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Inspection of aluminum alloys by a multi-frequency eddy current method

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Abstract

The paper proposes an experimental method of material inspection, which is based on digital processing of multi-frequency eddy current measurement data. The influences of various factors (conductivity, the gap between the sample surface and the sensor, the thickness of the sample) on the obtained hodographs are examined by taking the aluminum alloys for example, and the possibility of separation of various factors is analyzed. The results obtained are indicative of how much promise the proposed method offers for the inspection and testing of products made of aluminum alloys.

Keywords: Eddy current method; Material inspection; Digital signal processing; Aluminum alloy

1. Introduction

One of the nondestructive testing methods for metallic materials is an eddy current method [1] that makes it possible to estimate the internal structural state of the material [2], detect the surface and subsurface flaws [3], detect the fatigue cracks [4], and determine the crack location [5] and the geometrical parameters such as the thickness of metal sheet or dielectric coating on metal products [6]. The measured result of eddy current is determined by the combined action of a number of factors. Depending on the specific problem to be solved in non-destructive testing, it is necessary to isolate the effect of any one factor or group of factors. All the rest are in the number of the interfering factors and their effect should be excluded. The main factors affecting the eddy current measurements include electrical conductivity and magnetic permeability that depend on the chemical composition and structure of the material, the geometric characteristics of a particular sample or products, the value of the gap between the probe and the surface of the object under control for overhead probes. In addition, the results of the measurements depend on the design peculiarities of the used probes [7] and measurement modes [8,9]. The efficiency of the eddy current inspection can be improved by reliably separating the effect of various factors.

The most informativity is achieved by using of the method of eddy current multi-frequency measurements, which are followed by the construction and analysis of hodographs of the "probe – specimen" system. Such hodographs plot the combined effect of almost all factors important for the inspection and testing of materials. The main problem with multi-frequency measurements is that their result depends on the combined action of a very large number of factors. Upon reaching sufficient precision, the experimental hodographs allow to separate the effect of various factors. One way of solving this problem is to employ new methods of digital

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processing of signals from an eddy current measuring system [10,11].

The present paper considers a method of deriving experimental hodographs, which provides a significant reduction in the measurement error and thus allows us to distinguish the factors affecting the properties under inspection. The investigation is performed on aluminum alloys widely used in modern engineering as constructional materials [12].

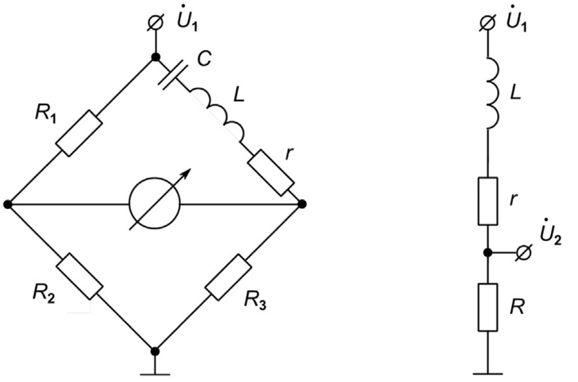
2. Experimental method

The eddy current testing helps us to determine the inductance and active resistance of the "eddy current probe – specimen" system. The tests are usually run with various bridge circuits and provide a smaller error in comparison to the direct measurement of system parameters. At the same time the bridge circuits make the measurement more difficult because of the necessity for constant bridge balancing. Besides, such balancing complicates considerably the test automation [13]. In this connection, the bridge measurements and direct detection of the probe impedance are conducted through the complex amplitudes of voltage and current. Both circuits are shown in Fig. 1.

Fig. 1(a) shows a resonant bridge circuit. The probe parameters are calculated by the formulae

$$\begin{aligned} L &= \frac{1}{\omega^2 C} \\ r &= \frac{R_1 R_3}{R_2} \end{aligned} \tag{1}$$

where L and r are the inductance and active resistance of the eddy current probe, respectively; C is the capacitance of the capacitor; R_1, R_2, and R_3 are the resistance values, at which the bridge is balanced; ω is the cyclic frequency of the sinusoidal input signal; and $\dot{U}_1$ in Fig. 1 is the complex input amplitude. Fig. 1(b) presents a circuit for the direct measurement of the probe impedance. In this case, the parameters are calculated by the formulae



(a) Resonant bridge circuit (b) Circuit for the direct measurement of impedance

Fig. 1. Circuits for the experimental measurements.

$$\begin{aligned} L &= \frac{R}{\omega}\frac{U_{10}}{U_{20}}\sin(\varphi_1-\varphi_2) \\ r &= R\left(\frac{U_{10}}{U_{20}}\cos(\varphi_1-\varphi_2)-1\right) \end{aligned} \tag{2}$$

where R is the resistance playing the role of the current-to-voltage converter; and U_{10} and φ_1 are the amplitude and initial phase of the input signal $\dot{U}_1$, respectively; and $\dot{U}_{20}$ and φ_2 are the amplitude and initial phase of the signal $\dot{U}_2$. All measurement results are shown as the hodographs plotted in the coordinates $\varDelta X/X_0 - \varDelta r/X_0$, where $\varDelta X = \omega(L - L_0)$ is the variation in the reactive resistance of probe in the presence of the specimen, $\varDelta r = r - r_0$ is the variation in the active resistance of probe in the presence of the specimen, X_0, L_0 and r_0 are the reactive resistance, inductance and active resistance of the probe without the specimen, respectively.

In both cases, a parametric probe of an encircling type is used. The probe presents a coil with 250 mm in length and 29 mm in effective diameter. A test specimen with round cross-section and longer than the coil is passed through the probe. Specimens are made of D16T duralumin and shaped to the rods with 400 mm in length and 22 mm in diameter. The measurements are made at fixed frequencies ranging from 200 Hz to 2 kHz. Each measurement for a given frequency is conducted with and without specimen for at least 10 times with the subsequent calculation of the probe parameters by Eqs. (1) and (2). The measurement results are represented in the hodographs as a series of experimental points, each of which corresponds to a specific frequency.

Along with the construction of experimental hodographs, the theoretical ones are calculated using the known values of probe characteristics, geometric parameters of specimens, and their specific electrical conductivity. The calculations are carried out by the formulas [1,3]

$$\begin{aligned} \frac{\Delta r}{X_0} &= -2\eta\mu \mathrm{Im}\left(\frac{\mathrm{I}_1\left(y\sqrt{j}\right)}{y\sqrt{j}\mathrm{I}_0\left(y\sqrt{j}\right)}\right) \\ \frac{\Delta X}{X_0} & 2\eta\mu \mathrm{Re}\left(\frac{\mathrm{I}_1\left(y\sqrt{j}\right)}{y\sqrt{j}\mathrm{I}_0\left(y\sqrt{j}\right)}\right)-\eta \end{aligned} \tag{3}$$

where μ is the relative magnetic permeability of the material; $\eta = (R_0/R_s)^2$ is the filling factor of the probe of effective radius R_s with a cylindrical specimen of radius R_0; $y = R_s\sqrt{\mu_0\mu\sigma\omega}$ is the generalized eddy current parameter; σ is the specific electrical conductivity of the conductor; $\mu_0 = 4\mu\pi 10^{-7}$ H/m is the magnetic constant; and $I_0(y\sqrt{j})$ and $I_1(y\sqrt{j})$ are the modified Bessel function of the first kind for zero and the first order [14], respectively. The calculation results of the theoretical hodographs are given as solid curves.

3. Digital signal processing in eddy current measurements

The digital processing of experimental signals was used to reduce the measurement error of complex voltage and current