# SURFACE LAYER THICKNESS MEASUREMENT FROM EDDY CURRENT PROFILING OF MAGNETIC COERCIVITY

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## INTRODUCTION

The use of eddy currents to measure the depth of surface modified layers in ferromagnetic materials has been the subject of numerous studies which are generally based on changes in impedance associated with differences in permeability (and to a lesser extent resistivity) in the surface modified layer compared to the core material (see for example reference 1). By changing the frequency, the material can be probed at different depths. Recently a different approach has been studied by Theiner et al[2] and others[3, 4] based on using eddy currents of different frequencies to probe spatial distributions of magnetic coercivity. This is obtained by measuring eddy current response while simultaneously cycling an externally applied magnetic field to near saturation. For a uniform material the impedance of the eddy current coil reaches a maximum at a field equal to the coercivity of the material, $H_c$.

In the case of a material with a surface layer having a value of $H_c$ different from the core one can observe two distinct maxima, one for each material. Double peaked curves are generally observed when the $H_c$'s are well separated. In this case the relative intensity of the peaks varies with eddy current frequency. More commonly the values of $H_c$ are not sufficiently separated to be resolved and the impedance curves will exhibit a single peak which shifts in value with eddy current frequency. This is the type of impedance curve generally encountered for case hardened parts. In this case the value of $H_c$ measured at a given frequency is an effective value over the thickness of the surface layer probed by the eddy currents. By varying the eddy current frequency one can therefore obtain an effective spatial profile of coercivity which can then be used to determine case depth.

In this paper experimental coercivity profiles obtained in this manner are presented for carburized samples. The profiles are then modeled theoretically using the Dodd and Deeds model[5,6] and shown to agree well with experiment. In particular a surprising and important feature of the analysis is that eddy current profiling can lead to $H_c$ values which are higher than the assumed values of $H_c$ in each of the layers. Using an analysis based on plane waves incident on a semi infinite half space, this is shown to be associated with reflections at the carburized layer interface.

## EXPERIMENTAL

Cylindrical sections of about 20 mm in length and 10 mm in diameter were cut from the longest straight portion of chain links made from 1008 steel whose case depths ranged from 0.40 to 0.70 mm. The cylindrical segments were then placed between two steel blocks

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20 mm in length with a square 10 mm by 10 mm cross section. This arrangement was used to increase the distance between the sample and pole pieces of the electromagnet so that the magnetic flux distribution would be uniform within the test piece.

The experimental apparatus consists of three blocks: i) the laboratory electromagnet and power supply, ii) the eddy current coil and Hall effect probe, and iii) an impedance analyzer and gaussmeter. The field of the electromagnet is controlled by a sweep generator which generates a triangular wave of 10.0 mHz frequency. This frequency was chosen so that the eddy currents produced by the magnetic field sweep would be negligible. A 200 turn encircling coil is placed around the cylindrical center portion of the sample assembly. The impedance of the coil is measured using an HP4192A impedance analyzer which is connected to microcomputer by an IEEE-488 bus link. The magnetic field is measured using a Hall probe placed on the sample and its output monitored by a gaussmeter which is also connected to the microcomputer via the IEEE-488 bus.

## RESULTS

Typical results of $H_c$ versus an effective penetration depth, $\delta_{eff}$, are presented in figure 1 for two chain samples having surface layer thicknesses of 0.58 and 0.71 mm. The effective penetration depth $\delta_{eff}$ is a convenient parameter which was used to convert frequency into an approximate penetration depth and is defined as

$$\delta_{eff}=\sqrt{\frac{1}{\pi f}\left(\frac{\rho}{\mu}\right)_{eff}} \qquad (1)$$

where f is the eddy current frequency and $(\rho/\mu)_{eff}$ is an effective value of the ratio of resistivity $\rho$ over permeability $\mu$ which was obtained, as described later, from a best fit between eddy current and metallographic data (equal to $2.08 \times 10^{-8}\Omega$-m).

It should be noted, however, that since the permeability is different in the core and surface the value of $\delta_{eff}$ does not correspond to actual penetration over the entire range of frequency. From figure 1 it is clear that the carburized surface layer exhibits a much higher value of $H_c$ (~4 kA/m) than the core (~0.25 kA/m) for both samples. Both samples exhibit a maximum which occurs at a penetration roughly equal to the layer thickness and the value of $H_c$ decreasing near the surface (i.e. at higher frequencies). At first this was thought to be due to an actual decrease of $H_c$ associated with a slight decarburization near the outer surface of the layer. However, as explained later it is more likely to be an artifact associated with reflections at the core/surface layer interface.

The value of the frequency, $f_m$, corresponding to the maximum value of $H_c$ for each sample, was found to be a reproducibly useful feature to nondestructively predict carburized layer thickness. This is shown in figure 2 where metallographic thickness is compared to eddy current thickness defined as $\delta_{eff}(f_m)$. The best fit to the data corresponded to a value of $(\rho/\mu)_{eff}$ $= 2.08 \times 10^{-8}\ \Omega$-m. A correlation coefficient $r^2 = 0.98$ and a standard deviation $\sigma = 0.033$ mm were obtained. This result can be considered to be very satisfactory since the optical measurement of case depth has an accuracy of ~0.05 mm.

## THEORETICAL ANALYSIS

### a) Coercivity profiles

In order to theoretically reproduce coercivity profiles such as shown in figure 1 the samples were modeled as cylinders of infinite length formed from two ferromagnetic materials, a thin surface layer with a large $H_c$ and core with a much lower $H_c$. This is a typical distribution of $H_c$ in case hardened parts.

The cylinder used in the calculations had a 5.0 mm diameter with a surface layer of 0.5 to 1.0 mm thick. A step function was used to describe the distribution of $H_c$ through the

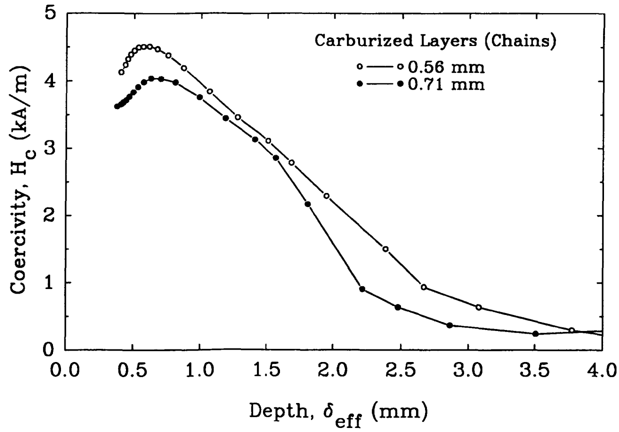


Figure 1. Experimental coercivity profiles as a function of the effective penetration depth, $\delta_{eff}$ for two chain samples with surface layer thicknesses of 0.56 and 0.71 mm. The value of $\rho/\mu$ corresponding to the solid line (best fit) is $(\rho/\mu)_{eff} = 2.08 \times 10^{-8}$ Ω-m.

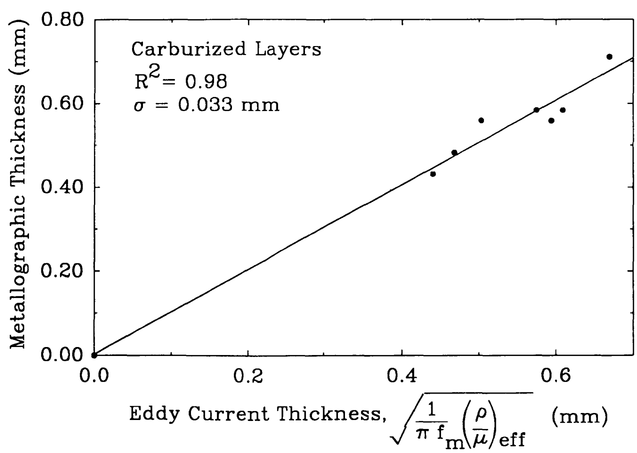


Figure 2. Correlation between the thickness of the surface layer measured using optical techniques and the eddy current thickness defined as $\delta_{eff}$ for $H_c = H_{cmax}$, the maximum value of coercivity.

radius of the sample where the highest coercivity, $H_c$ = 1.64 kA/m, was in the surface layer and $H_c$ = 0.875 kA/m in the core of the cylinder. The permeability of the surface layer and core were assumed to vary with the applied magnetic field as shown in figure 3. The permeability of the core, shown in figure 3, was obtained from measurements of the incremental permeability of an extruded tube steel which had approximately the same carbon content as for those steels used in case-hardened parts (0.4% carbon). The surface layer permeability curve was derived somewhat arbitrarily from the core permeability by decreasing the permeability (0.55 times) and shifting the field (2 times). The resistivity, ρ, for both layers was taken to be constant at $\rho = 2.0 \times 10^{-8}$ Ω-m. This value was kept constant since ρ does not vary significantly with chemical composition for most plain carbon steels in comparison with the large variations in permeability. For case hardened parts the carbon composition ranges from 0.8%

in the surface to 0.4% in the core from while ρ varies only a few percent for this range of compositions in plain carbon steels[4].

For the calculation we assumed an encircling eddy current coil which had the following dimensions: 2.25 mm inner radius, 2.575 mm outer radius and 3.2 mm length. The eddy current response of this coil was calculated using the Dodd and Deeds model [5, 6]. This model was used since it describes the response of a finite dimensioned encircling or surface coil.

The eddy current response as a function of the applied magnetic field, i.e. the impedance curve, |Z| versus H was calculated. From the impedance curve the value of the coercivity was obtained for each frequency by finding the magnetic field at which the maximum impedance occurs. By performing this calculation for a number of different frequencies a plot of $H_c$ as a function of penetration depth was obtained.

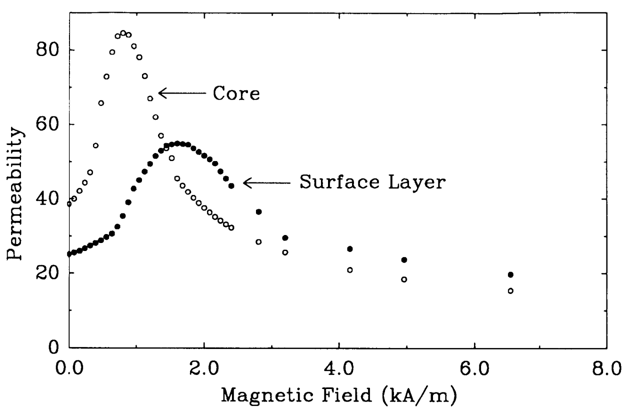


Figure 3. The variation of the relative incremental permeability as a function of the applied magnetic field for the core and surface layers of a cylinder used in the calculation of the impedance curves.

Results of two sets of calculations for layers of 0.5 and 1.0 mm thickness are given in figure 4. Although the numerical values of coercivity are different from the experimental ones presented in figure 1 the theoretical curves essentially display the same features. In particular we note a peak of coercivity at penetration depths of the order of the layer thickness with values of $H_c$ at the peak ~1.7 kA/m, i.e. greater than the value assumed for the surface layer (1.64 kA/m) and a gradual decrease at larger penetration depths. For the thicker layer a plateau is observed at very small penetration depths as expected since in this case eddy currents only penetrate the surface layer. The apparent decrease in $H_c$ observed experimentally in figure 1 for penetration depths smaller than the layer thickness is therefore reproduced theoretically even for the case of a surface layer with a uniform value of $H_c$. This behavior is further discussed below. The value of $\mu_{eff}$ used to calculate $\delta_{eff}$ from the frequency was chosen to be 38.36 in order that the peak in $H_c$ occur at $\delta_s$ = 1.0 mm for the case where the carburized layer depth was taken to be 1.0 mm. A slightly different permeability (40.22) would be required to match $\delta_{eff}$ and layer thicknesses for the 0.5 mm case. In both cases these values of permeability are somewhat lower than the assumed permeability of the surface layer at $H_c$ (~54, see figure 3).

b) peak in $H_c$ vs $\delta_{eff}$

The physical basis for the origin of the peak in the $H_c$ versus $\delta_{eff}$ curve is not immediately clear upon examining the results of the calculations. In order to explain this phenomenon we shall use a simple model based on a plane wave impinging on a semi-infinite half space. For a uniform material half space the intrinsic impedance, $\eta$, of a plane wave having an angular frequency, $\omega$, going through a material of resistivity, $\rho$, and permeability, $\mu$, is given

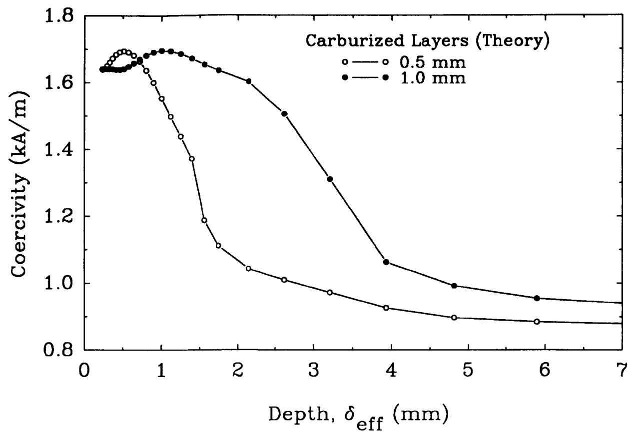


Figure 4. The calculated coercivity profiles as a function of the effective penetration depth for cylinders with surface layers of 0.5 and 1.0 mm thick. The resistivity, $\rho = 2.0 \times 10^{-7}\ \Omega$–m, and incremental permeability of 38.36 was used to calculate $\delta_{eff}$. Note that the general shape of the curves is in good agreement with figure 1.

by

$$\eta=\sqrt{j\omega\rho\mu} \tag{2}$$

The quantity measured in experiments is usually the modulus of the impedance which is given by

$$|\eta|=\sqrt{\omega\rho\mu} \tag{3}$$

By changing the magnetic field applied to the sample the incremental permeability, $\mu(H)$, can be varied. A typical $\mu(H)$ curve is peaked at $H_c$ for that material (see for example $\mu(H)$ for the core in figure 3) which results in a peak in the modulus of the impedance at $H_c$.

For a two layered structure we not only need to consider the intrinsic impedance of the electromagnetic wave in each of the layers but we must also take into consideration the reflections of the incident wave at the surface layer/core interface. We define the impedance, as seen at the surface of the semi-infinite half space, by an effective surface impedance, $\eta_s$, given by

$$\eta_s=\sqrt{j\omega(\rho\mu)_{eff}} \tag{4}$$

and the modulus of the surface impedance is

$$|\eta_s|=\sqrt{\omega(\rho\mu)_{eff}} \tag{5}$$

The value $\eta_s$ as defined by equation (4) is the impedance of a half space made of a uniform material which has an effective product $(\rho\mu)_{eff}$ which matches the impedance observed for the multiple layered structure.

The surface impedance for a sample consisting of an upper layer of thickness, $x_1$, with an intrinsic impedance, $\eta_1$, and a lower layer of infinite thickness with intrinsic impedance, $\eta_2$, is given by[7]

$$\eta_s=\eta_1\frac{\eta_2+\eta_1\tanh\gamma_1 x_1}{\eta_1+\eta_2\tanh\gamma_1 x_1} \tag{6}$$

where

$$\eta_i=\sqrt{j\omega\rho_i\mu_i} \quad i=1,2 \tag{7}$$

and the modulus of $\eta_s$ is given by

$$|\eta_s|=\sqrt{\omega(\rho\mu)_{eff}}=\sqrt{\omega\rho_1\mu_1}=\left|\frac{\eta_2+\eta_1\tanh\gamma_1 x_1}{\eta_1+\eta_2\tanh\gamma_1 x_1}\right| \tag{8}$$

where

$$\gamma_i=\sqrt{\frac{j\omega\mu_i}{\rho_i}} \tag{9}$$

is the propagation constant of the electromagnetic plane wave as it passes through the surface layer. Equation (6) was obtained using the transmission line analogy of wave propagation as discussed in Ramo, Whinnery and Van Duzer[8]. This analogy is based on the correspondence between the reflection coefficient and impedance mismatch at the surface layer/core interface. That is, there will be interference between the incident wave and the part of the incident wave which is reflected at the surface layer/core interface due to the difference in the intrinsic impedances for the electromagnetic wave in the two layers. The superposition of the incident and reflected waves produces a standing wave in the surface layer while the remaining portion of the incident wave is transmitted into the underlying layer. The reflection coefficient, R, given by

$$R=\frac{\eta_2-\eta_1}{\eta_2+\eta_1}=\frac{1-\frac{\eta_1}{\eta_2}}{1+\frac{\eta_1}{\eta_2}}=\frac{1-\sqrt{\frac{\rho_1\mu_1}{\rho_2\mu_2}}}{1+\sqrt{\frac{\rho_1\mu_1}{\rho_2\mu_2}}} \tag{10}$$

is a measure of the amount of energy reflected at the interface.

As we noted above the maximum impedance for a coil placed in a swept magnetic field, H, at a particular frequency occurs when $(\rho\mu)$ is at a maximum. This corresponds to $H_c$ for a single material medium. For a two material medium which has a single peak impedance curve the maximum impedance occurs when the quantity $(\rho\mu)_{eff}$ reaches its peak value as H is swept, i.e. at the maximum for equation (8). Equation (8) can be rewritten in terms of the reflection coefficient and the products $(\rho\mu)_{eff}$, and $(\rho_1\mu_1)$

$$(\rho\mu)_{eff}=(\rho_1\mu_1)\frac{|1+Re^{2\gamma_1x_1}|^2}{|1+Re^{2\gamma_1x_1}|} \quad (11)$$

In general the maximum does not occur at the maximum value of $(\rho_1\mu_1)$ as can be seen in equation (11). We show this in figure 5 where $\mu_{eff}(H)$, $\mu_1(H)$ and the squared term in equation (11) as a function of the applied magnetic field is presented ( $\rho = \rho_1 = \rho_2 = 2.0 \times 10^{-7}$ Ω-m) for a surface layer with $H_c$ = 1.60 kA/m and core with $H_c$ = 1.20 kA/m. In this figure we can clearly see a shift in the location of $(\mu)_{eff}$ maximum which occurs at a field of 1.67 kA/m compared to 1.60 kA/m for the surface layer alone. Although $\mu_1(H)$ is decreasing in the region near $H_c$ = 1.67 kA/m the value of $\mu_{eff}(H)$ (therefore $(\rho\mu)_{eff}$) is increasing since the squared term of equation (11) is sufficiently greater than 1 to compensate for the reduction in $\mu_1$.

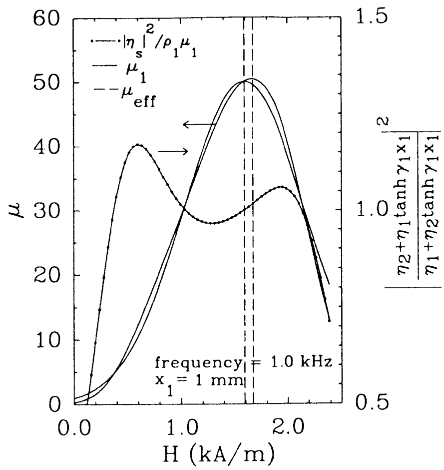


Figure 5. The variation of $\mu_{eff}$, $\mu_1$, and the squared term in equation (11) of the text as a function of the magnetic field. This figure shows how the measured values of coercivity can be shifted to values higher than $H_{c\,surf}$.

## CONCLUSION

A method was described for measuring the thickness of surface layers on ferromagnetic parts using an eddy current probe encircling a sample placed in a swept magnetic field. From the impedance curves for an eddy-current coil obtained at a number of frequencies a profile of $H_c$ versus penetration depth was obtained. The profile has a peaked structure and from this profile the thickness of the surface layer was determined by correlation between the actual thickness and the frequency at which the peak value of $H_c$ is reached. Calculations were performed which show that the value of $H_c$ measured using this technique is larger than the maximum value of $H_c$ in the sample. We have shown that this is due to reflections at the surface layer/core interface.

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