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Investigation of Variables Affecting Impedance Plane in Eddy Current Testing of Carburized Steels

Meisam Sheikh Amiri and Mehrdad Kashefi

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Impedance plane is one of the most important ways for presenting results in Eddy current testing, which includes major data for evaluation of results. In this study, the impedance plane was drawn for carburized steel with different surface carbon content. The influences of temperature, fill factor, and edge effect on impedance plane were investigated. The ability of Eddy current testing for determination of surface carbon content using normalized impedance was also shown. Results demonstrate a strong relationship between normalized impedance and surface carbon content (R^2 = 0.82). Besides the effects of temperature, fill factor, and edge effect on determination of surface carbon content were investigated. The fill factor and temperature have the largest and the least effect on correlation coefficient between surface carbon content and impedance plane, respectively.

Keywords edge effect, fill factor, impedance plane, surface carbon content, temperature

1. Introduction

Among the various forms of presenting test results for eddy current applications, impedance plane is the most theoretically well established. Impedance plane and movement of location of impedance point are the common way for investigation of cracks in materials (Ref 1, 2).

Generally, change in coil impedance with and without sample being inserted in the coil will be calculated to form impedance plan.

The theoretical principle for the method is based on calculating the impedance variations of inducting coil or probe with variables (Ref 1).

The process to calculate impedance plane can be summarized as follows:

Equation 1 shows how impedance of coil or probe is calculated.

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

Z, V, and I are impedance, voltage, and intensity of coil or probe, respectively.

Z consists of two parameters, resistance (R) and reactance (X), as can be seen in Eq 2. These parameters, in turn, can be calculated using Eq 3 and 4.

$$Z = R + iX \quad \text{(Eq 2)}$$

$$|R| = |Z|\cos(\varphi) \quad \text{(Eq 3)}$$

$$|X| = |Z|\sin(\varphi) \quad \text{(Eq 4)}$$

The normalized R and X are calculated using Eq 5 and 6 respectively.

$$\text{Normalized } R = (R - R_0)/X_0 \quad \text{(Eq 5)}$$

$$\text{Normalized } X = X/X_0 \quad \text{(Eq 6)}$$

Finally, impedance plane is formed by drawing normalized R vs. normalized X.

Many variables can affect the position of impedance point in the plane. These variables consist of resistance, reactance, and temperature of sample being tested as well as fill factor (lift off), edge effect and frequency of the current (Ref 3).

In their detailed studies, Brey and Shull have theoretically investigated the effect of parameters such as lift off and resistance on impedance plane (Ref 1, 2). Hagemaier has demonstrated the effect of cracks on impedance plane and illustrated the movement of impedance point in different condition such as crack direction, thickness lost, changes in resistivity and frequency (Ref 3). More recently, Zergoug has studied the relation between microhardness and impedance variations in eddy current testing (Ref 4). The effects of lift off and grain size of microstructure on impedance plane are also examined. They could prove the sensitivity of Eddy current testing to changes in microstructure for Al-Zn alloy and three types of steels (Ref 4). The impedance plane has also been simulated in rectangular spiral coil by Fava (Ref 5). Closed-form expressions for impedance of air-cored coils were first derived by Dodd (Ref 6) and Theodoulidis has also derived closed-form expression for the impedance of rectangular, air-cored coil of rectangular cross-section (Ref 7). The coil was located parallel or perpendicular to the surface of a conducting half-space. Foyet has studied the corrosion behavior of Al-2024 aluminum alloy coated with a chromate-free primer using impedance measurement (Ref 8). Although Jiles has widely studied the effect of stress on magnetic properties of materials (Ref 9), determination of residual stress in moderately shot-peened nickel-base superalloys was recently investigated by Abu-Nabah. Abu-Nabah has also studied the influence of

Meisam Sheikh Amiri and **Mehrdad Kashefi**, Department of Materials Science and Metallurgical Engineering, Engineering Faculty, Ferdowsi University of Mashhad, Mashhad, Iran. Contact e-mail: meisam2542@yahoo.com.

frequency, coil size, and lift off on results sensitivity (Ref 10). Determination of surface carbon content using Eddy current method has been investigated by the authors (Ref 11).

There is a further potential for investigation of variables affecting impedance plane, such as temperature, fill factor, and edge effect, on carburized steel.

2. Experimental Process

The present research was conducted on AISI4118 steel that is widely used in automobile industry. The composition of the steel is presented in Table 1. All the samples were prepared as rod specimens with 2.5 cm in diameter and 15 cm high and were carburized at 900 °C for 7 h in a gas carburizing furnace. The carbon potentials of the furnace were different for each sample but kept between 0.4 and 0.9. After carburizing, all the samples were cooled in air and normalized by means of induction heating process. Short austenetizing time and, therefore, elimination of surface decarburizing was the main reason for choosing the induction heating process. Finally, surface carbon content of all the samples was determined using spark discharge method (SPECTROLAB F) and is displayed in Table 2.

A sinusoidal current with a frequency ranging from 650 to 4 kHz was applied to the coil for all tests. A schematic representation of the device is shown in Fig. 1. Voltage and current in the coil were measured and the impedance of the coil was determined for each sample. Also, the phase angle is measured using time delay between voltage and current waveforms.

Apart from carbon content at the surface, the effect of three other variables, i.e., temperature, fill factor, and edge effect were studied using three levels for each variable as can be seen in Table 3.

3. Results and Discussion

The penetration depth of Eddy current and the carbon diffusion depth were calculated using skin depth formula (Ref 3) and Fick's laws of diffusion, respectively, for all the samples. Equation 7 was used to calculate skin depth (δ);

$$\delta = 50(\rho/\mu f)^{1/2} \quad \text{(Eq 7)}$$

where ρ, μ, and f are resistivity (μΩ-cm), relative permeability, and frequency (Hz), respectively (Ref 3).

Table 1 Chemical composition in weight percentage

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Fe
0.196	0.25	0.75	0.02	0.008	0.8	0.18	0.06	0.01	Rest

Besides, the maximum diffusion depth of carbon (x), resulting from carburizing cycles, was calculated using Eq 8

$$x = (D \cdot t)^{1/2} \quad \text{(Eq 8)}$$

where D and t are diffusion coefficient ($mm^2\ s^{-1}$) and time (s), respectively (Ref 12).

Table 4 and 5 shows the parameters that used to calculate skin depth and diffusion depth of carbon. As can be seen, the maximum calculated penetration depth (0.35 mm) is lower than minimum carbon diffusion depth (0.57 mm), provided that the test frequency is higher than 650 Hz. So, the electromagnetic responds of the samples can be used with great accuracy to determine their surface carbon content. The optimum test frequency was calculated using regression analysis over the frequency range 650 Hz to 4 KHz and the 650 Hz frequency was chosen for the study.

Figure 2 displays the effect of surface carbon content on changing the impedance point of the coil. Increasing the surface carbon content results in decreasing Z and φ. Z is the outcome of two parameters, i.e., resistance (R) and reactance (X) (Eq 2). By increasing the percent of carbon at the surface of specimens,

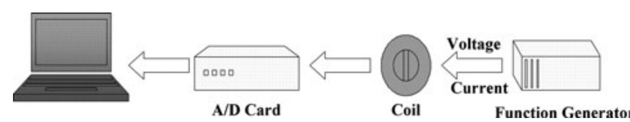

Fig. 1 General synopsis of the experimental apparatus

Table 3 Levels of temperature, fill factor, and edge effect used in experiments

Temperature, °C	Fill factor	Edge effect
Temperature levels		
30	0.96	1
80	0.96	1
0	0.96	1
Fill factor levels		
30	0.96	1
30	0.75	1
30	0.53	1
Edge effect levels		
30	0.96	1
30	0.96	3/4
30	0.96	1/2

Table 4 Parameters used to calculate skin depth of Eddy current

ρ, μΩ-cm (Ref 16)	μ (Ref 13)	*f*, Hz	δ, mm
24.5	750	650	0.35

Table 2 Surface carbon content of samples used in the research

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Percentage of surface carbon	0.83	0.45	0.53	0.71	0.81	0.88	0.68	0.65	0.91	0.72	0.88	0.74	0.78	0.44	0.55	0.88

the percent of pearlite increases (Fig. 3) which results in decreasing the magnetic permeability (μ). Since μ has a direct influence on X, by increasing the carbon content, X is dramatically reduced (Ref 1, 2, 13). On the other hand, by increasing the carbon percent to 0.7 (consequently increasing the pearlite percent), R increases due to an increase in phase boundaries and obstacles reducing the movement of electrons (Ref 14, 15). At the same time, by increasing the carbon percent even further (over 0.7), a small decrease in the resistance can be seen due to formation of cementite network at the grain boundaries (Ref 15). In any case, the dramatic decrease in X overshadows the increase or decrease in R and, as a result, Z decreases by increasing the carbon percent.

The effect of temperature on the impedance point in each specimen is shown in Fig. 4. An increase in the temperature results in an increase in the specimen's resistance (Ref 1) but a small increase in the temperature does not have a noticeable effect on μ and X (Ref 1). Consequently, an increase in temperature results in an increase in R without noticeable effect on X, resulting in increasing Z.

The changes in the coil's impedance with fill factor are shown in Fig. 5. Fill factor describes the degree of coupling of the magnetic field between the eddy current coil and the sample. In other word, fill factor compares the diameter of the coil to the diameter of the sample being tested (Ref 2).

By decreasing the fill factor, the magnetic field passing through the specimens decreases causing the Eddy currents which form in the sample also to decrease. Accordingly, the impedance curve is considerably changed (the impedance and phase angle increase with increasing in fill factor). Figure 6 represents the influence of edge effect on the impedance curve. When the entire sample is not within the coil, the edges of the specimen cause the magnetic field to deviate. Therefore, intensely affect the outcome of the Eddy current and weaken its effect in the sample (Ref 3). In addition, if the aim of eddy current testing is the investigation of chemical composition near the edges of samples, the two conditions will produce a combined response. Thus, the chemical composition may not be correctly measured (Ref 13).

Table 5 Parameters used to calculate diffusion depth of carbon

D_0, $m^2 \cdot s^{-1}$ (Ref 17)	Q, $cal \cdot mol^{-1}$ (Ref 17)	R, $cal \cdot mol^{-1} \cdot K^{-1}$	T, K	D, $mm^2\ s^{-1}$	t, s	x, mm
0.12	32000	1.987	1173	1.3×10^{-11}	25200	0.57

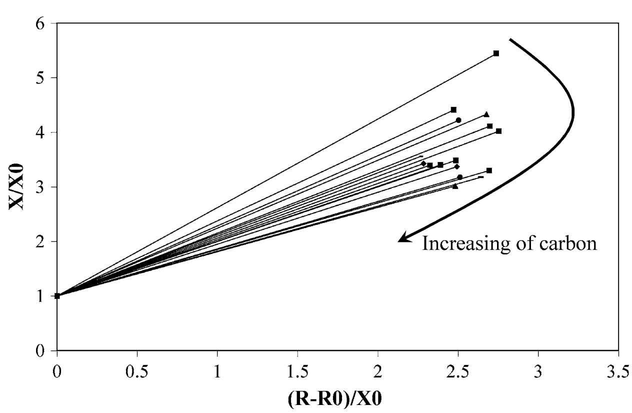

Fig. 2 Impedance plane and effect of carbon on location of impedance point

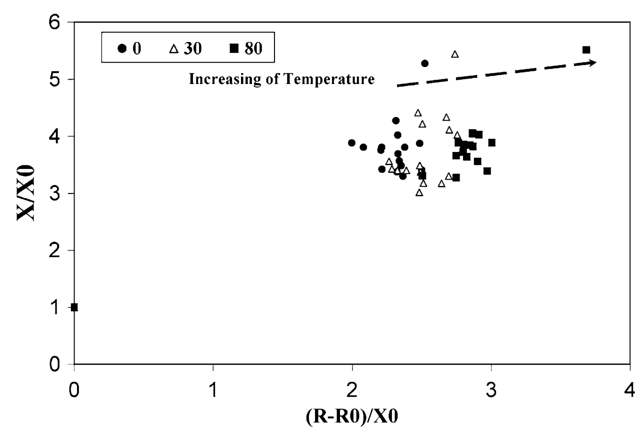

Fig. 4 Effect of temperature on impedance plane in carburized steels with different surface carbon content

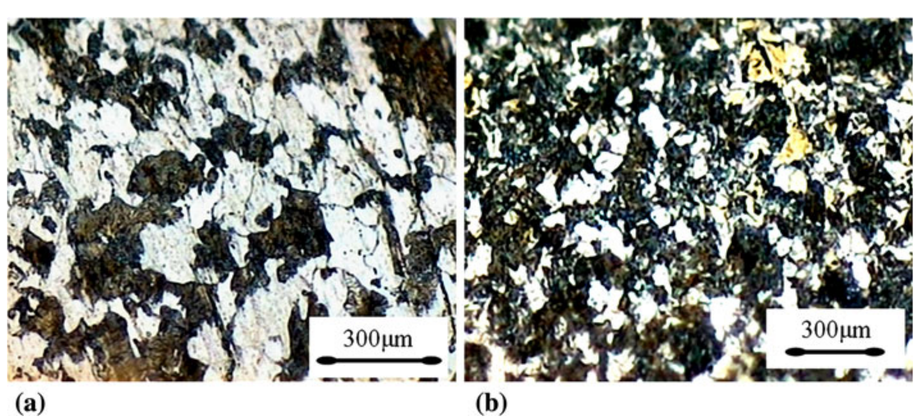

Fig. 3 Micrographs of surface of samples with (a) minimum and (b) maximum percentage of carbon

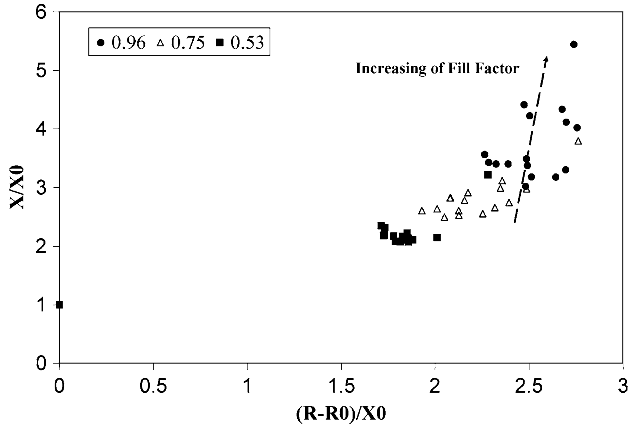

Fig. 5 Effect of fill factor on impedance plane in carburized steels with different surface carbon content

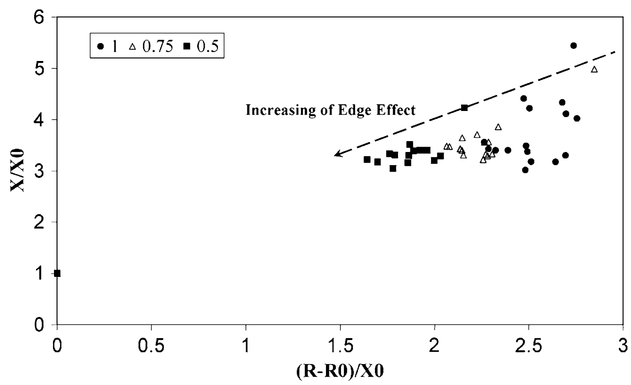

Fig. 6 Effect of edge effect on impedance plane in carburized steels with different surface carbon content

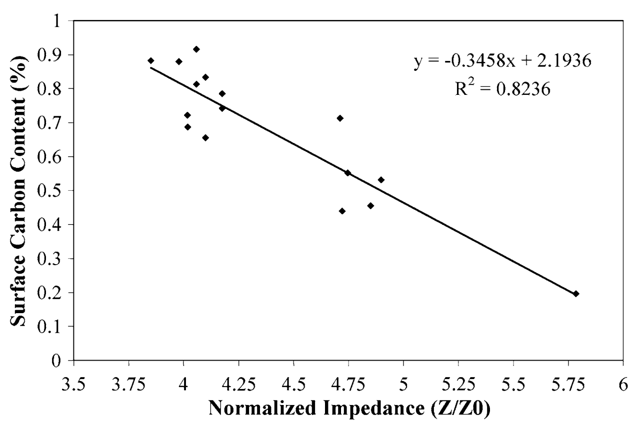

Fig. 7 Relationship between surface carbon percentage and normalized impedance

Finally, the practical importance of the effect of above-mentioned variables is investigated by applying Eddy current method to determine surface carbon content of carburized steel samples.

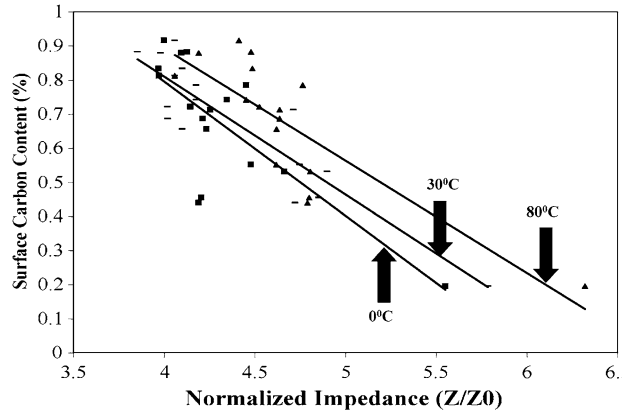

Fig. 8 Effect of temperature on the relationship between surface carbon percentage and normalized impedance

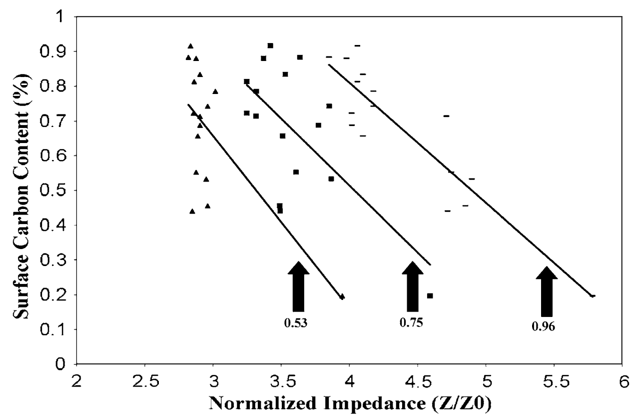

Fig. 9 Effect of fill factor on the relationship between carbon surface percentage and normalized impedance

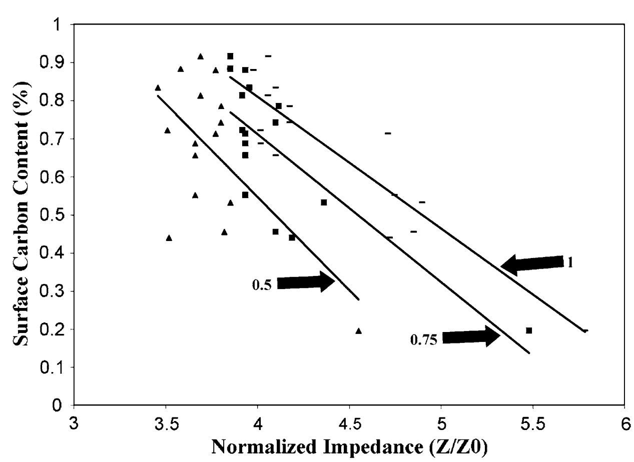

Fig. 10 Effect of edge effect on the relationship between surface carbon percentage and normalized impedance

Figure 7 displays the relationship between the surface carbon content and the normalized impedance obtained from Eddy current evaluation which indicates a very strong relation between the surface carbon content and the normalized impedance ($R^2 = 0.82$) that shows the Eddy current testing could be applied for quality control of carburized steels. Figure 8, 9, and 10 displays the influence of temperature, fill factor, and edge effect on the outcome of the Eddy current evaluation used for determining the surface carbon content of the samples, respectively. As can be seen, fill factor and edge effect cause errors as high as 17%.

In this regard, a proper coil with fill factor equal to 1 and a length shorter than the specimen (in order to eliminate the edge effect) should be designed. By fixing the two variables, the only factor affecting the outcome of the test is the temperature. Figure 10 shows the variation of evaluated carbon content at the surface for temperatures in the range of 0–80 °C using Eddy current method. Change in the temperature of the samples can cause an error as high as 13% in the carbon measurement. As a result, one has to keep in mind the temperature of the test and apply the corresponding corrections to the results. Equation 9 shows the temperature corresponding corrections for evaluation of the surface carbon content.

$$\%C = \left(-0.00002T^2 + 0.0021T - 0.394\right)(Z/Z_0) + \left(0.00008T^2 - 0.0083T + 2.3722\right) \quad \text{(Eq 9)}$$

where C, T, and Z/Z_0 are surface carbon content, temperature, and normalized impedance, respectively.

4. Conclusions

In this study, impedance plane was illustrated for carburized steel with different surface carbon content. The influence of temperature, fill factor, and edge effect on impedance plane was investigated. Determination of surface carbon content using normalized impedance shows a strong relationship ($R^2 = 0.82$) between surface carbon content and normalized impedance; the effect of temperature, fill factor, and edge effect on this relationship was also investigated to demonstrate the amount of error. By keeping fill factor and edge effect parameters constant at 0.96 and 1, respectively, the temperature corrections for evaluation of the surface carbon content was calculated.

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