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# DETECTION OF SUB-SURFACE DEFECTS IN SEMI-FINISHED PRODUCTS FROM ALUMINUM ALLOYS BY THE EDDY CURRENT METHOD

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**Abstract**

The article presents the results of tests aimed at detecting discontinuities in the subsurface layer of elements intended for further processing. For the initial identification of discontinuities, the method of computed tomography was used. Based on the tomographic images of selected typical defects and measurements of the electrical conductivity of the material, the parameters for the eddy current tests were determined. A series of discontinuities in the subsurface layer to a depth of about 0.48 mm were detected. This allowed, at a given stage of machining, relevant elements to be selected for further processing.

**Keywords:** eddy current testing, tomographic testing, subsurface discontinuities, standard depth of penetration, effective depth of penetration
**Article Category:** Research Article

## INTRODUCTION

Non-destructive testing is important in determining the condition of the material. Their particular application has found a place in defectoscopy used to detect defects and anomalies of materials in the form of discontinuities such as cracks, inclusions, voids, porosity and delamination. The main advantage of NDT is that it is non-invasive – no sampling is required. Generally, the tests do not interfere with the physical and functional properties of the object. In addition, these can be mobile tests, to be used at the site of production or operation of the object. Input materials for production, semi-finished products at individual stages of the production process, and then finished products and structures in use are subject to non-destructive evaluation. Each of the methods and techniques of non-destructive defectoscopy testing has specific possibilities and limitations of applications. Various, often complex factors determine the selection of a methodology for a specific task. The selection of the methodology depends on the type of the tested object, the characteristics of the expected defects, the place and organization as well as the costs of the tests. And so, important considerations in selecting the methodology are the type of the tested material (conductive, non-conductive, magnetic, non-magnetic), material structure, manufacturing method (casting, forging), surface condition (roughness, coating), geometric dimensions and shapes (simple, complicated geometry). When selecting the methodology, first of all the type and nature of the expected defects are taken into account – their type (crack, inclusion), location (surface, subsurface, internal), geometry (flat, volumetric), orientation in relation to the surface (transverse, oblique), minimum possible dimensions to be detected by a given technique. In terms of organizing the investigation process, the availability of the facility (time constraints, limitations of areas that can be tested), as well as working environmental and safety conditions are all important. From the cost savings perspective, it is important to minimize disrupting or slowing down the production or operation process while ensuring the required sensitivity and effectiveness of defect detection.

## TEST OBJECT

The subjects of the tests were elements of aluminum alloy after the die-casting process, intended for further machining. In the subsurface layers, small discontinuities up to several tenths of a millimeter long were found. These were discontinuities that were acceptable given the adopted criteria and further use of the product. Nevertheless, they caused significant difficulties in machining and extended the processing time.

## NON-DESTRUCTIVE MATERIAL TESTING

### Eddy current testing – physical basics

Non-destructive testing by the eddy current method is applicable to materials showing electrical conductivity. Eddy currents arise in an object placed in an alternating magnetic field. The eddy current density distribution induced inside the material is described by the relation:

$$J_x = J_0 e^{-x/\delta} \sin\left(\omega t - x/\delta\right) \tag{1}$$

where: $J_x$ is the eddy current density at a distance $x$ from the material surface, $J_0$ is the eddy current density on the material surface, $x$ distance from the material surface, $\omega$ pulsation for the frequency $f$ of the transducer operation, $\delta$ depth of eddy current penetration.

Among the material properties that affect the distribution of the eddy currents generated in the object, the electromagnetic properties – specific electrical conductivity $\sigma$ and magnetic permeability $\mu$, are of significant importance. Local changes of these two parameters, caused by material discontinuities (inclusions, segregations, cracks) or differences in the structure, cause changes in the distribution of eddy currents.

In the application of eddy currents to the tested objects, apart from the electromagnetic properties of the material, the frequency of the electromagnetic field of the transducer is important. This is related to the skin phenomenon. In AC circuits, as a result of the interaction of the magnetic and electric fields, the current density at the surface of a conductor is greater than inside it. The quantity characterizing the skin effect is the depth of the eddy current penetration into the conductor.

In applications of the eddy current method, the standard penetration depth is defined. The standard eddy current penetration depth is such a depth at which the eddy current density decreases *e*-fold in relation to its value on the surface. It is described by the relation:

$$\delta = \frac{1}{2\pi}\sqrt{\frac{10^7}{f\mu_r\sigma}} \tag{2}$$

where: $\delta$ – penetration depth [m], $f$ – frequency of the electromagnetic field [Hz], $\mu_r$ – relative magnetic permeability (dimensionless number), $\sigma$ – electrical conductivity [S/m].

The concept of the effective eddy current penetration depth is also used. It defines the contractual application limit of the eddy current method. In general, the effective penetration depth is defined as the minimum depth beyond which the test system can no longer detect further increase in sample thickness. The depth at which the eddy current density decreases $e^3$-fold in relation to their surface density is often taken as the effective depth of penetration. This definition, to better illustrate the issue, was used in the description of the tests results in this paper.

Table 1 and Figure 1 show the relation between the eddy current penetration depth and the frequency for an aluminum alloy with a conductivity of 18.32 MS/m. As can be seen from the graphs and the dependence (2), this depth, similarly to all conductive materials, strongly decreases with increasing frequency.

The sensitivity of the method, understood as the capability of detecting small defects, depends on the eddy current density. Increasing the frequency, and thus reducing the penetration depth of eddy currents, increases their density, which in turn gives greater sensitivity of the test. Detection of small defects located at greater depths (and therefore requiring a reduction in frequency) can be problematic.

Table 1.

| *f [kHz]* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | *10* | *60* | *100* | *250* | *500* | *750* | *1000* | *1250* | *1500* | *1750* | *2000* |
| *δ [mm]* | | | | | | | | | | | |
| 3.72 | 1.18 | 0.48 | 0.37 | 0.24 | 0.17 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 |
| *3δ [mm]* | | | | | | | | | | | |
| 11.15 | 3.53 | 1.44 | 1.11 | 0.71 | 0.50 | 0.41 | 0.35 | 0.32 | 0.29 | 0.27 | 0.25 |

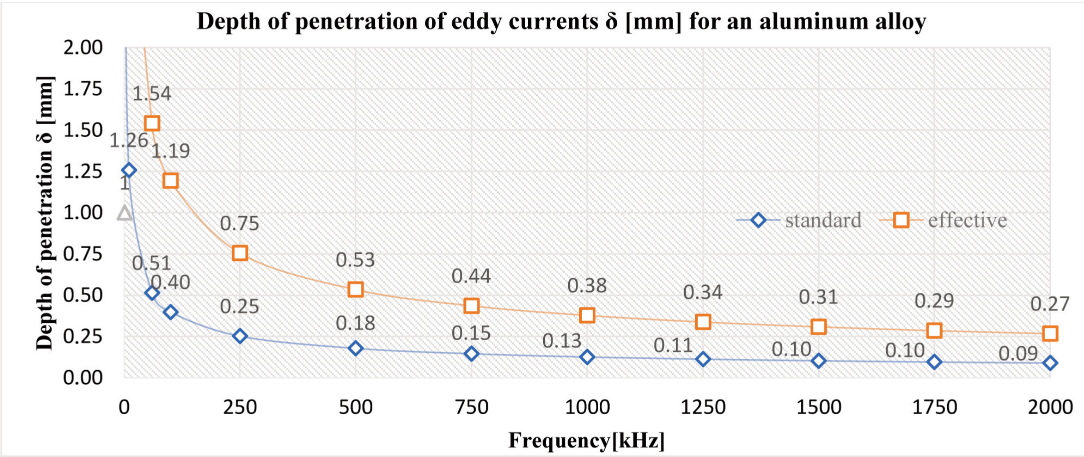


Fig. 1. The depth of penetration of eddy currents depending on the frequency for an aluminum alloy with a specific conductivity of 18.32 MS/m.

## Detection of subsurface discontinuities using the eddy current method

Material specimens with different electrical conductivities and types of defects ("flakes" and "pores" type) were taken from the semi-finished products intended for machining. Specimens 523 4B (Fig. 2.) and 4A (Fig. 6), described as "flakes", had a higher electrical conductivity than the "pores" specimens − specimen 7 (Fig. 8) and specimen 1 (Fig. 10).

The specimens were subjected to tomographic examination. The purpose of these tests was to illustrate subsurface discontinuities and to determine the parameters for further tests using the eddy current method (Fig. 3–5, Fig. 7, Fig. 9, Fig. 11–13). The detected discontinuities, depending on their geometry, were divided into two groups. The first group include discontinuities, in which one of the dimensions was three times larger than the other two. This group was called "longitudinal discontinuities" and the defects belonging to this group were assigned a characteristic dimension length of the discontinuity. The remaining discontinuities were classified as "volumetric discontinuities", and their characteristic dimension was the diameter of the sphere described on a given discontinuity.

Using the eddy current method, specific electrical conductivity of individual samples was measured. Then, dependencies of the depth of eddy current penetration on frequency were determined. Eddy current frequencies were selected to enable penetration of the subsurface layer of the assumed thickness with a sensitivity that allowed for the detection of discontinuities previously found by tomographic examinations. For selected frequencies, the depths of location of individual discontinuities were within the standard range of the eddy current penetration depth, between the standard and the effective (critical) depth and above the effective penetration depth. The parameters selected in this way made it possible to detect "longitudinal discontinuities", approx. 0.40 mm long, and also "volumetric discontinuities" with diameters ranging from 0.15 mm, beginning at depths of up to approx. 0.48 mm from the surface (Tab. 2, Tab. 3, Tab. 4, Tab. 5).

The test results showed that the eddy current technique used for the inspection allows for the elimination of elements that are dangerous from the point of view of further machining.

Fig. 2. Specimen 523 4B with marked (A, B, C) discontinuities of the internal structure subjected to ET tests.

Table 2. Test parameters of the sample 523 4B.

| Specific conductivity of the sample: 23.85 MS/m | | | | |
|---|---|---|---|---|
| f [kHz] | Standard penetration depth [mm] | | Effective penetration depth [mm] | |
| 700 | 0.123 | | 0.369 | |
| Discontinuity | Location depth [mm] | Characteristic dimension*) [mm] | Amp. ET signal | CT image |
| A | 0.08 | l = 0.41 | 0.25H | Fig. 3. |
| B | 0.09 | Φ = 0.15 | 0.25H | Fig. 4. |
| C | 0.14 | Φ = 0.51 | 0.45H | Fig. 5. |

*) l – length, Φ – diameter

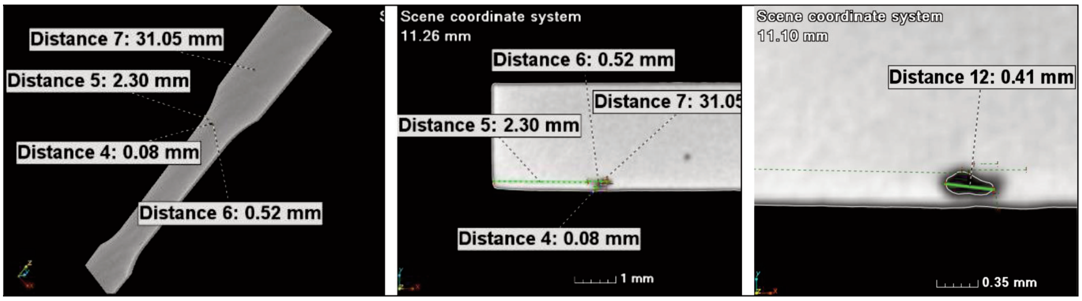


Fig. 3. Tomographic images of discontinuities A of Specimen 523 4B.

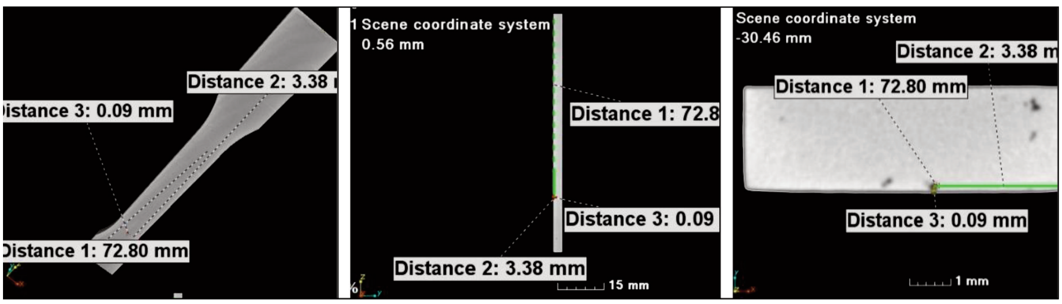


Fig. 4. Tomographic images of discontinuities B of Specimen 523 4B.

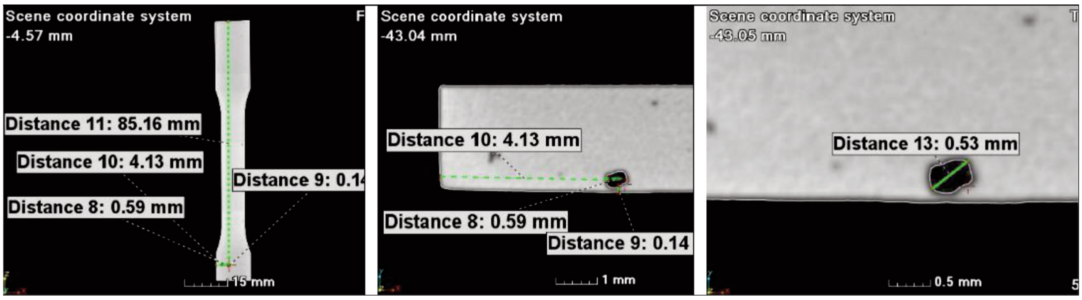


Fig. 5. Tomographic images of discontinuities C of Specimen 523 4B.

Fig. 6. Specimen 4A with marked (arrow) discontinuities
of the internal structure subjected to ET tests.

Tab. 3. Test parameters of the sample 4A.

| Specific conductivity of the sample: 23.92 MS/m. | | | | |
|---|---|---|---|---|
| f [kHz] | Standard penetration depth [mm] | | Effective penetration depth [mm] | |
| 700 | 0.123 | | 0.369 | |
| Discontinuity | Location depth [mm] | Characteristic dimension*) [mm] | Amp. ET signal | CT image |
| A | 0.48 | l = 0.44 | 0.30H | Fig. 7. |

*) l – length, Φ – diameter

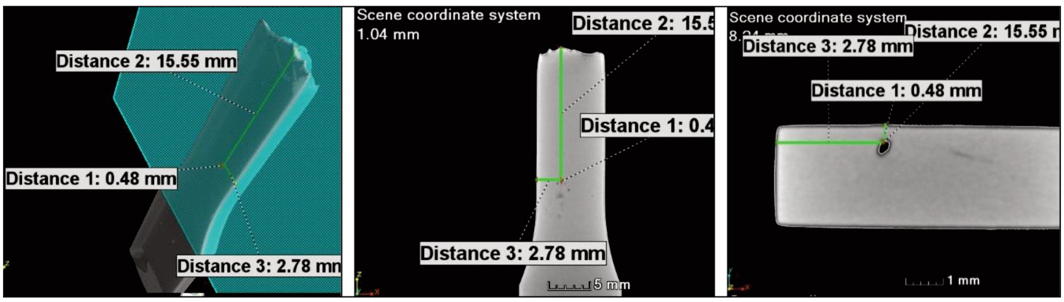


Fig. 7. Tomographic images of discontinuities of specimen 4A.

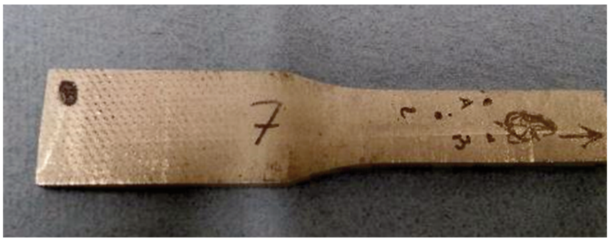

Fig. 8. Specimen 7 with marked (C) discontinuities
of the internal structure subjected to ET tests.

Tab. 4. Test parameters of the sample 7.

| Specific conductivity of the sample: 17.43 MS/m. | | | | |
|---|---|---|---|---|
| f [kHz] | Standard penetration depth [mm] | | Effective penetration depth [mm] | |
| 1000 | 0.120 | | 0.361 | |
| Discontinuity | Location depth [mm] | Characteristic dimension*) [mm] | Amp. ET signal | CT image |
| C | 0.20 | l = 0.51 | 0.35H | Fig. 9. |

*) l – length, Φ – diameter

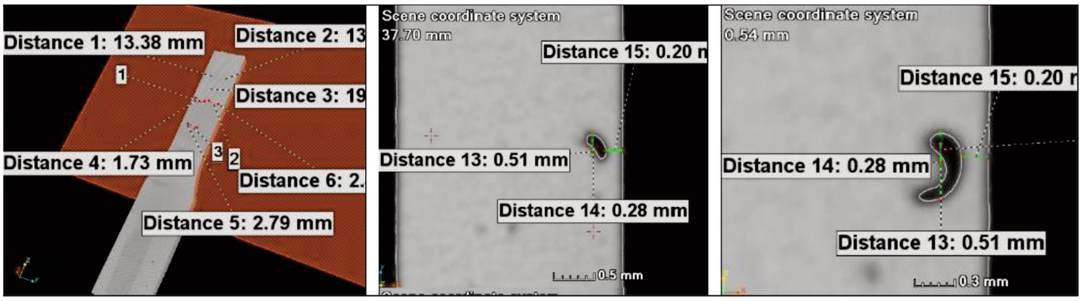


Fig. 9. Tomographic images of discontinuities C(3) of specimen 7.

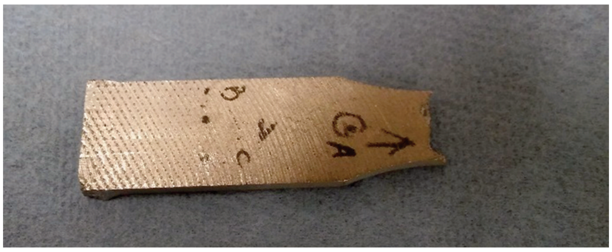

Fig. 10. Specimen 1 with marked (A, B, C) discontinuities
of the internal structure subjected to ET tests.

Tab. 5. Test parameters of the sample 1.

<table>
<tr><td colspan="5">Specific conductivity of the sample: 17.06 MS/m.</td></tr>
<tr><td>f [kHz]</td><td colspan="2">Standard penetration depth [mm]</td><td colspan="2">Effective penetration depth [mm]</td></tr>
<tr><td>700</td><td colspan="2">0.141</td><td colspan="2">0.422</td></tr>
<tr><td>1000</td><td colspan="2">0.122</td><td colspan="2">0.365</td></tr>
<tr><td>Discontinuity</td><td>Location depth [mm]</td><td>Characteristic dimension*) [mm]</td><td>Amp. ET signal</td><td>CT image</td></tr>
<tr><td>A</td><td>0.51</td><td>l = 0.40</td><td>not obtained (< 0.15H)</td><td>Fig. 11.</td></tr>
<tr><td>B</td><td>0.47</td><td>Φ = 0.50</td><td>not obtained (< 0.15H)</td><td>Fig. 12.</td></tr>
<tr><td>C</td><td>0.34</td><td>Φ = 0.43</td><td>not obtained (< 0.15H)</td><td>Fig. 13.</td></tr>
</table>

*) l – length, Φ – diameter

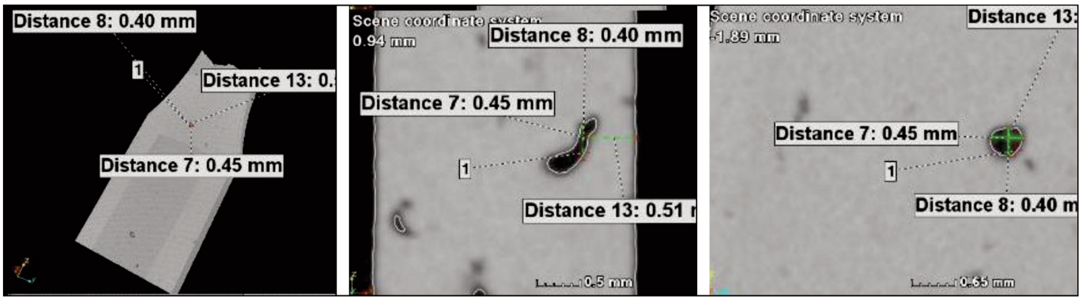


Fig. 11. Tomographic images of discontinuities A(1) of specimen 1.

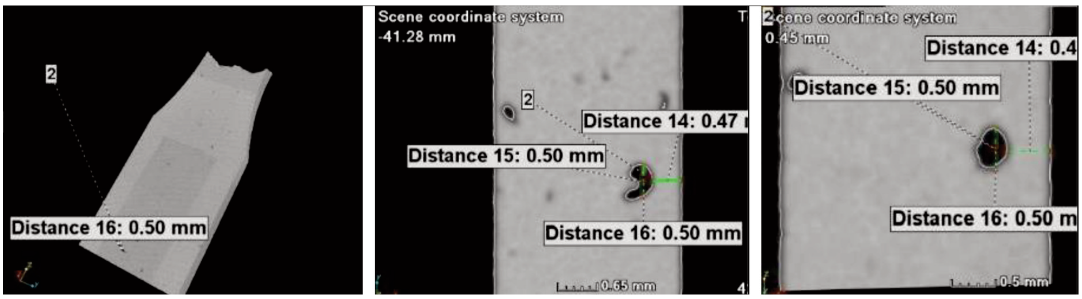


Fig. 12. Tomographic images of discontinuities B(2) of specimen 1.

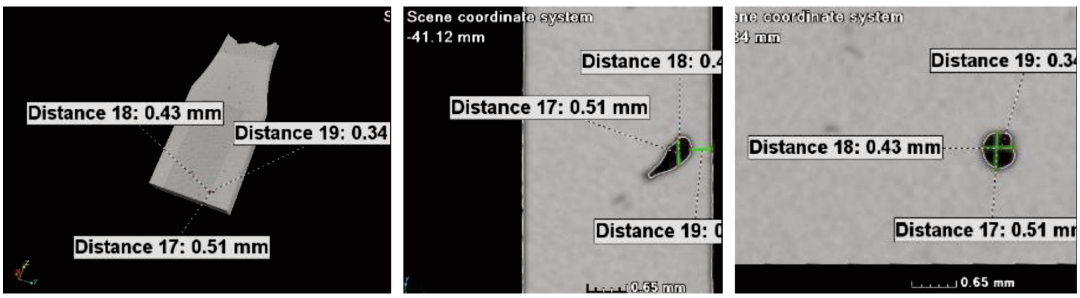


Fig. 13. Tomographic images of discontinuities C(3) of specimen 1.

## SUMMARY

- A mobile, standard eddy current defectoscope set was used for the tests.
- Based on the measurements of the electrical conductivity, theoretical values of standard and effective (critical) eddy current penetration were determined.
- Based on the results of computed tomography, selected subsurface discontinuities located at a depth of 0.08 to 0.51 mm were subjected to eddy current testing.
- The frequencies determining the values of the depth of penetration by induced currents into the areas of discontinuity were applied − in the range of the standard penetration depth, between the standard and the effective (critical) value and above the effective penetration depth.
- The eddy current method revealed defects whose depths of location were within the standard range but also above the standard depth of penetration of eddy currents.
- The greatest depth of the detected discontinuity was 0.48mm and was greater than the effective penetration depth of the eddy currents.
- The minimum length of the detected longitudinal defect was 0.40 mm and the diameter of the minimum detected volumetric defect was 0.15 mm.
- The obtained results allow for the selection of semi-finished products for further processing.

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