Finite element analysis of solenoid coil for deep crack detection in cylindrical forgings

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Abstract. The skin effect exists on the surface of the cylinder workpiece, and the existing eddy current probes cannot detect the deep cracks in the forgings. In order to improve the detecting depth of eddy current, based on the principle of electromagnetic induction, the solenoid coil size, location, etc. The influence of parameters on the eddy current penetration depth, considering the solenoid coil exciting current frequency, current density, hoisting height of solenoid coil, coil width, the thickness of the coil and the solenoid coil distance plate specimen under test, test parameters, such as adopting ANSYS software of eddy current density under different parameters with numerical simulation, analyzes the solenoid coil used for deep crack detection accuracy, on this basis, the optimal design can be used for the deep crack detection of solenoid sensor structure, It is applied to the main shaft of forgings with artificial deep crack. The simulation results show that the combined solenoid probe can be used to detect deep cracks in cylindrical forgings.

1. Introduction
When metal materials are used, there will be a lot of fracture phenomena, especially brittle cracking of materials and components, and many catastrophic accidents will follow, widely appearing in aircraft, trains, ships, pressure vessels, weapons and other aspects. Therefore, fracture has been paid great attention to by researchers from all walks of life and has been a major subject in the field of material research. Therefore, in order to prevent the fracture of metal parts in the process of use and processing, in addition to increasing the strength of the material itself, it is more necessary to find the signs of imminent cracking in time and conduct detection before the fracture poses a threat.

At present, non-destructive testing automation technology has been widely used in welding and casting testing. In modern times, many scientific researchers are still studying new methods to improve eddy current testing. Eddy current magnetic field has been widely used in material properties research, industrial testing and other fields. Eddy current testing is a non-destructive test that combines electromagnetic radiation, ultrasonic, infrared, electromagnetic and other technologies without damaging or affecting the functional performance of the equipment being tested. Technique for detecting defects in materials, equipment, components, physical and chemical parameters using instrumentation. At present, there is still a big gap between western developed countries and western developed countries, especially European countries, which have carried out the industrial revolution early and experienced more than half a century of industrial development, but China still has a rapid development in nondestructive testing in recent years. Eddy current nondestructive testing technology is based on the
theory of eddy current nondestructive testing. As early as the 1950s, Germany has been more advanced in the field of eddy current nondestructive testing than other countries in the world. They have changed the analysis method to provide more accurate theory and advanced equipment for identifying various influential factors of eddy current testing. After eddy current flaw detection technology also gradually by western countries, attaches great importance to Europe when it comes to heavy industry development period of the '50s, the eddy current testing this a technology, not only to prevent a large number of scrap metal materials, but also to the personal safety of workers, a lot of materials or equipment before delivery for eddy current testing internal injury, reduced the cost greatly, improve the manufacture efficiency of the whole industry, the advantages of eddy current flaw detection has become the current measuring national industrialization level is an important basis. For example, it is used in material separation, aircraft and ship maintenance and inspection and so on. Defects of materials are usually triggered from the surface and extended to the interior. According to existing theories, the lower the frequency, the greater the penetration depth. Based on this conclusion, we can reduce the frequency of the probe or reduce the size of the probe as much as possible, so that the energy can be more concentrated, so as to detect deeper cracks and even improve the detection accuracy. Some deep defects caused by weak magnetic field components can also be detected with high sensitivity and good directionality. In addition, many industries have established their own nondestructive testing associations, such as power companies, petrochemical companies, transportation companies, aerospace departments, nuclear energy industries, etc. At this time, China has also gradually launched an in-depth study of eddy current testing technology, and has vigorously carried out research institutes of non-destructive testing in the eastern, central, southern and northeastern regions of China, aiming to develop more accurate theoretical guidance and develop more sophisticated high-tech testing equipment.

Based on this, this article based on the theory of electromagnetism, using finite element analysis software and data processing method, to a size of 100 mm x 100 mm x 60 mm of SUS304 stainless steel metal plate as numerical simulation under test piece is calculated, according to the size of the eddy current probe, location, etc to study the influence of parameters on the eddy current penetration depth, so as to optimize the structure and parameters of eddy current probe.

2. Principle of eddy current inspection
Eddy current testing is included in the ranks of nondestructive testing methods, the fundamental principle and electromagnetic induction principle similar to a cornerstone, alternating magnetic field is placed in the conductor causes induced current, and eddy current and counterparts, it generated induced current, but the vortex inside the conductor some factors changes, the detection principle is shown in Figure 1. The size of the solenoid's electromagnetic field can be adjusted. A section of coil conductor is placed above the solenoid. When the magnetic field of the solenoid changes, there will be an electric potential difference in the conductor. If this section of coil is replaced by a closed coil, the induced electromotive force generated inside the coil will drive the electrons to flow directionally, thus generating the induced current. Therefore, the results of eddy current detection can be used to understand the internal conditions of the invisible material and judge the residual value of the material.

![Figure 1. Schematic diagram of eddy current detection](image-url)
If the closed circuit is a coil of n turns, then the instantaneous electromotive force can be expressed as:

$$\varepsilon = n \times \Delta \phi / \Delta t \ (\Delta t \to 0)$$  \hspace{1cm} (1)$$

Where, \(n\) is the number of coil turns, \(\Delta \phi\) is the change of magnetic flux, \(\Delta t\) is the time for change, \(\varepsilon\) is the induced electromotive force generated by \(s\).

3. Finite element analysis based on ANSYS

ANSYS finite element analysis is divided into three stages: pre-processing, calculation and post-processing. The whole process also includes the establishment of geometric model, the setting of element type, the definition of material properties, mesh division, applied load, solution, post-processing and other aspects. The following is a brief description of the research direction and content of this paper.

3.1. Define material properties

In this paper, the unit type is solid97, and the magnetic permeability coefficient of solenoid coil, plate specimen to be tested and air is set according to the requirements of task instructions, and then the resistivity of the plate to be tested and solenoid coil is set. The magnetic permeability coefficient of the plate was 1, and the resistivity was \(7.14 \times 10^{-7}\). The magnetic permeability coefficient of solenoid coil was 1, and the resistivity was \(1.72 \times 10^{-8}\). The magnetic permeability of air is 1.

3.2. Establish a geometric model

Firstly, all kinds of parameters are defined, and the model of test plate, air and solenoid coil is modeled. The coil was modeled first, and the body bonding of the four parts of the coil was performed by using the command Preprocessor/ Modeling/ copy/ Booleans/ Glue. Then the model of the flat plate to be tested was established and the spherical air body Overlap with a volume much larger than the flat plate was established. The model diagram as shown in Figure 2 was obtained.

![Figure 2. Solenoid coil lay model diagram](image)

3.3. Assigned materials

The previously defined material parameters are assigned to each individual, and the local coordinate system used by the body is defined to facilitate the later loading.

3.4. Grid division

There are many different meshing methods in ANSYS, such as mapping meshing method, extended meshing method, sweeping meshing method, and free meshing method. In this paper, the mapping grid division method and free grid division method are selected, and the free grid division method (Smart size) is used for the solenoid coil. Because the size of the solenoid coil is relatively small, the size level range is adjusted to 1 (fine), as shown in Figure 3. The meshing of air is relatively rough and the size level is adjusted to 6. The shape rules of the plate are divided into 30 equal parts by mapping grid, as shown in Figure 4.

![Figure 4. Shape rules of the plate](image)
3.5. **Apply load**

For the study of the problem in this paper, the excitation method of solenoid coil is to apply current excitation, so in the finite element analysis, it is necessary to load the current of the solenoid coil, pay attention to the direction of load, and sometimes change the coordinate system. In this paper, current density is used as the excitation type.

3.6. **Add constraints**

Because the requirement of current incentive not air impact, so let's add restrictions on air model, using the Solution/Define Loads/Apply/Magnetic/Boundary/Vector Poten all nodes are added in the air in all directions.

3.7. **Solution and post-processing**

After the solution is completed by ANSYS software, the results can be post-processed. Here, only the exciting current vector Figure 5 of solenoid coil, eddy current density cloud Figure 6 of plate, eddy current density vector Figure 7 of plate, eddy current density curve 8 of a point on the plate and its corresponding point under the plate.

![Figure 3. Free intelligent partition](image1)

![Figure 4. Mapping division](image2)

![Figure 5. Vector diagram of coil current](image3)

![Figure 6. Eddy current density inside the plate](image4)
4. The influence of changing the inner diameter of solenoid coil

Take 4 solenoids whose outer diameter is 15mm, inner diameter is ri=10mm, ri=9mm, ri=8mm, ri=11mm, respectively. The height and thickness of these solenoids are the same, both 5mm in height and 1mm in thickness. The exciting current density is J=1250000A/m². After completing the first two stages of ANSYS, the solution was carried out, and the eddy current density obtained was drawn into the eddy current density curve, as shown in Figure 9.

As shown in the figure, when other conditions are constant, the eddy current density on the surface of the solenoid coil is related to its inner diameter. The eddy current density decreases with the increase of the inner diameter of the coil, and the eddy current density of the solenoid coil decreases with the increase of the detection depth. When other conditions are constant, the decreasing range of the curve becomes slow with the increase of the inner diameter of the solenoid coil, and its standard penetration depth increases with the decrease of the inner diameter of the solenoid coil, that is, the penetration depth also increases.
5. Single coil parameter optimization

When a single solenoid coil is selected to test the test plate, the optimal parameters are obtained through the above comparison: outer diameter $r_o=17\text{mm}$, inner diameter $r_i=8\text{mm}$, height $h=7\text{mm}$, lifting height $d=1\text{mm}$, excitation current density is $4250000\text{A/m}^2$, excitation frequency is $10000\text{Hz}$; When the combined solenoid coil is selected to test the test plate, the following optimal parameters are obtained through comparison: the outer diameter of both solenoids is $r_o=17\text{mm}$, the inner diameter is $r_i=8\text{mm}$, the height is $h=7\text{mm}$, the lifting height is $d=1\text{mm}$, the current density is $4250000\text{A/m}^2$, and the excitation frequency is $10000\text{Hz}$.

When other conditions are constant, the eddy current density decreases as the depth of detection increases, and the drop range of single coil curve is larger than that of combined coil.

The standard penetration depth of a single solenoid coil is $5\text{mm}$, while the standard penetration depth of a combined solenoid coil is $16\text{mm}$. Therefore, it can be concluded that the combined solenoid coil is relatively stable for deep crack detection.

6. Conclusion

In this paper, the influence of the size of the solenoid coil on the eddy current penetration depth of the solenoid coil is studied.

When other conditions are constant, change the size of the solenoid coil, and the eddy current density on the surface of the solenoid coil will change.

Numerical simulation shows that by optimizing the size parameters of a single solenoid coil, the standard penetration depth of the concentric solenoid coil can be greatly increased, and the detection of deep cracks is relatively stable.

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