Analysis of Conductivity and Permeability Profiles in Hardened Steel

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Abstract. Researchers interested in model-based methods for the measurement of case depth have needed to assume a relationship between hardness and electromagnetic properties. For example, a recent two layer implementation assumes that the breakpoint in electromagnetic properties falls at a point where the hardness is midway between surface and substrate values. Depending on definitions, this location may or may not correspond to the so-called case depth (as measured destructively) for a given specimen. The true relationship between hardness (or microstructure) and electromagnetic properties has been explored in this paper.

1. Introduction

The nondestructive measurement of modified surface layers on steel components remains a difficult and elusive problem. The ability to characterize hardness profiles in components such as gear teeth and cam shafts is important for quality inspection purposes. In addition, the assessment of remaining case prior to remanufacturing operations could provide significant economic advantages. These potential benefits to industry have fueled a moderate amount of research in the area over the past few decades [1-4]. However, despite this research, a reliable general purpose method has failed to emerge. While instruments and techniques exist for the measurement of case depth, these approaches tend to be empirical and are very application specific. Such methodologies are easily confused by changes in the base material grade or variations in heat treatment. Recent advances in modeling and model-based eddy-current and alternating-current potential drop methodologies offer perhaps the best hope of a solution [5]. However, model-based methods are in their infancy and are, for now, confined to laboratory trials.

There are two problems associated with the model-based characterization of layered ferromagnetic materials. Firstly, even in the simple case of a single layer on an infinite substrate, there are a total of five parameters (surface and substrate permeability and conductivity, surface layer thickness) that need to be determined. Secondly, there is degeneracy in μ-σ at all but the very lowest frequencies. Despite these difficulties, broadband alternating current potential drop and eddy-current measurements, made with great care and accuracy, have been used with some success to estimate case depth [3]. This work was motivated by a documented tendency of these inverse methods to over predict case depth [5]. Models used to represent variations in conductivity and permeability within the specimens assume that these parameters track the hardness profile. Surprisingly, little work has been done looking at the relationship between hardness profiles and electromagnetic properties. Glorieux [6] studied the relationship between thermal conductivity, hardness and microstructure but did not look at electromagnetic properties. The purpose of this paper is to assess whether or not hardness profiles can be used to estimate electromagnetic property profiles.

While carrying out eddy-current measurements [7-8], some researchers have noticed an effect that can be explained by the presence of a surface layer having unexpected electromagnetic properties. A second objective of this research is to attempt to identify any anomalous surface properties or behavior such as reduced permeability.

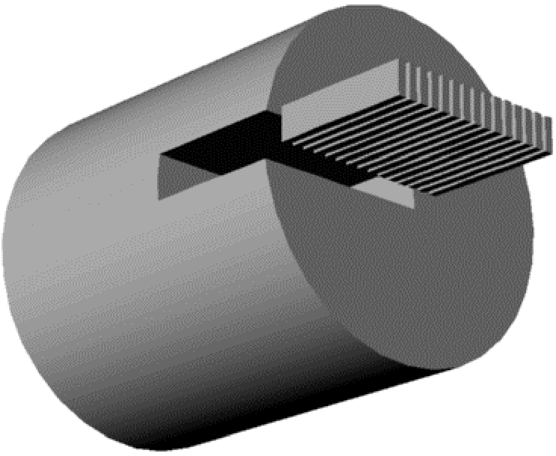

Figure 1. Slices were cut from the rod in an axial direction from the outside diameter of the rod to the central 'soft' interior.

2. Approach

In order to characterize electromagnetic property variations with depth in a heat treated component, it is necessary to make an individual assessment of samples cut from the component at different locations. Conductivity can be measured using a four-point DC resistivity measurement. Magnetic hysteresis measurements can then be used to determine magnetic B-H loop parameters. In both cases, it is convenient to use a specimen in the shape of a thin strip. For two reasons it is beneficial to choose a relatively large component with a deep case. Firstly, the effects of radius or curvature within a thin cut specimen can be readily neglected. Secondly, the transition region will be fairly large meaning that it can be sampled many times in order to build up an accurate representation of the region.

A 5 cm diameter steel rod (wt% 96.97 Fe, 2.07 Mn, 0.37 Cr) was induction hardened. During the induction-hardening process, carbon migrates towards the surface contributing to increased hardness. In some instances, decarburization is possible whereby near-surface regions actually lose carbon; this can complicate interpretation of electromagnetic measurement data. A number of 20 mm long axial slices were cut from the rod by means of electric-discharge machining (EDM). The slices were approximately 0.5 mm thick and 4 mm wide. The process of EDM results in a modified surface layer, the so-called white layer [9], basically a heat-affected zone. In order to eliminate the influence of the white layer on conductivity and magnetic measurements, the slices were hand-ground down to a final thickness of 100 µm.

A 100 mA constant current source was attached to either end of the strips using copper foil to ensure good electrical contact. The potential drop was measured at two points 1 cm apart between the current-injection points. Conductivity was calculated using the potential drop value and dimensional measurements obtained from the strip. Three separate thickness measurements were obtained from each strip and the value averaged. Magnetic hysteresis measurements were also carried out on the strips using a solenoid-field approach. Magnetic measurements provided values of magnetic remanence, coercivity, loss and initial permeability. Finally, a micro-hardness traverse was performed across the diameter of the original rod using a microhardness tester (Wilson® Tukon® Series 200) with a Vickers indenter. An applied load of 1000 gram was used. A minimum of five measurements were made at each depth to obtain an average hardness value.

A good fit of hardness data and electromagnetic property profile measurements can be achieved using the hyperbolic tangent function:

$$V = \frac{a_2 + a_1}{2} + \frac{a_2 - a_1}{2}\tanh(X - d) \qquad (1)$$

where V is the property being modeled (hardness, permeability, conductivity, etc), X is the depth below surface, a_1 is the initial (surface) value, a_2 the final (internal) value and d the midpoint of the function. In the case of a two-layer model where the layer thickness is defined as the midpoint between surface and substrate property values, the parameter d will be equal to the thickness of the upper layer. Equation (1) was fit to each set of electromagnetic and hardness profile data sets.

3. Results

Results from a micro-hardness traverse are shown in Figure 2. The data are typical for the induction hardening process, i.e. surface and core hardness values are constant, the transition region abrupt and symmetric. After fitting Equation 1, a midpoint of 16.4 mm is defined. This value represents the effective case depth that would be considered in a two-layer model [5]. In such a model, one set of electromagnetic properties are used to represent the upper 16.4 mm of the specimen and another set for all depths below 16.4 mm.

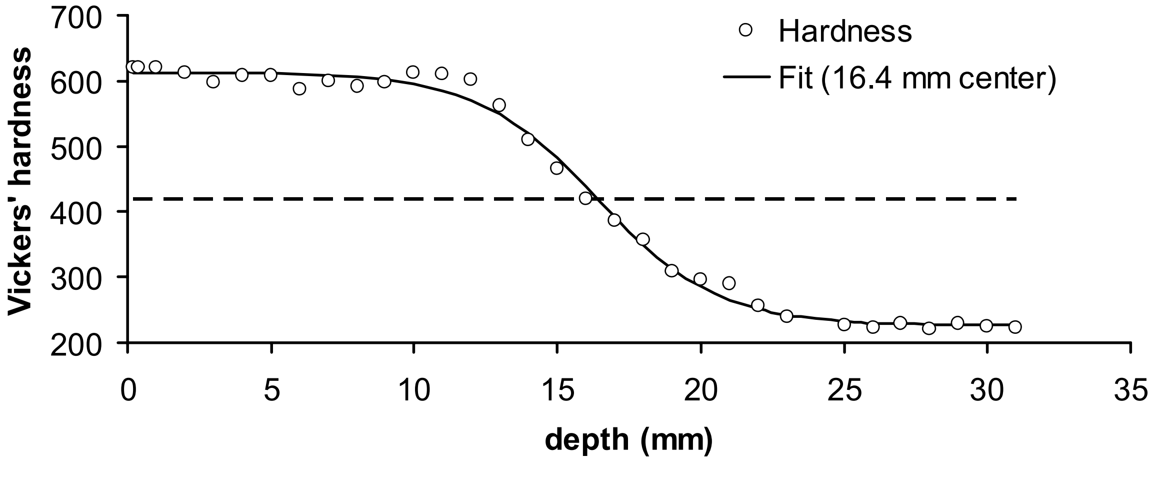

Figure 2. Results from a micro-hardness traverse of the 50 mm induction-hardened specimen. A fit of Equation 1 yields a midpoint value of 16.4 mm.

Remanence and initial permeability values are shown as a function of depth in Figures 3 and 4 respectively. Midpoint values come in at 18.7 and 19.1 mm respectively, the first indication that electromagnetic properties do not align with the hardness profile for the heat-treated steel specimen.

A similar set of curves was obtained for values of coercivity, loss and conductivity, the midpoint values being tabulated in Table 1. In Table 1, the percentage error between the Vickers hardness midpoint and electromagnetic property midpoints is given. This error can be used to estimate the over prediction made by model-based measurement systems due to the fact that electromagnetic properties do not align with hardness measurements. The issue is complicated by the fact that the error changes depending on which parameter is being studied. For example, the error is fairly small for conductivity (3.7 %) but very large for hysteresis loss (25.6 %). So, conductivity and hardness are closely correlated whereas loss and hardness are not.

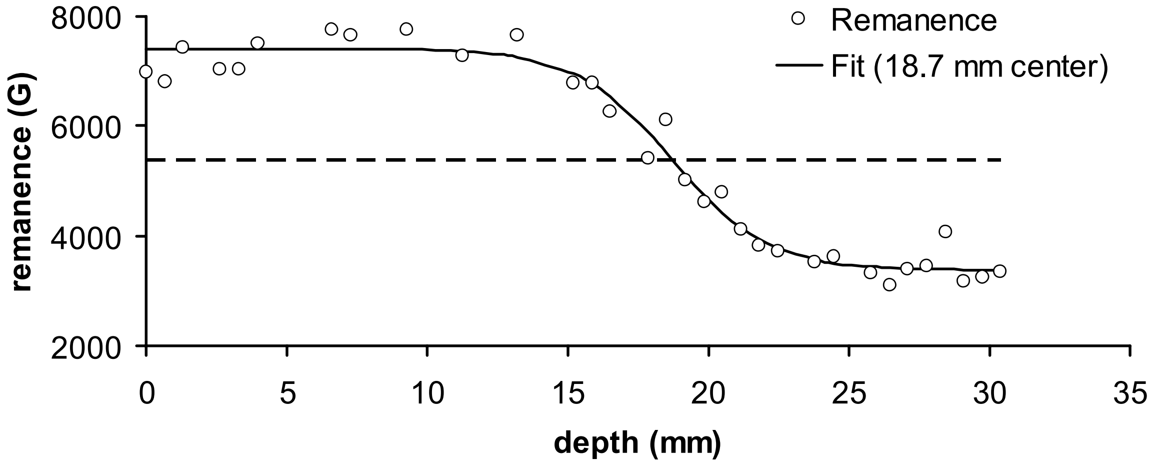

Figure 3. Magnetic remanence (Gauss) as a function of depth.

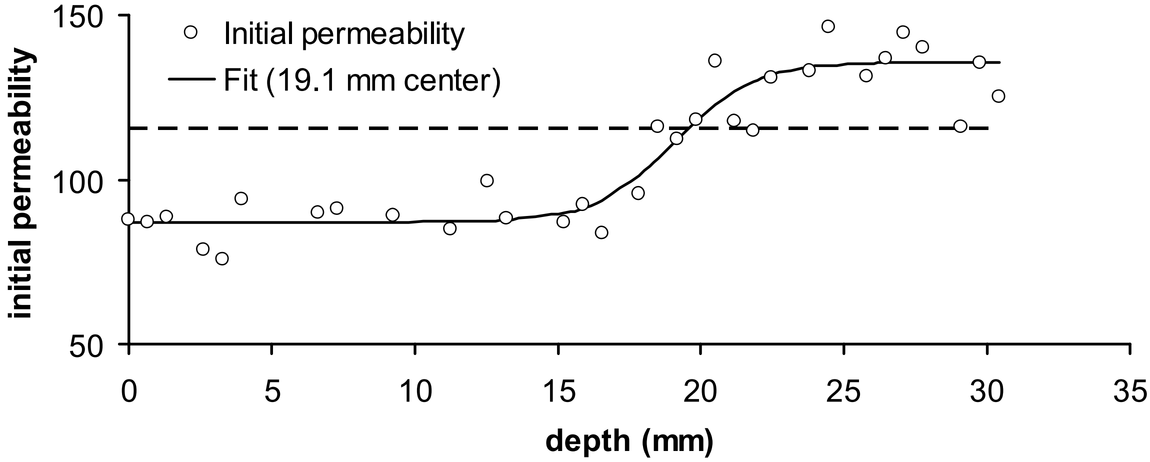

Figure 4. Initial permeability as a function of depth.

Table 1. Midpoint values following fitting of Equation 1. The percentage error can be used to estimate over prediction of a model-based approach that assumes alignment of hardness and electromagnetic properties.

Property	**Midpoint**	**Percentage Error**
Vickers hardness	16.4	n/a
Coercivity	17.9	9.1 %
Remanence	18.7	14.0 %
Conductivity	17.0	3.7 %
Initial permeability	19.1	16.4 %
Loss	20.6	25.6 %

In order to determine how the depth-dependent properties of the material compare with hardness values, it is convenient to normalize the data fitted by Equation 1. This normalization can be seen in Figure 5. From Figure 5 it can be clearly seen how model-based measurement systems overestimate case depth. Electrical conductivity values align fairly well with hardness measurements; however, magnetic measurements exhibit a significant lag with respect to actual hardness profiles. A two-layer model representing the hysteresis loss will have a thicker upper layer than a corresponding model representing Vickers hardness.

Micrographs were obtained from a variety of different depths, Figure 6. Of course it makes more sense to compare electromagnetic properties with microstructure rather than hardness. Hardness is a single-valued function of depth and cannot be expected to encompass all the complexities of the microstructure. For now only cursory attention is paid to the microstructure with a more complete analysis being saved for future studies. An ideal case-depth (ideal in the sense that it is free from arbitrary definitions such as those employed by Rockwell-C) can be defined at the hardness midpoint, see Figure 6. Visually speaking, a greater change in microstructure occurs at around 19 mm which happens to correspond to permeability and hysteresis-loss midpoint values. It is not unreasonable to assume large visual changes in microstructure lead to large changes in magnetic properties. Electrical conductivity is less affected by microstructure, perhaps correlating better with carbon concentration and therefore hardness.

Figures 7 and 8 show conductivity and magnetic coercivity as a function of depth. At first glance, these two figures may appear similar to those already presented. However, at the smaller depths some anomalous behavior can be observed. From the conductivity profile, Figure 7, it can be seen that the first four values are somewhat high. In other words, the outer 2-3 mm of the rod has a higher conductivity than expected. In addition, surface coercivity values, Figure 8, are somewhat lower than expected. For the time being, the origin of this phenomenon is unknown. However, it is likely that this effect, unless accounted for, could result in a significant error in model-based measurement systems.

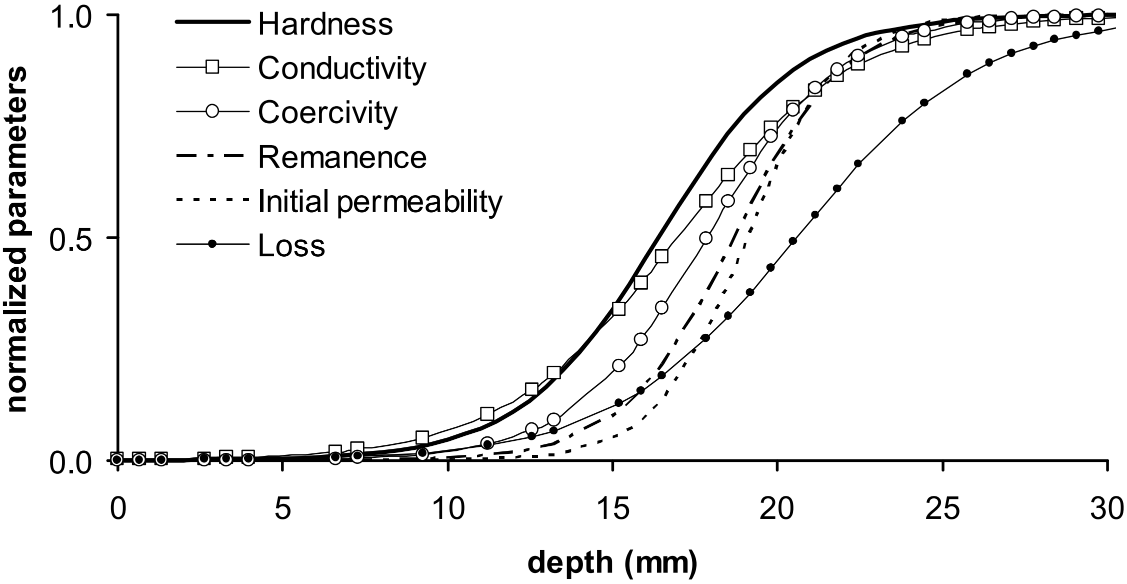

Figure 5. Normalized hardness and electromagnetic profiles. Significant discrepancies between hardness and some of the magnetic properties are observed.

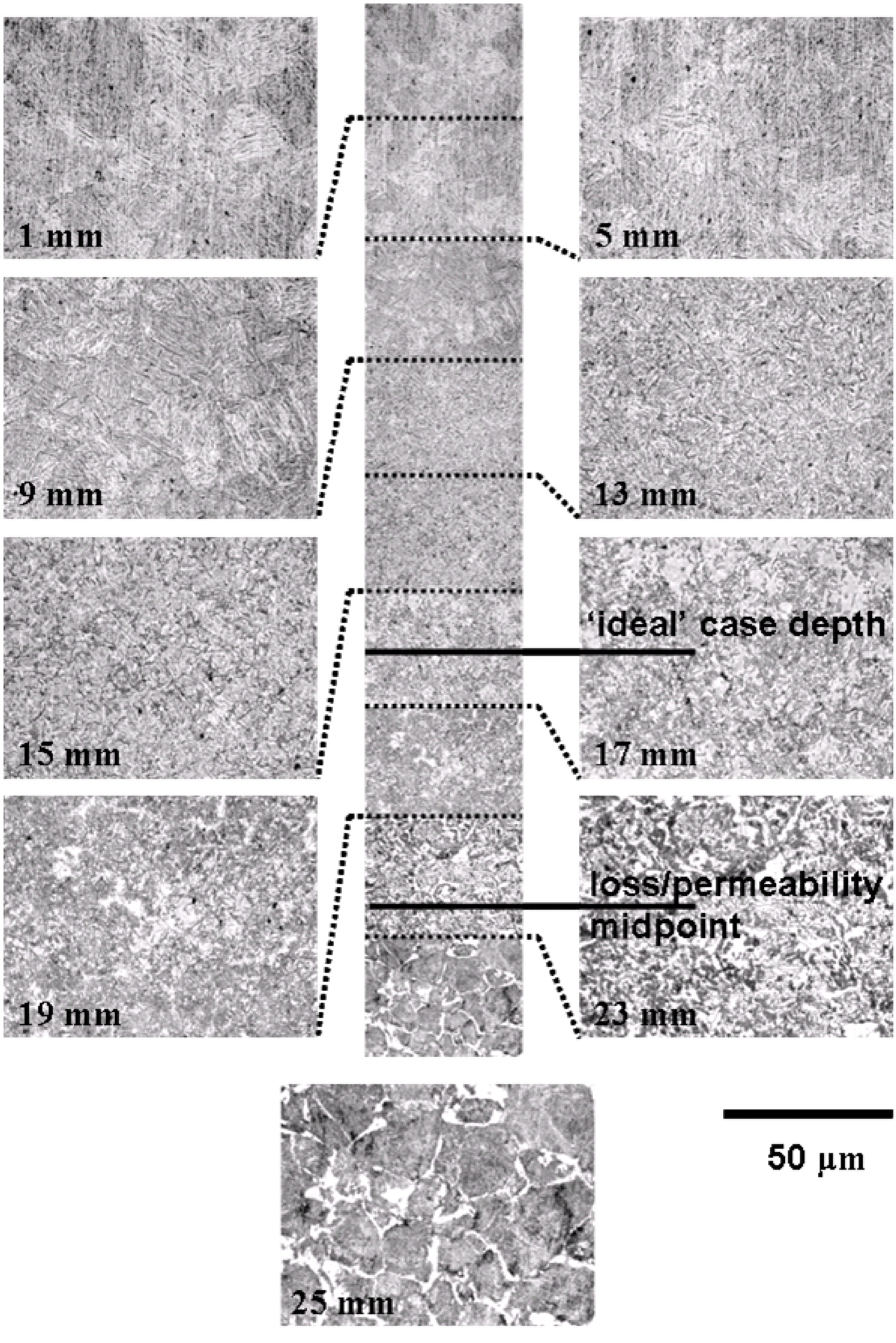

Figure 6. Micrographs taken at different depths (mm) below the surface of the induction hardened rod. The central strip is a composite and does not contain micrographs from all regions of the actual strip. Microstructures present: 2.5 mm to 12.7 mm: martensite, 15.2 mm to 17.8 mm: mixture of martensite and ferrite/pearlite, 20.3 mm: fine-grained ferrite/pearlite, 22.9 mm: coarse-grained ferrite/pearlite. The 'ideal' case depth (hardness midpoint) and loss/permeability midpoints are shown.

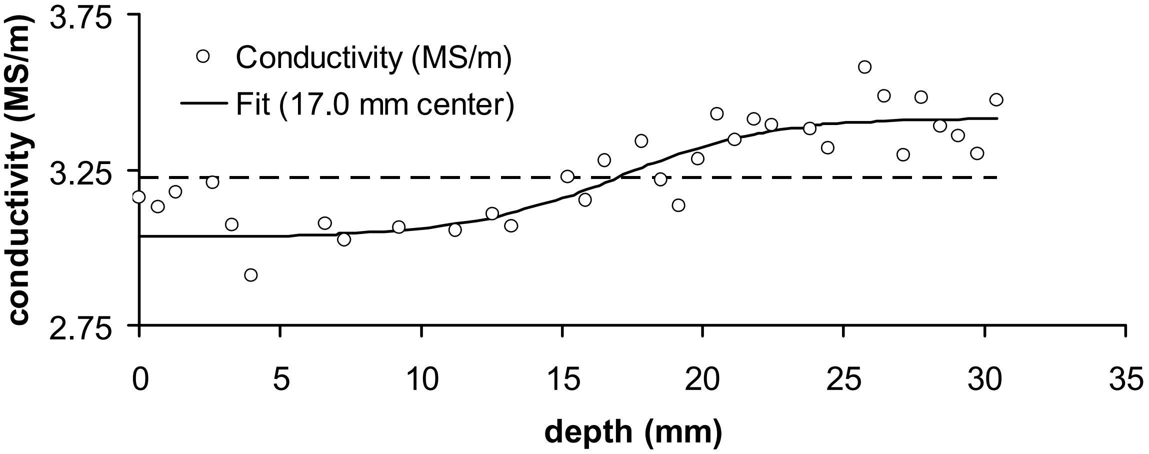

Figure 7. Conductivity as a function of depth. The top three mm of the rod have an unexpectedly high conductivity.

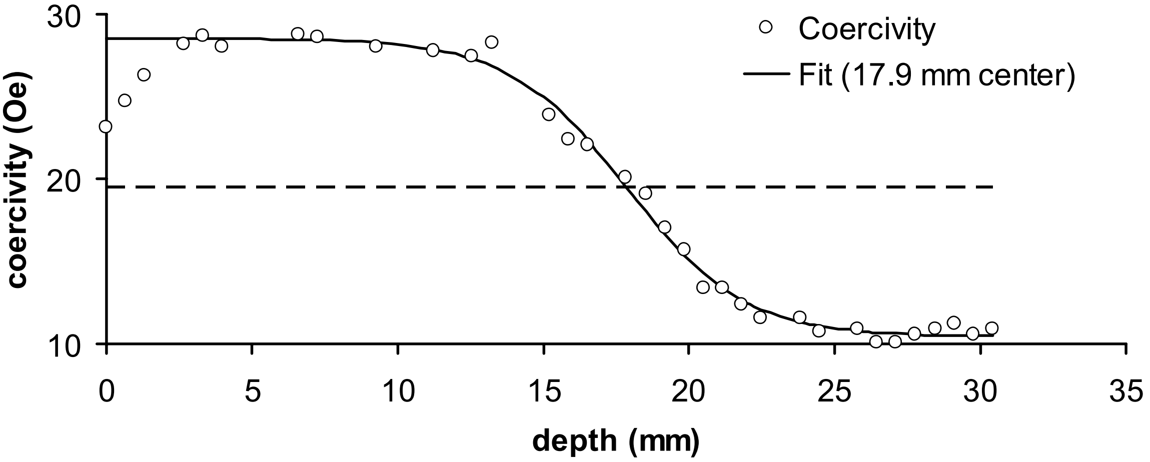

Figure 8. Coercivity as a function of depth. Surface coercivity values appear to be lower than expected.

4. Conclusions

The electrical and magnetic properties of an induction-hardened steel rod have been profiled and compared with hardness values and, to a lesser extent, microstructure. Electromagnetic properties such as the hysteresis loss and initial permeability appear to lag significantly behind the specimen's hardness profile leading to a potential over prediction by model-based measurement methodologies. Conversely, electrical conductivity appears to track hardness fairly well. A solution to enable model-based approaches to function correctly would be the application of a correction term specific to the material and treatment type. Future work will look at different materials and also correlate electromagnetic properties with microstructure in more detail.

Some anomalous values for surface conductivity (the upper 2-3 mm) and coercivity were observed. The effect is not obviously reflected in the micrographs but it is possible that the high surface conductivity could be a result of migrated carbon although we have no direct evidence for this. Future research should verify the phenomena and attempt to offer physical explanations, in the near future we plan to study carbon concentration in the individual strips. It is certain that high surface values of conductivity will impact model-based inversion strategies in a negative way so a thorough understanding is essential.

Acknowledgements

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References

[1] R. Palanisamy, Prediction of Eddy Current Probe Sensitivity for The Sizing of Case Depth in Ferrous Components, *IEEE Trans. Mag.*, **Vol. 23** , 1987, pp. 3308 – 3310.

[2] B. Zhu, M. J. Johnson and D. C. Jiles, Evaluation of wear-induced material loss in case-hardened steel using magnetic Barkhausen emission measurement, *IEEE Trans. Mag.*, **Vol. 36** , 2000, pp. 3602 – 3604.

[3] D. C. Jiles, R. Kern and W. A. Theiner, Evaluation of surface modifications in high strength steels, *Nondestructive Testing & Evaluation*, **10**, 317, 1993.

[4] B. Zhu, M. J. Johnson and D. C. Jiles, Magnetic Measurement of Material Loss in Case-Hardened Steel Using a New Barkhausen Effect System, International Magnetics Conference, Toronto, Canada, April 9-13, 2000: *IEEE Transactions on Magnetics*, **36**, 3602, 2000.

[5] H. Sun, J. R. Bowler, N. Bowler and M. J. Johnson, Eddy-Current Measurements on Case-Hardened Steel, Review *of Progress in Quantitative Nondestructive Evaluation*, **21B**, pp. 1561-1568, 2001.

[6] C. Glorieux, C. Desmet, W. Lauriks, M. Wevers, and H. Coufal , Photothermal and Elastic Characterization of a Hardened Steel Rod, *Progress in Natural Science*, 1996, pp. 406-408.

[7] J. H. Rose, C. –C. Tai and J. C. Moulder, Extreme Sensitivity of Eddy Currents to the Surface Condition of Nickel, *Review of Progress in Quantitative Nondestructive Evaluation*, **16**, pp. 249-255, 1997.

[8] J. C. Moulder, C. –C. Tai, B. Larson and J. H. Rose, Inductance of a Coil on a Thick Ferromagnetic Plate, *IEEE Trans. Mag.*, **34**, pp. 505-512, 1998.

[9] L. C. Lee, L. C. Lim,V. Narayanan and V. C. Venkatesh, Quantification of Surface Damage of Tool Steels After EDM, *International Journal of Machine Tools & Manufacture*, **28**, No. 4, pp. 359-372, 1988.