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On the Application of Eddy Current Non-Destructive Technique in Mass Production Heat Treating

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Non-destructive Eddy Current technique has long been used to detect discontinuities in materials. Although, recently, its application has been extended to distinguish and characterize materials microstructure. Based on different electromagnetic responses of materials with different microstructures, the present paper studies the ability of the Eddy Current method to distinguish unwanted parts resulting from improper heat treatment cycles. In order to characterize the microstructures, the responses resulting from current induction in 1045 mild steel samples with different microstructures were studied. The results show the high accuracy of the non-destructive eddy current method to distinguish different microstructures resulting from various heat treatment applications. The results show that eddy current non-destructive technique could be used in on–line characterization of undesired microstructure in mass production heat treatment lines.

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ABSTRACT

Non-destructive Eddy Current technique has long been used to detect discontinuities in materials. Although, recently, its application has been extended to separated and characterize materials microstructure. Based on different electromagnetic responds of materials with different microstructures, the present paper studies the ability of Eddy Current method to separate unwanted parts resulting from improper heat treatment cycles. In order to separate the microstructures, the responses resulting from current induction in 1045 mild steel samples with different microstructures were studied. The results show the high accuracy of the non-destructive eddy current method in separation of different microstructures resulting from various heat treatment applications. The results show that eddy Current non-destructive technique could be used in on–line separation of undesired microstructure in mass production heat treatment lines.

KEYWORDS

Heat treatment, eddy current, materials characterization, Separation of the microstructures

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 voltage 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 nondestructively.

2- EXPERIMENTAL PROCEDURE

For separation of different microstructures with the same chemical composition, four cylindrical samples with 22 mm diameter and 150 mm height were prepared from 1045 mild steel. The chemical composition of samples is shown in Table 1. Different heat treating cycles performed on samples to produce the microstructures corresponding to table 2.

In order to eliminate decarburized surfaces resulting from different heat treatments, all samples were machined up to1 mm in depth. Finally, the eddy current tests were performed on cylindrical samples. A schematic picture of the used eddy current system is shown in Fig. 1. The eddy current testing was performed at 27°C. For separation of microstructures, the tests were done in 12 frequencies between 50 to 5000 Hz.

Primary and secondary voltages and input currents were measured and the impedance of the coil were 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 (1), [14].

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

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].

For microstructures shown in table 2, saturated magnetic flux density (Bmax), coerctivity (Hc) and retentivity (Br) were measured at frequency of 50Hz.

The following process was done to measure these specifications of magnetic hysteresis curve.

The applied current into the first coil and the inducted voltage in the second coil were registered and, using (2) to (4) to measure Bmax, Br and Hc.

$$H = NI / l \quad (2)$$

$$V = -N\left(\frac{d\phi}{dt}\right) \quad (3)$$

$$B = \phi / A \quad (4)$$

Where N is the number of turns of the coil; H, field intensity; I, length of the core; V, voltage; Φ, magnetic flux; t, time; A, cross area of the samples.

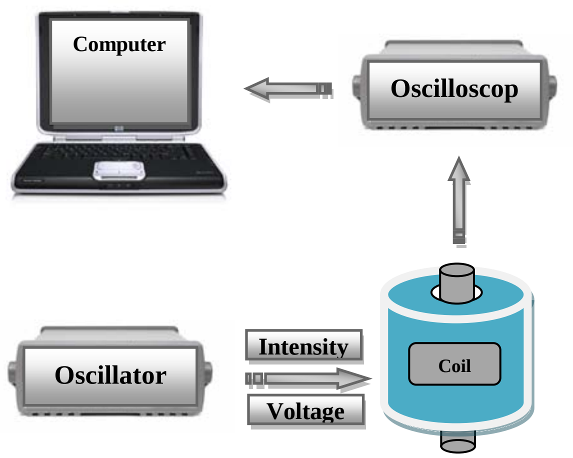


Figure 1: General synopsis of the experimental apparatus

TABLE.1 CHEMICHAL COMPOSITION OF STEEL

	Element, wt.%				
Steel	%C	%Si	%Mn	%P	%S
1045	0.44	0.25	0.57	0.004	0.030

TABLE.2 HEAT TREATMENT CYCLES

Cooling	Austenitizing time and temperature	Heat treatment	Samples
Off furnace	900°C - 60 min	Annealing	1
Air	900°C - 60 min	Normalizing	2
Salt-water	900°C - 60 min	Quenching	3
Salt-water	900°C - 60 min	Quench-Tempered in 650°C	4

3- RESULTS AND DISUSSION

3-1- Separation of the microstructures

It is well known that the response of eddy current 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 (Fig. 2).

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.

Rivera et al observed the effect of grain size on hysteresis curve (curve B-H) and discovered a reduction in magnetic saturation (Bmax) 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, inclusions and so on, in grain boundaries, b) internal effect which is related to magneto static energy originated from orientation in two adjacent boundaries [11].

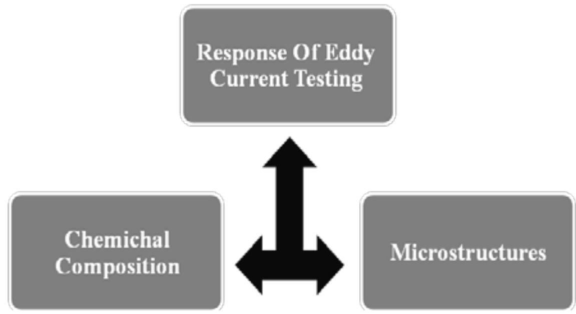


Figure 2: Schematic relation between chemical composition, microstructure and eddy current response [16].

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

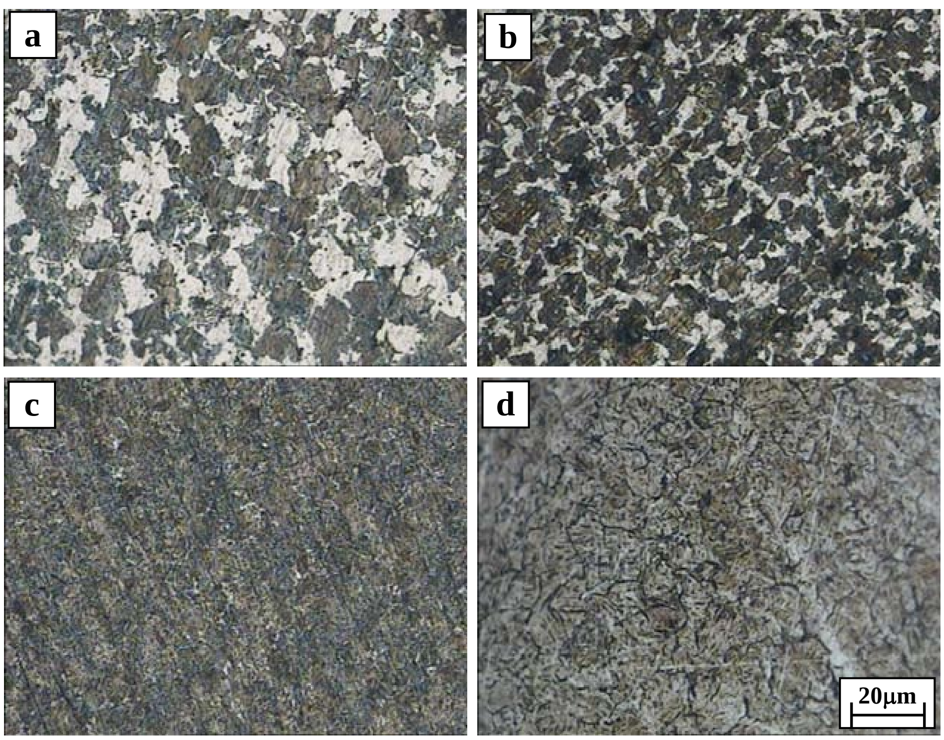


Figure 3: Optical microscopic images of microstructures resulted from heat treatments of a) annealed (ferrite-pearlite), normalized (ferrite-pearlite) c) quenched and full-tempered (full tempered martensite in 650º C), d) as quenched (martensite)

Magnetic properties are affected by grain boundaries, because a closed field is generated in boundaries which opposes to the movement of domain walls during magnetizing. As a result, the reason for variation of induction current responses with changing 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 and boundary density. The grain size of annealed sample is greater than the normalized one. Fig. 4 shows differences in Primary and secondary voltages in annealed and normalized conditions.

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 $B=\mu H$ 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.

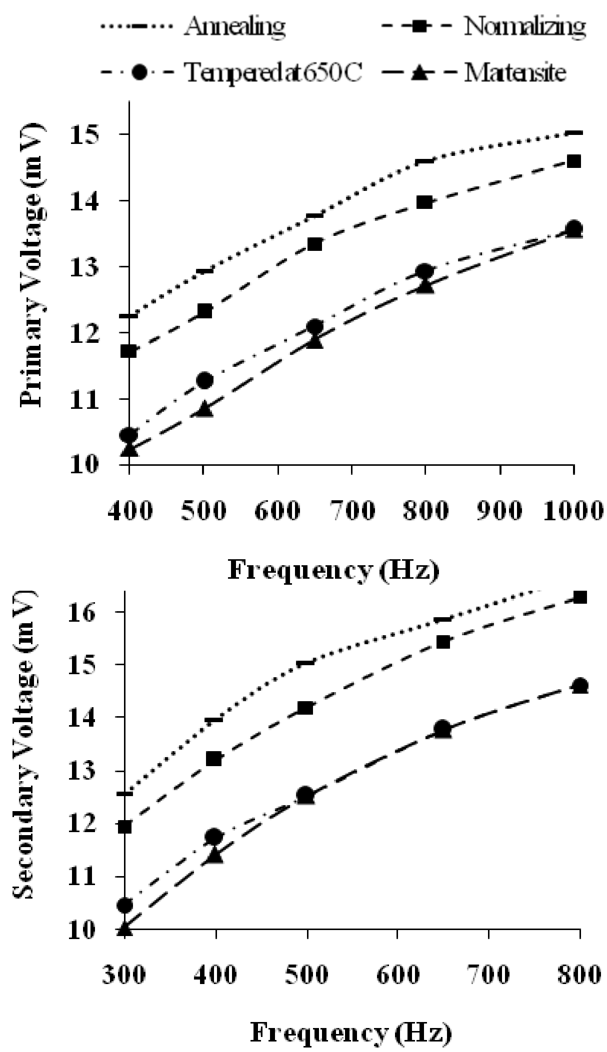


Figure 4: Variation curve of a) primary and b) secondary voltages versus frequency in optimum frequency range

3-2- Magnetic properties

In order to investigate the magnetic properties of different microstructures, specifications of magnetic hysteresis curve that is shown in Fig.5 (saturated magnetic flux density (Bmax), Coercivity (Hc), Retentivity (Br)), for the investigating microstructures were measured which are presented in table 3.

The amount of Bmax and Br for martensite microstructure is less than the one in annealed ferrite-pearlite and normalized microstructures (ferrite-pearlite microstructures). Besides, the amount of Hc for martensite microstructures is more than the one for ferrite-pearlite annealed and normalized microstructures. This result that the magnetic loss for martensite microstructure is more than the ferrite-pearlite one; and, therefore, the magnetic permeability is less.

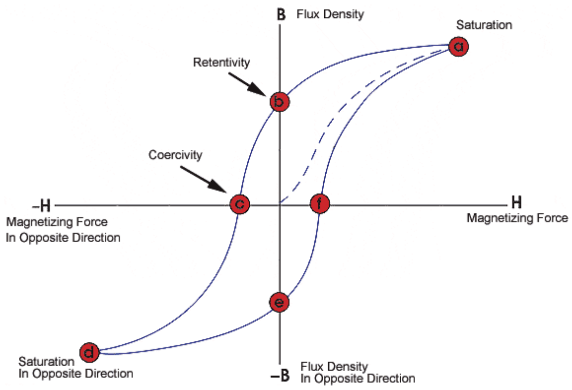


Figure 5: Schematic of a typical hysteresis curve that illustrates the magnetic properties

By considering (5) it can be said concluded that reduction in μ results into reduction of self-induction coefficient (L).

$$L = \mu N^2 A / l \quad (5)$$

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 (XL) and impedance (Z) are both reduced.

$$x_l = 2\pi f L \quad (6)$$

$$Z = \sqrt{X_l^2 + R^2} = V / I \quad (7)$$

According to (7), reduction in impedance is a good reason for output voltage of eddy current of martensite samples to be less than ferrite-pearlite one (Fig. 4)

On the other hand, the lack of clear difference in values of Bmax, Br and Hc for martensite and tempered martensite microstructures (table 3) makes microstructure separation using primary and secondary voltages almost impossible.

To investigate the application of eddy current method on separation of full tempered martensite microstructure, 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/Z_0) is called normalized impedance [2],[14],[15]. As it is shown in Fig. 6 the microstructures can be separated clearly using 200Hz frequency.

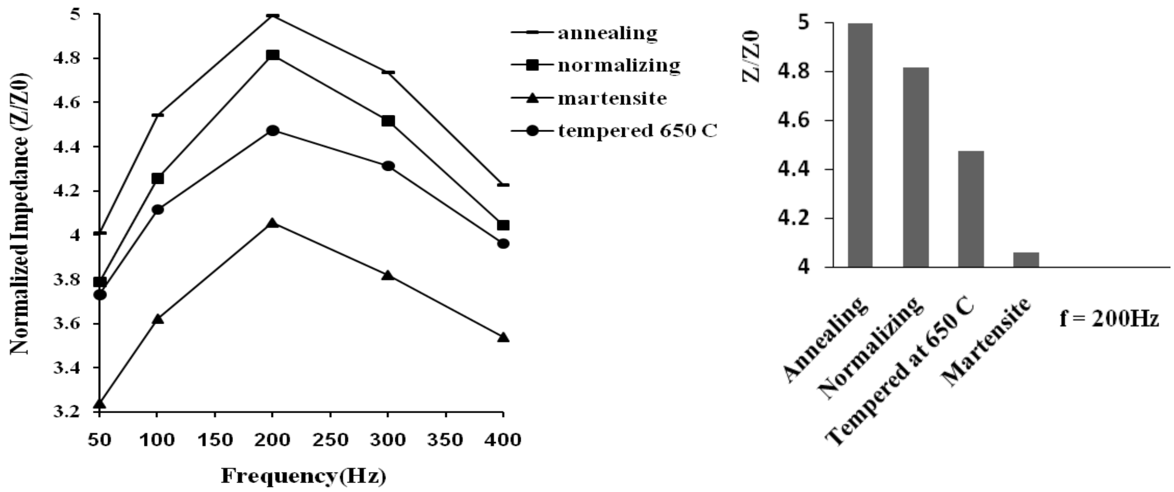
As the Fig. 6 shows, two normalized and full – tempered martensite microstructures with nearly same hardness values that presented in table 4 can be separated nondestructively. This again indicates the potential of application of Eddy Current method on separation of undesired parts in mass production heat treating of steel samples.

TABLE.3 SPESIFICATION OF MAGNETIC HYSTERESIS CURVE

Hc(A/m)	Br(Tesla)	Bmax(Tesla)	Microstructure
633	0.0055	0.0057	Ferrite-pearlite (annealing)
633	0.0053	0.0055	Ferrite-pearlite (normalizing)
643	0.0049	0.0052	Tempered martensite
699	0.0041	0.0047	Full Martensite

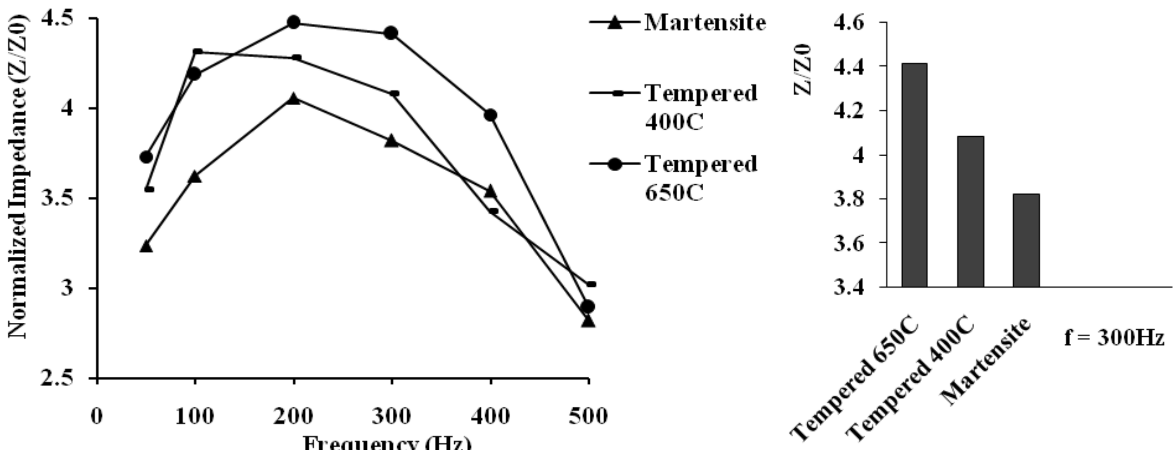
TABLE.4 HARDNESS VALUES FOR MICROSTRUCTURES

Microstructure	(annealing)	(normalizing)	Tempered Martensite	Full Martensite
Hardness	81 RB	87 RB	92 RB	58 RC



a b

Figure 6: Measured normalized impedance changes with frequency for a) four different microstructures b) in the optimum frequency of 200Hz.



a b

Figure 7: Normalized impedance for martensite and tempered martensite in 400˚C and 650˚C microstructures a) in a range of frequencies b) in the optimum frequency of 300Hz.

Finally, it is also shown that the non-destructive method is able to separate martensite, and tempered martensite (at 400ºC and 650ºC) microstructures.

Separating the tempered microstructures at different temperatures by destructive methods such as hardness test or microscopic observation is difficult and time consuming. In the present paper it is shown that the responses of eddy currents for the mentioned microstructures are different.

As shown in Fig. 7a, normalized impedance was measured in a frequency range for both mentioned tempered microstructures and then compared with the response from martensite microstructure. The highest difference was obtained in 300Hz frequency (fig. 7b). Therefore the optimum frequency for this separation was chosen as 300Hz.

4- CONCLUSION

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, the non destructive method of eddy current test 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, can be separated to an acceptable level using normalized output impedance (Z/Z_0).

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

4- Martensite , tempered martensite in 400℃ and tempered martensite in 650℃ microstructures, can be separated to an acceptable level using normalized impedance (Z/Z_0) output.

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