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Inline Non-Destructive Material Property Testing: The Future of Manufacturing

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Abstract

Across all industries, material specifications are tightening beyond previously understood process capabilities. Slight shifts in material grade, microstructure, heat treatment, or alloy composition can significantly impact long term material integrity. This study examines the feasibility of non-contact, 100% inline magneto-inductive testing on material/components destined for the automotive, aerospace, agricultural, and medical markets to ensure proper material quality standards.

To test the hypothesis that material grade, carbon content, density, and alloy composition can be accurately tested in real time during production, an experiment was conducted utilizing magneto-inductive test instrumentation and encircling coil. Throughout this experiment, and proposed future state of manufacturing, 100% of material was tested. Results yielded clear confirmation in accordance with the hypothesis.

This data driven subjective approach provided the ability to accurately, efficiently, and autonomously verify proper material grade had been used for the designated product. Ensuring proper material composition and material properties without slowing production using this testing method should be considered when improved quality is desired

Introduction

Understanding the deficiencies of the current historical approach to quality

Understanding the historical approach to quality first requires an understanding of the generally accepted process control procedures, specifically as they relate to material grade, microstructure, heat treatment, or alloy composition. Previously designed testing methods utilizing a periodic testing of a randomized lot sampling are demonstrating that they are no longer capable of meeting the current state quality specifications while maintaining the desired increased production throughput. Considerations must be made today to account for future specification requirements. Increased throughput requirements are driving the need for real time 100% inspection to ensure conformance to tighter specifications

Previously utilized testing methods required randomized sampling of a subset of material to be destructively tested and used as a representation of a production sequence. The challenge presented in the form of mid-production process shifting, specifically as it relates to material grade, microstructure, heat treatment, or alloy composition can create the challenge of hours of production before the next scheduled sampling. This time lapse has the potential of yielding hundreds (or thousands) of units of non-conforming product, which is at risk of loss quality and potential shipment of non-conforming product.

Post processing randomized sampling introduces both an inefficiency and a tremendous amount of risk that was previously deemed to be required. Utilizing the hypothesis that magneto-inductive testing methods can be used to test 100% of material inline at full production speeds will eliminate both the inefficiency and dramatically reduce risk.

Test Principle

The evaluation of material utilizing magneto-inductive test methods utilizes an encircling test coil or test sensor, as well as a testing instrument. Evaluation of material determined completely autonomously utilizing the test electronics requiring no operator intervention/interaction once the system has been set up. This test construct not only reduces the opportunity for operator error/interpretation of results, it also allows for full production manufacturing capacity.

The test methods as described can apply to both long continuous product as well as discreet components. This data driven approach compensates for the introduction of configuration variation while not impacting the principles magneto-inductive testing. This allows for a single instrument to able to test both continuous product, as well as discrete components. Utilizing this inline NDT approach allows for systematic testing of multiple test parameters (if desired) using a single test. By evaluating the characteristics as it relates to electrical conductivity and permeability the test considers any factors which may influence conductivity such as:

- Material grade
- Microstructure
- Heat treatment
- Density
- Alloy composition

Physics of Magneto-Inductive Testing

Before understanding results of magneto-inductive testing, we must first understand how it works. It must be understood that magneto-inductive testing is a comparative test, by which there is a comparison made from an acceptable sample to one that is considered not acceptable or beyond desired specification. The differences from said samples are determined by the electrical conductivity and magnetic permeability variances from the compared samples.

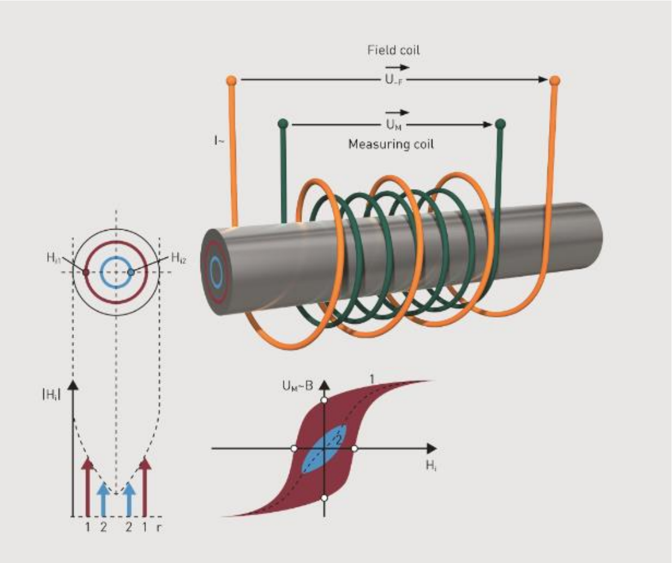

Figure 1: Common configuration of measuring coil [1].

The most common sensor type for magneto-inductive testing is an encircling coil. Within this coil is a pimary winding or "field coil" and a receiver winding or "measuring coil". The field coil induces an alternating magnetic field (eddy current) to the test sample. This alternating field can penetrate varying depths of the material based on the frequency used. Higher frequencies remain closer to the surface while lower frequencies penetrate much deeper. Measuring instrument variables such as amplifier current and coil winding design play a factor in the penetration depth. The primary field is also directly influenced by the material property features of the test specimen. Material with higher conductivity and permeability have a greater push-back to the induced signal therefore reducing penetration depth. Alloys with lower conductivity and permeability conversely allow for deeper penetration.

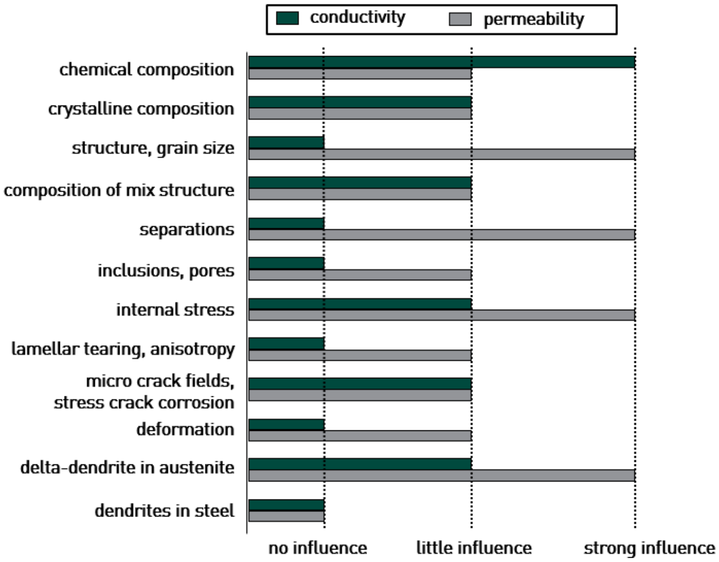

Figure 2: Observed condition affects on conductivity and permeability [2].

Material conditions will have different affects on conductivity and permeability which has an influence on phase and amplitude of received signal vs induced current. More directly, the measurement signal of each sample is plotted on an impedance plane (*Figure 3*) by observing the difference of amplitude and phase when comparing transmitter signals vs receiver signals. The relationship between resistance and inductive reactance can be oberved with the result of the amplitude and phase delay of the test. The magneto-inductive test instrument calculates this internally and presents the information in a user friendly manner for easy separation identification from one material characteristic to another. These plotted coordinates populate for each test taken where other observations such as regression of points can be used to quantify sample variations.

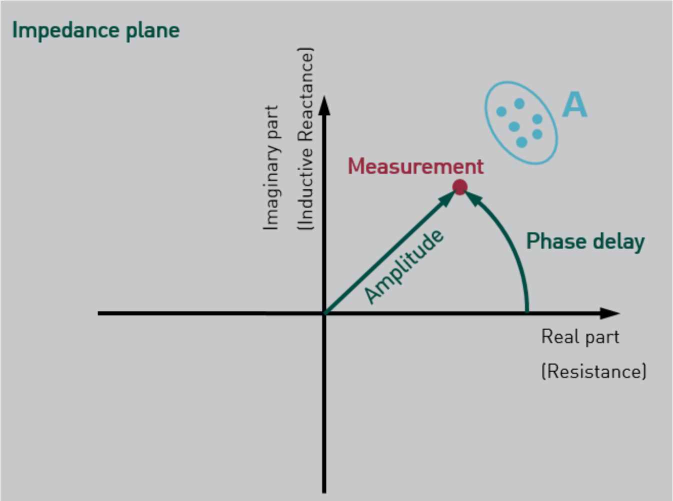

Figure 3: Impedance plane test result example [2].

Conditions for Accurate Results

It is important to understand the conditions that may affect the accuracy and repeatability of inline testing of component or long product materials. These conditions also have an effect on the material properties. For example, large differences in component temperature, positioning of sample within test sensor, and dimensional differences have an influence on material conductivity. An instrument capable of higher harmonic evaluation has the ability to disregard the conductivity effects and focus primarily on the permeability variations that are not as influenced by these conditions, thereby removing these influences. It is important to note that this higher harmonic evaluation cannot be used in non-ferromagnetic materials.

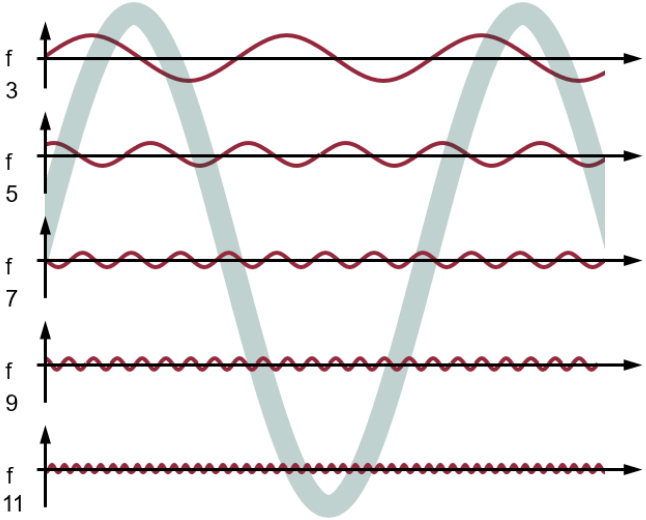

Figure 4: Harmonic frequencies vs fundamental [2].

The higher harmonic evalutation is a multiple of the fundamental test frequency. The fundamental and harmonic waves forms can be decomposed by means of a fourier transform.

Drafting of Test Criteria

To properly evaluate the hypothesis that magneto-inductive testing can displace destructive testing methods as it relates to material grade, microstructure, heat treatment, density, or alloy composition, the following trial was devised.

1. Sample set preparation:
    a. 2 sample sets have been devised consisting of:
        i. "continuous product" representative of bar/wire/pipe etc
        ii. "Discreet components" representing smaller components, gears, fasteners, spindles, etc.
    b. Samples are to be as close to the representative set as possible in order to not introduce geometry variation beyond what would occur in the production environment
    c. Each sample set to be evaluated validating both material conductivity and material permeability as the primary indicator of shifts in the following characteristics:
        i. Material grade
        ii. Microstructure
        iii. Heat treatment
        iv. Alloy composition
    d. Critical parameters to be considered when developing material masters for continuous product:

        i. Centering of product within coil
        ii. Consistent magnetic (gauss) levels along material length
        iii. Proper fill factor of test coil vs material diameter

    e. Critical parameters to be considered when developing material masters for discrete components:

        i. Critical zone(s) to be tested relative to sensor size
        ii. Specification of both upper and lower limits
        iii. Desired throughput speed
        iv. Proper fill factor of test coil vs material

Test Environment

Following the establishment of the adequate selection of test electronics and appropriate test sensor for the desired test task, care must be taken to ensure the testing environment is sufficiently magnetically clean. As it is understood that there are many factors that can cause unwanted influence on magneto-inductive testing including but not limited to ferrous metal within magnetic field, induction coils energizing/de-energizing, the switching on/off of motors with-in the field, or temperature variation. Selecting the proper testing frequency is critical to reduce the number of disturbing influences possible, however, care must be taken to ensure that there is little to no ferrous material within the magnetic field of the testing coil. Failure to recognize this critical parameter has the ability to reduce the effect of the desired test result.

This effect is directly correlated to the amount of mass that is of a condition other than what is being tested by the test sensor. If adequate care is taken to ensure that the amount of ferrous material is reduced to the amount possible, the test become much more stable. It is generally accepted that the most critical portion of the magnetic field, which must be accounted for, typically extends 1.5 times the width of the testing sensor.

Specifically if the test senor is 2” thick, the critical area surround the testing coil extends roughly 3” on each lateral orientation.

For the purposes of the trials carried out to test the hypothesis, a general laboratory environment was created taking care that the environment considerations were both conducive to the test as to isolate the variables, as well as, realistic to what can be replicated in a mill-type environment. The intent behind the set up was to create a testing environment that would test the hypothesis in the most objective way feasible while also maintaining a level of sustainability that can be achieved on the production floor.

Test Procedure and Results

Following a careful examination of the testing principle, test physics, testing environment, sample preparation, and test procedure to ensure that there were no disturbing outside influences, the test was performed in two separate groups: continuous products and discreet component materials. Based on the test part selected, the greatest success was found utilizing an approximate 70% fill factor (the ratio of coil opening filled by material) during the evaluation. Figure 5. The fill factor of 70% was found to apply to most materials and test objectives, however, under certain conditions it may need to be optimized based on certain applications, such as case depth evaluation. This ratio maintains the necessary distance from test sensor to the part, as well as provides sufficient spacing to allow for normal manufacturing variation in straightness and/or part placement while in production. For the purposes of this trial, a ferrous based powdered metal component was chosen.

Figure 5: Representation of suggested fill factor [3].

Discreet Component Testing Results

Upon performing the calibration testing utilizing 5-10 parts as an accepted test master group, testing was carried out in a randomized fashion. Figure 6 displays the accepted parts group. For the purposes of completeness it is necessary to calibrate the instrumentation utilizing both conforming and non-conforming parts. Following the calibration/set up, the sample parts were then re-run in a random sampling pattern.

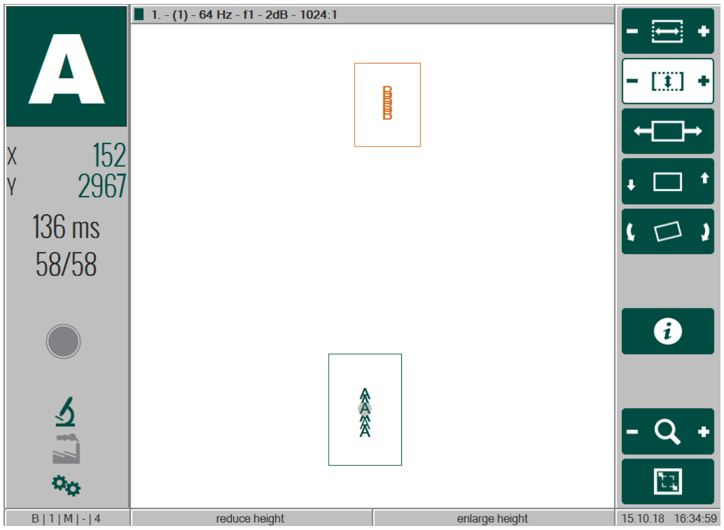

Figure 6: Upper and Lower Specification Bounds [3].

Figure 7 consists of the continuation study following the calibration. This resulted in a clear increase of the size of the accepted test class. However, given the test objective and testing specification, this was the desired result. For the purposes of this evaluation, the accepted part classification was based on the upper and lower bounds of the specification rather than the traditional 3 sigma of statistical variation.

The results of the examination yielded positive results in accordance with the hypothesis. Based on this outcome, the confidence to bring this solution into the production environment is quite strong.

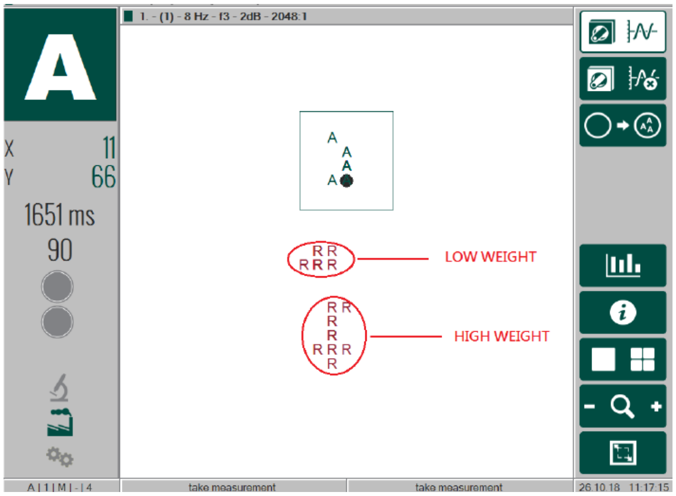

Figure 7: Result of Density Variation [3].

The test results in Figure 7 clearly demonstrate the ability to separate conforming parts from (in this test) under/over-weight parts. Utilizing this information allows production control of specification limits beyond those previously thought capable.

Continuous Product Testing Results

Continuous or long product testing has demonstrated as a strong application for magneto-inductive testing as there is no need for the material to stop within the test sensor for accurate interpretation of the material. Test speed is then only limited to the frequency used and the amount of coverage required on the material length.

Compared to component testing, the main difference in long product is the ability to hold the test signal active and maintain the travel of product through the test coil. The ability to show a bar chart representation of the entire piece length of the long material allows the user to acknowledge any variances of powder component density throughout the product length. Figure 8 shows long piece results of individual wires with varying powder percentages/density variations. Outputs can be assigned to sort the material based on how many times the long sample falls outside of a desired fill specification.

The correlation to these long piece results are directly tied to the impedance plane values of the calibrated test samples. Figure 9 shows the impedance plane view of the different fill percentages and their relationship to each other. With these results, it is possible to confirm the acceptable fill of powder-cored welding wire while properly rejecting and/or sorting for too much or too little fill.

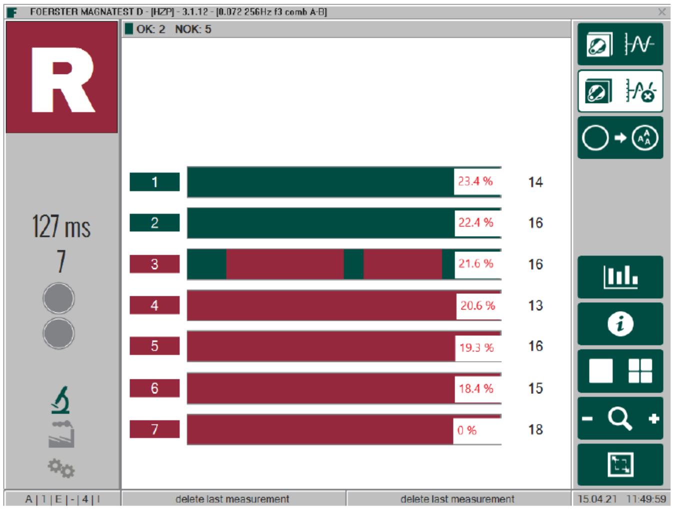
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Figure 8: Continuous test piece results of powder-cored wire alloy composition variations [4].

As demonstrated by Figure 8 the continous testing of wire has yielded a successful bench top trial sufficient to go into a production level environment. Figure 8 demonstrates production test results, with the green colored sections representative of conforming material, which in this case was indicative of samples that contained a minimum 22% filler. Test sample #3 in figure 8 shows a speciman that contained sections of both conforming and nonconforming material, which when utilizing the proper sorting output signals in conjunction with an ancillary marking device will allow nonforming material to be identified and subsequently from prodcution.

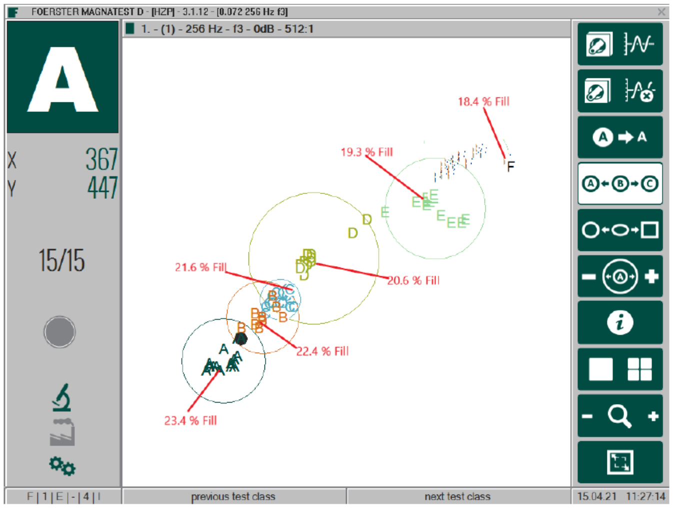
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Figure 9: Impedance plane results of powder-cored wire fill percentages [4].

Grade Verification Testing Results

Utilizing magneto-inductive testing for material grade verification was tested utilizing carbon steel bars with material grade as the only variable. The tested material consisted of the following alloys which were grouped into their representative test classes.

- 4130-represented by test class “A”
- 4140-represented by test class “B”
- 4340-represented by test class “C”
- 1038-represented by test class “D”
- 4150-represented by test class “E”
- 8640-represented by test class “F”

Figure 10 represents the demonstrated results. The magneto-inductive testing method proposed was able to easily and clearly designate between the material grades.

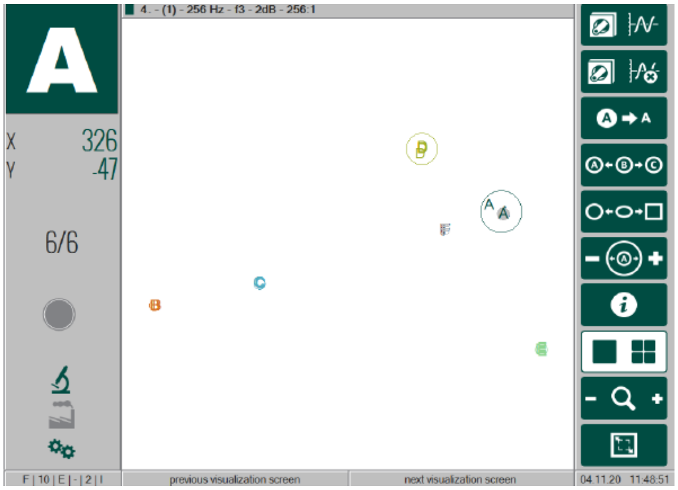

Figure 10: Impedance plane results of material grade testing [5].

Conclusion

Based on the data set(s) used to generate the figures in this document, it can be confidently concluded that the hypothesis has been proven in a positive manner. Magneto-inductive testing has the ability to displace traditional destructive testing methods. It must be noted that these methods should be validated using an application trial or bench top test to determine the proper frequency, test sensor, and line speed capability.

The instrumentation required as outlined and demonstrated in this document is to be run completely autonomously without operator interaction or intervention in conjunction with automatic sorting/paint marking. By utilizing magneto-inductive testing which is founded in material conductivity and permeability, It is possible to successfully differentiate conforming from non-conforming material as it relates to material grade, microstructure, heat treatment, density, and alloy composition. This method has proven successful for testing these characteristics as they are directly related to material conductivity and permeability.

Industries ranging from automotive, agricultural, oil/gas, aerospace, and medical have the ability to yield immediate and dramatic improvements in both efficiency and quality by introducing the test methodology outlined in this document. Due to ever-tightening specifications magneto-inductive testing has strong potential to yield considerable improvements.

Acknowledgements

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