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Nondestructive Measurement of Al Alloy Surface Strengthening Layer Depth Using Swept Frequency Eddy Current Testing

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Abstract. An innovative nondestructive measurement method of Al alloy surface strengthening layer depth using frequency sweep eddy current testing (SFECT) technology is proposed. Based on the analysis of the forming mechanism of Al alloy surface strengthening layer and the comparison of several possible detection methods, the applicability of SFECT method is discussed theoretically. By means of electromagnetic simulation software Ansoft Maxwell and orthogonal experimental design method, the SFECT coil model is built. The optimal design and simulation of the parameters of the SFECT coil are carried out, and optimal coil structure parameters and lift-off height are obtained. Simulation of depth detection of Al alloy surface strengthened layer using SFECT coil is implemented, and then preliminary experiment of Al alloy surface strengthening layer depth measurement with the self-fabricated SFECT coil is completed. The simulation and experiment results show that SFECT method can be applicable for nondestructive testing of Al alloy surface strengthening layer depth.

1. Introduction

Common surface deformation strengthening processing of Al alloy includes rolling, shot peening and vibration, which can improve the hardness, fatigue strength and wear resistance of Al alloy parts. After strengthening a thin surface hardened layer with a depth of about 0.07~0.5mm is formed [1]. The properties of Al alloy surface strengthening layer are usually evaluated by its depth, hardness and surface residual stress. The depth of surface strengthening layer is an important index to evaluate the quality of surface strengthening. Therefore, accurate measurement of Al alloy surface strengthening layer depth is of great significance to ensure the safe use of Al alloy parts.

Micro-hardness measurement and metallography are two widely used methods for measuring the depth of surface strengthened layer, both of which are destructive inspecting, and cannot perform on production site detection. The micro-hardness measurement method is to measure the micro-hardness gradient of the specimen profile by using micro-sclerometer, and the range of surface strengthening layer depth is judged according to hardness change. The specimen profile needs to be polished and grinded, and many points need to be measured to determine the depth of the strengthened layer [2]. By observing the metallographic structure change of the specimen under a metallographic microscope with high magnification, the range of strengthened layer depth to meet hardness requirement can be determined [3].

Presently nondestructive testing methods for metal surface strengthening layer depth are ultrasonic method, thermal radiation method, infrared method and eddy current method. Ultrasonic can be only used to inspect steel quenching hardening layer depth, and measuring error is sub-millimeter [4, 5]. The depth of Al alloy surface strengthening layer is about 1 mm, so ultrasonic method is not suitable. There is an obvious difference in the thermal conductivity between the carburized layer and the substrate of steel, so the depth of the carburized layer can be measured by thermal radiation method [6]. However, the thermal conductivity difference between Al alloy strengthened layer and the substrate is not obvious and difficult to detect. Therefore, the measuring method of hardened layer depth by thermal radiation is not applicable for measuring Al alloy surface strengthening layer depth. The infrared detection method can be interfered by various heat sources and light sources easily.

As stated above, there is a lack of effective nondestructive measuring method for Al alloy surface strengthening layer depth presently. An innovative nondestructive measurement method of Al alloy surface strengthening layer depth using swept frequency eddy current testing (SFECT) technique is proposed. By utilizing electromagnetism simulation software Ansoft Maxwell and orthogonal experimental design method, optimal design of the SFECT coil is carried out. The simulation and preliminary experiment of Al alloy surface strengthening layer depth measurement are made with the self-designed and fabricated SFECT probe.

2. Feasibility of nondestructive inspecting method of Al alloy surface strengthening layer depth

2.1. Skin effect in eddy current testing

Skin effect is the tendency of an alternating electric current to become distributed within a conductor so that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor. It is well known that the amplitude of eddy current density decreases with increasing depth. AC current density decreases exponentially from the surface towards the inside.

The skin depth, also called the penetration depth, is defined as the depth where the current density is just 1/e (about 37%) of the value at the surface; it depends on the frequency of excitation current and the electrical and magnetic properties of the conductor.

The penetration depth for a good conductor can be calculated from the following equation:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

Where δ is the penetration depth (m), f is the excitation frequency (Hz), μ is the magnetic permeability of the material (H/m), and σ is the electrical conductivity of the material (S/m).

2.2. Investigation of the relation between conductivity and Al alloy surface strengthening layer depth

After strengthening, the grain volume and density of Al alloy changed, and the electrical properties of the surface layer are different from that of the substrate, which is mainly reflected by the change of electrical conductivity. The electrical conductivity of the surface is lower than that of the substrate.

Al alloy is paramagnetic metal, its magnetic permeability in the electromagnetic environment is usually neglected, and its electrical conductivity can be used as a sensitive quantity [7]. The effective penetration depth of the skin effect can cover the depth range of the Al alloy surface strengthening layer, and can be regarded as equivalent to the depth of Al alloy surface strengthening layer.

According to penetration depth calculation formula, the relationship between the depth of strengthening layer and conductivity of Al alloy surface can be established, which can be used to indirectly characterize the depth of Al alloy surface strengthening layer. It is feasible theoretically to use eddy current testing (ECT) to detect the depth of Al alloy surface strengthening layer.

2.3. Applicability analysis of SFECT to inspecting of Al surface strengthening layer depth

Traditional eddy current testing usually uses single frequency sine wave as the excitation signal. Swept frequency eddy current testing (SFECT) technique is an innovated ECT technique, which introduces frequency sweep technology into eddy current testing field. The basis of this novel method is a change of frequency of the exciting signal in a wide range while the testing probe is in a fixed position. For SFECT the excitation frequency in the detection process is wide-band and continuously variable [8, 9].

The hardness of the strengthening layer and the substrate formed on the Al alloy surface after strengthening shows an obvious gradient distribution, so it can be inferred that, the electrical conductivity also presents a gradient distribution in the strengthening layer and the substrate.

A novel nondestructive SFECT method is proposed, which is used to detect the depth of the surface strengthening layer of Al alloy. The SFECT coil, also called as SFECT probe, is the core of the SFECT method. By using sine excitation signals with different frequencies, the detection range of the penetration depth of the SFECT coil can cover different depth of the surface strengthening layer [10-12].

When the response frequency of magnetic induction of the inspected workpiece is consistent with the frequency of excitation signal, the inductive electric potential produced by SFECT probe will appear inflection point, and the amplitude and phase change of SFECT probe will be higher than that of other frequency response signals. It is easy to detect the change of the inductive electric potential caused by the discontinuity of the detecting object.

During the change of SFECT probe excitation signal from high frequency to low frequency, the cumulative conductivity change curve of the workpiece can be obtained while the penetration depth increases gradually. Thus, layered sweep frequency detection of the workpiece can be performed. By calculating the slope of the curve, the conductivity of the workpiece corresponding to the penetration depth can be obtained, which is determined by the excitation signal frequency of the SFECT probe.

3. Parameter Optimal Design of the SFECT probe

3.1. Modelling of SFECT probe

The optimal design of the SFECT probe is carried out by finite element simulation. The sensitivity of the SFECT probe is calculated by changing relative parameters of the SFECT coil and the inductive voltage signal under different conductivity conditions.

The SFECT probe model is shown in figure 1.

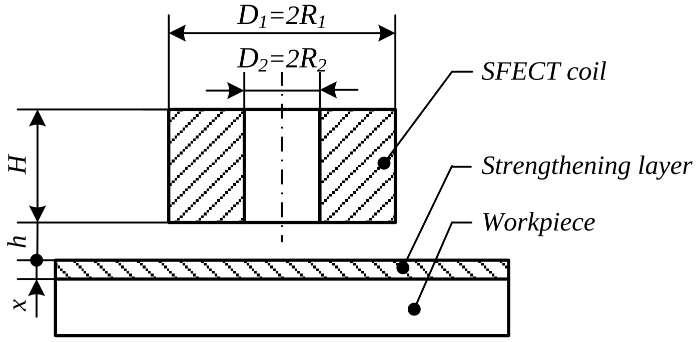


Figure 1. The SFECT probe model.

Where D_1, D_2 and H respectively denote the inner and outer diameter and height of the SFECT coil, h is the lift-off height, and x is the depth of the surface strengthened layer.

A 2024 aeronautical Al alloy plate is used as the model of the tested workpiece. A single cylindrical coil is chosen as both the excitation coil and the induction coil, whose axis is perpendicular to the surface of the workpiece, which can realize nondestructive testing of the surface and subsurface quality of the parts. Single coil has the advantages of small size, convenient winding and sensitive response to various factors affecting the electromagnetic performance of the tested object. The magnetic core is added to the cylindrical coil, which can enhance magnetic field intensity and focus magnetic field, so the detection sensitivity is higher.

In simulating, other factors such as temperature and noise can be suppressed effectively, which can increase the influence weight of the surface conductivity on the sampled induced voltage signal.

3.2. Dimension parameters optimal design of the SFECT probe

There are many factors that influence the sensitivity of the SFECT probe. The main factors include inner and outer diameter, thickness, and turn number of coil as well as excitation mode. If only carrying out single parameter optimization design, it is difficult to achieve expected measurement sensitivity, and precision and modelling and simulation process is complicated, which may cost too many times. Therefore, the factors affecting the sensitivity of SFECT probe are optimized based on orthogonal experimental design method.

The orthogonal test table L_{16} (4^4) with 4 factor and 4 level was designed. The inner radius R2, thickness W, lift-off height h and coil turn number N are used as 4 factors of the orthogonal test, and each factor was divided into 4 levels. The ratio of eddy current induction voltage ΔV to electrical conductivity Δσ is used to characterize the performance index of the SFECT coil, which is presented by C_P and used to evaluate the sensitivity of the probe. C_P is the index term, and E is the error term.

The dimension parameters of the probe are optimized based on orthogonal test method, 16 sets of orthogonal experiments are designed by using Ansoft Maxwell, then the simulation results are numerically analysed, and finally the optimal dimension parameters of the SFECT coil are obtained and shown in Table 1.

Table 1. Main parameters of the SFECT coil.

H(mm)	R_1(mm)	W(mm)	R_2(mm)	h(mm)	Wire Diameter(mm)	N(n)
9	12	9	3	0.5	0.3	900

4. Simulation of Al alloy surface strengthening layer depth inspecting by SFECT probe

4.1. Simulation

There is no obvious interface between the surface strengthening layer and the substrate of Al alloy formed by rolling strengthening, and its electrical conductivity, hardness and other parameters show continuous nonlinear changes with the depth, which is not easy to calculate and detect accurately. In order to make the simulation detection model of the workpiece closer to the actual state, it is necessary to take into account the distribution of the electrical conductivity in the depth direction when modeling. The workpiece can be equivalent to non-uniform multi-layer structure to be analysed discretely.

The multi-layer model of the workpiece (Al alloy plate) is shown in figure 2. The surface strengthened layer is divided into n layers, and the thickness x and conductivity σ of each layer are set respectively, which is used to equivalent to actual continuously varying conductivity [11].

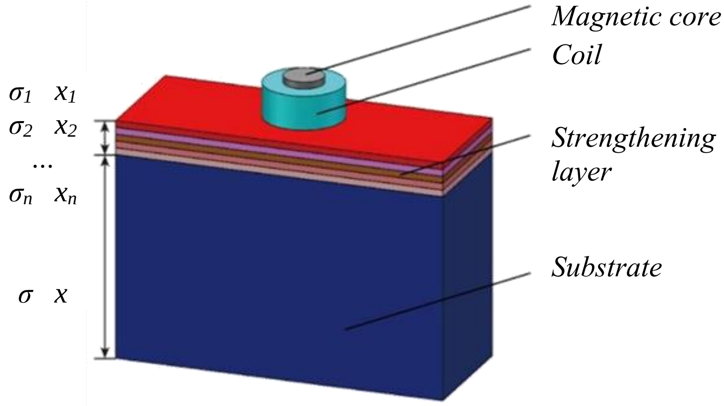


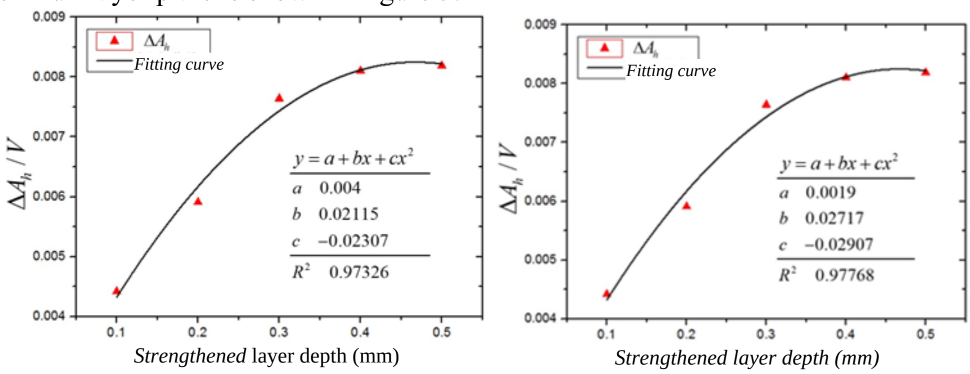
Figure 2. The multilayer model of the workpiece.

The more layers, the smaller the thickness of each layer, the more accurate the simulation result is and the closer to the actual state, but it will lead to a large amount of calculation. Considering the thickness distribution of the strengthening layer after rolling strengthening, the total thickness of the strengthened layer is taken as 0.1mm, 0.2mm, 0.3mm, 0.4mm, 0.5mm respectively, and the corresponding thickness of each layer is taken as 0.02mm, 0.04mm, 0.06mm, 0.08mm, 0.10mm.

The conductivity distribution in the depth direction of the strengthened layer is complex and cannot be detected accurately. In order to study the characteristics of the multilayer model by using SFECT, the conductivity distribution of the multilayer plate is simplified. The conductivity is simulated by finite element method according to linear distribution and quadratic function distribution respectively.

For the multilayer plate model with linear conductivity distribution, the conductivity of the five layers is set as 25Ms/m, 26Ms/m, 27Ms/m, 28Ms/m, and 29Ms/m respectively. For the multilayer model with nonlinear conductivity distribution, the conductivity of the five layers is set as 25Ms/m, 27Ms/m, 30Ms/m, 27Ms/m, and 30Ms/m respectively. The conductivity of the substrate is set as 30Ms/m.

The output inductive voltage of the designed SFECT probe is simulated with 10V sine AC voltage as the excitation signal and the scanning frequency starting from 7.5kHz with step size of 1.5kHz. According to the finite element simulation results, the difference between the inductive voltage eigenvalue and its asymptotic value under sweep frequency is calculated, and the quadratic polynomial is used to fit the simulation results. The fitting induction voltage amplitude with the strengthened layer depth of multilayer plate is shown in figure 3.



(a) Linear conductivity distribution (b) Quadratic function conductivity distribution

Figure 3. Variation curve of induction voltage with the strengthened layer depth of multilayer plate.

4.2. Simulation results discussion

Figure 3 shows that, for multilayer plate model, the simulation results obtained by linear conductivity variation are consistent with those obtained from nonlinear conductivity variation. The induction voltage amplitude increases with the depth of the strengthening layer in quadratic function. The coefficient of fitness of inductive voltage amplitude of multilayer model with linear conductivity change is 0.97329, and that of multilayer model with nonlinear conductivity variation is 0.97768, all of which is close to 1.

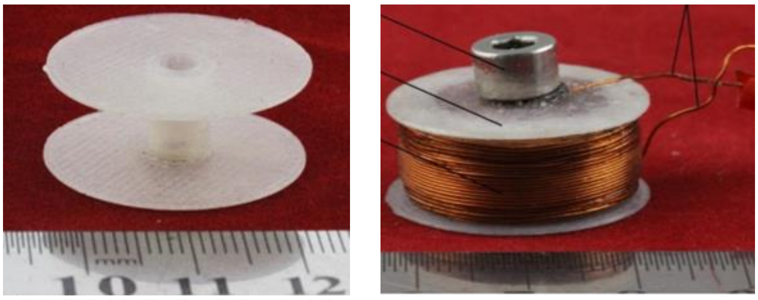
The simulation results show that, the fitting curve coincides with the simulation data, and SFECT method can be applied for nondestructive inspecting of Al alloy strengthened layer depth.

5. Experiment of Al alloy surface strengthening layer depth inspecting by SFECT probe

5.1. Fabrication of detection probe

According to the designed structure and geometric parameters of the SFECT coil, a SFECT probe is made and shown in figure 4.

The SFECT probe consists of a SFECT coil, a ferrite core and a coil skeleton. A cylindrical skeleton is fabricated by using a nylon rod. After the coil winding the skeleton is embedded in a cup ferrite, and then the coil and ferrite are embedded in a cup shield shell. The shield wire is drawn from the centre of the upper surface of the shell.



(a) The coil skeleton (b) The SFECT probe

Figure 4. The fabricated SFECT probe.

5.2. *The SFECT experiment device*

The depth inspecting system for Al alloy surface strengthening layer mainly consists of the SFECT probe, excitation module the workpiece, and data acquisition (DAQ) module. It is shown in figure 5.

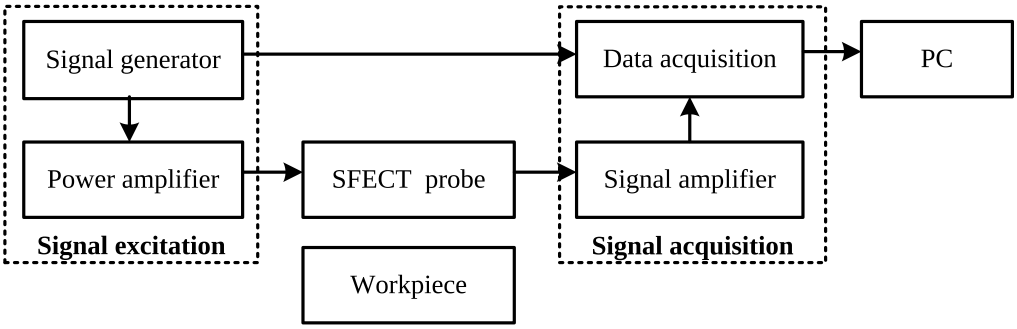


Figure 5. Composition scheme of the depth inspecting system of Al alloy surface strengthening layer.

To ensure that the output signal of the SFECT probe can effectively characterize conductivity of the surface layer of the workpiece, an Agilent AFG3102C function signal generator and a PINTEK HA-400 power amplifier are used to provide an exciting source. NI USB-6210 DAQ card and LabVIEW are used to complete data acquisition of the inductive voltage signal of the SFECT probe.

5.3. *Test results and discussion*

The data of induction voltage amplitude of 2024 Al alloy plate under different frequency excitation signals were measured and the SFECT curve was obtained as shown in figure 6.

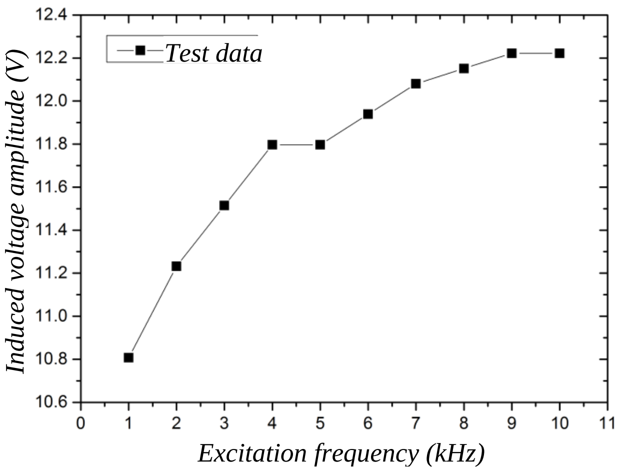


Figure 6. The SFECT test curve.

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It can be seen from figure.6 that, the induction voltage of the detecting coil increases gradually with the increase of the excitation signal frequency and the growth rate slows down, which keeps the consistent change law of the sweep frequency curve obtained in the simulation. The experimental result shows the correctness of the parameters of the SFECT coil designed by the simulation and the applicability of the SFECTprobe.

6. Conclusions

(1) Based on the difference of electrical conductivity between the surface strengthening layer and the substrate, the relation between conductivity and the depth of Al alloy surface strengthening layer is investigated, and Al alloy surface strengthening layer depth can be characterized by its conductivity.

(2) An innovative nondestructive measurement method of Al alloy surface strengthening layer depth using SFECT technology is proposed and its feasibility is verified theoretically.

(3) By utilizing electromagnetism simulation software Ansoft Maxwell and orthogonal experimental design method, the SFECT coil model is built; after the SFECT coil design and simulation, optimal coil structure parameters and lift-off height are obtained.

(4) The SFECT probe is fabricated and experiment of Al alloy surface strengthening layer depth inspecting is completed. The preliminary experiment shows that, it is appropriate to measure Al alloy surface strengthening layer depth by proposed SFECT method.

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