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Nondestructive Evaluation of Additively Manufactured Metal Components with an Eddy Current Technique

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ABSTRACT
The ability of Additive Manufacturing (AM) processes to ensure delivery of high quality metal-based components is somewhat limited by insufficient inspection capabilities. The inspection of AM parts presents particular challenges due to the design flexibility that the fabrication method affords. The nondestructive evaluation (NDE) methods employed need to be selected based on the material properties, type of possible defects, and geometry of the parts. Electromagnetic method, in particular Eddy Current (EC), is proposed for the inspections. This evaluation of EC inspection considers surface and near-surface defects in a stainless steel (SS) 17 4 PH additively manufactured sample and a SS 17 4 PH annealed plates manufactured traditionally (reference sample). The surfaces of the samples were polished using 1 micron polishing Alumina grit to achieve a mirror like surface finish. 1.02 mm (0.04"), 0.508 mm (0.02") and 0.203 mm (0.008") deep Electronic Discharge Machining (EDM) notches were created on the polished surface of the samples. Lift off and defect responses for both additive and reference samples were obtained using a VMEC-1 commercial instrument and a 500 kHz absolute probe. The inspection results as well as conductivity assessments for the AM sample in terms of the impedance plane signature were compared to response of similar features in the reference sample. Direct measurement of electromagnetic properties of the AM samples is required for precise inspection of the parts. Results show that quantitative comparison of the AM and traditional materials help for the development of EC technology for inspection of additively manufactured metal parts.

Keywords: NDE, Additive Manufacturing (AM), Electromagnetic Testing, Eddy Current (EC), Conductivity, Surface Defect

INTRODUCTION
Nondestructive Testing and Evaluation (NDT&E) of additively manufactured (AM) components is necessary to validate the performance of AM processes as well as quality and safety of AM parts [1], [2]. Development of adequate NDT&E techniques for examination of AM parts is the key challenge in quality inspection and control of the additively manufactured parts [3]. Particular NDT&E techniques can be used for material examination based on the physical and geometrical properties of the materials as well as possible types of defects in the parts [4]. A variety of flaws and defects can be generated during the powder-based additive manufacturing process of metal alloys including gas or lack of fusion porosities, cracks, and metallurgical anomalies [5]. Electromagnetic methods, in general conventional eddy current (EC) and array eddy current (AEC), have numerous advantages and capabilities as a promising method for inspection of metal AM parts [6], [7]. Eddy Current Testing is a NDT&E technique which is widely used within a number of fields such as in nuclear, aerospace, marine, petroleum and gases industries. EC is based on induction of electrical current in materials by electromagnetic induction process, the sample has to be a conductor. The EC technique has the advantage of being non-contact, fast and does not require

any couplant or media (no contamination) to transmit the energy into the part [8]–[10]. EC techniques can be used for detecting surface and subsurface defects such as cracks and scratches, as well as material properties such as conductivity, stresses, and surface irregularities. Electromagnetic properties of the materials such as electrical conductivity and magnetic permeability have significant impact on the detected signal in eddy current NDT&E. Therefore, for application of EC technique for AM parts and components, electromagnetic properties of deposited materials need to be evaluated and compared to the traditional manufactured materials for the optimization and comparison of the inspection efficiency.

In this study, material properties (conductivity and lift-off) and capability of defect detection has been evaluated using the EC technique.

MATERIALS AND METHOD

Two types of samples were used for assessment of EC technique for evaluation of material properties and defect detection in stainless steel 17 4 PH. These samples include an additively manufactured SS 17 4 PH parts manufactured by Selective Laser Melting (SLM) method, and a traditionally manufactured SS 17 4 PH annealed plate. In addition, a traditionally manufactured SS 17 4 plate as a reference sample were used for comparison. EC behavior in every sample was measured using a VMEC-1 with a 500 kHz eddy current absolute probe. This single frequency for testing was used to simplify comparison and ensure that different tests could be directly compared.

Samples

Two experimental samples were prepared for EC testing. The first, a traditionally manufactured (TM) stainless steel sample, consisted of a plate with a uniform thickness of 6.35 mm (0.25”). Three notches were cut using Electric Discharge Machining (EDM) with a depth of 1.02 mm (0.04”), 0.508 mm (0.02”) and 0.203 mm (0.008”) with each notch being a distance of 22.9 mm (0.9”) apart. The surfaces of the samples were ground with a series of 60, 240, 320, 600, and 800 grit abrasives before final polishing. A mirror-like surface was achieved by use of a Leco Spectrum System 1000 using 15, 5, 1, and 0.03 micron polishing grit abrasives. The second sample is an additively manufactures (AM) SS 17 4 Ph sample. This sample is manufactured by Selective Laser Melting (SLM) method in a powder bed. An AM step sample with 25.4 mm (1") width and 101.6 mm (4") length is manufactured for this experiment.

Reference Sample

Six samples were prepared for use to compare against the TM and AM steel. These samples included ferrite, SS 304 stainless steel, a copper-nickel alloy, a magnesium alloy, and 7075-0 and 7075-T6 aluminum alloys. A block of each sample was, like the experimental TM and AM steel, grinded using 60, 240, 320, 600, and 800 grit abrasives. The samples were then polished using 15, 5, 1, and 0.03 micron polishing grits subsequently. An additional aluminum sample was notched with defects identical in spacing and width to those of the experimental samples. This notched sample ensured that the testing equipment functioned as intended in the presence of surface defects.

Figure 1: Standard conductivity samples used for lift-off and conductivity assessments.

Additively Manufactured Samples

The AM sample used in this experiment consisted of a step SLM manufactured segment of SS 17-4. Though this sample is stepped as opposed to the uniform 6.35 mm (0.25”) thickness of the TM plate, the effects are negligible for the scope of this experiment. In this application, EC testing is only used at the surface down to a shallow penetrating depth within the sample. Additionally, the width of the samples and the spacing between notches is great enough to negate edge effects during testing.

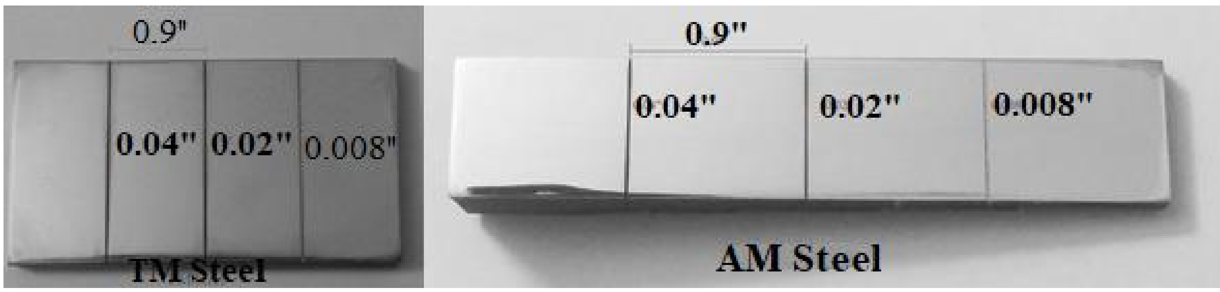


Figure 2: The TM (left) and AM (right) samples after grinding and polishing.

Conductivity Measurement Using Eddy Current NDE

In eddy current testing (EC), different measurements can be carried out through the selection of the testing parameters such as test frequency. In conductivity measurement, the test frequency selected should be sufficiently high so that eddy current penetration is limited only to a fraction of the test material thickness based on the skin depth relation (Eq. 1). The effects of test frequency on the conductivity measurement has been evaluated by many researchers [11].

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}} \quad \textbf{(Eq. 1)}$$

where;

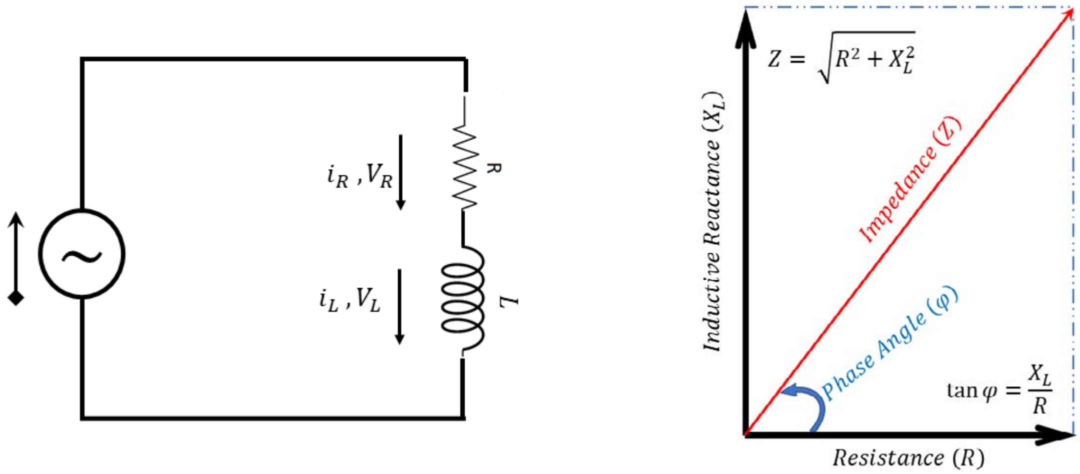
$\delta =$ Depth of penetration (mm)

$f =$ Testing frequency (Hz)

$\sigma =$ electrical conductivity (%IACS)

Impedance Plane Diagram

The Impedance plane diagram is a tool to use for representation of impedance (resistance (R) and inductive reactance (X_L)) variation due to change in material inhomogenities (defects) or properties. This change in impedance reveals important information about the integrity of the part and material condition. As a result, the impedance plan diagram is a major milestone in enhancing the defectability, interpretation, and, in turn, the reliability of eddy current response information. Figure 3 shows the representation of the circuit diagram of an eddy current inspection system as well as the related impedance plane.



(a) **(b)**

Figure 3: Eddy current electromagnetic testing method (a) circuit diagram of an eddy current inspection system, (b) impedance plane.

Conductivity Measurement

Conductivity is a measure of a material's ability to conduct an electric current. When an electrical potential difference is placed across a conductor, its movable charges flow and giving rise to an electric current. The conductivity, σ, is defined as the ratio of the current density to the electric field strength. Conductivity is the reciprocal (inverse) of electrical resistivity, ρ, and has the SI units of Siemens per meter ($S.m^{-1}$) and CGSE units of inverse second (s^{-1}).

Lift-off Curves

When a test coil is remote from any conductive material, impedance is at a position of high inductive reactance and low resistance. The high value for the air point on the inductive reactance scale occurs because there is no secondary flux available to reduce primary flux; the low value on the resistance scale occurs because the only resistance detected is that of the coil wire.

RESULTS AND DISCUSSION

Eddy current technique allows to identify and sort the conductivity properties of the conductive metals by their relative conductivities. Although Conductivity of a metal can be found using 4 point Alternating Current Potential Drop (ACPD) measurements, the process is complicated and needs to be done with higher accuracy.

Conductivity Measurement

For the purposes of simplicity only EC probe was used to compare the conductivities of the two samples. To get an idea of where the conductivity curves of AM and TM steel lies, a standard EC conductivity reference block (Figure 1) was used. Figure 4 shows the lift-off curves for the materials in conductivity standard sample as well as AM and TM SS 17 4 PH samples using 500 kHz frequency probe.

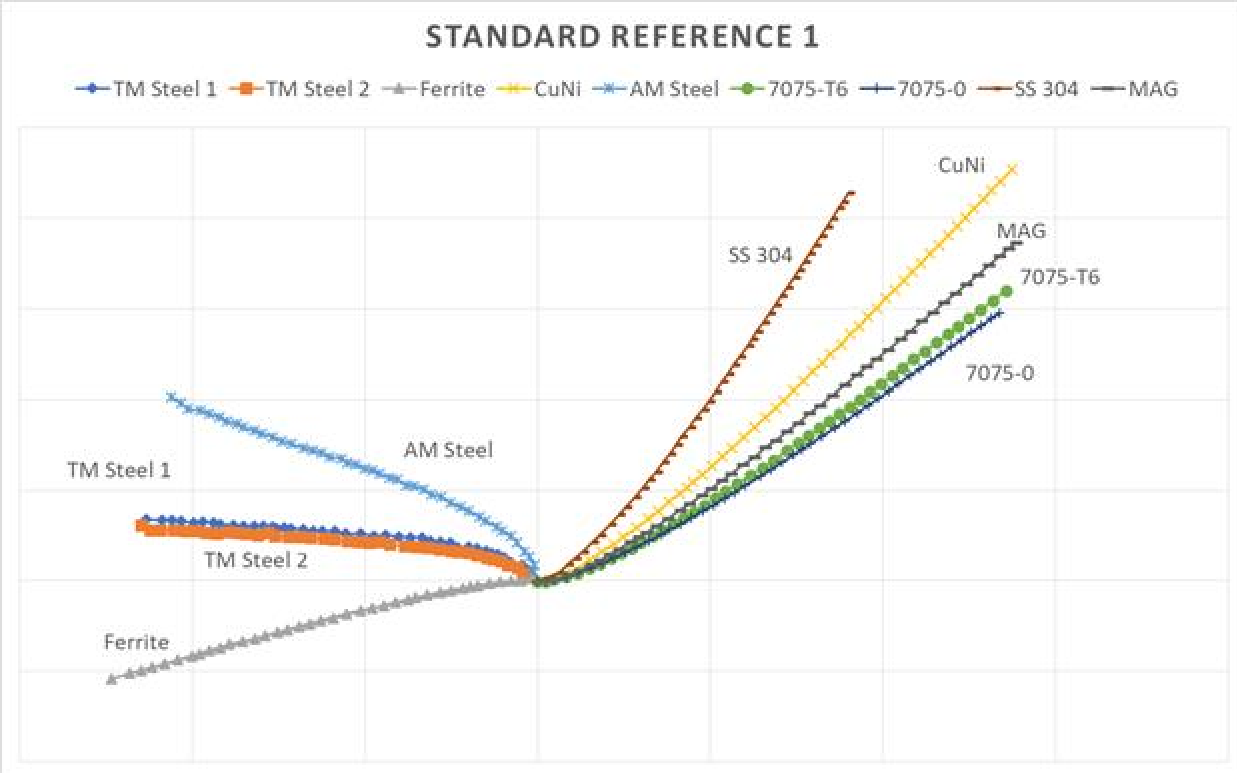


Figure 4: Lift-off curves for comparison of the conductivity for standard conductivity sample set as well as TM and AM SS 17 4 PH samples.

As can be seen from the lift-off curves in Figure 4 at 500 kHz testing frequency, we can conclude that the SS 17 4 PH is categorized as a magnetic material while the conductivity of SS 17 4 PH is less than Ferrite. Furthermore, the comparison for the conductivity between TM and AM SS 17 4 PH shows that the conductivity of TM SS 17 4 PH is higher than AM SS 17 4 PH.

After determining the range of conductivity and magnetic characteristics of the SS 17 4 PH, a closer look at the conductivity of the samples in Figure 5 shows the behavior of the lift-off curves for conductivity measurement between a non-magnetic material (Aluminum) and SS 17 4 PH (TM and AM).

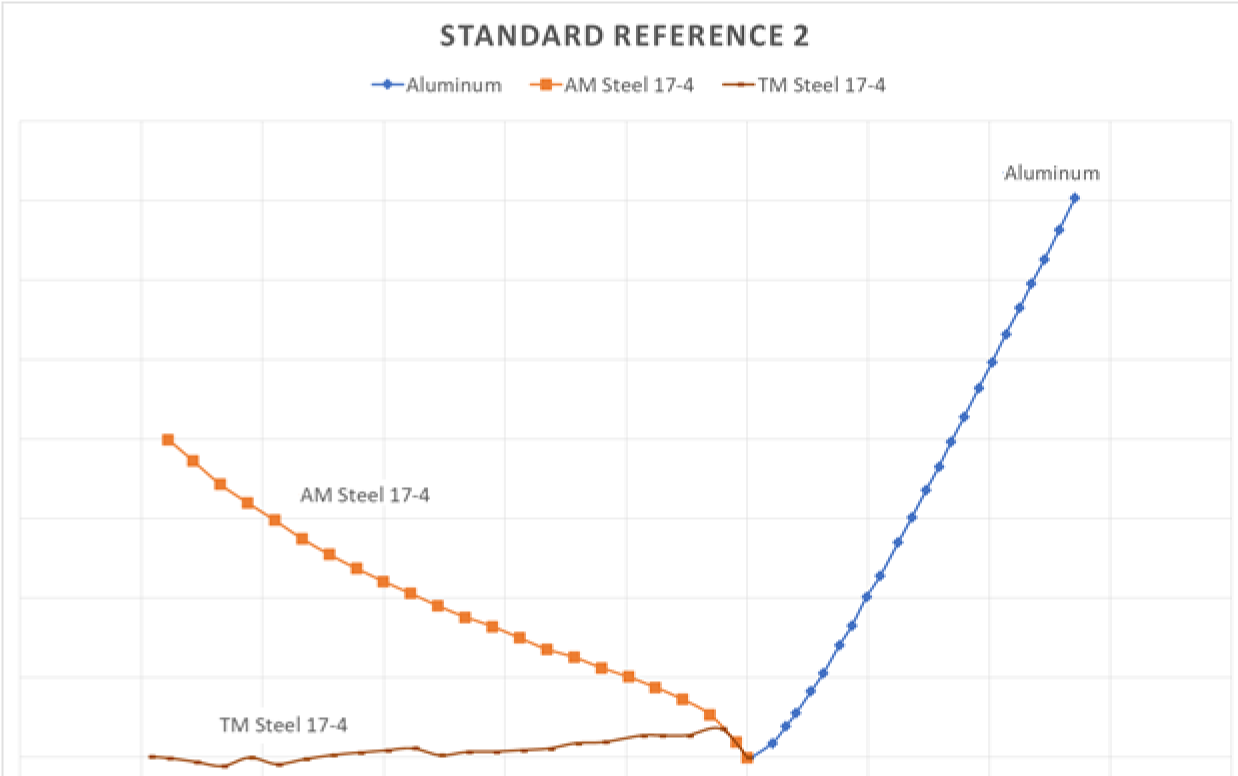


Figure 5: Lift-off curves for comparison of the conductivity for a non-magnetic material (Aluminum) as well as TM and AM SS 17 4 PH samples.

Discontinuity signal display

One of the most important applications of eddy current testing is detection and evaluation of cracks and other discontinuities. Figure 6 compares the behavior of the surface-breaking defects (cracks) in TM SS 17 4 PH sample using 500 kHz absolute frequency probe.

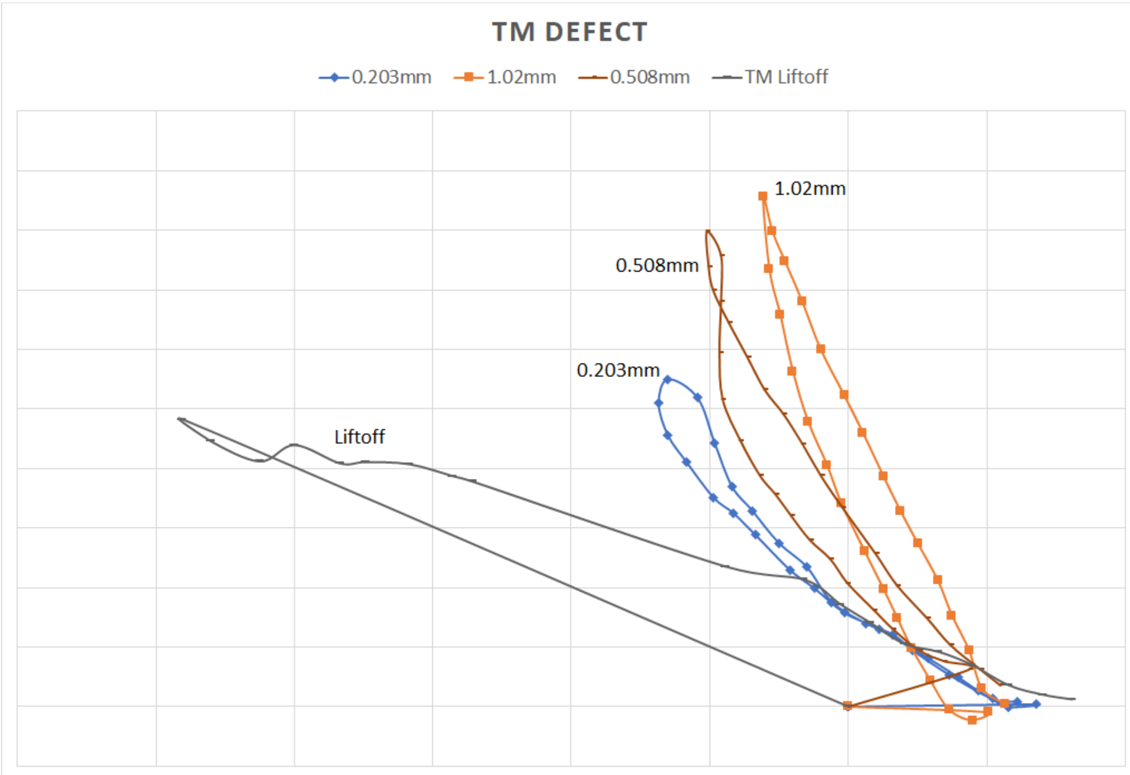


Figure 6: Results of the surface-breaking defects (cracks) in TM SS 17 4 PH sample using 500 kHz absolute frequency probe.

Figure 7 compares the behavior of the surface-breaking defects (cracks) in AM SS 17 4 PH sample using 500 kHz absolute frequency probe. As can be seen from the graph in Figure 7, the amplitude and phase of response signal for similar surface discontinuities have been changed when comparing to the TM material. This indicated the difference in electromagnetic properties of the materials. Distortion in the response signal is also higher in AM sample which can be due to the surface condition in AM sample and the experimental uncertainties.

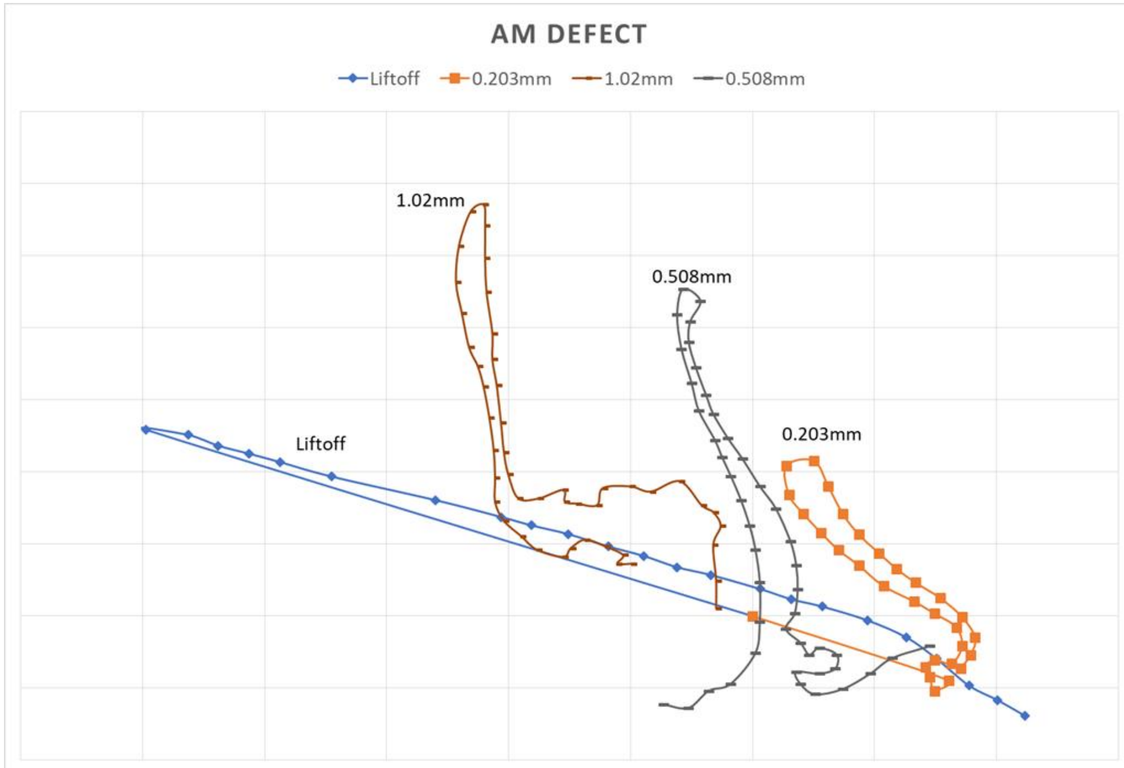


Figure 7: Results of the surface-breaking defects (cracks) in AM SS 17 4 PH sample using 500 kHz absolute frequency probe.

SUMMARY

One of the major advantages of the eddy current method is also one of its limitations. That is eddy current test result can be influenced by different variables including material conductivity, probe frequency, and the thickness and size of surface and subsurface discontinuities. However, the major limitation of the eddy current method is that response to these variables is vectorially additive. Another advantage of EC method which is very useful in case of AM material inspection and process monitoring is that the results are usually instantaneous. As soon as test coil responds to the test specimen, the results in impedance plane can be interpreted. Meanwhile, data on a large quantity of test material can be acquired in in-situ testing. This is a very important feature when considering EC for in-situ monitoring in additive manufacturing. Application of EC for AM needs a good understanding of the material properties and behavior under the electromagnetic interaction. Conductivity assessment of the additively manufactured SS 17 4 PH using lift-off curves showed that the conductivity of the additively manufactured (AM) SS 17 4 PH differs from the traditionally manufactured (TM) SS 17 4 PH. In the 500 kHz testing frequency, the comparison of the conductivity responses (lift-off curves) show that the conductivity of TM SS 17 4 PH is higher than AM SS 17 4 PH. Further evaluation of the other properties and quantitative assessment of the conductivity differences are necessary for study the effect of these differences on the discontinuity detection signals. The difference among the response signals for the similar surface discontinuities for TM and AM were observed which indicates the difference in material properties.

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REFERENCES

(1) L. W. Koester, H. Taheri, T. A. Bigelow, P. C. Collins, and L. J. Bond, “Nondestructive testing for parts fabricated using additive manufacturing,” *Mater. Eval.*, vol. 76, no. 4, 2018.

(2) L. W. Koester, L. J. Bond, P. C. Collins, H. Taheri, and T. A. Bigelow, “Non-Destructive Evaluation of Additively Manufactured Metallic Parts,” in *Metals Handbook*, {New & Rev., ASM International, 2018.

(3) L. Koester, H. Taheri, L. J. Bond, D. Barnard, and J. Gray, “Additive manufacturing metrology: State of the art and needs assessment,” in *AIP Conf. Proc. 1706*, 2016, p. 130001.

(4) H. Taheri, “Classification of Nondestructive Inspection Techniques with Principal Component Analysis (PCA) for Aerospace Application,” in *ASNT 26th Research Symposium*, 2017, pp. 219–227.

(5) H. Taheri, M. R. M. Shoaib, L. W. Koester, T. A. Bigelow, P. C. Collins, and L. J. Bond, “Powder based additive manufacturing - A review of types of defects, generation mechanisms, detection, property evaluation and metrology,” *Int. J. Addit. Subtractive Mater. Manuf.*, vol. 1, no. 2, pp. 172–209, 2017.

(6) E. I. Todorov, “Measurement of electromagnetic properties of powder and solid metal materials for additive manufacturing,” in *Proc. SPIE 10169, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, and Civil Infrastructure*, 2017, vol. 1016907, no. April, p. 1016907.

(7) E. Todorov, P. Boulware, L. Cronley, K. Gaah, and C. Reichert, “Evaluation of Laser Powder Bed Fusion Additive Manufacturing with Array Eddy Current Technology,” in *26th ASNT Research Symposium*, 2017, pp. 248–258.

(8) M. Mosayebi, S. F. Karimian, and T. P. Chu, “NDT Using Digital Laser Speckle Image Correlation (DiLSIC),” in *ASNT 26th Research Symposium*, 2017, pp. 185–193.

(9) H. Taheri, F. Delfanian, and J. Du, “Wireless NDI for Aircraft Inspection,” in *ASNT 22nd Research Symposium*, 2013, pp. 120–126.

(10) H. Taheri, J. Du, and F. Delfanian, “Development and application of wireless eddy current system for nondestructive testing,” *IOSR J. Electron. Commun. Eng.*, vol. 12, no. 6, pp. 41–50, 2017.

(11) M. Lu, H. Xu, W. Zhu, L. Yin, Q. Zhao, A. Peyton, and W. Yin, “Conductivity Lift-off Invariance and measurement of permeability for ferrite metallic plates,” *NDT E Int.*, vol. 95, pp. 36–44, 2018.