A non-destructive testing method for metal stress based on conductivity measurement

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Abstract. Military weapons and equipment have been working under harsh and complex conditions for a long time during their service. Due to external loads and environmental corrosion, load-bearing beams, engine blades, fixed connectors and other stressed components are prone to fatigue defects and even brittle fractures caused by stress concentration. Socio-economic and operating personnel’s life safety poses a huge threat. Based on electromagnetic eddy current testing, this paper mainly studies the influence of metal material stress on material conductivity and establishes a mathematical model of conductivity and stress through experiments to provide theoretical help for sensor measurement signal processing.

1. Introduction
Stress detection technology plays a more and more important role in the service state monitoring of components in various modern industrial fields, especially in large-scale projects such as aerospace, deep-diving detection, and bridge construction. Once sudden damage occurs, it will cause huge damage to many aspects of national property, life safety and social development. Therefore, it is extremely important to monitor the service status of such important projects and equipment. All destructive damages are the result of release after the stress has accumulated for a long time and exceeds the limit that the material can withstand. Therefore, appropriate detection methods are adopted to monitor the stress state to ensure that the equipment is at a safe stress level. The normal work inside has extraordinary significance. The study of metal stress non-destructive testing technology based on electromagnetic testing will be a research hotspot in the future development.

Although there are still many problems that have not been clearly explained, it is of great significance for people to fundamentally understand and explain this phenomenon.

Since the conductivity measurement can realize the non-contact and non-damage detection of the structure, it has attracted the attention of many experts and scholars at home and abroad, and some research results have been obtained. At present, the stress non-destructive testing technology has been applied in many fields such as mechanical structure and design, aerospace, petrochemical industry, but in the field of civil structure. Therefore, research on metal stress non-destructive testing technology based on conductivity measurement will be a research hotspot in the future.
2. The effect of stress on conductivity

2.1. Residual Stress
During the manufacturing and use of equipment components, they will be affected by various processes and external conditions. After these factors disappear, if the above-mentioned effects and influences on the components cannot disappear completely, there will still be effect and influence remaining in the component. And the residual effect and influence are called residual stress or residual stress. Residual stress is a kind of stress, and its state of existence varies with material properties and conditions. The existence state of residual stress varies with material properties, generation conditions, etc., and the classification methods are also inconsistent. According to the scope of action, it can be divided into macro residual stress and micro residual stress.

According to the theory of metal electrons, when the electron wave passes through an ideal crystal lattice (the temperature is 0K), the electron wave will not be affected by the scattering effect. This is because the periodicity of the ideal crystal lattice is intact. Only at the crystal point Where the integrity of the array is destroyed, the electron waves will be scattered (incoherent scattering). This is the real cause of resistance in metals. In the crystal lattice, there are many reasons for the integrity of the lattice period to be destroyed. For example, the change in the amplitude of the ion motion (thermal vibration) caused by temperature (usually expressed by the mean square value of the amplitude), the heterogeneous atoms (impurity doping) of crystal, dislocations and point defects will destroy the periodicity of the ideal crystal lattice. In this way, electron waves scatter in these places and generate resistance, thereby reducing conductivity.

2.2. Pressure
During hydrostatic compression, the resistivity of most metals decreases. This is because under the condition of huge hydrostatic pressure, the distance between metal atoms is reduced, and the internal defect morphology, electronic structure, Fermi energy and energy band structure will all change, which will obviously affect the conductivity of the metal.

The resistivity of metal under hydrostatic pressure can be calculated by the following formula:

$$\rho_p = \rho_0 (1 + \varphi P)$$  \hspace{1cm} (1)

Where: $\rho_0$ - Resistivity of metal in vacuum;
$P$ - Stress;
$\varphi$ - Pressure coefficient.

According to the characteristics of the influence of pressure on the conductivity of metals, metals are divided into two types: normal and abnormal metals. The so-called normal metal means that as the pressure increases, the resistivity of the metal decreases, and vice versa. For example, iron, cobalt, nickel, platinum, copper, silver, and gold are all normal metals. Abnormal metals mostly exist in alkali metals and rare earth metals.

3. Stress-Conductivity Mathematical Model
Boditzmin found through experimental research \[4\] that when the metal specimen is stretched, the relative change of the material resistivity is related to the relative change of its volume, as shown in the following formula:

$$\frac{\Delta \rho}{\rho_0} = C \frac{\Delta V}{V}$$  \hspace{1cm} (2)

Where: $\rho_0$ - Material initial resistivity;
$V$ - Volume;
$C$ - Coefficient determined by processing method and material type;
$\Delta \rho$ - Change in resistivity;
$\Delta V$ - Change in volume.

In the above formula, the volume change of a metal material is the elastic deformation that occurs in the elastic range under the action of an applied load. In the tensile model, the axial and horizontal linear strain can be used to express the relative change of the material volume. For the volume formula, first find the logarithm and then perform multivariate differentiation to obtain:

$$
\frac{\Delta V}{V} = \frac{\Delta w}{w} + \frac{\Delta h}{h} + \frac{\Delta l}{l} = (1 - 2\mu) \varepsilon
$$

When $\mu = 0.5$, the deformation volume of the material will not change. Because of the metal material, the volume will increase when stretched. According to the relationship between resistivity change and strain:

$$
\frac{\Delta \rho}{\rho_0} = C(1 - 2\mu) \varepsilon
$$

According to generalized Hooke's law:

$$
\varepsilon = \frac{\delta}{E}
$$

Thus the following formula can be obtained

$$
\frac{\Delta \rho}{\rho_0} = C(1 - 2\mu) \frac{\delta}{E}
$$

Where: $\mu$ - Poisson's ratio;

$\delta$ - Stress (tensile stress is positive, compressive stress is negative);

$E$ - Young's modulus.

It can be seen from the formula (6) that as the tensile stress increases, the metal resistivity increases, and the corresponding conductivity decreases. In addition, in the above formula:

$$
\Delta \rho = \rho - \rho_0
$$

According to formula (6) and formula (7), we can get:

$$
\rho = \rho_0 + C(1 - 2\mu) \frac{\delta}{E} \rho_0
$$

Thus:

$$
\sigma = \frac{\sigma_0}{1 + C(1 - 2\mu) \frac{\delta}{E}}
$$

Where: $\sigma_0$ - Material initial conductivity;

It can be seen from equation (9) that the conductivity of metal materials is related to the Young's modulus, Poisson's ratio and material coefficient of the material, and decreases with the increase of tensile stress.

4. Detection experiment

4.1. Experiment platform

In order to measure the relationship between the electrical conductivity and stress of the test piece and verify the accuracy of the model, tensile experiments were performed on aluminium alloy 6063 and pure aluminum 1060. The detection system is mainly composed of WDW-E100D microcomputer-controlled tensile testing machine, Sigmatest-2.069 conductivity tester and the tested part. The detection system is shown in Figure 1.
4.2. Experimental steps
First the appropriate tested part is selected for preparing for the experiment. As the purchased aluminium alloy 6063 and pure aluminium specimens are not absolute standards, there are some scratches or small holes on the surface of some specimens, which will seriously affect the normal stress distribution, so they are not used. After the tested part is selected, we make a name mark, and evenly mark the five conductivity measurement points on the surface where the conductivity measurement is to be performed, and mark them as points A, B, C, D, and E, as shown in Figure 2. In order to ensure the accuracy and reliability of the conductivity measurement results, the principle of selecting measurement points is to evenly distribute them in the middle of the test piece. The stress distribution and electrical conductivity change of the fixed end are more complicated and affected by many factors, so they will not be considered for the time being. The point distribution is shown in the figure below:

![Figure 2. Electrical conductivity test points](image)

The tested part is clamped on the electronic testing machine. First, we use the tools to clamp one end of the test piece in the lower end fixture, adjust the verticality of the test piece, and then clamp the other end of the test piece in the upper end fixture. In the process of fixing the upper clamp, it cannot be done in one step. The experimental opportunity continuously generates a pre-tightening force within 1N of the material. At this time, it is necessary to continuously lower the height of the upper clamp to eliminate the pre-tightening force until the tested part is completely fixed. After the tested part is fixed, the tensile stress is continuously increased by the microcomputer control of the experimental machine, and the amplitude of each increase is appropriately selected by the material elastic limit.

Each time the stress value is increased, the conductivity value of the material must be measured. The conductivity measurement adopts the method of multi-point measurement to get the average value, and each point adopts the method of three measurements to get the average value, which ensures the accuracy of the measurement result. Record the measured value after the measurement is completed for data processing.
4.3. Experimental results and analysis

In order to reduce the influence of the error, five different measurement points are taken on the test piece, and each point is measured five times under the same stress level to obtain an average. The average value is regarded as the actual conductivity value under the stress. The measurement results of tensile load and electrical conductivity are shown in Figure 3.

![Figure 3. Change of Al alloy conductivity with tensile load](image)

It can be seen from Figure 3 that when the aluminium alloy 6063 specimen is stretched in the elastic range, the conductivity decreases with the increase of the tensile force. The initial value of the conductivity is 20.411 MS/m. When the load is 25 kN, the conductivity is 20.279 MS/m. The change was 0.132, and the relative change rate was 0.65%. A similar method was used to conduct a tensile test on pure aluminium 1060 and measure its conductivity. The results are shown in Figure 4.

![Figure 4. Change of pure Al conductivity with tensile load](image)
The maximum conductivity of pure aluminium 1060 is 34.983 MS/m. When the tensile load is 12 kN, the conductivity is the smallest, which is equal to 34.793 MS/m. The change is 0.19 MS/m, and the relative change rate is 0.64%. The goodness of fit using linear equations to fit the experimental data is 0.9271 and 0.9847, respectively. The linear fitting equations obtained according to the experimental results are basically consistent with the fitting equations obtained from the simulation results, which proves the use of mathematical models to characterize the conductivity of metal materials. The feasibility of the relationship with stress.

5. Conclusion
Using the piezoresistive strain effect of metal materials, a mathematical model of the relationship between metal stress and conductivity is established through theoretical deduction and empirical formulas. According to the piezoresistive effect, Hooke's law and strain formula, the relationship between metal stress and electrical conductivity is deduced, and the influence of parameters such as Young's modulus, Poisson's ratio and material coefficient in the model is analysed. Finally, the two models are compared. The characteristics of the metal qualitatively determine the relationship between metal stress and electrical conductivity. By building an experimental platform for tensile stress testing, the conductivity change of the stretched aluminium alloy plate was studied, the consistency with the model formula was verified, and the change characteristics and material parameters of different materials were calibrated.

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