Non-destructive testing of the part surface layer after grinding

Неруйнівний контроль поверхневого шару деталі після шліфування

Неразрушающий контроль поверхностного слоя детали после шлифования

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У статті розроблено методика і прилад для пошарового неруйнівного контролю фізико-механічного стану поверхневого шару шліфованих сталевих деталей на основі використання поля вихрових струмів, порушуваних накладним електромагнітним датчиком.

Ключові слова: *неруйнівний контроль, вихрові струми, залишкові напруги, пошарове вимірювання, магнітний потік, магнітна проникність, достовірність вимірювання.*

В статье разработаны методика и прибор для послойного неразрушающего контроля физико-механического состояния поверхностного слоя шлифованных стальных деталей на основе использования поля вихревых токов, возбуждаемых накладным электромагнитным датчиком.

Ключевые слова: *неразрушающий контроль, вихревые токи, остаточные напряжения, послойное измерение, магнитный поток, магнитная проницаемость, достоверность измерения.*

A method and a device are developed for layer-by-layer non-destructive testing of the physical-and-mechanical state of the surface layer of ground steel parts based on the use of an eddy current field excited by an overhead electromagnetic sensor.

Key words*: non-destructive control, eddy currents residual stresses, layer-by-layer measurement, magnetic flux, magnetic permeability, measurement accuracy.*

1. Introduction

Ensuring the quality of the surface layer of ground machine parts is impossible without effective control of this quality. In turn, this control is performed by destructive and non-destructive measurement methods. In the conditions of single and small-scale production, non-destructive quality control methods are more preferable, since they are free from additional costs for the production of test samples. The capabilities of modern computer-aided measurement allow increasing and adjusting the scientific plausibility of the data obtained by increasing the number of similar measurements and using statistical mathematical models for measurement processes.

2. Literature Review

One of the most common methods of non-destructive testing of the physical and mechanical state of the surface layer is electromagnetic analysis, based on the method of eddy currents and Barkhausen noise measurements [1-3]. However, the technique of layer-by-layer measurement of the physical characteristics of the surface layer in the frequency range of 60-4000 kHz has not yet been developed.

In mechanical engineering technology, there are serious studies of technological residual stresses based on the method of Academician N. N. Davidenkov (1879-1962), but they are associated with the destruction of the samples under testing [4-6].

Non-destructive testing, including the use of X-rays and the Wulff–Bragg's condition, has been conducted for more than 100 years beginning from 1913 [7-14]. However, more effective applications were found not in technology, but in medicine: computed tomography (CT) scan, magnetic resonance imaging (MRI).

The non-destructive method to study the ground machine parts surface integrity was proposed by researcher V.A. Kazakov working in the scientific school of Professor A.V. Yakimov (1925-2016). Devices for non-destructive testing and the corresponding technique presented below were developed based on phase measurements of electrical signals [15-16].

The non-destructive testing technique based on both the scientific provisions of the electromagnetic field theory and the phenomenon of the skin effect [17-18]. Besides, the relationship between the mechanical and electromagnetic properties of the material being ground is also used [19].

3. Research Methodology

In physics, specifically electromagnetism, the magnetic flux Φ through a surface is the surface integral of the normal component of the magnetic field B over that surface. Magnetic flux is usually measured with a fluxmeter, which contains measuring coils and electronics, which evaluates the change of voltage in the measuring coils to calculate the magnetic flux.

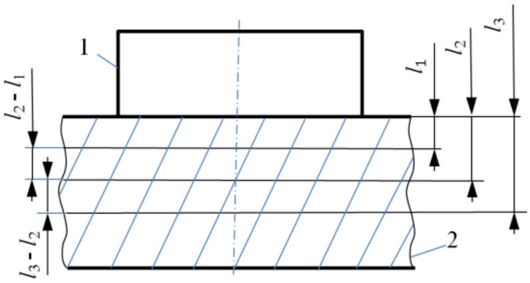

Fig.1. Layer-by-layer non-destructive testing scheme in which 1 is the overhead eddy current sensor; 2 is the part under testing (after grinding).

Initial assumptions for subsequent research are the following. Let’s assume that the path traversed by the field deep into the material is much smaller than the path traversed by the field along the surface. The validity of this is ensured by the correct choice of the frequency of the electromagnetic field. The material to be tested consists of layers within which the value of “internal stress” (generalized physical-and-mechanical property) is constant, but different for individual layers. The magnetic flux, penetrating into the material, is deformed due to the influence of anisotropy of internal stresses.

In a separate layer of material with a thickness of dx, the deformed magnetic flux can be written as

$$d\Phi = B_x \, dx \, l_w \, e^{i\Psi},$$

where B_x is the magnitude of the magnetic field (magnetic flux density) in layer x, Wb/m^2 (and also Tesla or T); Ψ is the phase angle shift (angle increment) due to layer dx influence, rad; l_w is the sensor width, m.

The total magnetic flux Φ (in Wb), deformed due to the influence of the material, can be written as

$$\Phi = \int B_x \; l \; e^{i\Psi_x} \, dx. \qquad (1)$$

As the total magnetic flux Φ penetrates into the material, the magnetic flux density B_x decreases according to the law [2, 3]:

$$B_x = B_o e^{-\alpha x}, \qquad (2)$$

where α is the proportionality factor.

In turn

$$\alpha = \sqrt{\frac{\omega\gamma\mu}{2}}, \qquad (3)$$

where $\omega = 2\pi f$ is the angular frequency of the electromagnetic field which corresponds to the penetration depth l of this field, rad/s; f is the ordinary frequency, Hz; γ and $\mu = \mu_r \cdot \mu_0$ are the electrical conductivity (S/m) and magnetic permeability (H/m) of the substance (material) under the test; μ_r and μ_0 are the relative permeability and permeability of free space, respectively.

We assume that there is a constant equivalent “stress” $\sigma = \text{const}$ in each layer dx which causes the appearance of a constant phase shift angle Ψ. For example, for n layers, we get according to Eq. (1)

$$\Phi = \int_0^{l_1} B_0 e^{-\alpha_1 x} l dx \, e^{i\Psi_1} + \int_{l_1}^{l_2} B_0 e^{-\alpha_2 x} l e^{i\Psi_2} dx + \ldots + \int_{l_{n-1}}^{l_n} B_0 e^{-\alpha_n x} l e^{i\Psi_n} dx \qquad (4)$$

where each of the $l_1,\ l_2,\ \dots,l_s,\dots,\ l_n$ is the greatest depth to which the total magnetic flux Φ penetrates the material at a given frequency, numerically equal to the “equivalent depth” of the field penetration at frequencies $\omega_1,\ \omega_2,\dots,\ \omega_n$, respectively. Therefore

$$\Phi = a_1 e^{i\Psi_1}\int_0^{l_1} e^{-\alpha_1 x}\,dx + a_2 e^{i\Psi_2}\int_{l_1}^{l_2} e^{-\alpha_2 x}\,dx + \dots + a_n e^{in}\int_{l_{n-1}}^{l_n} e^{-\alpha_n x}\,dx, \qquad (5)$$

where $a_1 = a_2 = \dots = a_s = \dots = a_n = \mathrm{B}_0 l_w$; $\alpha_1, \alpha_2, \dots, \alpha_s, \dots \alpha_n$ are the attenuation factors.

According to Eq. (3) in the case been considered

$$\alpha_s = \sqrt{\frac{\omega\gamma_s\mu_s}{2}}. \qquad (6)$$

From Eq. (5) we get

$$\Phi = a_1 e^{i\Psi_1}\frac{e^{-\alpha_1 l_1-1}}{-\alpha_1} + a_2 e^{i\Psi_2}\frac{e^{-\alpha_2 l_2}-e^{\alpha_2 l_1}}{-\alpha_2} + \dots + a_n e^{i\Psi_s}\frac{e^{-\alpha_n l_n}-e^{-\alpha_n l_{n-1}}}{-\alpha_n} \qquad (7)$$

or

$$\Phi = A_1 e^{i\Psi_1}(1-e^{-\alpha_1 l_1}) + A_2 e^{i\Psi_2}(e^{-\alpha_2 l_1} - e^{-\alpha_2 l_2}) + \dots A_n e^{i\Psi_n}(e^{-\alpha_n l_{n-1}} - e^{-\alpha_n l_n}), \qquad (8)$$

where α_n the attenuation factor for the given frequency in the layer n.

At a high frequency (among high, middle, and low frequency) $\omega_1 = \omega_H$ of the electromagnetic field penetration into substance the only upper layer l_1 will be captured. Since for $x \geq l_1$ we have $e^{-\alpha_1 x} \ll 1$ then the value $e^{-\alpha_1 x}$ can be neglected by considering the stresses within the so called “first” layer, i.e. for $\sigma_2 = \sigma_3 = \dots = \sigma_n = 0$ we will get

$$\Phi = A_1 e^{i\Psi_1}(1-e^{-\alpha_1 l_1}) \qquad (8)$$

Given an error of about 5% when determining the layer l_1, we get the condition $e^{-\alpha_1 l_1} = \frac{1}{20} = 0.05$, i.e., $e^{\alpha_1 l_1} = 20$, or $\alpha_1 l_1 = ln20$. So,

$$l_1 = ln20/\alpha_1. \qquad (9)$$

In turn, according to Eq. (6)

$$\alpha_1 = \sqrt{\frac{\omega_1\gamma_1\mu_1}{2}} = \sqrt{\frac{\omega_H\gamma_1\mu_1}{2}}. \qquad (10)$$

At the middle frequency ω_M, with the capture of two layers (Fig. 1) in which $\sigma_2 \neq \sigma_1$ accounting the Eq. (8), we have

$$\Phi = A_1 e^{i\Psi_1}(1-e^{-\alpha_1 l_1}) + A_2 e^{i\Psi_2}(e^{-\alpha_2 l_1} - e^{-\alpha_2 l_2}). \qquad (11)$$

Taking into account the above accuracy of the layer thickness $(l_2 - l_1)$ of about to 5%, we get (when there are two layers)

$$e^{-\alpha_2(l_2-l_1)} = \frac{1}{20} = 0.05. \qquad (12)$$

Thus,

$$l_2 - l_1 = ln20/\alpha_2\,. \qquad (13)$$

Taking into account Eq. (9), we obtain

$$l_2 = \frac{ln20}{\alpha_1} + \frac{ln20}{\alpha_2} = ln20\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right).$$

Equations (8) and (11) take the following form, respectively

$$\Phi = A_1 e^{i\Psi_1}(1 - e^{-ln20}), \qquad (14)$$

$$\Phi = A_1 e^{i\Psi_1}(1 - e^{-ln20}) + A_2 e^{i\Psi_2}\left\{e^{-(\alpha_2/\alpha_1)ln20} - e^{-[(\alpha_2/\alpha_1)+1]\,ln20}\right\}. \qquad (15)$$

That is, in general case

$$\Phi = A_1 e^{i\Psi_1}(1 - e^{-ln20}) + A_2 e^{i\Psi_2}\left\{e^{-(\alpha_2/\alpha_1)ln20} - e^{-[(\alpha_2/\alpha_1)+1]\,ln20}\right\} + \ldots +$$

$$+ A_n e^{i\Psi_n}\left\{e^{-(\alpha_n/\alpha_{n-1})ln20} - e^{-[(\alpha_n/\alpha_{n-1})+1]\,ln20}\right\}. \qquad (16)$$

Under certain conditions, the total phase angle shift from the action of n layers with fixed properties will be

$$\Psi(n) = tan^{-1}\frac{a_1^{(n)} sin\,\Psi_1 + a_2^{(n)} sin\,\Psi_2 + \cdots + a_n^{(n)} sin\,\Psi_n}{a_1^{(n)} cos\,\Psi_1 + a_2^{(n)} cos\,\Psi_2 + \cdots + a_n^{(n)} cos\,\Psi_n}, \qquad (17)$$

where $a_1^{(n)}$, $a_1^{(n)}$, …, $a_n^{(n)}$ and Ψ_1, Ψ_2, …, Ψ_n are the previously found factors.

For the small phase angles shifts, Eq. (17) takes the form

$$\Psi(n) = tan^{-1}\frac{a_1^{(n)}\,\Psi_1 + a_2^{(n)}\,\Psi_2 + \cdots + a_n^{(n)}\,\Psi_n}{a_1^{(n)} + a_2^{(n)}\,\Psi_2 + \cdots + a_n^{(n)}} \qquad (18)$$

4. Results

The obtained expressions with their recurrent use allow forming an algorithm for determining the phase angle shifts that are caused by the influence of the physical-and-mechanical properties of the surface layers. Moreover, the total phase angle shift from the action of n layers can be expressed as a function of the corresponding phase angle shifts from the influence of intermediate $(n-1)$ layers.

A device for non-destructive testing of the physical and mechanical state of the surface layer of steel parts was developed and manufactured (Fig. 2).

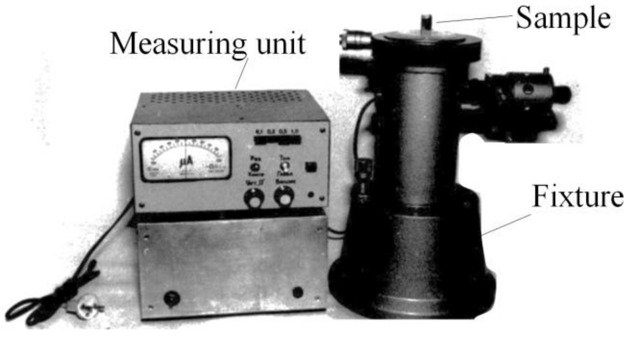

Fig.2. Device for non-destructive testing the machine parts surface layer

Further research in the field of non-destructive testing is carried out by the Department of Mechanical Engineering Technology in two areas. First area is using more advanced mathematical models of field theory, i.e. for scalar, vector, tensor fields, etc [20]. Second area is using the applied measurement theory [21-23].

5. Conclusions

1. A technique of layer-by-layer analysis of the physical-and-mechanical state of the surface layer of ground machine parts has been developed, which can be used in the diagnosing the state of the surface layer of parts made of hard-to-machine materials.

2. The essence of the developed technique is to use the skin effect, which causes an exponential attenuation of the eddy currents intensity in the surface layer of the part under the influence of an electromagnetic field from a special overhead electromagnetic sensor. Changing the frequency of the electromagnetic field in the range of 60-600 kHz (and up to 4 MHz) leads to a different penetration depth of eddy currents, so that the maximum frequency of the current feeding the sensor corresponds to the minimum eddy currents penetration depth.

3. The proposed technique is based on the fact that the test results of the subsequent layer include the data of the previous layer. Therefore, it is necessary to provide phase synchronization of measurements made at different frequencies of the exciting electromagnetic field (or frequencies of the current feeding the sensor).

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