The amplitude-sensitive eddy current method for investigation of the plastically deformed metal zone beneath the indent obtained by ball indentation

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Abstract. The paper presents the analysis of the results of plastic deformation zones obtained by the ball indentation into the surface of a non-magnetic metal plate using the amplitude-sensitive eddy current method. Calculation and experimental methods were used in the research. A two-dimensional finite-element model of an eddy current probe installed above a local plastically deformed zone on the metal plate surface was developed. The finite-element modelling of the electromagnetic field of eddy currents induced in the aluminium plate during multi-frequency excitation was made. It is found that the amplitude-sensitive eddy current method is appropriate not only to estimate the plastic deformation zone propagation depth, but also to detect a zone with the maximum stress values beneath the indent (hydrostatic core zone). An experimental verification of the proposed model was done. The specific zones in the deformed metal beneath the indent were detected by the eddy current method and the hydrostatic core size was evaluated.

1. Introduction
Safe operation always plays an important role in manufacturing facilities. For this purpose, to avoid serious accidents, it is necessary to identify stresses concentration zones in the most loaded metal structures accurately. One of the promising non-destructive testing methods allowing to determine the stress-strain state parameters of the metals and the sizes of the plastic deformation zones is the amplitude-sensitive eddy current method [1, 2]. During plastic deformation of a metal, its electrical conductivity varies largely due to a change in the interatomic distances of the crystal lattice. As a result, the concentration and mobility of electrons alter greatly. For some metals and alloys the change in electrical conductance within strain hardening can reach 25%. The presence of obvious ratios between the electrical conductivity and deformation degree define appliance of the amplitude-sensitive eddy current method to study the local zones of metal plastic deformation.

In this paper indents, obtained by ball indentation, are considered as plastic deformation zones. The strain distribution in the metal beneath the indent is known quite well nowadays [3–5]. It allows to have a clear picture of the metal plastic deformation zone parameters beneath the indent at given indenter shapes and print sizes. Besides, in our recent papers (for example, [6]), it was found that estimation of the propagation depth of the plastic deformation zone beneath the indent can be
calculated from the amplitude values of the added voltage during polyharmonic excitation (by the amplitude-sensitive eddy current method).

The current research is devoted to a more detailed study of the strain distribution nature in a metal beneath indents by the amplitude-sensitive eddy current method. Particularly, the task was to determine the hydrostatic core zone — the zone with ultimate stress values, which is located in the metal directly beneath the indent (figure 1).

In the classical Hill-Johnson model, the hydrostatic core zone (position 1 in figure 1) is represented as a hemisphere. The center of the hydrostatic core finds out at a depth approximately equal to the indent radius and the extent of this zone in the direction of indentation is comparable with the indent depth. It is assumed that the main deformation processes during indentation occur in the hydrostatic core zone and the strain intensity here remains constant with increasing indenter penetration depth. Also, it can be considered for technically pure plastic metals such as copper and aluminum to be the average strain degree in the hydrostatic core zone near 30% \([7]\). In the elastoplastic deformation zone (position 2 in figure 1) the values of plastic deformations decrease as they move deeper into the metal \([8]\). Herewith, the metal area located directly nearby the hydrostatic core zone is characterized by the highest strain intensity gradients. The study of identifying the hydrostatic core zone using the eddy current method may lead to the possibility of detecting potentially dangerous zones in metals with extremely high concentration values of residual stresses and estimating their sizes.

2. Methods
Initially, a two-dimensional finite-element model was developed consisting of an eddy current probe installed on a 10-mm thick aluminum plate (figure 2). The indent with the diameter of \(d = 12\) mm and the depth of \(t = 3\) mm, obtained using a ball indenter with the diameter of \(D = 15\) mm was simulated. The eddy current probe was based upon the opposite side of the indent over the aluminum plate. The probe consists of a coaxially located excitation and flip coils with the diameter of 10 mm. The electrical conductance of the undeformed metal was 38 MS/m.

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**Figure 1.** The Hill-Johnson model of indent plastic strain distribution obtained by a ball indenter:
1 – a hydrostatic core zone with a radius \(r_1\); 2 – an elastoplastic deformation zone with a radius \(r_2\);
3 – an elastic deformation zone; 4 – a ball indenter.

**Figure 2.** Finite-element two-dimensional model of eddy current probe (ECP) installed over the indent obtained by a ball indenter: 1 – ECP excitation coil, 2 – ECP flip coil, 3 – undeformed material, 4 – elastoplastic deformation zone, 5 – hydrostatic core zone, 6 – indent.
The deformed metal area beneath the indent was modeled on the basis of the Hill-Johnson scheme as two specified regions – the hydrostatic core zone (position 5 in figure 2) and the elastoplastic deformation zone (position 4 in figure 2). The area beneath the indent has higher conductance than undeformed one. Based on the reference data and assumption that the average value of the strain degree in the hydrostatic core zone is about 30% and in the elastoplastic deformation zone is nearly 8%, the values of electrical conductance in these zones was equal to 45.6 MS/m and 39.9MS/m respectively [7].

The dependence between the added voltage and the excitation current frequency was established to detect the deformed metal area. An increase in the excitation current frequency leads to a decrease in the penetration depth of eddy currents, which allows making a qualitative assessment of the change in electrical conductivity in the plastically deformed area. The higher the gradient of deformation and electrical conductivity in the investigated area is, the greater the increment of the added voltage. Thus, an increase in the added voltage of eddy currents, the penetration depth of which is less than the thickness of the object, indicates a variation in the conductivity of the deformed metal. The amplitude of the excitation current was chosen 1 A, to make an adequate investigation. The frequency of the excitation current \( f \) fluctuated between 0.05 and 5 kHz. As a result, the ratios between the added voltage \( |U_{\text{add}}| \) and the frequency \( f \) were obtained. Taking into account this analysis, the specified zones in the deformed metal beneath the indent were identified.

To confirm the results, the influence of the aluminum plate strain degree on the added voltage magnitude during the multi-frequency excitation was investigated. The examination of developed model was performed on the 10-mm thick aluminum plate with an indent. The indent parameters were as close as possible with a model indent - the actual diameter of the real indent was \( d = 11.9 \) mm, the depth \( t = 2.93 \) mm (the model indent parameters: \( d = 12 \) mm, \( t = 3 \) mm). A two-winding transformer consisted of excitation and flip coils with 23 turns was used in the experiment. The coils total resistance was 1.65 Ohms. The distribution of the added voltage versus the excitation current frequency was computed to study the strain gradient in the zone beneath the indent which was made by ball indenter.

### 3. Results and Discussion

The simulation results were represented as a relation between the added voltage \( |U_{\text{add}}| \) and the excitation current frequency \( f \) in figure 3.

![Figure 3](image)

**Figure 3.** The relation between added voltage \( |U_{\text{add}}| \) and the excitation current frequency \( f \) (the simulation results).

The relation \( |U_{\text{add}}|(f) \) can be divided into three frequency intervals. In the frequency range from 0.05 to 0.42 kHz the added voltage increase and reach a peak at \( f = 0.42 \) kHz due to a decrease in the aluminum sample thickness because of the indent presence. In the frequency range from 0.42 to 1 kHz
the added voltage decreases due to the transition to the area of high contact deformations in the hydrostatic core zone. These deformations lead to a significant change in the electrical conductivity of the material. With a further increase in the excitation current frequency above 1 kHz the added voltage rises too because of the transition from the hydrostatic core zone to the elastoplastic deformation zone. It should be noted that the maximum rate of the function increment \( |U_{\text{add}}(f)/f| \) (the third frequency range is considered) is achieved at \( f \approx 1.5 \) kHz. It indicates the border of the plastic deformation and the hydrostatic core zones.

The results of the model experimental verification are demonstrated in figure 4.

![Figure 4](image_url)

**Figure 4.** The dependence of \( U_{\text{add}} \) (a) and \( |\Delta U_{\text{add}}/\Delta f| \) (b) on the excitation current frequency \( f \) (experimental results).

Figure 4 (a) shows the dependence of the added voltage on the eddy current excitation frequency in the aluminum plate. The maximum value \( U_{\text{add}} = 0.24 \) mV was registered at a frequency of \( f = 0.48 \) kHz. Thus, the shape of \( U_{\text{add}}(f) \) curve registered during the experimental study (figure 4 (a)) as well as the frequency at which the \( U_{\text{add}} \) maximum value is reached are close to the results of the finite element model calculation (figure 3).

The dependence of the first derivative of the added voltage \( |\Delta U_{\text{add}}/\Delta f| \) on the frequency \( f \) (figure 4 (b)) should be analyzed for determining the hydrostatic core size \( r_1 \). The border of the hydrostatic core zone and the elastoplastic deformation zone is characterized by maximum stress and strain gradients. Accordingly, significant changes in the electrical conductivity of the aluminum plate occur in this region. Moreover, there will be an increase in the increment rate of the \( U_{\text{add}}(f) \) curve. It can be inferred from the graph (figure 4 (b)) that the local maximum of \( |\Delta U_{\text{add}}/\Delta f| \) curve corresponding to the largest change in electrical conductance is attained at the frequency of \( f \approx 1.08 \) kHz. The hydrostatic core radius \( r_1 \) for this case can be approximately determined as the difference between the thickness of the controlled material \( b \) (in our experiment \( b = 10 \) mm) and the penetration depth of the eddy currents \( \delta \) at a defined frequency. For the excitation frequency \( f = 1.08 \) kHz the penetration depth of the eddy currents in the aluminum plate corresponds to \( \delta = 2.48 \) mm. It means that the hydrostatic core radius determined by the eddy current method in the following way is \( r_1(\text{ECP}) = 10 - 2.48 = 7.52 \) mm.

In accordance with the microhardness results of the plastically deformed metal zone beneath the indent [8], the hydrostatic core zone radius \( r_1 \) equals to the indent radius, i.e. in our experiment \( r_1 \approx 6 \) mm. It should be noted that the penetration depth of eddy currents is a conditional parameter indicating a decrease in the eddy current density by \( e \) times. The presence of a conductivity gradient leads to a change in the penetration depth of the eddy currents into the deformed metal and to an increase in the added voltage. The absolute error of hydrostatic core radius measurement equals to
\[ \Delta r_{(ECP)} \approx 1.52 \text{ mm} \] may be due to both the electromechanical properties anisotropy of the deformed metal and inaccuracy in the estimation of the calculated value of \( r_1 \) by the indentation method. The actual size of the radius also may depend on the material as well as on the indent and indenter sizes.

4. Conclusion

The problem of determining the plastic deformation zone in the aluminum plate beneath the indent using the eddy current method is considered in the paper. The calculation and experimental methods of this research showed the similar dependence of the added voltage \( |U_{add}| \) on the excitation current \( f \). It is shown that using the dependence of the first derivative \( |\Delta U_{add}/\Delta f| \) on the frequency \( f \) makes it possible to estimate the hydrostatic core zone radius and also to identify the border of the hydrostatic core and the elastoplastic deformation zones in the metal beneath the indent. The difference between the calculated value of \( r_1 \) determined by the indentation method and the value of \( r_1 \) evaluated using the eddy current method can be due to both the electromechanical properties anisotropy of the deformed metal and inaccuracy in the estimation of \( r_1 \).

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