Industrial Problems Encountered in the Eddy Current Inspection of Steel

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Industrial Problems Encountered in the Eddy Current Inspection of Steel

Abstract
It is anticipated, that through exposing some of the problems encountered in industrial applications of eddy current technology, technical assistance may be generated through the theoretical community. The specific problem examined involves the development, storage and utilization of calibration masters. Although the use of probes versus coils greatly reduces the number of calibration masters in that probes are not sensitive to overall geometry and mass variations, the eddy current response is influenced by near probe geometry variations. At present, an empirically derived algorithm is relied upon to characterize this phenomenon although it is hoped that an appropriate theoretical model will be developed. In addition to geometry, the non-linear permeability present in ferromagnetics, and the microstructural and compositional variations greatly increase the complexity of constructing such a model.

Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering
INDUSTRIAL PROBLEMS ENCOUNTERED IN THE EDDY CURRENT INSPECTION OF STEEL

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ABSTRACT

It is anticipated, that through exposing some of the problems encountered in industrial applications of eddy current technology, technical assistance may be generated through the theoretical community. The specific problem examined involves the development, storage, and utilization of calibration masters. Although the use of probes versus coils greatly reduces the number of calibration masters in that probes are not sensitive to overall geometry and mass variations, the eddy current response is influenced by near probe geometry variations. At present, an empirically derived algorithm is relied upon to characterize this phenomenon although it is hoped that an appropriate theoretical model will be developed. In addition to geometry, the non-linear permeability present in ferromagnetics, and the microstructural and compositional variations greatly increase the complexity of constructing such a model.

There are two kinds of talks one encounters at technical conferences such as this one, those which expose and those which solve problems. This presentation will be of the former type and will attempt to elucidate in a more detailed fashion some of the difficulties encountered in the eddy current materials sorting of steel. It is hoped that constructive feedback will be generated from the theoretical community, to the benefit of those of us in industry. The specific problem examined today will involve the influence of steel component curvature on eddy current response.

It might be helpful to review exactly how the influence of component curvature on probe response became a concern and how the problem is being dealt with presently. The important theoretical factors in developing a model descriptive of the phenomenon will be examined.

Most of those present here should be familiar with the basic differences between through coil and probe eddy current inspection techniques. Yet the relative advantages for specific applications are not always appreciated. In Table 1 a detailed comparison is presented for the specific application of heat treatment materials sorting. Both techniques provide excellent sorting capabilities, are available in relatively inexpensive commercial systems and provide inspection speed capacities comparable to many production operations. The coil technique, however, does not focus on the component region of interest whereas the probe can be often located to examine the area of concern. In view of this insensitivity to overall geometry variations, the use of probes, in many applications, substantially reduces mastering requirements.

The most serious limitation in the use of probes involves the strict demands for probe-specimen orientation control, and the dependence of probe response on local component geometry variations. It is with this last point that we are primarily concerned in this presentation, namely the dependence of eddy current response on component curvature.

The populations of eddy current response for four different carburized steel cylinders are shown in Fig. 1. In these data a comparison is being made between properly and improperly heat treated materials. In directing our attention to the influence of curvature, it is observed that the eddy current response increases statistically with diameter. This may be interpreted as an increase in the penetration of flux and a corresponding increased interaction with the detection coil in the probe. A similar influence of curvature is observed for a hollow cone (see Fig. 2).

The variation in probe response due to curvature introduces a mastering difficulty tending to decrease the advantage that probes enjoy over through coil techniques. This effect is presently accommodated through a normalization procedure in which empirically derived algorithms adjust the mastering response (see Figs. 3 and 4).

The curves generated from these algorithms are shown in Fig. 5 in relation to the pertinent statistical data. From an engineering standpoint, this approach is satisfactory in establishing sorting limits. However, through the development of a viable theoretical model, increased confidence, predictability, and the suppression of the amounts of statistical data required may be obtained. There are four major
areas requiring consideration in constructing an appropriate theoretical model. They are:

1. The nature and distribution of the probe field.
2. The nature and distribution of the field generated eddy currents.
3. The construction of a mathematical model accommodating the specific boundary conditions as well as the nature and distributions of field and eddy currents.
4. The influences of simplifying approximations on the representative character of the proposed models.

The nature and distribution of the field are dependent upon the specific probe characteristics. These characteristics include coil current, frequency, number of turns, coil area, orientation, and the influence of core material. In addition, the probe may be composed of multiple coils for separating the field generating primary from the detecting secondary, or in a differential arrangement to suppress extraneous noise. The influence of probe characteristics could prove to be one of the most difficult considerations in any theoretical treatment.

The origin, nature and distribution of the eddy currents will be dependent upon the field, the probe-specimen geometry and the electromagnetic properties of the steel specimen. There are few theoretical attempts to explain eddy current phenomena in ferromagnetic, non-linear permeability (μ) materials in contrast to linear, non-ferromagnetic conductors. Analytical solutions have been primarily restricted to assumed linear conditions.

Utilizing the concepts of a linear relationship between the phasor quantities B and H and a representation of hysteresis through complex permeability (in which the B/H characteristic is elliptical through the introduction of a phase lag φ between B and H), D. O'Kelly (1, 2, 3, 4) has calculated the flux distributions and the hysteresis and eddy current losses in steel plates (Fig. 6). The principles applied to the analysis of the fundamental component of B and H were also applied to harmonics providing additional accuracy (2). One other popular approach involves the numerical analyses of network models in which non-linear effects are accounted for in a discretized fashion (5, 6).

For non-linear conditions, many numerical techniques have been utilized with digital computers to obtain solutions. However, most finite element computations have ignored hysteresis effects or employed representation techniques. As one can see, there are several available theoretical approaches to choose from in modeling eddy currents while taking into account non-linear effects.

In the treatments above, it is commonly assumed that the material is homogeneous and isotropic. In actual eddy current inspection of steel, microstructural and compositional variations will greatly influence electromagnetic properties. These effects are especially pronounced when the process involves special compositional treatments such as carburizing, in which a hardened surface layer is created through the impregnation of carbon (Fig. 7). The resulting carbon gradient produces both a compositional effect and will significantly alter the microstructure.

Carbon, both in solution and in precipitated forms, reduces permeability (μ) (Fig. 8) and the saturation induction B_s (Fig. 9) while the coercive force H_c (Fig. 10) and hysteresis loss (Fig. 19) are increased (7). Heat treatment and thermal history have a synergistic influence with composition on the electromagnetic properties. This synergism influences the electromagnetic properties in steels in the same manner as its controls the mechanical properties, namely through regulating microstructure. Many of the variations in magnetic properties are the result of morphological differences and not simply base composition changes. As one might expect, these combined effects are more pronounced at higher carbon levels.

The precise manner in which the electromagnetic properties of steel depend upon composition and microstructure may be classified under four headings:

1. The carbon and alloy content of the primary magnetic phases (i.e. martensite or ferrite).
2. The structure of the primary ferromagnetic phases.
3. The volume percent and distribution of retained non-ferromagnetic (paramagnetic) austenite.
4. The volume percent and distribution of non-ferromagnetic carbides.

The influence of non-magnetic phases has been aptly described in "Metallurgy and Magnetism" by James Stanley (7):

"Non-ferromagnetic phases or inclusions such as graphite in cast iron or slag in wrought iron have an effect on the magnetic properties similar to that produced by cutting an air gap in a solid magnetic ring. A similar effect takes place when the gaps are internal which is in reality what happens when a non-ferromagnetic phase or inclusion is present. This is shown in Fig. 43" (Fig. 12) "For the case of steel with different amounts of carbon (the cementite of the pearlite is relatively non-magnetic)."
Although carbon is one of the major modifiers of electromagnetic properties it is by no means the only one. Silicon, aluminum and other alloying elements are known to reduce saturation values and permeability (Fig. 14). The influence of these alloy additions is also very dependent upon the heat treatment.

Composition and microstructure will correspondingly affect electrical conductivity (Fig. 15). Increasing alloy additions, when in solution, will generally decrease conductivity. When microstructural factors become important, the effects become more difficult to predict. Nevertheless, the eddy currents generated will be affected through variations in conductivity.

Extensive efforts have been made at Timken Research to determine the electromagnetic properties of the steels of interest. This effort has included an examination of the influence of composition and heat treatment. Preliminary results may be qualitatively summarized as follows.

In Fig. 16 the B - H characteristic curves for core and case structures are compared. The case displays substantially reduced magnetic properties. This decrease is either the result of high carbon content, high carbide content or the presence of retained austenite. Further exploration of this reduction in properties will be performed in order to understand the individual contributions of the carbon and retained austenite.

The effects of over-tempering are presented in Fig. 17 for core and case respectively. The drastic increase in magnetic properties in the case is attributed to the decomposition of retained austenite into bainite, although the precipitation of carbides and the associated migration of the BCT martensite structure to the equilibrium BCC ferrite structure may also be playing a significant role. In the core, similar increases occur although in view of the originally high properties the improvement with over-tempering is not as dramatic. The increase observed in the core may be attributed to the precipitation of carbides and the corresponding formation of high magnetic properties.

These hysteresis curve effects need to be more fully understood as they depend upon alloy content and heat treatment. The frequency of inspection is also a parameter of great importance in case carburized component inspection in view of the influence that frequency has on depth of penetration.

Once the specific conditions of probe field, material properties and geometry are well defined, the development of a comprehensive mathematical model and the selection of appropriate approximations are all that remain. These two factors were indirectly examined in the previous discussions regarding the available analytical models. Any attempt at combining all of the above considerations in constructing a theoretical model for the effect of curvature on the eddy current response in case carburized steel may prove intractable. Nevertheless, continued research efforts are scheduled at The Timken Company and substantial benefits are anticipated. For those engaged in similar efforts, or who may be able to provide insight into this complex problem, the development of future correspondence would be greatly appreciated by the authors.

REFERENCES
7. J. K. Stanley, "Metallurgy and Magnetism", ASM, 1949, Cleveland, Ohio
### TABLE 1
**Comparison between Coil vs Probe Eddy Current Material Sorting of Case Carburized Cylinders**

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TECHNIQUE</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SORTING CAPABILITY</strong></td>
<td>COIL</td>
<td>Good sort for many applications</td>
<td>Ambiguities exist for some heat treat conditions</td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td>Good sort for many applications</td>
<td>Ambiguities exist for some heat treat conditions</td>
</tr>
<tr>
<td><strong>AVAILABILITY AND EXPENSE</strong></td>
<td>COIL</td>
<td>Inexpensive commercial systems available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td>Inexpensive commercial systems available</td>
<td></td>
</tr>
<tr>
<td><strong>AREA OF EXAMINATION</strong></td>
<td>COIL</td>
<td>Whole part examined</td>
<td>Does not focus in area of interest</td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td>Focuses on area of interest</td>
<td>Restricted to examining only one area of part</td>
</tr>
<tr>
<td><strong>PART-PROBE ORIENTATION</strong></td>
<td>COIL</td>
<td>Not critically sensitive to part position in coil</td>
<td>Lift off and part probe must be controlled or compensated for</td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1 (Continued)**

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TECHNIQUE</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HANDLING AND INSPECTION SPEED</strong></td>
<td>COIL</td>
<td>Continuous fast, simple, amenable to many high speed production lines</td>
<td>Sophisticated handling required</td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MULTI MODE/MULTI FREQUENCY CAPABILITY</strong></td>
<td>COIL</td>
<td>Presently employed in available systems</td>
<td>Would require discontinuous operation, results in reduced speed</td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MASTERING AND CALIBRATION</strong></td>
<td>COIL</td>
<td>Easy calibration with reference master</td>
<td>Requires separate master for every part...inventory nightmare</td>
</tr>
<tr>
<td></td>
<td>PROBE</td>
<td>Easy calibration reduces mastering inventory substantially</td>
<td>Must account for near probe geometry variations</td>
</tr>
</tbody>
</table>
FIG. 1 EDdy CURRENT RESPONSE FOR HOLLOW STEEL CYLINDERS

- AVERAGE (x) = \( x + 3 \phi \)

FIG. 2 EDdy CURRENT RESPONSE FOR HOLLOW CONE (REGION OF VARIATION RESULTING FROM ECCENTRICITY IN CARBURIZED CONE CASE DUE TO DISTORTION IN QUENCHING)

APPROXIMATED ASYMPTOTE

FIG. 3 PLOT OF ALGORITHM, \( Y = 117 - 176.6 \exp \left(-0.95729x\right) \).
EMPIRICALLY DERIVED TO FIT \( x + 3 \phi \) (A)

FIG. 4 PLOT OF ALGORITHM, \( Y = 135 - 163 \exp \left(-0.87604x\right) \).
EMPIRICALLY DERIVED TO FIT \( x + 3 \phi \) (B)

FIG. 5 SUPERIMPOSITION OF CURVES GENERATED FROM ALGORITHMS ON EDdy CURRENT DATA

FIG. 6 IDEALIZED ELLIPTICAL REPRESENTATION OF HYSTERESIS

<table>
<thead>
<tr>
<th>Typical B/H Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idealized B/H Curve Assuming Sinusoidal Flux Density B</td>
</tr>
<tr>
<td>Idealized B/H Curve Assuming Sinusoidal Magnetization Force H</td>
</tr>
</tbody>
</table>

(See Refs. 1-4)
FIG. 7
COMPOSITIONAL AND MICROSTRUCTURAL EFFECTS IN CARBURIZATION

FIG. 8
Max. Permeability Vs. Carbon 0.6% Silicon

FIG. 9
SATURATION INDUCTION
4711 A, GAUSSES

FIG. 10
Effect of Carbon on Coercive Force (Koster)

FIG. 11
Hyysteresis Loss, Eqv. sp. Grd. for B=10,000

FIG. 12
Steels Prepared From Electrolytic Iron and Graphite
Deoxidized With Silicon
Tests Made on Normalized Carbon Steel Rings
Furnace-Cooled From 700°C (1290°F) After Machining
Pure Iron Annealed 50 Hours 875°C Carbon 0.002%
(See Ref. 7)
FIG. 13
Quenching Temperature°F
1470 1650 1830 2010
1380 1560 1740 1920 2100
Plain Carbon Steels, Water-Quenched

Retained Austenite, %

1.75% C
1.60%
1.33%
0.97%
0.57%
0.32%

1.33% Carbon Steel 100mm Diam.
Water-Quench
Oil-Quench

Quenching Temperature°C

(SEE REF. 7)
FIG. 16
CORE - HARDENED AND TEMPERED

FIG. 17
CORE - OVERTEMPERED

CASE - HARDENED AND TEMPERED

CASE - OVERTEMPERED