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MEASUREMENT OF THE MECHANICAL STATE OF SUBSURFACE LAYERS BY EDDY-CURRENT METHOD

V. Augutis R. Ramanauskas, V. Vasauskas

Kaunas University of Technology, Lithuania

1. INTRODUCTION

Methods of structural strength and lifetime control for short and safe components are traditionally based on the most structural and functional materials. Mechanical tests do not give a reliable data because of inconsistency of wear and fracture mechanism of specimens and real structural members. For the structural members the essential charges of anisotropy (texture) of the initial material occur after various technological operations [1]. Because of this it is necessary to develop nondestructive methods of structure control of structural members under loading directly in technological process, that subjects components to a 100% test (i.e. testing of all items) and which can guarantee their safety. The determination of Young's modulus (E), hardness (H), and strain hardening exponent (n) by means of indentation experiments can be successfully achieved by establishing the relation between the bulk tensile response of a material and the local indentation test. The uses of indentation tests are also relevant of the structural integrity assessments of components, where tensile specimens may not be readily available. Alternative methods are required; therefore we turn to nondestructive methods directly applied to the structure number, such as eddy-current technique [2].

The objective of the study was to determinate and quantify the changes in the magnetic and mechanical properties in the layers of microstructure after quenching, the hardening depth and surface hardness using CS-pulsed eddy current technique, and to correlate them with technological parameters.

2. BACKGROUND

The idea to develop a measuring device for stress measurement by eddy-current in steels is not new [3]. Trying to investigate the characteristics of material surface layer, it is possible to carry out measurements by exciting a converter of eddy-currents with various frequencies, thus accumulating information from different materials layers. However, such a measurement technique is not operative and of not sufficient resolution, because there prevail the properties of upper layer. In order to avoid this situation we propose to excite the converter in leaps.

The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current and the electrical conductivity and magnetic permeability of the specimen. The depth of penetrate decreases with increasing frequency and increasing conductivity and magnetic permeability. The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called the standard depth of penetration (δ):

$$\delta = \sqrt{\frac{1}{\pi \cdot f \cdot \sigma \cdot \mu}}; \qquad (1)$$

where f is the frequency of exciting signal; σ is the electrical conductivity of material; μ is the magnetic permeability.

Low frequency eddy-currents penetrate into metal deeper, while high frequency eddy-currents flow only through a thin surface layer.

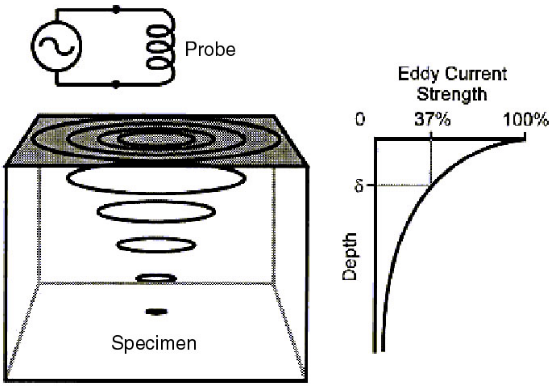

Fig. 1. Eddy current distribution in conductive material

The advantage of using a step function voltage is that it contains a continuum of frequencies. As a result, the electromagnetic response to several different frequencies can be measured with just a single step. Since the depth of penetration is dependent on the frequency of excitation, information from a range of depths can be obtained all at once. If measurements are made in the time domain (that is by looking at signal strength as a function of time), indications produced by flaws or other features near the inspection coil will be seen first and more distant features will be seen later in time.

As the spectrum of such pulse shape is described by 1/f law, then the weight of low frequencies in the total signal increases and the depth material properties are reflected better.

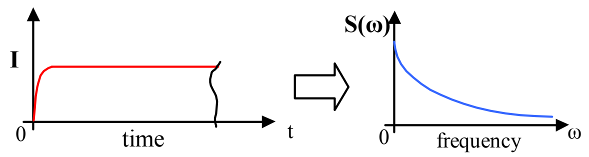

Fig. 2. Eddy-currents excitation signal and its spectrum

Equivalent circuit of eddy current probe

The basic of eddy-currents converter is induction coil. The total impedance of the coil, then it is not surrounded by conductive surface, is

$$Z_0 = R_0 + j\omega L_0 . \qquad (2)$$

where R_0 is resistance of the coil; L_0 is inductance of the coil.

When the sensor coil is nearby any metallic object, AC current generates an oscillating magnetic field that induces eddy currents in metal. The eddy currents circulate in a direction opposite that of the coil, reducing the magnetic flux in the coil and thereby its inductance. The eddy currents also dissipate energy, increasing the coil's resistance. If target is made from magnetic metal, the sensor response is a mixture of eddy current and magnetic reluctance. Magnetic reluctance describes the way in which magnetic material modifies the effective permeability in a magnetic circuit. As a magnetic target approaches the coil, eddy currents reduce the inductance, while reluctance increases the inductance. Since these effects are in opposite directions, they may cancel each other. The net result is an easily avoidable null point in the sensor response at small standoff values.

In low frequency the complex impedance of the sensor coil is represented a series LR circuit (Fig. 3). Both inductance, L_{IN}, and resistance, R_{IN}, change with target position, magnetic permeability μ, electrical conductivity.

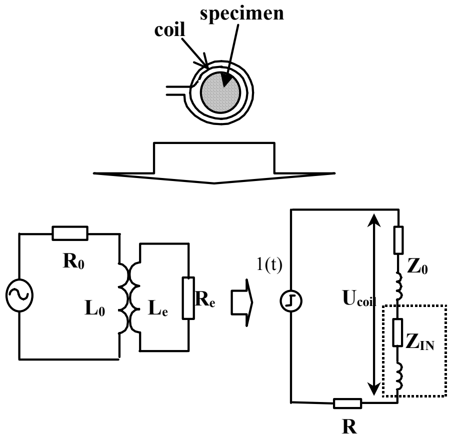

Fig. 3. Model of a coil with test object. R_e , $j\omega L_e$ – resistance and inductive reactance of eddy current circuit.

$$\begin{aligned} Z &= Z_0 + Z_{IN}, \\ Z_{IN} &= R_{IN} + j\omega L_{IN}; \end{aligned} \qquad (3)$$

where R_0 is the resistance of empty coil; L_0 is the inductance of empty coil; R_{IN} is the inserted resistance; L_{IN} is the inserted inductance.

In high frequency parasitics capacitances between coil wires, between coil and target, come to effect (5-10 pF). Because of that, resultant test circuit becomes more complicated.

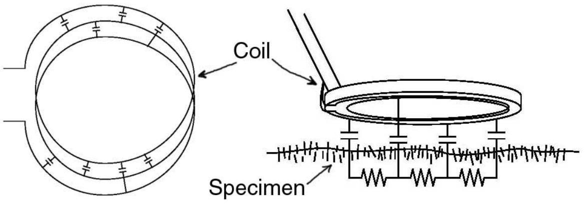

Fig. 4. Coil parasitics.

The capacitive reactance (X_C) can be dropped as most eddy current probes have little or no capacitive reactance.

To evaluate the inserted resistances R_{IN} and X_{IN}, which appear when the coil interacts with metal, is very difficult, because they depend upon many factors such as coil geometric and electrical parameters, properties of material to be investigated (magnetic permeability μ, dielectric constant (permittivity) ε, electrical conductivity σ):

$$Z_{IN} = f\left(Z_0, \omega, \mu, \varepsilon, \sigma, \ldots\right) \qquad (4)$$

The interaction of the investigated object with eddy-currents converter (induction coil) is rather difficult to be described mathematically, because $\mu = f(d)$ and $\sigma = f(d)$ are unknown.

In the present work we try to relate electrical circuit parameters to the mechanical characteristics of the investigated object by neural network

3. EXPERIMENTAL METHODS

Experiments were carried out by two methods: by destructive method when hardness distribution is determined in subsurface layer and by proposed by us method.

Tests were carried out with safety components taken from automobile (correcting rods, steels), made of steel 40X which were subjected to the following heat-treatment conditions: undefined coaling rate, normalized, conventionally tempered and hardened. Cylindrical samples, 30 mm in diameter and 40 mm in length were used.

To determinate the mechanical properties of the steel at room temperature, to carry out HV0.05 hardness measurements on metallographics microsections, tensile tests (for determine strength) elongation and reduction of area were performed.

For tempered samples there have been carried out Vickers micro hardness measurements using the microhardness tester ПМТ-3 with a load of 0,5 N (HV 0,05). Each data point was obtained from averaging three measurements.The hardness measurements were carried out on the surface, parallel to the surface at the depth of 90μm and perpendicular to the latter.

After quenching and tempering an average hardness of 800HV 0,05 could be detected.

Device structure

Transient response of converter (coil), then it is excited by leaps:

$$U_{out} = \frac{R}{R_0 + R_{IN} + R}\left(1 - e^{-\frac{t(L_0+L_{IN})}{R_{01}+R_{IN}+R}}\right). \qquad (5)$$

The coil impedance (and voltage) changes only slightly as the probe passes the different test objects, typically less than 1%. This small change is difficult to detect by measuring absolute impedance or voltage. Special instrument had been developed for detecting and amplifying small impedance changes. It is a bridge circuit (Fig. 5), which enabled us to compare the sample transient responses with the standard sample transient response. A precondition is assumed that the transient response front, corresponding to high frequencies, reflects samples hardness difference at small depth, while the fall of flat part, corresponding to low frequencies-hardness differences in deeper layers.

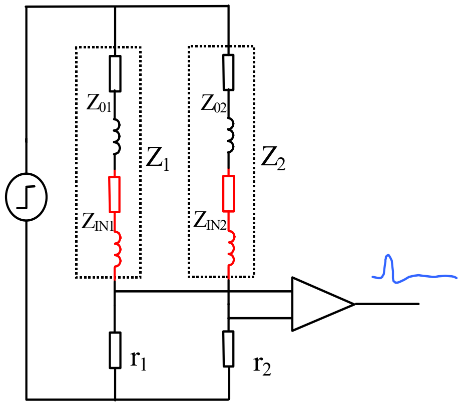

Fig. 5. Circuit of eddy current instrument

Since the impedance of two coils is never exactly equal, balancing is required to eliminate the voltage difference between them. It is achieve by subtracting a voltage equal to the unbalance voltage.

The bridges output voltage:

$$U_{out} = E\cdot\frac{r_1}{R_{01}+R_{IN1}+r_1}\left(1-e^{-\frac{t(R_{01}+R_{IN1}+r_1)}{L_{01}+L_{IN1}}}\right)-$$

$$-E\cdot\frac{r_2}{R_{02}+R_{IN2}+r_2}\left(1-e^{-\frac{t(R2+R_{IN2}+r_2)}{L_{02}+L_{IN2}}}\right),$$

if $$\frac{r_1}{R_{01}+R_{IN1}+r_1} = \frac{r_2}{R_{02}+R_{IN2}+r_2} = A,$$

then

$$U_{out} = E\cdot A\left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}}\right). \qquad (6)$$

where: $\tau_1 = \frac{L_{01}+L_{IN1}}{(R_{01}+R_{IN1}+r_1)_1}$, $\tau_2 = \frac{L_{02}+L_{IN2}}{(R_{02}+R_{IN2}+r_2)}$.

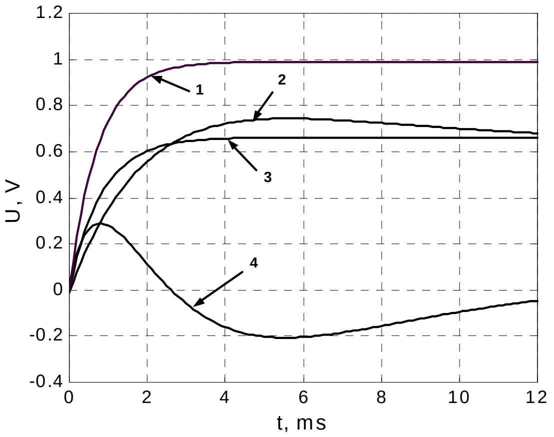

Fig. 6. 1 – transient response of empty coil; 2,3 – transient responses of coil with different samples; 4 – Differential transient response

4. EXPERIMENTAL AND RESULTS

The dependences of samples subsurface (near-surface) layer hardness on depth, measured with Vickers method are illustrated in Fig.7.

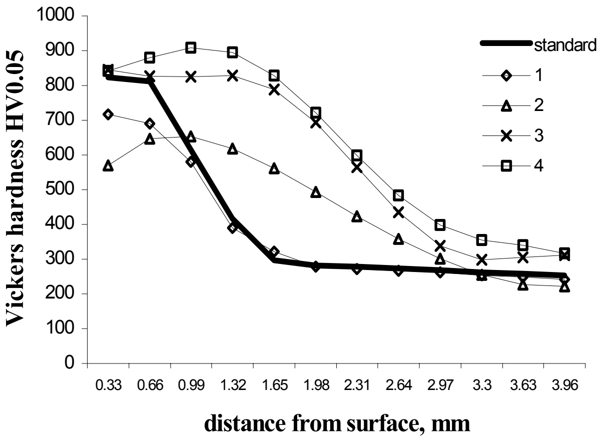

Fig. 7. Depth profiles of hardness for carbon steel 40X

The transient responses obtained by pulse eddy-currents technique are given in Fig. 8.

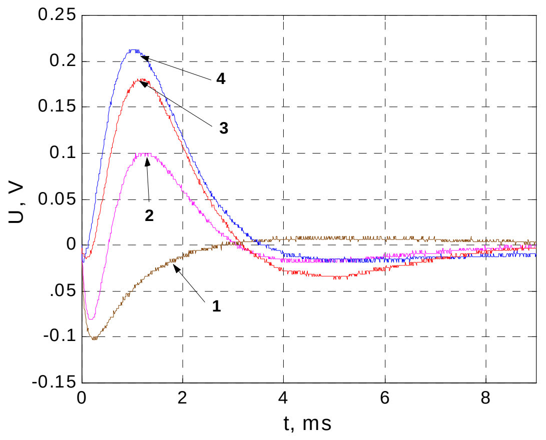

Fig. 8. Differential transient responces (in comparison with a standart sample (Fig.7.)).

Comparing the obtained dependences (Fig.7) and transient responses (Fig.8), it is possible to draw a conclusion that on the basis of converter transient responses one can compare between each other hardness of separate samples in different materials layers.

Attempting to obtain exhaustive information about the hardness distribution on the surface layer, it is necessary to relate the transient responses of standard samples with their hardness diagrams. For this purpose, there should be used neural networks. By training the network with known hardness samples, it becomes possible to determine also the hardness distribution of the controlled sample in a subsurface layer. An example of such a determination is shown in Fig.9.

Having carried out the measurements and comparison of responses, there was determined that the neural network identifies the training samples without error, but coming across the "unknown" samples, hardness of deeper layers it determines erroneously.

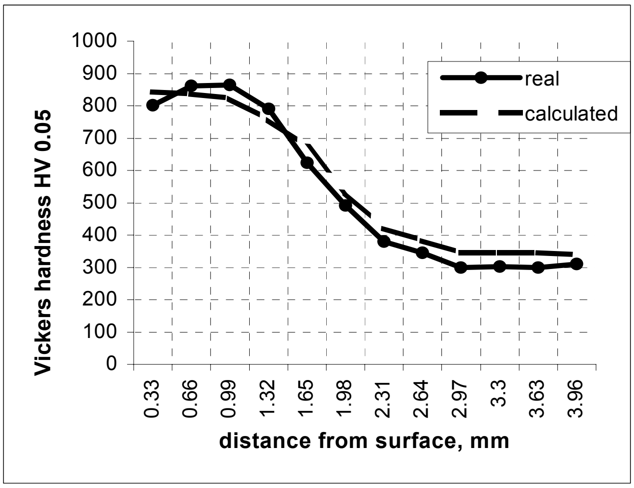

Fig. 9. Hardness diagrams: (–•–) real and (----) calculated by neural network

This occurs due to several causes: 1) measurements with Vickers methods are local and the results may very much differ an average hardness value, while eddy-currents technique measures hardness of the sample on certain surface area restricted by the measurement coil; 2) too small number of the samples designed for network training.

Others applications of eddy current testing

The pulse eddy current technique, mentioned above, can also be used to detect internal structure changes of steel after hardening and quenching it. Tested samples – 95X18 steel 6×8×100 mm of size steel sticks are heat treated and quenched in different temperatures and time (Table 1). In case of that, the internal structure is different. The tree point-bending test of v-notched specimen is often used in cleavage fracture research. To investigate correct damage micromechanism one should first have knowledge of the stress and strain distribution in the specimen. In this paper evaluation is made of stress intensification curves obtained from eddy-current method experiments of bending test.

TABLE 1. Heat treatment conditions

Sample No.	Treatment temperature T_{gr}°C	Quenching temperature T_{atl}°C	Quenching time t, h	Hardness HRC
1	1000	407	1	55
2	1100	407	1	57
3	1050	500	1	52
4	1100	520	1	53
5	1050	520	4	46
6	1100	520	4	45

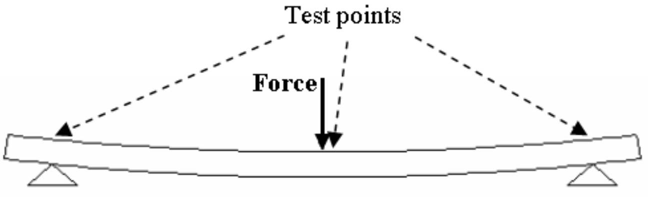

Fig. 10. Test points for structural investigation

Fig. 11 shows differences between transient responses, which are estimated in various places (in the middle and at the endings) of samples. It is also seen that transient response of samples changes depending on treatment conditions.

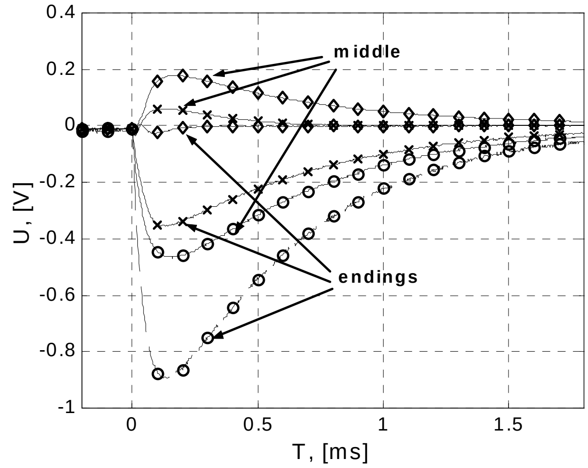

Fig. 11. Differential transient responses: (-o-) sample No.2; (-x-) sample No. 4; (-◇-) sample No. 6. (Table 1)

5. CONCLUSIONS

The results of series of Vickers hardness measurements in a range of heat-treated steels have been presented. They were analysed using a recently developed eddy-current method. Excellent fits were obtained provided that sufficient data was available in the critical range of indentation depth, from 0.5 to 1.0 mm.

The obtained results show that the proposed technique is perspective when one must evaluate promptly the properties of steel tempered layer.

Attempting to obtain exhaustive information about the hardness distribution on the surface layer, it is necessary to relate the transient responses of standard samples with their hardness diagrams. For this purpose, there should be used neural networks.

Further experimental and modelling work in this area will be aimed at obtaining the estimates for such properties of steel tempered layers as yield strength based on the proposed technique.

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Authors: V. Augutis**,** Prof. Dr. Habil. Kaunas University of technology, Faculty of Telecommunications and Electronics, Department of Electronics and Measurements Systems, Studentu st. 50-445, LT-3000, Kaunas, Lithuania; R. Ramanauskas, Master of electronic engineering. Kaunas University of technology, Faculty of Telecommunications and Electronics, Department of Electronics and Measurements Systems, Studentu st. 50-445, LT-3000, Kaunas, Lithuania, phone: +37068430750, E-mail: ramurama@one.lt; V. Vasauskas, Ass. Professor. Kaunas University of Technology, Department of Mechanics, Mateikos 1-4, LT-3028, Kaunas, Lithuania, phone: +37037410707, E-mail: vcapas@ktu.lt