EDDY CURRENT CHARACTERIZATION OF APPLIED AND RESIDUAL STRESSES

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ABSTRACT

An exploratory investigation was conducted to evaluate the applicability of state-of-the-art eddy current nondestructive evaluation techniques to the characterization of applied and residual stresses in structural steels. Eddy current response versus stress measurements were developed for ASTM Type A533B and A471 steels under tensile, bending and residual stress loading conditions. A "shrink fit" specimen was used to establish applicability to residual stresses. Results show that an eddy current approach can be used to provide an accurate quantitative measure of surface stresses. The technique can also be used to map surface stress contours. Details of the procedure are described along with the test results and proposed applications. Recommendations for further work needed to optimize and expand the technique are included.

INTRODUCTION

Accurate knowledge of the stresses and strains associated with the service loading of structural components is critical to the design of safe, efficient hardware. Common practice is to estimate expected loading conditions through the use of analytical methods and subsequently, to verify these estimates through model testing or in-service monitoring of operating equipment. Experimental measurement of stresses and strains involves the use of "strain gages" (electrical resistivity gages designed to respond to changes in strain) which must be mounted (with adhesives) on the hardware of concern at the specific locations of interest. The hardware is
then loaded and measurements of strain made at each gage. The
strain measurements are converted to applied stress values using
Youngs Modulus for the structural material involved yielding an
experimental stress analysis. This approach to stress analysis,
while often used successfully, has several significant limitations.
Specifically, strains can only be measured at the predetermined gage
locations, expensive and complex slip ring or telemetering equipment
is required to monitor strains in rotating equipment and strain
gages alone cannot be used to detect residual stresses which may
have developed during fabrication. In view of these limitations,
alternate methods of monitoring stresses and strains have long been
the subject of research and development efforts aimed at improving
experimental stress analysis capabilities. To date, considerable
attention has focussed on the applicability of nondestructive
evaluation methods (NDE) to measure applied and residual stresses.
Progress in this area has been limited despite intense research
investment. In a recent EPRI report and related publications, Ruud
has presented an extensive state-of-the-art review of NDE methods
for residual stress measurements.\textsuperscript{1–3} This work has led to the
conclusion that x-ray diffraction techniques combined with the
destructive methods of hold drilling and ring boring will remain
the most reliable approaches to residual stress measurements for
the near future. Problems and limitations associated with other
techniques such as ultrasound, electromagnetics, neutron diffraction,
etc. place these concepts into the long range development category.
Similar conclusions were developed in a recent survey conducted by
Mordfin.\textsuperscript{4}

Despite this rather discouraging prognosis, recent experience
at Westinghouse clearly indicates that the presence of applied or
residual stresses have a very significant effect on the eddy current
response associated with the characterization of small surface
defects. These observations led to questions concerning the possible
applicability of state-of-the-art eddy current NDE methods for the
characterization of applied and residual surface stresses. This
report describes the results of an exploratory investigation into
the use of eddy current (EC) methods to measure surface stresses in
both a low alloy pressure vessel steel (ASTM A533) and a heavy
section forging steel (ASTM A471).

PRINCIPLES OF EC TESTING

The basic concept underlying the use of eddy current techniques
to characterize the properties of materials is the relationship
between material structure (microstructure, texture, etc.) and
electromagnetic behavior.

More specifically, eddy current testing relies on the electro-
magnetic interaction between a coil driven by an alternating electric current and the material under test. This interaction is governed by Faraday's law which says that an electrical conducting loop (coil) placed in a changing magnetic field has a voltage generated across the ends of the loop which is proportional to the time rate of change of the field enclosed by the loop. If the loop is closed, a current flows in the loop in the direction opposite to the change in the magnetic field. If the loop is replaced with a conducting plate, the changing magnetic field produces a current in the plate which flows in closed loops and is referred to as an eddy current field. Eddy current testing uses as the source of the changing magnetic field an inspection coil which is driven by an alternating electric current. The voltage across the coil is proportional to the time rate of change of the magnetic flux generated by the coil. However, as the coil is brought near a metallic surface the total magnetic flux seen by the coil is changed by the currents generated in the surface. In turn, the coil voltage is altered.

With the coil driven by a sinusoidal varying current, the relationship between the voltage and current is given by the steady state equivalent of Ohms law, \( V = IZ \) where \( V \) is the voltage across the coil, \( I \) is the current in the coil and \( Z \) is the impedance of the coil. In general, the impedance is composed of two orthogonal components. One is associated with the resistance losses in the coil and the other associated with the inductance of the coil. The effect of bringing the coil near a metallic surface is to alter the coil impedance by introducing changes in both the loss and inductive components. For a particular coil-material interaction, the exact value of the coil impedance will depend on: (1) the coil geometry, (2) the spacing between the coil and the material, (3) the electrical conductivity of the material, (4) the magnetic permeability of the material and (5) the frequency at which the coil is excited. In general, the characterization of materials with a conventional eddy current NDE system involves the measurement of impedance changes rather than impedance alone. Specifically, the presence of a surface flaw can produce a significant change in impedance as compared to the unflawed material yielding an effective flaw detector. All eddy current data reported in this investigation involve the measurement of impedance changes.

In order to measure applied or residual stresses with a conventional eddy current approach, the application of stress must change either the conductivity or permeability of the material such that a detectable change in test coil impedance occurs. For ferromagnetic materials it is well known that the application of stress (strain) will alter both the electrical and magnetic properties. This phenomenon provides the basic concept underlying the possible use of eddy current techniques to measure applied and residual stresses in structural steels.
### Table 1
Test Material Properties

#### Chemical Composition, Wt %

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Cu</th>
<th>Al</th>
<th>Sn</th>
<th>Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A533</td>
<td>0.20</td>
<td>1.38</td>
<td>0.013</td>
<td>0.005</td>
<td>0.25</td>
<td>0.65</td>
<td>0.18</td>
<td>0.57</td>
<td>---</td>
<td>0.19</td>
<td>0.043</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>A471</td>
<td>0.29</td>
<td>0.68</td>
<td>0.007</td>
<td>0.012</td>
<td>0.27</td>
<td>3.05</td>
<td>1.00</td>
<td>0.64</td>
<td>0.09</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

#### Room Temperature Tensile Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2% Yield Strength ksi (MPa)</th>
<th>Tensile Strength ksi (MPa)</th>
<th>% Elongation</th>
<th>% Reduction in Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>A533</td>
<td>95 (656)</td>
<td>107 (738)</td>
<td>25</td>
<td>65</td>
</tr>
<tr>
<td>A471</td>
<td>111 (766)</td>
<td>130 (897)</td>
<td>20</td>
<td>60</td>
</tr>
</tbody>
</table>
TEST MATERIAL

The test materials selected for evaluation in this investigation included two ferromagnetic steels widely used in the power generation industry. These included a low alloy, intermediate strength pressure vessel steel; ASTM A533 and a low alloy heavy section forging steel; ASTM A47l. The chemical composition and room temperature tensile properties of the test materials are given in Table 1. Both steels were tested in the quenched and tempered condition. The A533 steel had a bainitic structure and a prior austenitic grain size of 6 to 8 (ASTM E112). The A47l steel was also bainitic and had a prior austenitic grain size of 7 to 9 (ASTM E112).

TEST PROCEDURE

Evaluation of the interaction between eddy current response and both applied and residual stresses was conducted with the three simple test specimens illustrated in Figure 1. Tensile tests were conducted with both the A533 and A47l steels. Bend and residual stress (shrink fit specimen) tests were limited to the A47l steel. All test surfaces in each specimen were prepared by point machining to a 16 microinch (0.4μ) finish. The tensile test specimens were used in the as machined condition. The bend bar was stress relieved for 1 hr at 1000°F (538°C) in an inert environment prior to testing. The top and bottom faces of the shrink fit specimen were lightly hand sanded to remove a surface oxide which developed during the 1000°F (538°C) shrinking operation.

The shrink fit test specimen was designed to develop a variation in residual stresses along the axis of the disc bore, thus the tapered pin. However, work in this investigation was restricted to the top and bottom surfaces of the original specimen. The specimen was designed to develop maximum bore face hoop stresses on the order 70 ksi (483 MPa) at the top surface and zero at the bottom face.

For the tensile and bend bar experiments, an eddy current probe was hand held on the appropriate test specimen surface as the load was increased in convenient increments. The eddy current response was then recorded as a function of the calculated applied stress. Both the tensile and bend tests were conducted with a servo-hydraulic universal test machine. Data were collected while loading and unloading the specimens and several runs were conducted in most experiments.

In the case of the residual stress (shrink fit) specimen, a hand held probe was used to map the O.D. to I.D. eddy current
response associated with variations in stress. Again several traces were made on the top and bottom of the test disc.

In all cases the eddy current data were collected with a 0.25 in. (0.64 cm) diameter, "pancake" type probe driven at 400 kHz by a Zetek EM3300 nondestructive testing instrument. Prior to

Fig. 1. Test specimens used to evaluate eddy current-stress interactions.
loading the test specimens, the instrument was balanced to a zero reading with the coil in contact with the specimen surface. Limited data were also collected with the coil driven at 10 kHz to explore frequency affects.

TEST RESULTS

The results associated with each test specimen and method of loading involved in this investigation are presented separately in the following sections.

Tensile Testing

Figures 2 and 3 show the correlation between eddy current response (change in impedance) and applied stress for the A471 and A533 steels, respectively. Note that in both cases an excellent linear correlation exists between tensile stress level and eddy current response. Figure 3 shows that the data are reproducible and relatively little scatter is encountered in the test. The differences in results under loading and unloading conditions appear to reflect a small magnetic hysteresis affect. Note that the relationship between eddy current response and applied stress is different for each steel. Figure 4 presents test results developed for the A533 steel at 10 kHz. Note that it is the qualitative response that is of interest and any differences in response at 10 kHz versus 400 kHz (Fig. 3) simply reflect a difference in instrument calibration for the two frequencies.

Bend Testing

The NiCrMoV type ASTM A471 steel bend bar was tested under three-point loading to evaluate bending conditions and to establish the applicability for mapping stress contours. Figure 5 shows the correlation between eddy current response and applied stress under increasing and decreasing load conditions in three-point bending. In this case the probe was located at the center of the specimen (maximum stress point) and data collected as the specimen was loaded and unloaded. Two sets of data were collected. As in the tension tests (Figures 2-4), the correlation between eddy current response and applied stress is good, the data are reproducible and little scatter is encountered in the test.

Figure 6 presents the results of the eddy current evaluation of the bend bar under three-point loading conditions where the specimen was loaded to a maximum outer fiber bending stress of 100 ksi (690 MPa). The 12 in. (30.5 cm) long bar was supported at the 1 in. (2.54 cm) and 11 in. (280 cm) axial positions and loaded at the 6 in. (15.2 cm) position. In this case the probe
Fig. 2. Eddy current response vs. applied stress.

Fig. 3. Eddy current versus stress response.
Fig. 4. Eddy current versus stress response, 10 kHz.

Fig. 5. Eddy current response versus applied stress (bending).
was moved to scan the as-loaded bar surface between the loading span and the eddy current response recorded as a function of probe position along the axis of the bar. Two sets of data were collected to demonstrate reproducibility. In addition, data were collected under "no-load" conditions for comparison purposes. Figure 7 shows the "no-load" results. Note that the eddy current results for the loaded bar form a triangular pattern nearly identical to the expected stress contour for a rectangular bar in three-point bending (a uniform triangular stress gradient as noted in Fig. 6). The fact that the peak load position as indicated by the eddy current data does not line up directly with the 6 in. (15.2 cm) axial position (expected maximum load point) was caused by misalignment of the bend bar discovered after collection of the data.

The data in Figure 6 again demonstrate good reproducibility and little data scatter for the case of the loaded and unloaded specimen. Clearly, the eddy current characterization of applied stress developed in this investigation can be used to accurately map stress conditions in a simple test specimen.

Residual Stress Characterization

The shrink fit test specimen was used to evaluate the applicability of the eddy current-stress correlation to the characterization of residual stresses. In this case the disc
specimen with the pin in place was examined at 400 kHz with the 0.250 in. (0.64 cm) diameter probe. Specifically, eddy current data were collected along four arbitrarily selected radii on the top and bottom surfaces of the disc. The same instrument calibration was used for both the bend bar and shrink fit specimen evaluation. The shrink fit specimen results are presented in Figures 8 and 9. Figure 8 shows the data collected on the bottom or "no-load" surface of the disc. The probe positions (1 through 5) represent 0.5 in. (1.27 cm) increments along each radius from the O.D. to I.D. of the disc. Note that at the 0 and 270° positions some variation in eddy current response is encountered along each radii. At the 90 and 180° positions the eddy current response is more uniform and more representative of the expected "no load" conditions.

Figure 9 presents the eddy current data collected on the top surface of the disc (along the same radii examined on the bottom surface). Note the significant differences in these data as compared to the bottom surface results. The high level eddy current readings indicate the presence of significant tensile stresses and a stress gradient decreasing from the disc bore is clearly evident at each radii. Note that the apparent stress contours reflected by the eddy current readings vary significantly along each of the four radii selected for examination. These results plus the "no load" data (Fig. 8) indicate that the shrink fit stresses are not uniform around the disc bore.
Fig. 8. Eddy current evaluation of shrink fit specimen (unloaded face).
Fig. 9. Eddy current evaluation of shrink fit specimen (loaded face).
Comparison of eddy current versus applied stress data developed for the A533 and A471 steels with the tensile specimens (Figures 2 and 3) shows a significant difference in eddy current response at a given applied stress level. This is not unexpected in view of the different materials involved. Specifically, the calibration for a low noise "zero" signal is different for each material and as such, it is apparent that a quantitative correlation between eddy current signal and applied stress requires a calibration on the material of concern. It is interesting to note that the slopes of the eddy current response vs. applied stress data for both steels are similar and perhaps a correlation with the differential change in eddy current reading versus stress could provide a calibration applicable to a wide variety of steels. A considerable amount of additional data developed for a range of steels would be required to establish and verify this assumption.

The small differences in eddy current response associated with loading and unloading conditions were observed in both the tensile tests with the A533 steel (Fig. 3) and the bending tests with the A471 steel (Fig. 5). This effect appears to reflect magnetic hysteresis behavior and indicates that residual magnetism in the test piece could influence the test results. Again, further investigation of this phenomenon is required to identify potential problems.

Comparison of the data developed under tensile (Fig. 2) and bending (Fig. 5) conditions with the A471 steel shows a significant difference in eddy current response at a given applied stress level. However, this difference is the result of a change in instrument calibration rather than the influence of loading mode. The data presented in Figures 5, 6, 8 and 9 were developed with the same calibration and show consistency between loading modes.

The data presented in Figure 6 which show the eddy current response for the three point bend bar under load most clearly illustrates the potential advantages of an eddy current approach to the characterization of near surface applied tension stresses. Comparison of the "no load" data (Fig. 7) with the "loaded" case results demonstrates that the procedure is easily capable of distinguishing applied stress effects from background noise level caused by variations in structure and surface finish. Based on the calibration curve shown in Fig. 5, the data in Figure 6 imply the capability to measure stresses to a sensitivity or accuracy level of about ±10%.

With regard to technique sensitivity, note that the eddy current probe essentially provides an average value of impedance
change for the volume of material being scanned. Thus, it is apparent that probe size (diameter) as well as frequency (depth sensitivity) may affect test results particularly in cases of sharp stress gradients (such as the three-point bend test). Experiments with various probe sizes and types are ultimately required to optimize probe design for the characterization of stresses in different components.

The shrink fit test specimen was designed to yield a simple method for the evaluation of residual stresses. As our experience indicated, the "simple" test was not so simple. Following essentially standard practice for shrink fitting we managed to get the pin in crooked and the subsequent eddy current test results developed on both disc faces clearly attest to this fact. The pin had a 2 in. (5.08 cm) long straight section before the start of the taper so that the taper alone was not the cause of the misalignment problem. Examination of the data collected on the loaded face of the disc (Fig. 9) shows that only at the 180° position did the eddy current response decrease to a level approaching that encountered on the unloaded face. Each of the other radii examined show considerable residual stresses throughout the wall of the disc. The estimated stress contour for the test disc (based on a straight pin shrink fit) is shown in Figure 10. Note that this contour corresponds well to the eddy current results shown at the 0 and 90° positions. However, note also that if we assume the calibration curve developed with the bend bar (Fig. 5) applies to the shrink fit specimen, the estimated stress levels far exceed the expected loading conditions.

Subsequent ultrasonic evaluation of the reflection coefficient at the disc bore-pin interface on the shrink fit specimen clearly revealed that the pin was not in uniform contact with the bore face resulting in irregular loading of the disc. Specifically, no interference fit appeared to exist between the 270° and 10° positions on the disc bore. Under such irregular loading conditions it is unreasonable to assume that the idealized loading case shown in Figure 10 truly represents the actual disc loading conditions. In fact, based on the eddy current response-applied stress calibration for the A471 steel (Fig. 5), data developed on the shrink fit disc indicate residual stresses in excess of the materials yield. Unfortunately, due to the complex loading conditions present in the test disc (due to the misaligned pin) it was not possible to compute the actual stress levels involved (the detailed three-dimensional analysis required was beyond the scope of this investigation). Consequently, we were unable to confirm the eddy current stress estimates. However, the experiment clearly indicates the potential of the eddy current method to map residual stress patterns.

Comparison of the results of this investigation with other
ongoing and past work related to the nondestructive evaluation of applied and residual stresses shows that the eddy current approach is very promising. Although the procedure may only be applicable to the characterization of surface stresses (as in the widely used x-ray approach) the relatively simple equipment involved and the ease of application (hand held probe) are outstanding potential advantages.

![Graph showing calculated stress contour for shrink fit test specimen.](image)

**Fig. 10.** Calculated stress contour for shrink fit test specimen.

All eddy current response versus applied stress data developed in this program represent near surface tensile stress conditions. We estimate that the eddy current surface penetration is no more than about 0.001 in. (0.025 mm) with the 400 kHz probe and not much more at 10 kHz. Much lower test frequencies (< 1 kHz) would be required to significantly increase the depth of eddy current penetration. Lower frequency scanning would reach deeper into the metal surface and the corresponding response would essentially indicate an average estimate of the near surface stresses. However with an appropriate variable frequency examination it would be possible to integrate the results to develop a near surface stress profile. Such an approach could be valuable for the characterization of surface stresses related to crack initiation concerns as well as for detailed stress analyses.
The identification and characterization of compressive stresses is an important aspect of stress analysis; however, tensile stresses are primarily responsible for material damage and our work has concentrated in this area. We expect that an eddy current approach similar to that used in this investigation could be applied to the characterization of compressive stresses and this approach is under investigation.

SUMMARY AND CONCLUSIONS

Results developed in this investigation clearly indicate that conventional eddy current nondestructive evaluation equipment and techniques can be used to accurately characterize applied and residual tension stresses in structural steels. Both stress contours and quantitative estimates of surface stress levels can be developed. The pertinent conclusions associated with this effort are summarized below.

1. A 0.25 in. (0.64 cm) diameter eddy current probe driven at 400 kHz with a conventional eddy current NDE instrument can be used to characterize tensile, bending and residual surface stresses in ASTM type A533 and A471 steels. A nearly linear correlation between eddy current response and applied stress was shown to exist.

2. The test data developed in this program show that the eddy current approach to the characterization of surface tensile stresses exhibits little scatter and is reproducible. Estimates of applied stress on the order of ± 10% of the actual values were demonstrated.

3. The eddy current response (change in impedance) versus applied stress correlation is material dependent and a calibration must be developed for the material of concern.

4. Test data collected at 400 kHz and 10 kHz yield similar results; however, it is expected that lower frequencies may penetrate deeper into the material surface and thus indicate subsurface stress conditions.

RECOMMENDATIONS

The program described in this paper was of an exploratory nature and by design, covered in limited depth a wide range of subjects. In view of the success, encouraging results, and tremendous potential it is reasonable to pursue the eddy current characterization of stress in more detail. Specifically, the
technique must be optimized, verified for other conditions and the limitations identified. Recommendations for further work include:

1. Evaluation of the applicability to the characterization of compressive stresses.

2. Exploration of test frequency effects to determine the feasibility of subsurface stress measurements.

3. A more detailed evaluation of the effect of material variables, including surface finish and surface contamination.

4. Evaluation of the applicability to weldments.

5. A systematic comparison of eddy current results with x-ray and hole drilling analyses of residual stresses.

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REFERENCES


