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"Research Note"

NONDESTRUCTIVE EVALUATION OF MECHANICAL PROPERTIES OF DUCTILE CAST IRON PARTS USING EDDY CURRENT SIGNALS*

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Abstract– The present research investigates improvement of Eddy Current (EC) technique as a nondestructive method for measurement of ductile cast iron microstructural and mechanical characteristics. Six samples of heat treated ductile cast iron have been selected to study the relations between pearlite content and EC outputs. These outputs include voltage and normalized impedance as well as calculated parameters of harmonic analysis. Furthermore, correlation between mechanical properties such as hardness, yield strength and ultimate tensile strength in samples containing different ferrite-pearlite matrices and the magnetic responses has also been found. High correlation coefficients of the relations indicate an acceptable level of accuracy in comparison with destructive method.

Keywords– Nondestructive evaluation, eddy current, ductile cast iron, mechanical properties

1. INTRODUCTION

Eddy Current (EC) nondestructive method has long been used for detection of cracks and defects in electrically conductive materials. In recent years, it has also been utilized for nondestructive evaluation of metallurgical properties of ferrous products as a reliable and cost effective alternative to time consuming conventional destructive methods such as metallography and mechanical tests [1].

Considering the advantages, some research has been performed to prove the capability of EC method throughout the recent decade. For instance, assessments of decarburizing depth [2, 3], surface carbon content [4] and wear rate [5] have been investigated in steel parts. Ductile cast iron has also been the subject of EC material characterization studies, which proved a good relationship between cast iron microstructural properties and EC output voltage [6, 7].

In the present research, a technique has been used for ductile cast iron characteristics measurement including detection of pearlite percentage as well as estimation of mechanical properties (hardness, yield strength and ultimate tensile strength).

2. EXPERIMENT

Six grey cast iron rods of 35 mm diameter and 25 cm length and composition of 3.6%C–2.09%Si–0.63%Mn–0.01%P–0.01%S were used for the present study. In order to obtain different microstructures, all specimens were first austenised by heating at 900 °C for 80 minutes followed by cooling to 670 °C at cooling rate of 55 °C/min. Then, in ferritization step, they were heated at 730 °C for different periods of time ranging from 5 to 180 minutes. The heat treatment resulted in the formation of microstructures with

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various ferrite/pearlite fractions and the same chemical composition. All specimens were cut into 3 parts. The first part was used for Brinell hardness measurement and metallographic investigations including phase fraction calculation using MIP image processing software. The second part of specimens was used to prepare tensile test samples according to ASTM A395 standard. To perform eddy current tests, the third part was machined into a rod shape with a diameter of 30 mm. In this study, an encircling coil of 31 mm internal diameter and 100 mm length using sinusoidal alternative current with a frequency ranging from 10 Hz to 1000 Hz was applied to obtain specimens' electromagnetic responses. A schematic diagram of the used EC system can be found elsewhere [3].

Finally, the relationships between EC output signals and pearlite content/mechanical properties were plotted at each frequency and linear regression analysis was used to determine the best output signal at the optimum frequency.

3. RESULTS AND DISCUSSION

Figure 1 shows sample microstructures and the determined pearlite percentages using destructive metallography treatment. Obtained values for metallographic investigation and mechanical properties are shown in Fig. 2. Performing EC test, induced voltage was directly measured and normalized impedance (Z/Z_0) was calculated [3]. Figure 2 presents the metallurgical characteristic values versus EC outputs at the optimum frequency of 50 Hz as well as the best fit for each of the presented data.

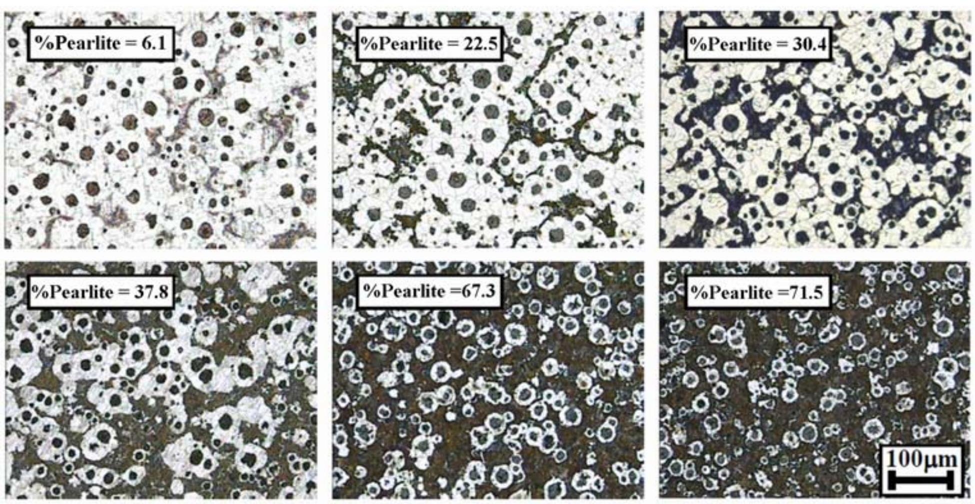

Fig. 1. Microstructures of heat treated samples containing different pearlite percentage

High regression coefficients, especially for normalized impedance indicate that the obtained equations can be used in nondestructive measurement of metallurgical characteristics in a fast manner with acceptable accuracy.

Using the same chemical composition for all samples and performing stress relieving heat treatment indicate that different magnetic properties and subsequent changes in electromagnetic responses is, to a great extent, due to differences in microstructure of the samples. Thus electromagnetic responses are indirectly affected by microstructure as depicted by "Relation A" in Fig. 3. On the other hand, it is well known that mechanical properties of ductile cast iron mainly depend on microstructure, especially the ratio of ferrite/pearlite percentage. As a result, we can also consider a relationship between mechanical properties and electromagnetic responses. This is presented as "Relation B" in Fig. 3.

As shown in Fig. 2, different amounts of ferrite/pearlite play a key role in relationships between ductile cast iron characteristics and the EC outputs and therefore, should be discussed in detail.

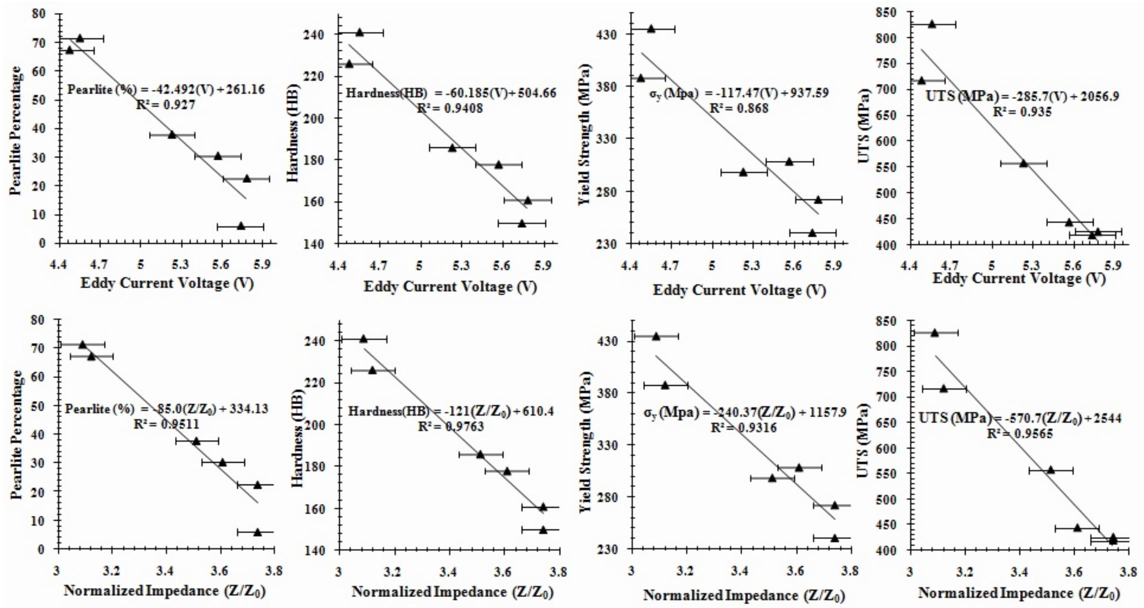

Fig. 2. Metallurgical characteristics values versus eddy current outputs (voltage and normalized impedance)

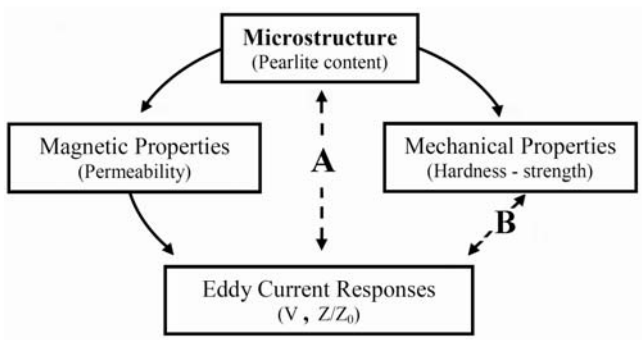

Fig. 3. Indirect relationships between eddy current responses and A) Microstructure B) Mechanical properties. (Solid and dash lines present direct and indirect relationships, respectively)

It is well known that ferromagnetic materials possess uniformly magnetized regions which exhibit a parallel orientation of all magnetic moments within this so-called magnetic domain. The orientation of domains and consequently domain walls shape results from the balance of several competing energies. When an external magnetic field (H) influences these materials, domain walls tend to move and rotate and orient along the field in order to reduce total energy of the system. Microstructural features such as dislocations, inclusions and grain boundaries pin the domain walls and prevent their alignment. The nature of pinning sites for domain walls in pearlite microstructure is mainly determined by cementide lamella. The large interfacial area of cementide lamella which increases volume fraction of pinning sites, increases energy loss during magnetization process [8]. Therefore, more magnetic field intensity (H) is required to overcome the obstacles against aligning and reaching the magnetic induction to saturation state (Bs). As the Bs value mainly depends on chemical composition [9], more required H represents less value for permeability (μ). As a result, for all samples, by increasing pearlite percentage (consequently hardness, yield strength and UTS) hysteresis loss will increase and magnetic permeability will decrease. Considering the direct relation between the permeability and self-induction coefficient (L), it can be concluded that decreasing in μ results in decreasing of L and induction resistance (X_L). Thus the impedance and induced voltage decrease with increasing the pearlite percentage and therefore hardness, yield strength and UTS. Figure 2 verifies the conclusion.

As output signals of eddy current are in sinusoidal form, harmonic analysis (Fast Fourier Transformation) can be used as a tool to analyse the obtained magnetic responses of ferromagnetic materials [2]. To study its application, harmonic analysis was applied on obtained voltage at the frequency of 50Hz. Calculated real (Re) and imaginary (Im) parts of each harmonic were utilized to obtain modulus (Π) according to (1).

$$\Pi = \sqrt{(\mathrm{Re})^2 + (\mathrm{Im})^2} \tag{1}$$

In the present investigation, harmonics 3, 5 and 7 were used to study the relations. Relations between pearlite percentage/mechanical properties of the cast iron samples and values of harmonic 7 modulus are shown in Fig. 4.

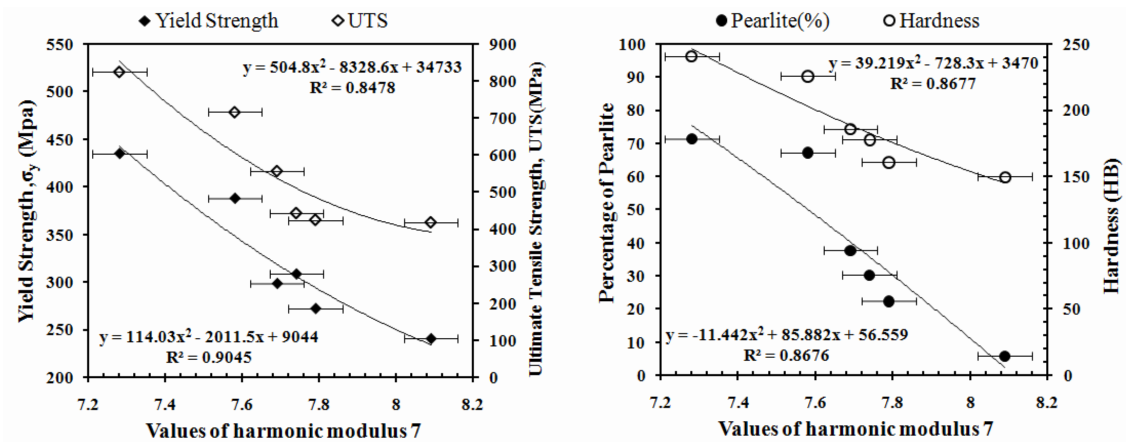

Fig. 4. Relations between values of the vector modulus with the microstructural and mechanical characteristics

4. CONCLUSION

In the present paper, application of the eddy current method as a nondestructive measurement technique has been improved in determining pearlite percentage, hardness, yield strength and ultimate tensile stress of ductile cast iron samples by considering both voltage and normalized impedance as EC outputs. High reliability of the method has been proved by high correlation coefficients obtained for the relations between metallurgical characteristics and the EC outputs, especially normalized impedance.

REFERENCES

1. Jiles, D. C. (1990). Review of magnetic methods for nondestructive evaluation (Part 2). *NDT and E International*, Vol. 23, pp. 83-92.
2. Mercier, D., Lesage, J., Decoopman, X., & Chicot, D. (2006). Eddy currents and hardness testing for evaluation of steel decarburizing. *NDT and E International*, Vol. 39, pp. 652-660.
3. Kahrobaee, S., Kashefi, M. & Saheb Alam, A. (2011). Magnetic NDT Technology for characterization of decarburizing depth. *Surface and Coatings Technology*, Vol. 205, pp. 4083-4088.
4. Sheikh Amiri, M. & Kashefi, M. (2009). Application of eddy current nondestructive method for determination of surface carbon content in carburized steels. *NDT and E International*, Vol. 42, pp. 618–621.
5. Gorkunov, E. S., Kharlamov, V. V., Kogan, L. Kh. & Zadvorkin, S. M. (2005). Evaluating the wear in steel–steel and iron–iron friction pairs by the eddy-current method. *Russian Journal of Nondestructive Testing* Vol. 41, pp. 218–223.

6. Uchimoto, T., Takagi, T., Konoplyuk, S., Abe, T., Huang, H. & Kurosawa, M. (2003). Eddy current evaluation of cast irons for material characterization. *Journal of Magnetism and Magnetic Materials,* Vol. 258-259, pp. 493-496.
7. Konoplyuk, S., Abe, T., Uchimoto, T., Takagi, T. & Kurosawa, M. (2005). Characterization of ductile cast iron by eddy current method. *NDT and E International*, Vol. 38, pp. 623–626.
8. Koo, K. M., Yau, M. Y., Dickon, H. L. N. & Lo, C. C. H. (2003). Characterization of pearlite grains in plain carbon steel by Barkhausen emission. *Materials Science and Engineering A*, Vol. 351, pp. 310-315.
9. Thompson, S. M. & Tanner, B. K. (1994). The magnetic properties of specially prepared pearlitic steels of varying carbon content as a function of plastic deformation. *Journal of Magnetism and Magnetic Materials,* Vol. 132, pp. 71-88.