ON THE APPLICATION OF NON-DESTRUCTIVE EDDY CURRENT METHOD FOR QUALITY CONTROL OF HEAT TREATED PARTS[1]

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Abstract

Recently, characterization of properties of materials has been the focus of intense investigation. Magnetic response of steels parts to an applied field, using non-destructive Eddy Current method, is sensitive to microstructure of the part. By calibrating this correlation any change in microstructure such as grain size or any specific phase percentage could be detected which can be used for quality control of heat treated parts in mass production. To investigate the ability of the method for separation of different microstructures, cylinders of steel (CK45) have been subject to different heat treatment cycles including normalizing, annealing ,quenching and quenching &full tempering. To study and evaluate the effect of grain size, various grain sizes produced in samples of CK20 steel. Determining the optimum frequency, eddy current testing was applied for all samples and the response to electro-magnetic field such as primary and secondary voltage and normalized impedance has been established and correlation coefficient (R^2) has been calculated. The study shows Eddy Current method could be successfully used to distinguish and separate undesired parts during mass production heat treating. The results indicate that a good relationship can be established between grain size and normalized impedance (R^2=0.96). Besides, to separate different microstructures (CK45), best correlation appeared to be for normalized impedance with the applied frequency of 200Hz.

Keywords: Eddy current method; Microstructure detection; Materials characterization; Grain size.

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1 INTRODUCTION

Nowadays, application of non destructive methods is not limited to detect defects and cracks. Considering the advantages of non destructive methods in industrial quality control, in the recent years, research are focused on non-destructive determining the mechanical and physical properties of materials as a substitute to destructive method which, in return, results in saving time and energy as well as providing 100% quality control in mass production lines.

Of all these methods, non destructive Eddy Current technique has individual advantages. Sensitivity of the method to chemical composition, microstructure, mechanical properties and residual stress makes it a reliable alternative to conventional destructive methods such as metallographic and mechanical tests.(1,2)

Hughes(3) 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).

Konoplyuk discovered an appropriate relation between the hardness of ductile cast iron and the output voltage of Eddy Current device.(4) Uchimoto and Check found the same relation for gray cast iron.(5,6) Using harmonic analysis(7) and difference in magnetic properties between ferrite and pearlite phases, decarburized depth was also studied.(8) Zergoug found Relation between mechanical micro-hardness and impedance variations.(9) Rumiche et al investigated the effect of microstructure on magnetic behavior of carbon steels by electromagnetic sensors,(10) and the effect of grain size on magnetic properties were also investigated and proved by other researchers.(11-13)

The goal of the present study, using magnetic response of mild carbon steels, is to separate different microstructures and predict grain size nondestructively.

2 MATEIALS AND METHODS

Four cylindrical samples from mild steel (CK45) with 22 mm diameter and 150 mm height were prepared for separation of microstructures. The same procedure was used to make samples for grain size detection using CK20 mild steel. Table 1 shows chemical composition of the samples.

To produce different microstructures, CK45 samples were subjected to different heat treating cycles corresponding to Table 2. Table 3 presents heat treating cycles performed on CK20 samples to produce different grain size with the same microstructure (perlite – ferrite).

In order to eliminate decarburized surfaces resulting from different heat treatments, all samples were machined up to 1 mm in depth. Finally, the Eddy Current tests were performed on the cylindrical samples. A schematic diagram of the used Eddy Current system is shown in Fig. 1. The Eddy Current testing was performed at 27℃ with the fill factor of 0.98. For separation of microstructures and grain size evaluation, the tests were done in frequencies between 50 to 5000 Hz and 10 to 1000 Hz, respectively. Grain size was measured, destructively, using Clemex software.

Primary and secondary voltages and input currents were measured and the impedance of the coil was calculated. In order to obtain calculated parameter, voltage (V) and intensity (I) of the coil were used to calculate the impedance (Z) of the coil for all samples using equation(1).(14)

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

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/Z0) is called normalized impedance [2].(13,15)

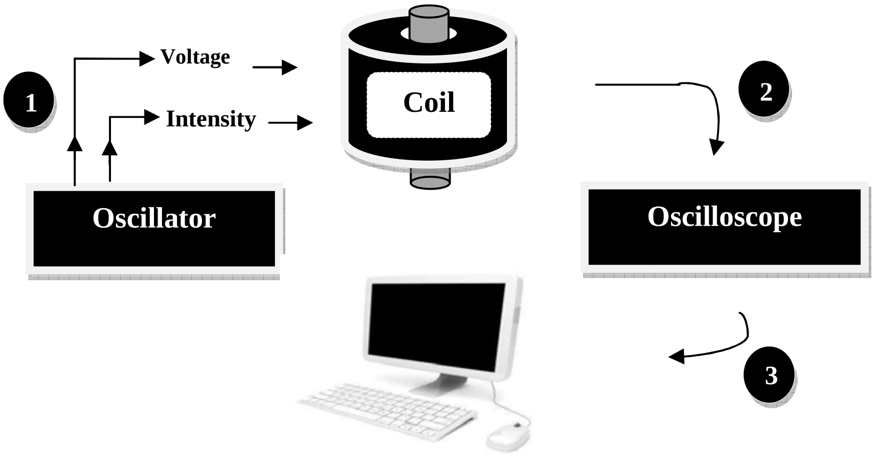


Figure 1. General synopsis of the experimental apparatus.

Table 1. Chemical composition of samples

	Element, wt.%				
Steel	%C	%Si	%Mn	%P	%S
CK45	0.44	0.25	0.57	0.004	0.030
CK20	0.18	0.25	0.57	0.006	0.009

Table 2. Heat Treatment Cycles for producing different microstructures

Samples	Heat treatment	Austenitizing time and temperature	Cooling	Hardness
1	Annealing	900℃ - 60 min	In furnace	81 RB
2	Normalizing	900℃ - 60 min	Air	87 RB
3	Quenching	900℃ - 60 min	Salt water	58 RC
4	Quench-full Tempering	900℃ - 60 min	Salt water + tempering at 650℃	92 RB

Table 3. Heat Treatment Cycles for producing different grain size

Samples	Austenitizing temperature	Austenitizing time	Cooling	ASTM Number
1	900℃	30 min	In air	10.91
2	900℃	30 min	In furnace	10.24
3	980℃	30 min	In furnace	8.57
4	1070℃	30 min	In furnace	7.68

3 RESULTS AND DISCUSSION

3.1 Separation of the Microstructures

It is well known that the response of Eddy Eurrent testing is affected by microstructure and chemical composition of the sample.(2) Microstructure is directly influenced by chemical composition; therefore, it is possible that the response of Eddy Current testing is indirectly affected by microstructure provided a similar chemical composition has been chosen.

Besides, performing annealing and normalizing heat treatments, same microstructures (ferrite- pearlite) but with different grain size will be produced. This, in turn, could have an effect on magnetic properties of material such as magnetic permeability. As a result, electromagnetic responses of materials could be directly related to their microstructures and grain size (Fig.2).

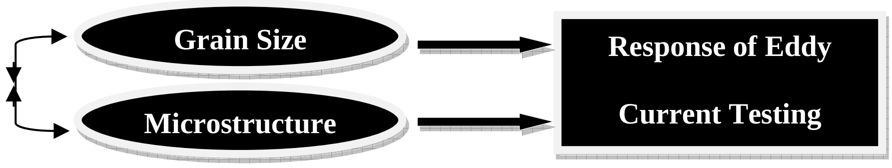


Figure 2. Schematic relation between microstructure, grain size and eddy current response.

Rivera et al observed the effect of grain size on hysteresis curve (curve B-H) and discovered a reduction in magnetic saturation (B_{max}) by increasing in grain size.(12) In general, grain boundary affects the movement of domain walls with two mechanisms; a) external effect which is related to segregation, precipitation and inclusions in grain boundaries, b) internal effect which is related to magneto static energy originated from orientation in two adjacent boundaries.(11)

Optical microscopic images of four investigated microstructures consistent with Table 2 are shown in Fig. 3.

To perform eddy current tests, the test frequency was altered from 50 to 5000 Hz. It was shown that the most significance difference between the outputs is in the frequency range of 500 to 1000 Hz for primary voltage and 300 to 800 Hz for secondary voltage. This range of frequency was chosen as an optimum frequency range.

In Fig. 4 variation curves of eddy current outputs versus frequency for four different microstructures in the optimum frequency range are shown.

Magnetic properties are affected by grain boundaries, because a closed field is generated in boundaries which opposes to the movement of domain walls during magnetization. As a result, the reason for variation of induction current responses with changes in the grain size is related to the amount of grain boundaries in the passage of magnetic field. Therefore the opposition of grain boundaries against field passing, results into reduction of the gained input and output voltage of the coil.

Comparing annealed and normalized microstructures, the factors which cause the difference in magnetic Eddy Current response of two microstructures are grain size or boundary density. The grain size of annealed sample is greater than the normalized one. The differences in primary and secondary voltages in annealed and normalized conditions can be seen in Fig.4.

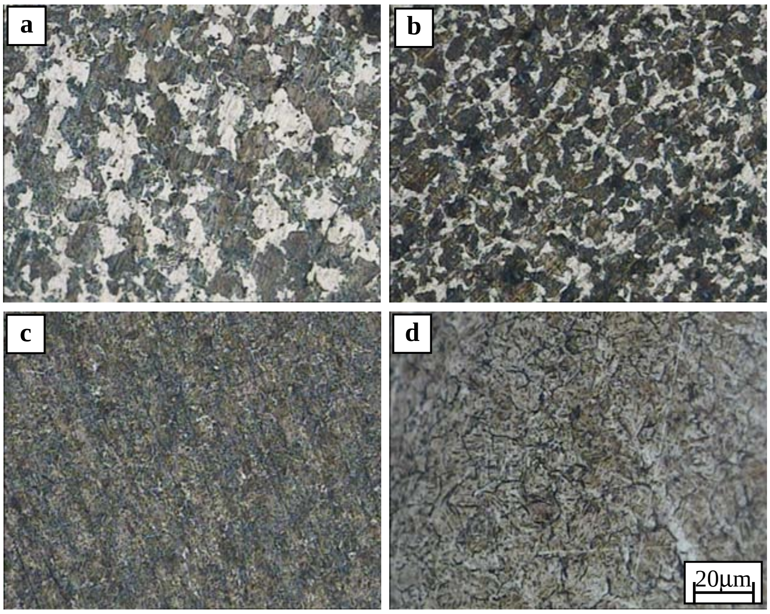


Figure 3. Optical microscopic images of microstructures resulted from heat treatments of a) annealed (ferrite-pearlite), normalized (ferrite-pearlite) c) quenched and full-tempered (full tempered martensite in 650º C), d) as quenched (martensite).

As a rule, increasing in magnetic field intensity (H) results in increasing in magnetic flux (B) into the material. This relation is depicted by equation B=μH which builds up the shape of hysteresis curve where magnetic permeability (μ) is the straight slope of the curve. By taking the high hardness of the achieved martensite structure (58 RC) into account, it can be understood that the amount of magnetic loss in martensite structure is more than ferrite-pearlite one and, therefore, the magnetic permeability is less.(2)

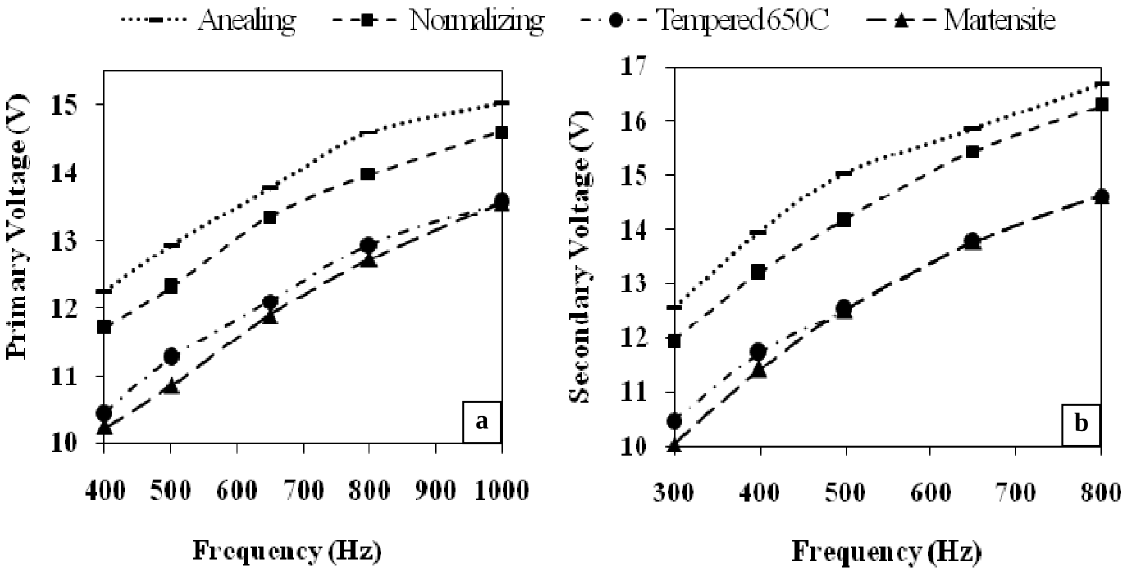


Figure 4. Variation curve of a) primary and b) secondary voltages versus frequency in optimum frequency range.

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

$$L = \mu N^2 A / l$$

(2)

Where μ is magnetic permeability; N, number of turns round the coil; A, cross section area and l, the coil length. In result, according to the following equations, by reduction in magnetic permeability (μ), induction resistance (X_L) and impedance (Z) are both reduced.

$$x_l = 2\pi f L$$

(3)

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

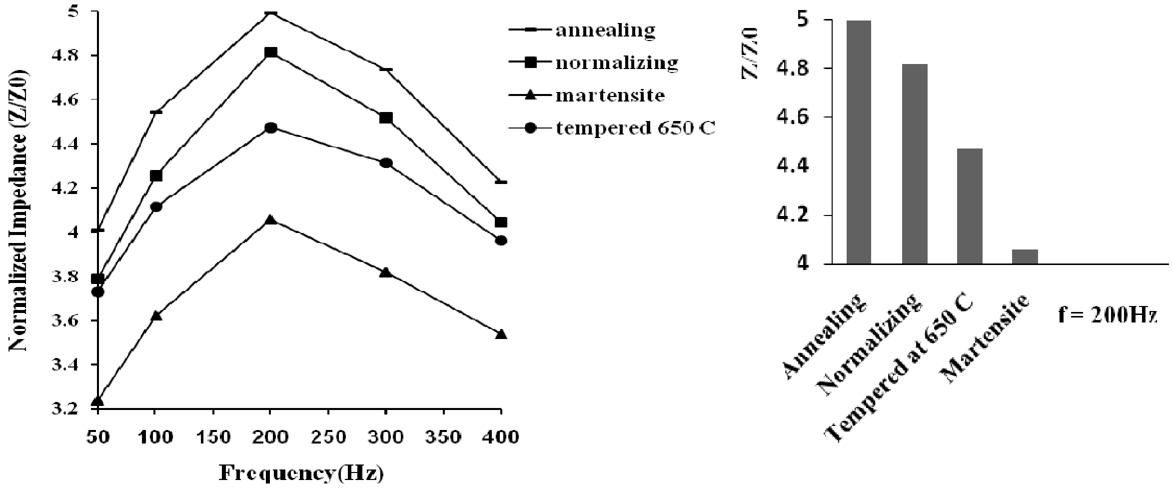
(4)

According to (4), reduction in impedance is a good reason for output voltage of Eddy Current of martensite microstructure to be less than the ferrite-pearlite one (Fig. 4).

On the other hand, separation between martensite and tempered martensite microstructures using primary and secondary voltages was almost impossible.

To investigate the application of Eddy Current method on separation of these microstructures, normalized impedance was calculated for each sample in the frequency range of 50 to 400 Hz. As it is shown in Fig. 5, the microstructures can be separated clearly using 200Hz frequency.

Besides, as the Fig. 5 indicates, two normalized and full –tempered martensite microstructures with nearly same hardness values (Table 2) can be separated nondestructively. This again indicates the potential of application of Eddy Current method on separation of undesired microstructures in mass production heat treating of steel parts.



a

b

Figure 5. Normalized impedance changes with frequency for a) four different microstructures; b) in the optimum frequency of 200Hz.

3.2 Grain Size Evaluation

Figure 6 presents microstructure of samples related to heat treating cycles presented in Table 3.

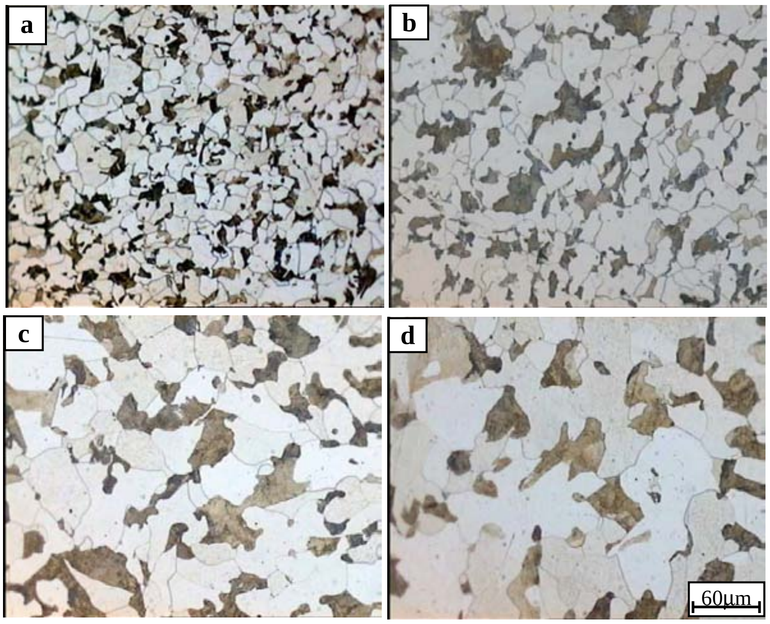


Figure 6. Optical microscopic images of microstructures with different grain size (according to the Table2), sample a)1 b)2 c)3 d) 4.

Figure 7 shows how correlation coefficient (R^2) used to determine optimum frequency considering different electromagnetic responses. As can be seen, the best correlation coefficient was at 200Hz. As a result, 200 Hz frequency been used to investigate grain size evaluation by Eddy Current method in this study.

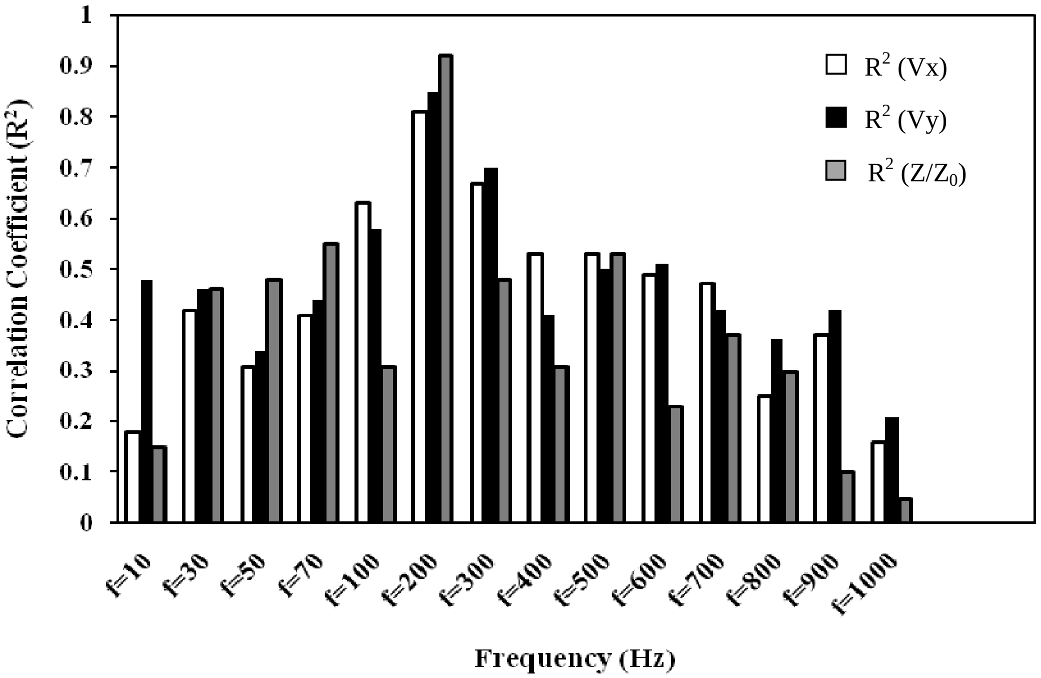


Figure 7. Correlation coefficient between grain size and primary (V_x), secondary (V_y) voltages and normalized impedance (Z/Z_0), in order to determine the optimum frequency.

Figures 8 and 9 show relation between ASTM Number of samples with primary and secondary voltages of the coil as well as normalize impedance, respectively.

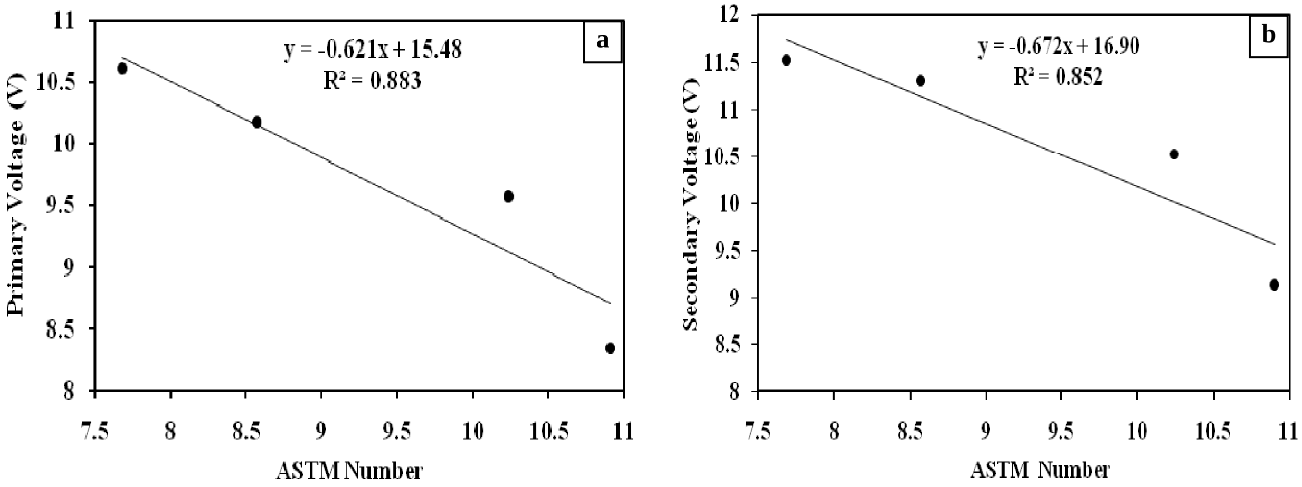


Figure 8. Relation between ASTM Number of samples and a) primary, b) Secondary voltages at 200 Hz.

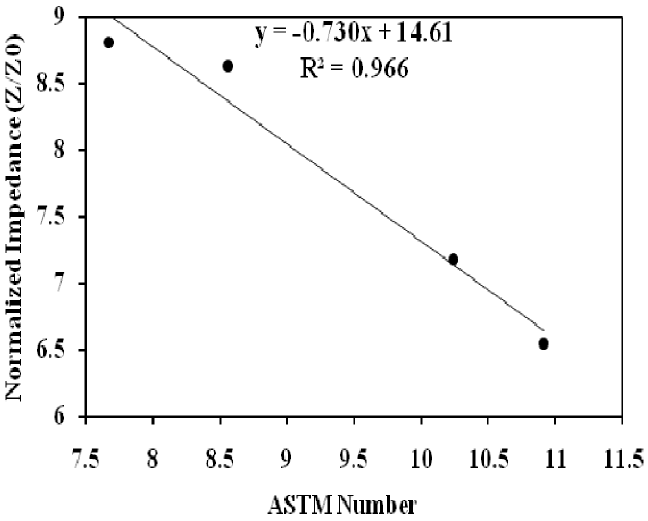


Figure 9. Relation between ASTM Number of samples and normalized impedance at 200 Hz.

Again, increasing in ASTM Number (increasing in grain boundary density) results in more resistance to passage of magnetic field. This, in turn, causes reduction of the gained voltage (primary and secondary) of the coil. As discussed earlier, normalized impedance can also be used to evaluate grain size, nondestructively.

Considering Figures 8 and 9, the best correlation coefficient (R^2 =0.96) was measured using normalized impedance (Z/Z_0).

4 CONCLUSIONS

Eddy current non-destructive method can be successfully used to separate different microstructures resulting from various heat treating cycles.

1- According to the difference in magnetic properties of microstructures (CK45), Eddy Current testing can separate the resulting microstructures from annealing, normalizing and quenching processes on basis of primary and secondary voltages of the coil.

2- Martensite and tempered martensite in 650°C in CK45 mild steel, can be separated to an acceptable level using normalized impedance (Z/Z_0).

3-Full–tempered martensite and normalized microstructures can be separated nondestructively regardless their similar hardness values.

4- Grain size in CK20 mild steel can be best evaluated (R^2 =0.96), using normalized impedance (Z/Z_0) output at 200 Hz frequency.

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