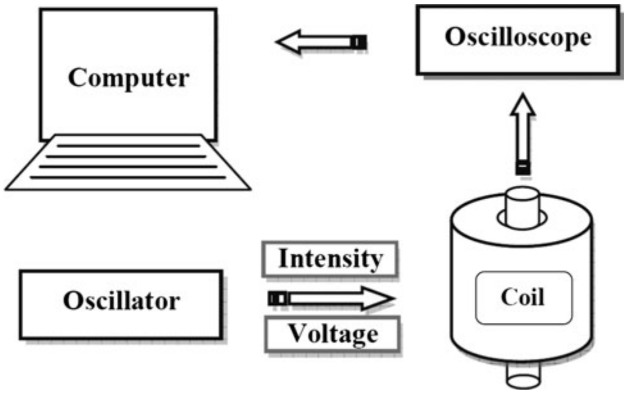

Fig. 3 General synopsis of the experimental apparatus

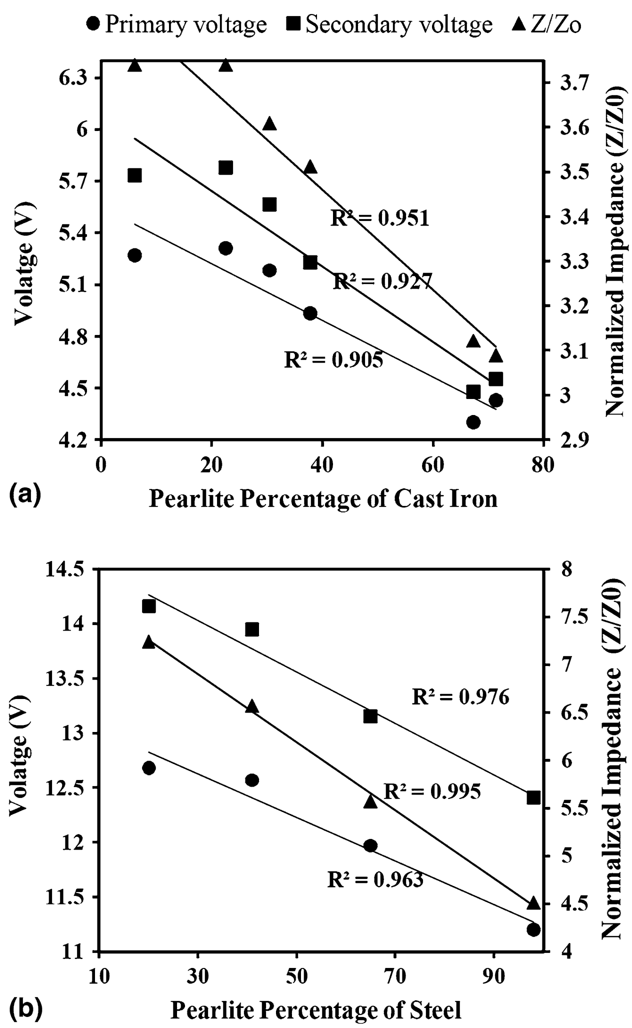

Fig. 4 Relations between pearlite percentages and eddy current outputs for (a) cast iron at 50 Hz and (b) steel at 650 Hz

of cast iron and steel parts. In summary, the results can be used to separate steel and cast iron samples with different hardness values which can be related to their different microstructures.

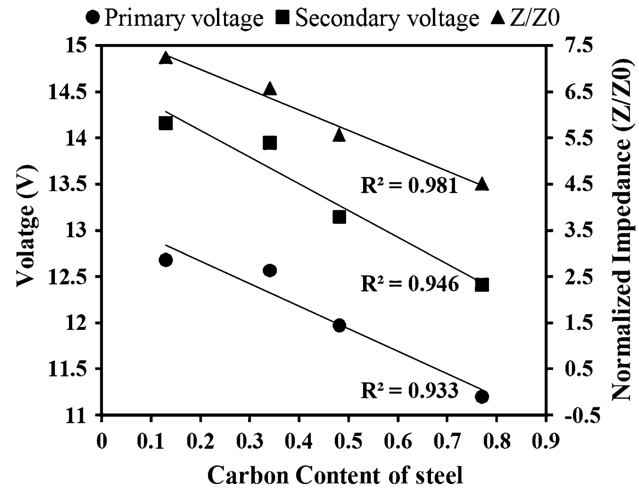

Fig. 5 Relations between carbon contents of steels and eddy current outputs at 650 Hz

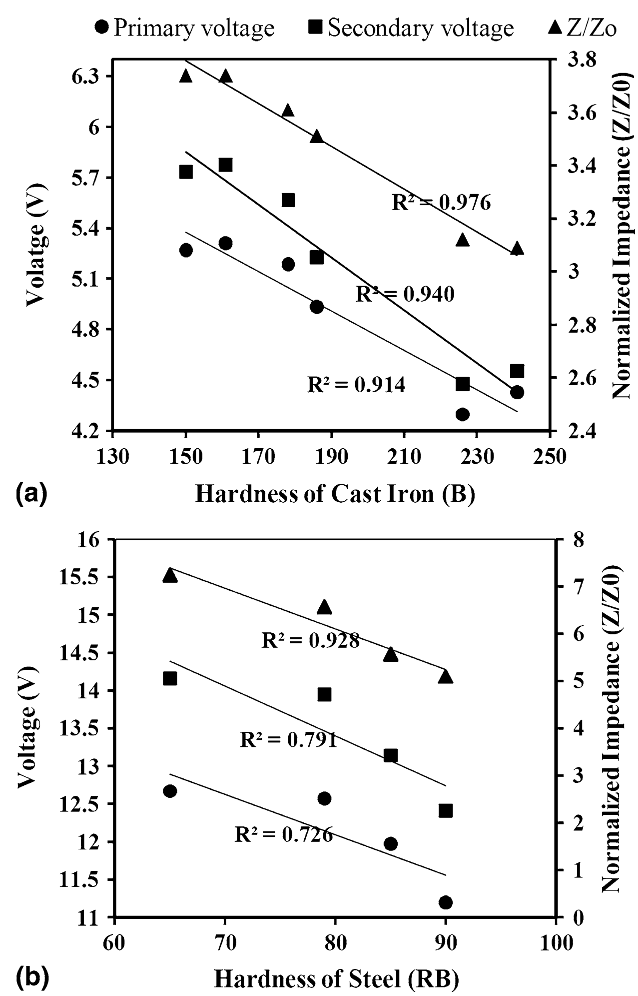

Fig. 6 Relations between hardness values and the eddy current outputs for (a) cast iron at 50 Hz and (b) steel at 650 Hz

4. Discussion

Two major factors affect the eddy current response: the microstructure of the sample and the residual stress (Ref 1, 2).

The annealed microstructure (ferrite-pearlite) of the samples studied in this research has very little residual stress, and hence, the effect of residual stress can be neglected. The samples were also surface machined to remove the decarburized layer and its subsequent effect on the eddy current outputs. Thus, in the present study, the eddy current outputs are affected mainly by the microstructures of the samples (pearlite content).

The difference in the eddy current response of dissimilar microstructures (caused by a variance in chemical composition in carbon steel or heat treatment in cast iron parts) is due to their different magnetic properties.

The difference in carbon content/heat treatment is the main cause of different pearlite percentages in the steel/cast iron samples and hence, the direct correlation between eddy current outputs and microstructure leads to an indirect relation between the chemical composition and the eddy current outputs (Ref 15). On the other hand, microstructural changes, or in other words, different pearlite percentages, have a direct effect on the hardness values of cast iron and steel samples. Therefore, there will be an indirect relation between hardness and the eddy current response. Figure 7 shows the relation between these parameters.

Several studies have been carried out to investigate the relationship between magnetic hysteresis curve parameters and the microstructure of steel (Ref 4) and cast iron parts (Ref 10). The results indicate that by increasing the pearlite content of steel and cast iron samples, the coercivity (Hc) will increase and the saturated magnetic flux (Bs) decreases.

The major effect of increasing the pearlite content is the increase in the magnetic hysteresis loss. This correlation is due to two reasons: an increase in the number of carbide layers and an increase in grain boundary area due to boundary formation between ferrite and cementite in the pearlite lamellar structure. Both of these act as barriers and prevent the alignment of magnetic domains. Thus, higher magnetic field intensity (H) is required to overcome these barriers and align the domains, and as a consequence, a greater coercivity is needed.

Therefore, by increasing the pearlite content and hardness in all the samples, hysteresis loss increases, and magnetic permeability (μ) decreases. On the other hand, considering Eq 3, it can be concluded that by decreasing μ, self-induction (L) will decrease.

$$L = \mu N^2 A / l \quad \text{(Eq 3)}$$

where A is the cross-sectional area of the coil.

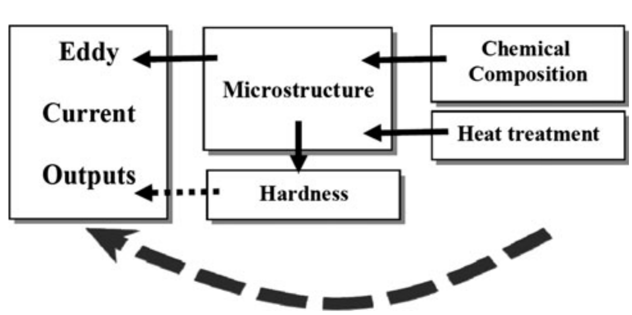

Fig. 7 Schematic relation between chemical composition, microstructure, hardness, and eddy current outputs

Subsequently, according to the following equations, by decreasing μ, induction resistance (X_L) will decrease. It is well known that in ferromagnetic alloys, the effect of permeability or reactance is stronger than the effect of resistance (R), and hence, the impedance (Z) will also decrease.

$$X_L = 2\pi f L \quad \text{(Eq 4)}$$

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

Consequently, the impedance decreases by increasing the pearlite content, hardness, and carbon content. The decrease in impedance is the reason behind the decrease in the output voltage of the eddy current (Fig. 4-6).

5. Conclusion

It was shown that the measured (primary and secondary voltages) and calculated (normalized impedance) parameters are related to the microstructural characteristics of steel and cast iron parts. By increasing the pearlite fraction in samples which had undergone similar heat treatment, a clear trend in the eddy current response was observed. Both the measured and calculated parameters decreased with increasing the pearlite content, hardness, and carbon content of the samples. The highest correlation coefficient of all the investigated correlations was obtained using the normalized impedance.

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