Investigation the effect of heat treatment on brass defect measurement using Eddy Current Testing

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Abstract. Eddy current technology has been used as a non-destructive method of measuring material properties for many years. Most applications of the eddy current technique lie in locating surface or subsurface flaws and evaluating material characteristics. This paper investigated the effect of heated brass material on material conductivity and defect measurement using eddy current testing (ECT). The ECT signal is compared and analyses in order study the effect of annealing on electrical properties of brass material. Brass block sample is designed and artificial defect with depth of 0.5mm 1.00mm and 2.00mm fabricated using Electrical discharge machining (EDM) machine. Industrial standard ECT set is used inspect the conductivity depth of defect brass sample before and after annealing process. Different frequency of ECT coil excitation are applied in order to determine the suitable ECT inspection frequency on brass material. The experimental results show the heat treatment decrease the conductivity of brass material. Due the changes of electrical properties on heated brass, the measurement of depth defect affected the value of amplitude ECT signal. Where the heated brass material reduced 10% IACS signal.

1. Introduction

Massive effort has been made in studying advanced NDT techniques capable of detecting defects in alloy composites including ultrasound, stereography and X-ray. In industry especially aerospace, some traditional methods such as visual inspection, coin tapping, and ultrasonic pulse echo and low-energy radiography are already in use. More recently, late technologies like ultrasonic phased array scanning, electrical potential technique, near-field microwave, lamb waving sensing and electrical resistance change method are catching more and more attention from research labs and industry[1][2][3]. However, heated brass material structures too complicated to inspect by conventional non-destructive testing methods.

An application of eddy current testing which has rapidly grown in importance is the detection and sizing of surface and subsurface defects in materials. With recent improvements in design of electrical equipment and probes, the method is both more reliable and accurate [4][5]. The geometrical shape, the amplitude, and the frequency of the applied field are main factors in determining the magnitude and the direction of eddy currents induced by harmonically varying magnetic fields[6][7].
Object variables themselves, produce a varying magnetic field. This magnetic field associated with the test object is called the secondary field, which, in the case of nonmagnetic test objects, opposes the primary field to an extent that depends on the conductivity, size of the object, and the test frequency [8][9]. The timing or electrical phase angle of the induced eddy currents varies, depending upon the test object parameters and the test frequency. The secondary field associated with these currents also varies similarly. This secondary field is monitored by observing its effects on the current or voltage of the primary test coil, or upon currents or voltages induced in one or more other sensing coils placed nearby[10][11].

Previous work on the use of eddy current techniques for alloy material have shown that material defect can be detected, and variations in alloy properties also successfully revealed. Using eddy current testing, surface and subsurface defect detected with better sensitivity than other popular NDT technique such as particle magnetics testing, radiography and infrared thermography[12][13]. To detect the flaw in alloy, one simple way is to scan the inspected object using a single-coil probe of appreciate design and keep the lift-off constant. When a defect or any kind of discontinuity occurs in the object in which eddy current is induced, the paths of the currents are diverted and changes in impedance of the coil take place in a way in accordance the nature of the defect[14][15]. Although these investigations reported many interesting results, little work has examined on specific alloy such as brass material. In particular, the effect of heat treatment on eddy current testing remains unexplored. The aim of the present work is to investigate the effects of heat treatment on electrical conductivity brass material. The paper also explores the influence of annealing process on depth defect measurement using ECT technique.

2. Methodology

2.1. Sample preparation

The specimens were all made from commercial brass. This brass is widely used in the automotive, aerospace and military industry for its high achievable strength, cast ability, pressure tightness, low weight and the fact that it can be machined and welded. The chemical composition of the brass alloy used in this works is shown in Table 1.

| Elements | wt.% |
|----------|------|
| Copper   | 85   |
| Tin      | 5    |
| Lead     | 5    |
| Zinc     | 5    |

The first step is produced the design of the sample block. The block is design using the AutoCAD software. Brass is used in stainless steels, high resistance to corrosion from acids, increases strength and toughness. The length of the sample block is 125mm with have three slots. The slots have different depth with the first depth of slot is 0.5mm, the second slot is 1.0mm and the third slot is 2.0mm. Besides, the thickness of the sample block is 15mm. All the two of the sample blocks are produce with the same size and same material. Figure 1 shown the designed for the sample block.
This project used brass alloy steel as sample block. It is strong compare with other steel and have a strong machinability average. The first step in sample fabrication is to milling the brass material into the required size dimension. The machine will use to shape the small surface due of the short drill size. The brass calibration block surface will have the smooth finishing being use as a calibration block. The length of brass material is 260mm, width 25mm and the thickness of the brass is 15mm. This material will include the above process. This dimension is for one sample block. This project needs to provide two pieces of sample block. All the sample block dimension is same with two each other. Electronic discharge machine (EDM) is also call as a wire cut machine. The function of this machine is to fabricate different depth slot of defect on brass material sample. The slots on the calibration block are divided on three different parts of slots under the depth value of the slots. The value is 0.5mm, 1.0mm, and 2.0mm. For the second sample block process is same with first sample block, but the different type of process in this step is annealing process. Figure 2 shown the milling, wire cut process and finished brass sample for ECT testing. This process is about making slot on the sample block. By the type of slot is 0.5mm, 1.0mm and 2.0mm about the depth of slot. All the diameter of the slots were the same with 0.2 width.

2.2. Heat treatment
It is a common practice to heat-treat the brass alloy in order to improve its mechanical properties. The experimental alloys were then cut and subjected to the heat treatment in the heat treatment lab at TATIUC. The brass sample were firstly austenitized in a box furnace in argon atmosphere for one hour and then cooled down to room temperature. In this research work, the effect of the different heat treatment on characteristic eddy current testing for depth defect measurement evaluate. Figure 3 shown the heat treatment for brass material.
The temperature selected to carry out all the solution heat treatments was 540°C. ASTM standards recommend for the brass alloy a solution heat treatment of 540°C for 4 to 12 hours [13][14]. In this research work a solution heat treatment time of 4 hours was mainly used to evaluate the material properties. Figure 4 shown the heat treatment machine and Figure 5 shown the complete annealing process for brass material sample.

![Figure 3. Heat treatment procedure for experimental brass.](image)

2.3. Conductivity testing

Electrical conductivity for brass material sample measurements at room temperature were performed using ECT instrument. This instrument measures the conductivity by an eddy-current technique and displays it as a percentage of the International Annealed Copper Standard (% IACS); with 100% IACS defined to be 1.7241 μΩcm at 20°C[16][7]. Moreover, this instrument features temperature compensation to adjust the reading to a standard lab condition of 20°C and an effective constant penetration depth of 1.27 mm. According to ASTM standard E 1004-91, the accuracy of the results obtained from this test can be affected by the following parameters:

- Quality or degree of coupling between the probe coil and the metal.
- Electromagnetic field penetration through thin test objects.
- Discontinuities or in homogeneities in the metal near the position of the probe coil.
- Variations in the temperature of the probe coil, test object and standards.
- Surface conditions of the test object.
- Test object geometry.
To avoid these interferences in the electrical conductivity measurements, the following actions were taken:

- The area of the sample to be examined was ground with SiC paper to obtain a flat smooth surface.
- The thickness of the sample was at least the same as the standards.
- Sample showing visible imperfections were rejected.
- It was ensured that the standards, instruments and sample were at the same temperature before any measurements were taken.
- The instrument was calibrated against three known aluminum standards and compensated for temperature.
- Touching of the standards and sample during the measurements was avoided.
- The edge effect was avoided by always taking the measurements at the center of the sample.
- The calibration of the instrument was verified at the end of the testing of each sample.

Figure 6 show the calibration references and ECT standard probe to calibrate the conductivity of probe for brass conductivity. This calibration references standard need to calibrate on the STD1 for the first calibrates and the last one is on the STD2. For every STD, it have the own value of conductivity. This is to ensure the conductivity of brass that will be check later will give the sharp value of brass conductivity for non-annealing and annealing process.

Conductivity probe is the probe that used to find the conductivity of the brass material. Conductivity of the brass need to find out because we need the value of the brass conductivity to place the value of conductivity in the equation for depth of penetration. Conductivity brass need to find out because the brass material that have been produced as references block was a scrap material of industries and the value conductivity is not be the same with the original conductivity value. Conductivity is about the material that allows flowing the current.

The differentiation of the conductivity for references block making from brass material is not have the large of different value because the brass material does not contain carbon for the annealing process that have been perform on the reference block. For other one references block is about the normal process and not perform annealing process.

Figure 6. Sample calibration and ECT probe for conductivity inspection

Figure 7 is shown the step to perform conductivity test. The first step is to calibrate the probe on STD1 and ensure the conductivity value is 60.95. This calibration is to ensure the sharp calibration for conductivity probe. The probe is calibrate using calibration block on STD2 and the conductivity reading should be 8.63. Figure 7(c) show the measurement of brass alloy steel. This step is to define with collect the average of conductivity from all side and edge. After collect all the point of conductivity value, find the constant value of conductivity to make sure the value conductivity of brass is fix and sharp.
2.4. Eddy Current Testing for depth defect measurement
To carry out this experimental work, an industrial standard ECT equipment illustrated in Figure 8 is used to scan brass sample material with artificial defect. Three frequency of 0.4 MHz, 1.7 MHz and 7.3 MHZ are employed for this investigation. Throughout the studies a scanning lift-off of 1mm was maintained.

3. Results

3.1. Electrical Conductivity Measurements
Estimating the conductivity of the brass sample after and before the heat treatment could be done using an eddy current conductivity. The coil impedance in air was measured first over a frequency range 0.5 kHz to 500 kHz [17][18]. Then the impedance due to the unflawed sample material was measured over the same frequency range by putting the probe at points far away from cracks. Ideally, the impedance change due to the unflawed tube could be obtained by simply subtracting impedance in air. In practice, parasitic shunt capacitance has a noticeable effect on the coil impedance at high frequencies but a correction has been applied to the data. Finally, the effective value of coil lift-off and brass sample conductivity have been determined by fitting the measurement data with the calculation based on the theoretical model for a coil on flat surface.

When making conductivity tests, the sample should be at least 3d thick so that changes in the thickness of the sample do not affect the measurements [19][20]. When electrical conductivity in % IACS and permeability in H/mm are known, the standard depth of penetration can be calculated using skin effect equation.

The accuracy of the instrument was verified against standards. The variations are seen in Table 2. The results obtained indicate that the error of the electrical conductivity measurements performed in this research work is small. In the eddy current testing, the all of the metal is need to check the conductivity to find the value of electricity of the brass. Conductivity of the brass is for annealing process is 23.62 IACS. The value of conductivity for brass material using annealing process is more low conductivity from non-annealing process.
Table 2. Conductivity for non-annealing and annealing heat treatment brass

| Process       | Conductivity brass |
|---------------|--------------------|
| Non annealing | 23.79 IACS         |
| Annealing     | 23.62 IACS         |

The behavior of the electrical conductivity is shown in Table 2. It is clearly seen that the electrical conductivity decreases up to 0.17 IACS. In this case, the decrease of the electrical conductivity is associated with a decrease in the yield strength of the alloy structures.

3.2. Depth of defect measurement

Measurements were carried out with the brass sample before and after process of heat treatment and quenching process. A set-up procedure ensures that the ECT have a common axis in line with the surface of the brass sample. Care over alignment and the fact that the coil mount is a close sliding fit in the surface brass sample ensure that the coil is scanned parallel to the inner surface of the plate sample and variations in the critical lift-off parameter, $\lambda$, are minimized.

![Figure 9. Signal slot for depth of defect 0.5mm, 1.0mm, 2.0mm (7.3MHz non-annealing)](image)

![Figure 10. Signal slot for depth of defect 0.5mm, 1.0mm, 2.0mm (1.8MHz non-annealing)](image)

![Figure 11. Signal slot for depth of defect 0.5mm, 1.0mm, 2.0mm (0.4 MHz non-annealing)](image)

The coil impedance change due to the crack was measured as the z-coordinate of the coil was varied incrementally as it passed symmetrically over the defect. Again, the measurement data have been corrected for lift-off effect by minimize the variation of lift-off during the scan process. For the detection of depth defect more than 1 mm in brass material the frequency of operation has to be chosen low enough to allow for the penetration of the electromagnetic field, yet high enough for signal processing and flaw identification. As a compromise value, this frequency was chosen to be 0.4.
MHz, 1.8 MHz and 7.3 MHz respectively. The maximum depth of defect in this work is 2 mm which is 71 percent of the skin depth at that frequency. Skin depth is a measure of the depth of penetration of the normally incident electromagnetic field (spatial frequency \( k = 0 \)). Higher spatial frequency components of the field do not penetrate as deeply, and it is therefore convenient to define a modified skin depth.

Eddy currents are more concentrated at the surface and decrease in intensity with distance below the surface of the metal. This effect is known as the "skin effect." The depth at which eddy current density has decreased to \( 1/e \), or about 37% of the surface density, is called the standard depth of penetration [17]. Although eddy currents penetrate deeper than one standard depth of penetration, they decrease rapidly with depth. At two standard depths of penetration, the eddy current density has decreased to \( 1/e \) squared or 13.5% of the surface density. At three depths, the eddy current density is down to only 5% of the surface density.

The depth of penetration is dependent of test drive frequency, the test material's conductivity. The depth of penetration decreases with increasing frequency, conductivity and permeability. In this work, the heat treatment on brass material changes the conductivity material that effects the depth measurement.

For the three frequency of ECT inspection employed in this study, it is of interest to compare their performance in depth defect measurement on brass heated samples. To this end, C-scans of the same area for an annealing and non-heated sample are presented in Figures 10 to Figure 15.

![Figure 12](image1.png)

**Figure 12.** Signal slot for depth of defect 0.5mm, 1.0mm, 2.0mm (0.5MHz annealing)

![Figure 13](image2.png)

**Figure 13.** Signal slot for depth of defect 0.5mm, 1.0mm, 2.0mm (1.8 MHz annealing)

![Figure 14](image3.png)

**Figure 14.** Signal slot for depth of defect 0.5mm, 1.0mm, 2.0mm (7.4 MHz annealing)

From the results above, it can be observed that the difference frequency of coil excitation and the heat treatment exhibited different sensitivity to the same depth of defect. This is due the annealing and quenching process change the conductivity brass material as shown in Table 3.1. However, its level of sensitivity to defect would differ based on frequency probe configuration as well. For brass material the best frequency for defect inspection depth between 0.5mm to 2.0mm is 7.3 MHz. Thus, probe setting parameters in conjunction with minimize lift-off effect is a potential tool for optimize ECT
procedure. Table 3 show the value of signal amplitude for all the frequency base on the three slots on the brass sample for non-annealing calibration block. While the graph for signal amplitude is show in Figure 15.

**Table 3.** Signal amplitude for non-annealing heat treatment process

| Slot (mm) | Frequency (MHz) |
|-----------|-----------------|
|           | 7.3             | 1.8            | 0.4            |
| 0.5       | 100%            | 83%            | 60%            |
| 1.0       | 100%            | 100%           | 62%            |
| 2.0       | 100%            | 100%           | 100%           |

![Graph for signal amplitude non-annealing process](image)

**Figure 15.** Graph for signal amplitude non-annealing process

Table 4 show the value of signal amplitude for all the frequency base on the three slots on the calibration block for heat treatment brass sample block. The graph for signal amplitude above is show in Figure 16.

**Table 4.** Signal amplitude for annealing process

| Slot (mm) | Frequency (MHz) |
|-----------|-----------------|
|           | 7.4             | 1.8            | 0.5            |
| 0.5       | 100%            | 69%            | 38%            |
| 1.0       | 100%            | 100%           | 58%            |
| 2.0       | 100%            | 100%           | 100%           |

![Graph for signal amplitude annealing process](image)

**Figure 16.** Graph for signal amplitude annealing process
It has been shown that electrical conductivity can be employed as a non-destructive method to monitor the effect of heated treatment on microstructure that affect the ECT defect measurement. It has been also found that heated brass material exhibits a decrease electrical conductivity. This is related to the differences in the microstructure shape, since the electrons flow more easily through non heated material.

4. Conclusion
This paper investigated the effect of heat treatment on brass alloy electrical properties. ECT technique utilize in order to determine the changes of conductivity and ECT signal on defect measurement. The analysis of the variation of ECT signal for heated brass material offer great simplification results in terms to understand the changes of brass alloy material properties due to the effect of heat treatment. The ECT technique working detection of defect based on the changes of impedance when the probe cross the defect on material surface or subsurface. The signals obtained from different depth of defect were discussed. The effect on conductivity combined with the best frequency of operation is discovered.

5. References
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