Research on Non-destructive Testing Method of Coating Thickness of Turbine Blade

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Abstract. Turbine blades are an important component of the turbine section of a gas turbine engine. High-temperature blade coating is a key technology for the manufacture of turbine engines, and its complex surface structure is currently lacking an effective non-destructive evaluation method for coating thickness. In this paper, the eddy current field is directly exciting in the substrate metal of the turbine blade coating system to achieve non-destructive detection of the coating thickness and substrate material. The results show that a new method of coating non-destructive testing based on the principle of array induction logging three-coil system is proposed. The shielding coil effectively cancels the direct coupling signal and enhances the signal from the coating and the substrate; when the distance between the transmitting coil and the main receiving coil is 8cm and the scale factor $\alpha$ is about 0.7047, the signal-to-noise ratio is increased by 102 times, and when the scale factor $\alpha$ is about 0.9032, the signal-to-noise ratio is increased by 215 times, the focusing effect is obvious while the scale factor $\alpha$ raises, and the sensitivity is also greatly improved; the receiving array is more than 4cm away from the transmitting coil, reflecting the more obvious change of coating thickness. When the distance between the transmitting coil and the main receiving coil is 4–9cm, and the scale factor $\alpha$ is about 0.9032, the imaginary part of the measurement signal reflects the coating thickness changes more sensitively, and the real part of the measurement signal reflects substrate material changes more sensitively.

1. Introduction
As a large-scale power plant, turbines are widely used in power generation and various industrial fields. Turbine blades are an important component of turbine sections in turbine engines. The high-speed rotating blades are responsible for sucking the high-temperature and high-pressure airflow into the burner to guarantee the engine's work [1]. Therefore, the turbine blades are required to withstand high temperature [2], and the high-temperature blade coating is deposited on the surface of the substrate to provide heat insulation of substrate material and cooling to make the blades run normally at high temperatures, this is a key technology for the manufacture of turbine generators. Most of the coatings used in practical applications adopt a double-layer structure. The surface layer is a ceramic layer, which plays a role of heat insulation; between the ceramic layer and the substrate is a bonding layer, which plays a role in improving the physical compatibility of the substrate and the ceramic layer [3]. However, the coating of high-temperature blades in service is prone to thinning or shedding (essentially to reduce the effective coating thickness), resulting in a greatly reduced protective effect [4]. Due to the complex spatial configuration of the blade and the multi-layer heterogeneous film structure, there is currently no effective means of defect and performance non-destructive evaluation.
[5]. The existing non-destructive evaluation methods of coating thickness include infrared detection, high-frequency eddy current and terahertz detection, but there are problems such as low sensitivity, poor efficiency and non-in-situ detection, which restricts the theoretical research and technical development of advanced coatings. In this paper, using COMSOL finite element analysis software, applying the principle of array induction logging three-coil system (one transmit and two receives: transmitting coil, main receiving coil and shielding coil) in the oil logging method [5-6], a new method for non-destructive coating detection is proposed. The method excites the eddy current field directly in the substrate metal [7-8], and the shielding coil effectively cancels the direct coupling signal and enhances the signal from the coating and the substrate. When the distance between the transmitting coil and the main receiving coil is 8 cm and the scale factor α is about 0.9032, the signal-to-noise ratio is increased by 215 times, the focusing effect is obvious, and the sensitivity is also greatly improved.

2. Methods

2.1. Three-coil system apparent conductivity

It can be known from reference 9 that the three-coil system sub-array structure is based on the double-coil system, the shielding coil B is introduced, and the receiving coil R is connected in series, and the winding direction of the coil is opposite. The formulas required for this article are:

The formula of scale factor α = \( \frac{3}{N_B} \) where \( N_B \) is the number of shielding coil turns, \( N_R \) is the number of receiving coil turns.

The apparent conductivity formula of three-coil system is \( \sigma_a = \frac{N_T N_B \sigma_{aTR} + N_T N_B \sigma_{aTB}}{L_{TR} \sigma_{aTR} + L_{TB} \sigma_{aTB}} \), where \( \sigma_{aTR} = -\frac{V_{TR}}{K_{TR}} \) is the apparent conductivity determined by the double-coil system TR, \( \sigma_{aTB} = -\frac{V_{TB}}{K_{TB}} \) is the apparent conductivity determined by the double-coil system TB, \( K_{TR} = \frac{\omega^2 \mu^2 I_T A_T A_B N_T N_R}{2 L_{TR}} \) is the instrument constant of double-coil system TR, \( K_{TB} = \frac{\omega^2 \mu^2 I_T A_T A_B N_T N_R}{4 \pi L_{TB}} \) is the instrument constant of double-coil system TB.

2.2. Principle of eddy current testing

According to reference 10, based on Faraday’s law of electromagnetic induction, when the excitation coil with AC current is close to the conductor, eddy current will be generated inside the conductor, then it will conversely form a magnetic field. When there is damage in the conductor, the internal eddy current will change, so the magnetic field will also change. The reaction to the detection coil is the change of induced voltage. According to the change of voltage on the coil, the damage can be detected, and the thickness of the damage, the change of coating and substrate material can be also detected.

3. Results

Figure 1 is a physical picture of turbine blade. The turbine blade coating system consists of 300μm ceramic layer, 100-1000μm intermediate bonding layer and 5100μm substrate superalloy. Since the conductivity of the coating is equivalent to that of the air, the change of the thickness of the bonding layer can be regarded as the change of the coating thickness. In induction logging, voltage signal (induced electromotive force) is directly measured. In order to amplify the influence of measurement signal on coating thickness, material and substrate material, the voltage signal is calibrated as apparent conductivity, and the measurement signal is represented by apparent conductivity. Modeling and simulation are carried out by COMSOL. X-axis is the distance between receiving coil and transmitting coil (unit: micron), and y-axis is apparent conductivity (unit: S /m), that is, measurement signal. The left picture is the real part, the right picture is the imaginary part. Figure 2 shows mesh generation of turbine blade coating model.
3.1. The influence of the change of bonding layer thickness on the measurement signal

Figure 3. Scale factor $\alpha=0.7047$, bonding layer thickness 100~1000$\mu$m measurement signal changes.

Figure 4. Scale factor $\alpha=0.8074$, bonding layer thickness 100~1000$\mu$m measurement signal changes.

Figure 5. Scale factor $\alpha=0.9032$, bonding layer thickness 100~1000$\mu$m measurement signal changes.
By comparing, it shows that the measurement signal decreases while the transmitting and receiving distance increase; at the same receiving position, the measurement signal increases with the increase of the bonding layer thickness; figure 3, figure 4 and figure 5 are enlarged and compared, while other parameters are consistent, the larger the scale factor $\alpha$, the smaller the amplitude of the measured signal, but the more obvious the change is, that is, the better the focusing effect, the more sensitive to the thickness of the bonding layer.

3.2. The influence of the change of bonding layer material on the measurement signal

The results show the measurement signal decreases with the increase of the transmitting and receiving distance; at the same receiving position, the measurement signal is almost unchanged. Therefore, the influence of bonding layer material changes on the measurement signal is negligible.

3.3. The influence of the change of substrate material on the measurement signal

Figure 6. Scale factor $\alpha = 0.7047$, substrate material $10^4$~$10^7$ S/m measurement signal changes.

Figure 7. Scale factor $\alpha = 0.8074$, substrate material $10^4$~$10^7$ S/m measurement signal changes.

Figure 8. Scale factor $\alpha = 0.9032$, substrate material $10^4$~$10^7$ S/m measurement signal changes.
Since the change of the substrate material has an effect on the measurement of the coating thickness, the influence of the change of the substrate material of $10^4 \sim 10^7$ S/m on the measurement signal is studied. By comparing, it can be seen that the measurement signal decreases with the increase of the transmitting and receiving distance; at the same receiving position, the measurement signal decreases with the increase of the conductivity of the substrate; The scale factor law has the same effect on the measurement signal as the change of the bonding layer thickness.

4. Discussions

In order to more intuitively understand the air where the transmitting coil is located and the current signal strength changes within the substrate, and a two-dimensional current modulus diagram was drawn. Figure 9 shows the air region current modulus diagram of receive-coil position 4cm~10cm.

![Current Modulus Diagram](image)

Figure 9. The air region current modulus diagram of receive-coil position 4cm~10cm.

Figure 9 shows that the transmitting and receiving distance is greater than 9cm, the current modulus is almost zero. Therefore, when multi-array receiving coils are arranged, it is best to select within 9cm.

5. Conclusions

(1) Based on the principle of array induction logging three-coil system, a new method of non-destructive coating detection is proposed. The shielding coil effectively cancels the direct coupling signal and enhances the signal from the coating and the substrate; when the distance between the transmitting coil and the main receiving coil is 8cm and scale factor $\alpha$ is about 0.7047, the signal-to-noise ratio is increased by 102 times, and when the scale factor $\alpha$ is about 0.9032, the signal-to-noise ratio is increased by 215 times, the scale factor $\alpha$ is increased, the focusing effect is obvious, and the sensitivity is also greatly improved;

(2) Multi-array layout: the receiving array is more than 4cm away from the transmitting coil, reflecting the more obvious change of coating thickness;

(3) When the distance between the transmitting coil and the main receiving coil is 4~9cm, and the scale factor $\alpha$ is about 0.9032, the imaginary part of the measurement signal reflects the change in coating thickness more sensitively, and the real part of the measurement signal reflects the change in substrate material more sensitively.

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