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MODELING EDDY CURRENT ANALYSIS DATA TO DETERMINE DEPTH OF WELD PENETRATION

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ABSTRACT

The Applied Engineering Technology Group in the Engineering Sciences and Applications Division at Los Alamos National Laboratory is currently providing the design, engineering, assembly, and testing of an eddy current instrument for weld inspection. This instrument is designed to provide an *in situ* weld depth measurement of nuclear weapons primary components during fabrication. The goal of this effort is to improve the accuracy and reliability of the measurement of the weld joint depth and provide a mechanism for inspection without removing the part from the fixture. This feature is essential to accommodate the re-welding process if the inspection fails. The production system consists of a commercially available eddy current instrument and eddy current probe connected to a portable PC. The objective of the system software is acquire and analyze voltage and phase angle data to produce a near-real time estimate of weld depth. The data obtained from the instrument are perfectly suited for analysis by a neural network technique. This paper compares the effectiveness of a neural network application with traditional mathematical models for the analysis of weld depth information.

KEYWORDS: eddy current inspection, weld penetration, neural networks

INTRODUCTION

The Applied Engineering Technology Group in the Engineering Sciences and Applications Division (ESA-AET) at Los Alamos National Laboratory (LANL) is providing the design, engineering, assembly, and testing of an eddy current instrument for weld inspection of nuclear weapons primary components (pits). An eddy current technique for pit weld inspection was originally developed and implemented in the 1980s at the Rocky Flats Plant [1]. The objective of the inspection was to determine the minimum depth of weld penetration given a minimum acceptable performance criterion. The inspection was performed after the welding process was completed, and the part was removed from the fixture. The part was rejected if the weld failed inspection – an extremely costly outcome.

This instrument currently in development at Los Alamos is designed to provide an *in situ* weld depth measurement of pits during the fabrication process. The goal of this effort is to improve the accuracy and reliability of the measurement of the weld joint depth and provide a mechanism for inspection without removing the part from the welding fixture. This feature is essential to accommodate the re-welding process if the inspection fails.

This paper describes the evolution of the data analysis methodologies for the eddy current hardware system under development. The first section provides a brief introduction to eddy current inspection. The second section describes the experimental setup to demonstrate the effectiveness of the system. The third section details the preliminary results of the methods used to analyze the experimental data. Finally, the application of the experimental results to the production environment is discussed.

EDDY CURRENT INSPECTION

Eddy current testing is an electromagnetic technique used for non-destructive testing (NDT) [2]. The technique can only be used for interrogating conductive materials with applications that range from testing for surface and sub-surface defects to testing metallurgical characteristics. The technique is commonly used in the aerospace, automotive, chemical processing and power industries to examine components for cracks, voids, porosity, and weld defects and to study properties such as hardness, permeability, and conductivity.

During eddy current testing, an energized electric coil is passed over a conductive sample. The magnetic field from the coil induces circulating (eddy) currents on a conductive surface. The induced eddy currents are localized to the surface adjacent to the coil. The magnetic flux associated with the eddy currents opposes the magnetic flux of the coil. When the eddy currents in the sample material are interrupted by the presence of surface discontinuities or material variations, the impedance of the coil changes and causes a phase shift in the voltage across the coil. By measuring the changes in impedance and the phase shift of the magnetic coil as it passes over the surface, one can identify characteristics of the test specimen. Figure 1. illustrates the magnetic flux produced in the sample material by the eddy current probe.

Test frequency determines the depth of penetration into the test object; as frequency is increased, penetration decreases and the distribution of eddy currents increases near the object's surface. Test frequency also affects the measurement sensitivity to variations in material properties and defects. The depth of penetration decreases with increasing frequency and is a function of electrical conductivity and material magnetic permeability. The standard depth of penetration is the depth at which eddy current density has decreased to 1/e or about 37% of the surface density.

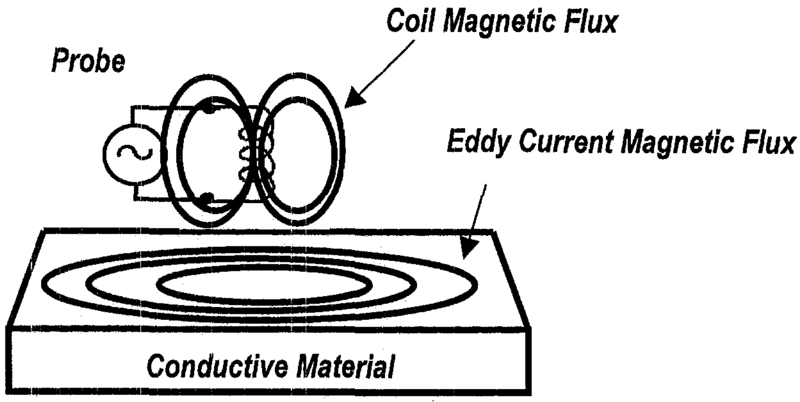

Figure 1. Induced eddy currents in sample material.

WELD DEPTH DATA ANALYSIS

The production system consists of a commercially available eddy current instrument and eddy current probe connected to a portable PC. The objective of the system software is to acquire and analyze voltage and phase angle data to produce a near-real time estimate of weld depth. Weld depth is determined by measuring the distance from the outer surface of the part to the unwelded region of the butt joint as depicted in Figure 2.

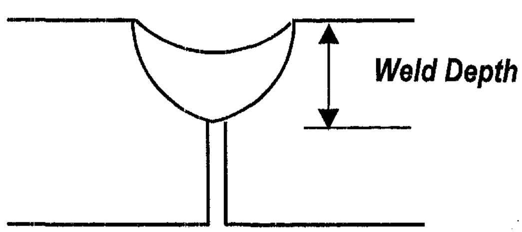

Figure 2. Cross section of welded region.

Experimental System

Prior to the introduction of the eddy current inspection system into the welding glovebox, experimentation in a cold laboratory was necessary to test the hardware and software systems. A surrogate material, Incoloy 825, was chosen, because its electrical conductivity is similar to that of plutonium. A flat test sample was fabricated with a continuous groove that represents a weld depths ranging from 0% to 100%. The eddy current instrument was used to inspect the Incoloy part under a variety of environmental conditions and varying system parameters to establish a correlation between operating parameters and the measurement of weld depth. The objectives of the experiments were:

1) characterization of the precision of measurements on a single day,
2) simulation of instrument drift between measurements on subsequent days, and
3) determination of variables/parameters that have an effect on prediction of weld depth.

The most critical input variables that impacted the analysis were experimentally determined to be 1) frequency, 2) rotation angle, 3) horizontal and vertical gains, 4) liftoff, 5) null point, and 6) temperature. Later experiments revealed that each eddy current probe used performed differently. Liftoff was eliminated as an input variable by enhancement to the system. Rotation angle, null point, and temperature were eliminated through procedural changes. The outputs of the inspection system are horizontal (real) voltage and vertical (imaginary) voltage from which voltage magnitude and phase angle are calculated. The goal of the eddy current data analysis is to establish a correlation between phase angle and weld depth.

Mathematical Modeling

The correlation between phase angle and weld depth was determined mathematically at Rocky Flats by modeling the phase angle data using a hyperbolic fit as shown in the equation below. Here, T is the weld thickness, A and B are constants, and ϕ is the phase angle.

$$T = \frac{1}{A + B\phi} \qquad (1)$$

This fit accurately predicted the weld thickness in the LANL experiments in the range of 30% to 97%. To extend this range, a new model was developed using an inverse cubic with a correction factor as shown below [3].

$$T = A + B\phi^{-3} + C\phi^{0.5} \quad (2)$$

This model extended the range from 22% to 97% percent with an accuracy of 99%. Although the mathematical model produced excellent results, the model does not account for instrument drift, probe differences, noisy data, or differences in instrument settings. Small deviations in the data greatly affect the fit. Thus, a different model would have to be derived for every combination of instrument parameters and probe used.

The data obtained from the instrument are well suited for analysis using a neural network technique. Neural networks are a computer-based technology that can provide a solution to difficult problems when other traditional techniques have failed or are not applicable. Standard software techniques rely heavily on the developer's knowledge of the rules governing a system and the underlying relationships. Neural networks are able to learn subtle relationships and present solutions to problems even when the input data are fuzzy, noisy, or incomplete. Because of their adaptability, neural networks can model imprecise, real-world systems more effectively.

RESULTS

A back propagation algorithm was developed to perform an analysis of eddy current data over a wide range of instrument settings and experimental conditions. The training set consisted of 32,000 data points from ten experiments. The test set consisted of 14,000 data points from four experiments. The inputs for the neural network were frequency, horizontal gain, vertical gain, and phase angle. The output was weld depth. The objective of the analysis was to gauge the feasibility of a neural network approach. Therefore, no attempt was made to "fine tune" or optimize network parameters such as number of hidden node layers, number of hidden nodes, learning rules, learning coefficients, or momentum terms.

Of the four test sets, the network predicted weld depth with a composite accuracy of 92%. This was below the desired accuracy rate of 95%. However, for the primary region of interest (45% to 80% weld depth), the error ranged from zero to five percent. A comparison of the weld depth predicted by the neural network versus the actual weld depth for one experiment is shown in Figure 3.

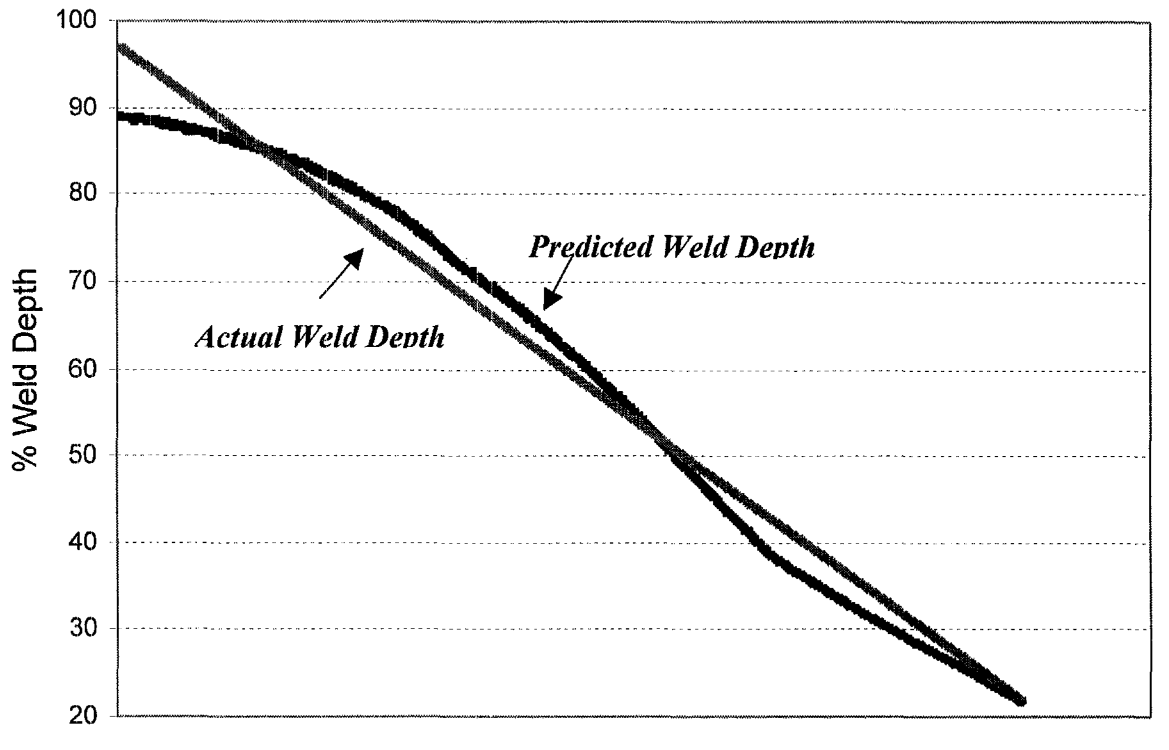

Figure 3. Predicted versus actual weld depth.

CONCLUSIONS

The neural network model developed for the analysis of experimental eddy current data yielded promising results. The model will be further refined and enhanced to include additional variables. Experimental data can only provide a partial picture of the efficacy of this analysis technique for this application. The technique will be employed to the analysis of actual weld inspection data. The predictions will be compared to destructive analysis results from pit welds to assess the relative merits of a mathematical approach to a neural network approach.

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