Improving the Reliability of Eddy Current Testing as a Means of Induction Hardening Quality Control of Forged Axle Shafts

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April 22, 2002

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I Executive Summary

The goal of this project was to relate Eddy Current (EC) test output to case depth and surface hardness. In addition to correlating destructive and non-destructive measurements of case depth and surface hardness, sources of EC variability were isolated and quantified. Experiments were devised to investigate the effects of shaft temperature and position on EC output. Since all frequencies are not necessarily sensitive to case depth or surface hardness, a mathematical model was used to predict which frequencies should contain relevant information. The model indicates that low frequencies are sensitive to case depth, while high frequencies are sensitive to surface hardness.

Using only the Y output at the lowest test frequency (25 Hz), a regression model has been developed that accurately predicts case depth. Further refinement of the model may be possible by examining other low frequencies and by suppressing environmental effects. No relationship was observed between EC output and surface hardness. Since conductivity is temperature dependent, it is expected that the EC output will vary with temperature. A correction for the temperature effect was determined and added to the regression equation. The results of our study on axial position near the flange indicate that a change of 0.1” will cause a change of 0.013” in the case depth prediction of the regression model. Shaft centering (at the bearing section) within the test coil has also been proven to have an effect on EC output. Similar deviation is seen regardless of direction skewed from center. Overall, a 0.1” change in centering will cause a change of 0.010” in the case depth prediction of our model. While axial position and shaft centering effects are not severe at American Axle & Manufacturing, these issues were important in explaining the EC output deviations seen in testing performed at MTU.

II Introduction

American Axle & Manufacturing (AAM) forges automotive axles for use in sport utility vehicles made by Ford and General Motors. The axle shafts are induction hardened to form a martensitic case around a pearlitic 1050-modified steel core; this promotes resistance to wear and fatigue. The current quality control method to evaluate the case is the destructive testing of one axle every four hours. This axle is assumed to be representative of all axles produced since the previously tested axle. Lots are released for sale or held for further evaluation based on the results of this testing.

In addition to the destructive testing, AAM has Eddy Current (EC) testing equipment in place that they would like to use to quantitatively test every axle by non-destructive means. Using Eddy Currents as a primary means of quality control has the potential to save AAM money and decrease the amount of shafts destroyed for quality purposes. However, the accept/reject criteria for the EC test are not well defined. The focus of this project is to discover the relationships that exist between the EC test output and the specified materials properties of surface hardness and case depth.

This paper will discuss:

- AAM’s quality control process
- Current hardness and case depth regression equations used by AAM
- Best frequencies for measuring surface hardness and case depth determined both theoretically and experimentally
- A study of EC output as it relates to case depth performed at MTU
- Determination of a temperature correction factor and integration into the regression equation
- Effects of shaft position on EC output
- Conclusions, recommendations, and suggested future projects

III Background

Material Specifications and Quality Control Procedure at AAM

AAM's hardening specification for the bearing location has four criteria. The shaft must meet the following requirements: surface hardness >60HRC; at 3.3 mm below the surface, >60 HRC; at 7.5 mm below the surface, <50 HRC; total case depth 0.250"-0.400". Once every four hours a shaft is destructively tested for these four properties. This test takes about 20 minutes and destroys the shaft.

EC Output and Explanation of the Impedance Plane

EC testing estimates the case depth and surface hardness from differences in electrical properties (conductivity and permeability) between the case and core. This test method takes a matter of seconds and the axle shaft incurs no physical damage.

When a shaft is EC tested, Eddy Currents are generated in the shaft in response to current passing through a coil surrounding the part. The coil is made up of a primary and secondary winding. The primary winding induces Eddy Currents in the shaft and the secondary coil measures the response from the shaft. The measured voltage of the circuit is out of phase with the applied current, as seen in Figure 1. The amplitude (Z_o) and phase lag (ϕ) of the measured voltage define a vector (Z) on an impedance plane, as shown in Figure 2. The EC output of AAM's testers is shown in terms of the vertex (P) of this vector.

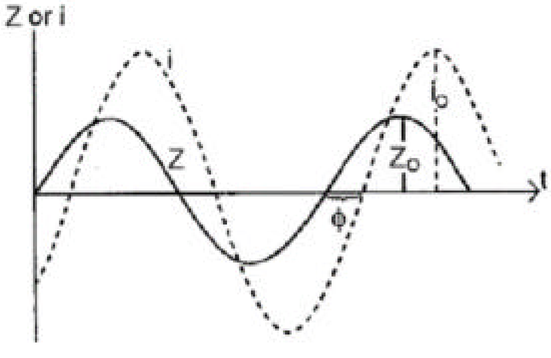

Figure 1: Applied current i and the out of phase response, Z

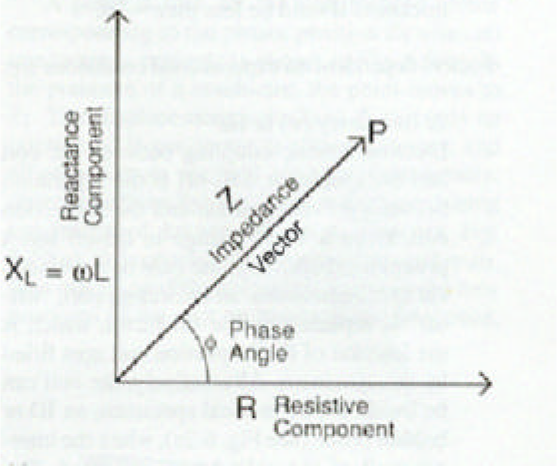

Figure 2: Vector Z plotted on an impedance plane

The EC output from the IBG tester is comparative. This means that the test uses a compensation shaft and the measurement from the test shaft is subtracted from the compensation shaft. The output is multiplied by current such that the results are in units of millivolts. An example of the output on the Eddy liner P-4 that was used for this project is seen in Figure 3. On this graph, the vertices from tests at eight different frequencies are plotted and connected. The test frequencies for this test were 25, 80, 250, 630, 1600, 4000, 10000, and 25000 Hz. A second set is also used at AAM: 20, 40, 100, 250, 630, 2000, 6300, 25000 Hz.

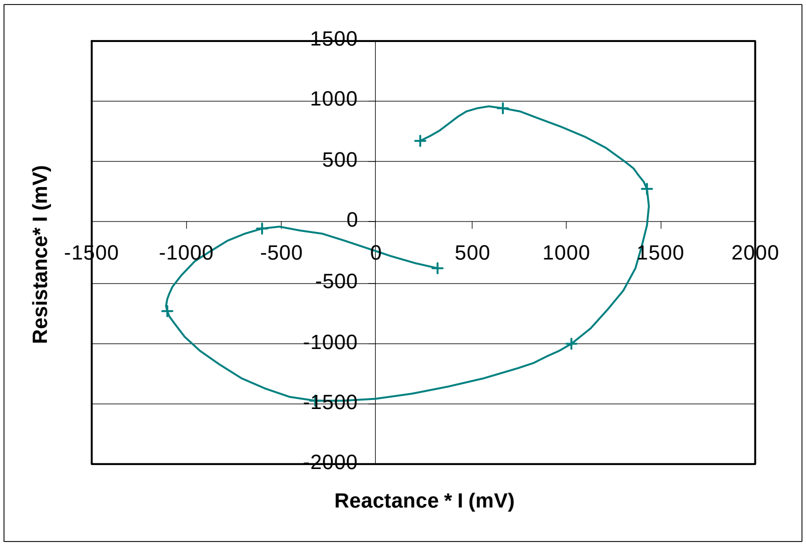

Figure 3: EC output from the P-4 Eddy Liner used for this project

For each frequency there is a reactive (X axis) and resistive (Y axis) component. The reactive and resistive components at each frequency (16 data points total) have different sensitivities to the properties that are being measured: case depth, surface hardness, or other environmental effects.

IV AAM's Current Prediction of Case Depth and Surface Hardness from EC Output

The goal of this study was to determine the accuracy of AAM's current regression models for predicting case depth and surface hardness.

AAM has a model that outputs quantitative case depths and surface hardness values based on the EC output when the 20 – 25000 Hz frequencies are used. The model for case depth involves the following frequency components: 20-X, 100-X, 250-Y, 630-X-Y, 2000-X, 6300-X, and 25000-Y. The model for surface hardness uses: 20-X, 40-X-Y, 100-X-Y, 2000-Y, 6300-X-Y, and 25000-X-Y.

Procedure

At MTU's request, AAM ran 40 shafts through their EC tester over eight consecutive days. For each five shafts, a sixth shaft was taken off the line and destructively tested. This sixth shaft was assumed to have properties similar to the five that were EC tested. The EC results were related to quantitative case depths and surface hardness values using their model.

Results

The modeled and actual destructive results can be seen in Tables 1 & 2.

Modeled	Destructive	Difference
.001"	.001"	Des. - Mod.
268	280	12
259	280	21
279	280	1
256	300	44
279	300	21
268	300	32
259	300	41
272	300	28

Table 1: AAM's modeled case depth vs actual case depth

Modeled	Destructive	Difference
HRC	HRC	Des. - Mod.
62.6	61.3	-1.3
64.4	60.5	-3.9
62.8	60.7	-2.1
64.5	61.2	-3.3
64.8	61	-3.8
65.2	60.3	-4.9
66.2	61.6	-4.6
66.5	60.1	-6.4

Table 2: AAM's modeled surface hardness vs actual surface hardness

Conclusions

There is little correlation between the predicted and actual values of case depth and surface hardness (R^2 values for case depth and surface hardness are 0.015 and 0.044, respectively). It is hypothesized that a more accurate model can be developed to predict case depth and surface hardness. By considering the theoretical sensitivity to case depth and surface hardness at each frequency, AAM's model can be refined to focus on the impedance points that are most responsive.

V Theoretical Sensitivity of Eddy Current Test Results for Case Depth and Surface Hardness

The goal of this experiment was to determine which frequencies were the best predictors of case depth and surface hardness.

Procedure

A mathematical model was adapted to simulate AAM's Eddy Current output. The output of this model relies on the properties of the shaft according to Equation 1.

$$Z/wL_o = Z_R(r_a, r_b, b, \sigma_a, \sigma_b, \mu_a, \mu_b, f) + Z_i(r_a, r_b, b, \sigma_a, \sigma_b, \mu_a, \mu_b, f) \quad \text{[Eqn. 1]}$$

Where Z/wL_o is the normalized impedance, Z_R and Z_i are the resistive and reactive components of impedance. Z_R and Z_i are dependent upon the geometry of the shaft in terms of shaft radius, r_a, the radius of the core, r_b, and the coil radius, b. Z_R and Z_i are also dependent upon the conductivity and permeability of the case, σ_a and μ_a, and the core, σ_b and μ_b.[1]

In the current state, the mathematical model does not accurately simulate the output of AAM's EC testers. A corrective factor accounting for the electrical manipulations performed by IBG's EC testers should result in accurate simulation. Nevertheless, the model does predict the theoretical sensitivity of Eddy Currents to changes in case depth and surface hardness at different frequencies.

It was found that this model is based on a much simpler equation that calculates the depth of EC penetration, Equation 2. This equation was used to determine which frequencies will be most sensitive to case depth and surface hardness.

$$D = 2(\rho/f\mu_r)^{1/2} \text{ in.} \quad \text{[Eqn. 2]}$$

Where D is the depth of penetration in inches, ρ is the electrical resistivity in $\mu\Omega$-cm, μ_r is the dimensionless relative permeability, and f is frequency in Hertz. Equation 2 is represented graphically in Figure 5.

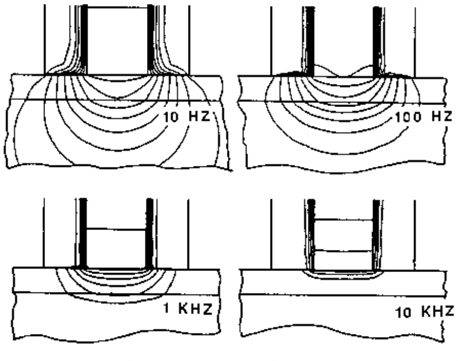

Figure 5: Depth of Penetration for low and high frequencies

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[1] The actual equation is not presented in this paper because it is complex and in the form of computer code. A version of the model will be supplied to AAM in the form of a Mathematica file.

As illustrated in Figure 5, lower frequencies have a greater penetration depth than higher frequencies. This fact has great relevance when studying EC sensitivity to hardness and case depth. From the depth of penetration, it can be inferred that low frequencies contain indicators of case depth, while high frequencies should contain indicators of surface hardness.

The electrical resistivity of a material varies according the relationship:

$$\rho = \rho_{\rho\tau}[1 + \alpha(T - T_{\rho\tau})] \text{ Ohm*m} \qquad \text{[Eqn. 3]}$$

where $\rho_{\rho\tau}$ is the room temperature value of resistivity and α is the temperature coefficient of resistivity. The relationship between electrical resistivity and temperature for typical steel is shown in Figure 4.

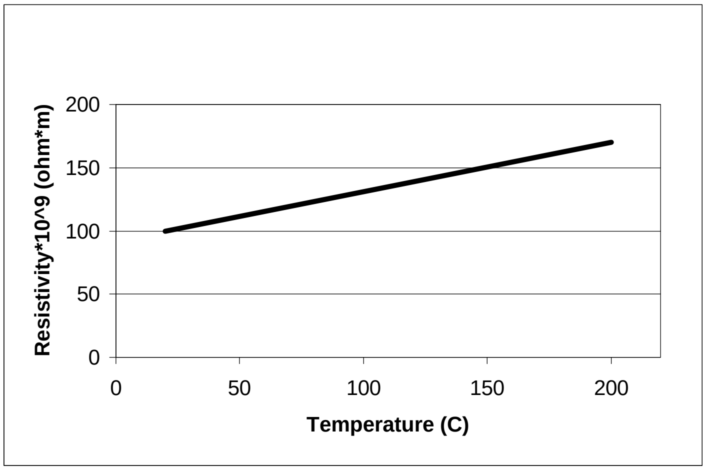

Figure 4: The effect of temperature on resistivity of typical steel

The depth of EC penetration is directly related to a material's resistivity; the resistivity of steel goes up as temperature rises. The change in resistivity is the basis for the temperature effect that is investigated in part VII.

Conclusions

AAM should limit the impedance points used for case depth to low frequencies and surface hardness to high frequencies.

There is a well-defined linear relationship between resistivity and temperature. Thus, there should be a well-defined relationship between EC output and temperature.

VI Experimentally Determined Sensitivity of Eddy Currents to Case Depth and Surface Hardness

The goal of this experiment was to experimentally determine which frequencies are the best predictors of case depth and which are the best predictors of surface hardness.

Procedure
Fourteen shafts from AAM were EC tested at the bearing location using the two previously mentioned sets of frequencies. The shafts were destructively tested at MTU for surface hardness (HRC) and case depth (optical measurements of total case depth and Vickers microhardness traverses).

Results
Destructive measurement of case depth and surface hardness yielded ranges of 0.234" – 0.267" and 59.0 – 62.1 HRC, respectively. The results from destructive testing can be found in Table 3; the EC output from the same shafts is shown in Figure 6.

Shaft #	HD (HRC)	CD (.001")
1	62.1	265
2	61.2	267
3	61.1	256
4	60.9	267
5	61.1	234
6	60.2	246
7	61.1	264
8	59	267
9	60	266
10	60.5	238
11	61.5	262
12	61.1	265
13	61.1	263
14	60.3	243

Table 3: Destructive test data for the fourteen axle shafts tested at MTU.

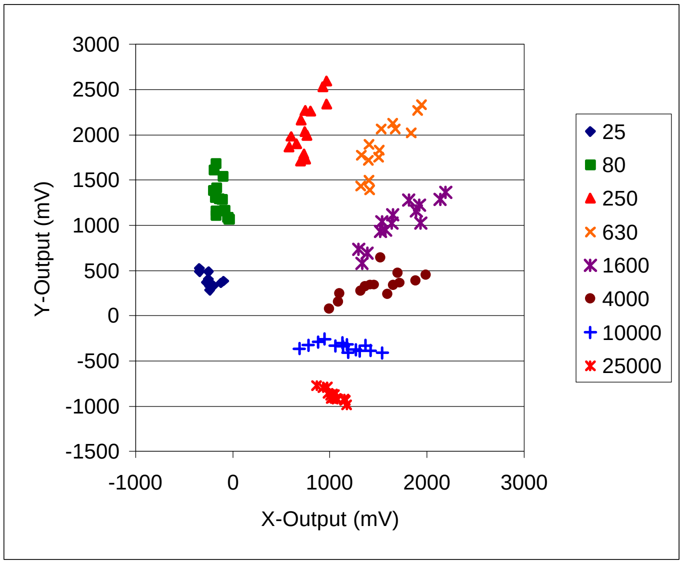

Figure 6: EC output for the fourteen axle shafts tested at MTU.

A regression analysis was performed between case depth or surface hardness and EC results at each frequency x,y combination. This was done to determine experimentally which frequency (or frequencies) are most predictive of case depth and surface hardness. The R^2 values of the regression formulas are found in Figure 7.

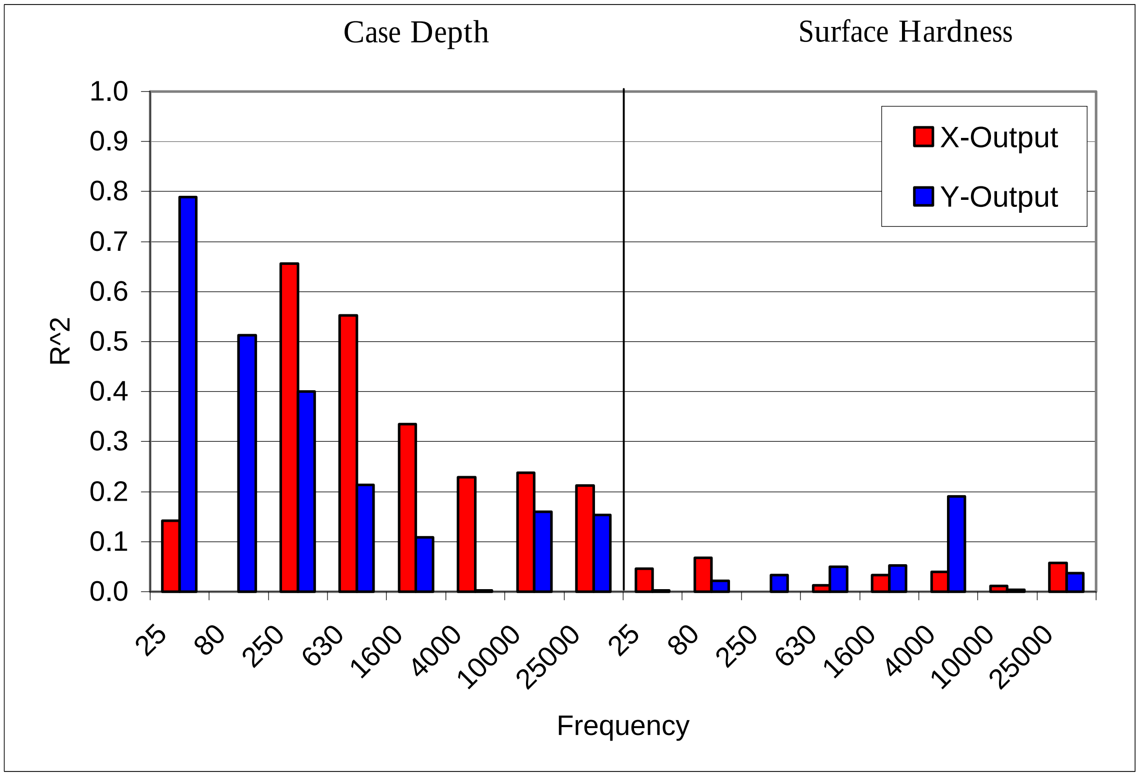

Figure 7: R^2 values showing the relationship between case depth and EC output and surface hardness and EC output for the shafts tested at MTU.

Figure 7 shows that the Y output at 25 Hz (Y-25) is the most sensitive to case depth with an R^2 value of 0.79. Due to this correlation, the regression equation between case depth and Y-25 will be used to predict the case depth directly from EC output. The resultant regression graph can be seen in Figure 8. A comparison between the actual case depth and the case depth predicted by the regression equation is presented in Table 4.

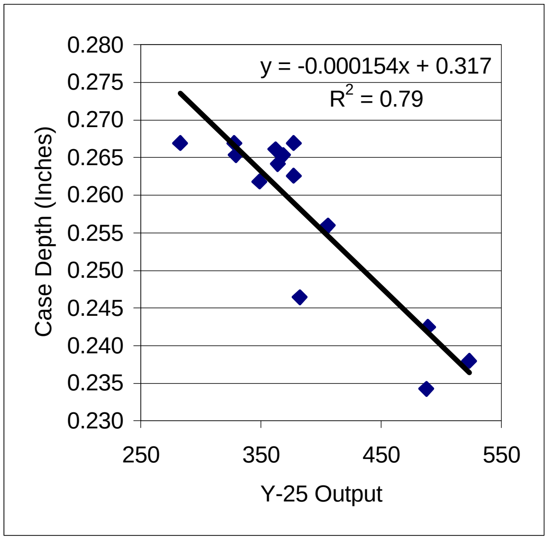

Figure 8: Case depth regression for Y-25 output

Shaft	Y-25 Predicted CD Inches	Predicted - Measured Case Depth (Inches)
1	0.266	0.001
2	0.259	-0.008
3	0.255	-0.001
4	0.267	0.000
5	0.242	0.008
6	0.258	0.012
7	0.261	-0.003
8	0.274	0.007
9	0.261	-0.005
10	0.236	-0.002
11	0.263	0.002
12	0.260	-0.005
13	0.259	-0.004
14	0.242	-0.001

Table 4: Error in case depth prediction

Conclusions

The following equation can be used to model the EC relationship to case depth.

Case Depth (Inches) = 0.317 -1.543*10^{-4} (EC Y output @ 25Hz) [Eqn. 4]

No relationship between surface hardness and EC output was observed. As a result, a model could not be created to predict surface hardness.

The model was tested with the data from the fourteen shafts. The greatest difference between what the model predicted and the destructive test measurement was 0.012”. The case depth prediction accuracy could be improved by a couple of methods. The mathematical model predicts that low frequencies contain the most information about case depth. Investigation of frequencies below 25 Hz may reveal other pertinent frequencies that could be included as variables in the regression equation. Examining a wider range of data would verify that the model correctly identifies both in and out-of-spec shafts.

VII Temperature Effect

The goal of this experiment was to determine a corrective equation for EC output of shafts tested above room temperature.

Procedure

One axle was tested at the bearing location in three separate trials. The shaft being tested was heated up to 65°C and placed into the test setup. The compensation shaft remained at room temperature. As the shaft cooled, measurements were taken in 5 degree intervals from 60°C to 25°C, and at every degree between 35 and 30°C. A thermocouple was used to monitor the temperature.

Results

The variation as the shaft cools down can be seen in Figure 9. This graph depicts the results from trial #3.

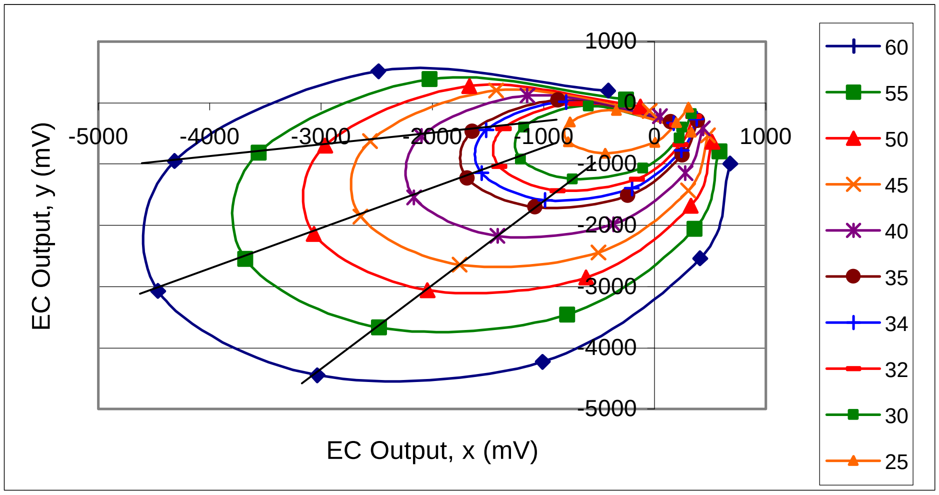

Figure 9: Effect of decreasing temperature on EC output (trial 3)

A linear relationship between the EC output at each frequency and temperature occurs. Therefore, the EC output at an elevated temperature can be corrected using a linear equation. The slope of the temperature vs. Y-25 regression line can be incorporated into Equation 4 to correct for the observed temperature effect. Future studies may discover other frequencies relevant to measuring hardness and case depth. A temperature correction is possible for all frequencies as seen in Figure 9.

Conclusions

To reflect the impact of varying temperature on the regression model, Equation 4 would need to be modified to:

Case depth (inches) = $-1.543*10^{-4}$ [EC Y output @ 25Hz + $2.803*10^{-2}$ (ΔT)] + 0.317 [Eqn. 5]

Use of Equation 5 applies only to the compensation shaft used at MTU. A similar relationship would need to be developed independently for each test setup.

VIII Axial Position Effect

The goal of this study was to examine the effect of testing in close proximity of the flange, which was observed to have a profound effect on EC output.

Procedure

The testing for axial positioning was over the length of the bearing and in the midsection of the shaft. The test was taken in increments of 2 mm. The position of the coil relative to the compensation shaft remained constant throughout each test.

Results

As the position was moved from the edge of the bearing towards the flange, the EC results moved closer to the origin as seen in Figure 10. At the midsection of the shaft, axial position had a minor, random effect on EC results as seen in Figure 11.

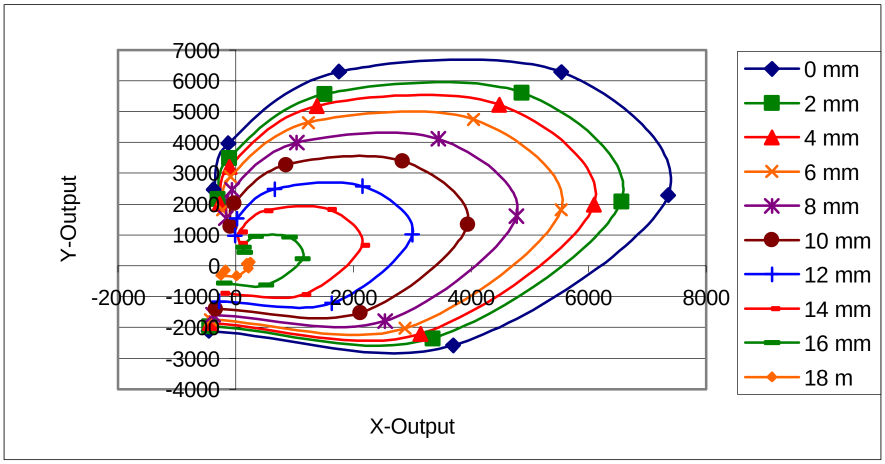

Figure 10: The effect of changing Axial Position on EC output at the bearing.

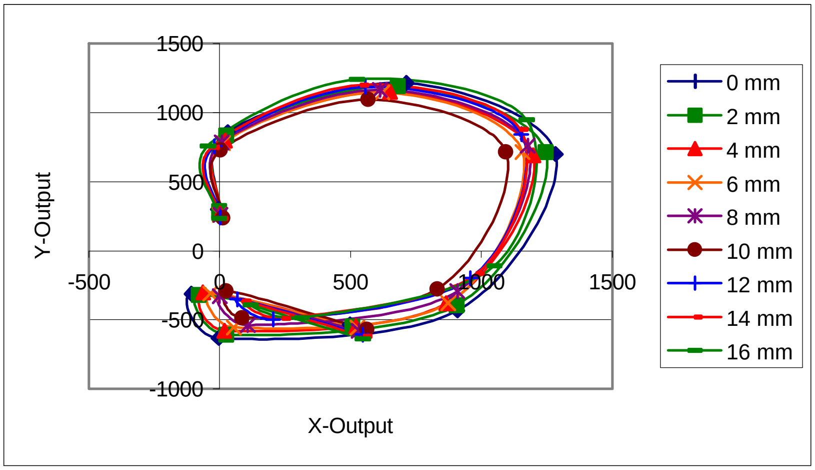

Figure 11: The effect of changing Axial Position on EC output at the midsection.

Conclusions

The EC output varies linearly with location along the bearing at each frequency combination. The shaft used in this study was destructively tested and showed little random variation. The change in EC output can primarily be attributed to changing location, and not changes in case depth. This change in output will affect the model developed to determine the case depth. A 0.1” change in axial position will cause a 0.013” change in predicted case depth.

Axial positioning only affects EC testing near the flange. This is because EC theory assumes a constant cylindrical bar in an infinitely long coil, which does not hold near the flange.

IX Lateral Position of the Coil

The goal of this study was to investigate the effect of shaft centering on EC output.

Procedure

Changes in the lateral position of a shaft during EC testing do not affect the theoretical EC output. To determine if this assumption holds in practice, a test was performed at the bearing while the shaft was in the approximate center of the coil. Further tests compare the output observed at the center to the output observed as the shaft is moved to the top, bottom, left, and right of the coil, see Figure 12. The results are in Figure 13.

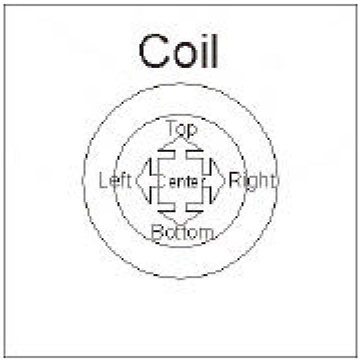

Figure 12: Schematic representation of shaft centering

Results

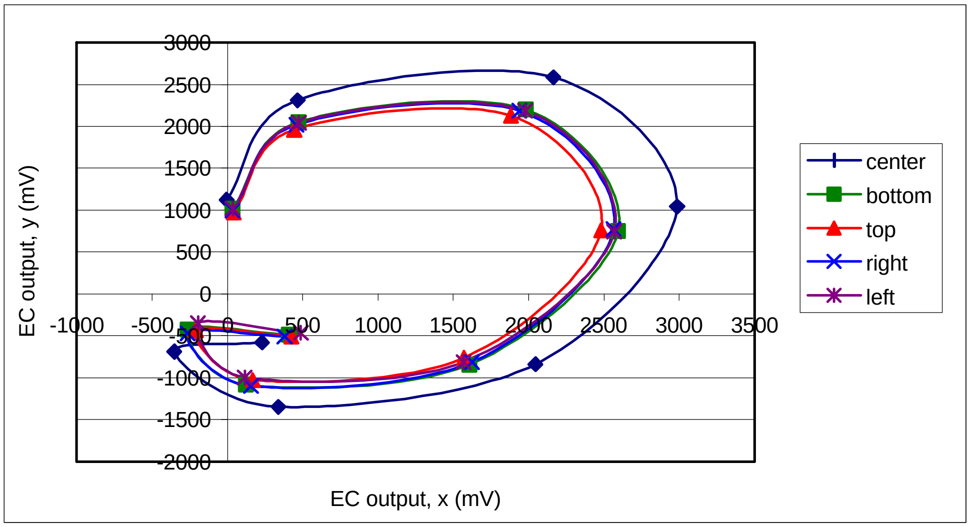

Figure 13: The effect of shaft centering on EC output.

Conclusion

EC output changes when centering is varied; a 0.1” change in centering causes a 0.010” change in predicted case depth. This change is contrary to EC theory, and is attributed to the proximity of the flange to the test location.

X Summary

Based on theoretical findings, AAM should focus on lower frequencies (25 Hz and below) in the attempt to predict case depth. This has been proven through a series of destructive vs. non-destructive testing in which the best R^2 value occurred for the Y-25 component. The model developed from this component is more accurate in predicting case depths then the current model at AAM. No relationship could be found between EC output and surface hardness.

These measurements are only useful when environmental effects do not distort the EC output. The temperature effect can be corrected because of the linear relationship that occurs between EC output and temperature. Axial and lateral positions were problems for measurements made at MTU, but should be negligible for AAM.

XI Recommendations

Use of Present Results

It is important to note that AAM's EC testers compare a compensation shaft to a test part. The compensation shafts used at AAM are different than the compensation shaft used at MTU. The end result is that Equations 4 & 5 presented in this paper will be inaccurate if used with any other compensation shaft. To accurately predict case depth using a model, AAM should follow the procedures presented in this paper. An appropriate case depth prediction equation must be developed for each EC test setup.

The mathematical model based on EC theory will be supplied to AAM in the form of a Mathematica file. This model can be used to predict how Eddy Currents will react to changes in the material properties of a shaft. The model can also be used to predict which frequencies should be best for predicting case depth or surface hardness.

The temperature study illustrated a strong linear relationship between position on the impedance plane (EC output) and temperature. While it is a simple matter to incorporate a temperature correction term into a model that predicts case depth, it is likely uneconomical to implement. The temperature of every shaft would have to be measured before the corresponding case depth could be accurately predicted. It is recommended to have awareness of the potential variability in EC test output due to temperature rather than measurement and subsequent correction.

Note: A regression model that accurately predicts case depth or surface hardness cannot be developed unless the shafts used to create the model are all tested at the same temperature. When implemented, accurate prediction of case depth or surface hardness with such a model is unrealistic without accounting for shaft temperature.

XII Future Projects

Several issues were raised as a result of this research:

- The findings of this project dictate that AAM should focus on the lowest test frequencies to predict case depth. The P-4 Eddyliner used for testing at MTU has the capability to test at frequencies as low as 5 Hz. AAM should investigate frequencies between 5 – 25 Hz to develop a multivariable model for predicting case depth.

- This project examined only in-spec shafts exhibiting a narrow range of surface hardnesses and case depths. Examining both in-spec and out-of-spec shafts is paramount to the ability to accurately predict larger deviations in material properties.

- No relationship between surface hardness and EC output was observed in these studies. In theory, high frequencies should be able to provide information about surface hardness. By eliminating environmental test variations with a stable test setup a relationship may be discovered.

- The conductivity and permeability of different phases and micro-constituents are different. Since EC tests measure differences in these properties, it would be worthwhile to investigate the effects of carbides, phases, and other microstructural features on EC output.

- Magnetization may have some effect on EC testing. Induction hardening and EC testing impart both electrical and magnetic fields on the shaft, possibly resulting in residual magnetism that may interfere with subsequent testing.

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