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Electromagnetic-acoustic method of ultrasonic pulse excitation and reception in metal products

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The problem of the main factors influence on the electro-magnetic energy to ultrasound conversion in test-ing of electrically conductive or ferromagnetic materials is considered. The necessity to provide the polarizing magnetic field induction maximum value and the maximum current in the electromagnetic-acoustic transducer high-frequency coil is shown. A converter for co-radiation and reception of pulses of ultrasonic vibrations has been developed and tested, providing useful information signal amplitude of up to 50 dB.

Keywords: magnetic field; electromagnetic field; electrically conductive material; ferromagnetic material; ultrasonic oscillations; electromagnetic-acoustic transducer.

Розглянуто питання про вплив основних факторів на перетворення електромагнітної енергії в ульт-развукову при діагностиці електропровідних або феромагнітних матеріалів. Показано, що необхідно забезпечувати максимальне значення індукції поляризуючого магнітного поля і максимального струму в високочастотній котушці електромагнітної-акустичного перетворювача. Розроблено та випробувано перетворювач для спільного випромінювання і прийому імпульсів ультразвукових коливань, який забезпечує амплітуду корисного інформаційного сигналу до 50 dB.

Ключові слова: магнітне поле; електромагнітне поле; електропровідний матеріал; феромагнітний матеріал; ультразвукові коливання; електромагнітно-акустичний перетворювач.

Вопрос о влиянии основных факторов на преобразование электромагнитной энергии в ультразву-ковую при диагностике электропроводных или ферромагнитных материалов. Показано, что необходимо обеспечивать максимальное значение индукции поляризующего магнитного поля и максимального тока в высокочастотной катушке электромагнитно-акустического преобразователя. Разработан и испытан преобразователь для совместного излучения и приема импульсов ультразвуковых колебаний, который обеспечивает амплитуду полезного информационного сигнала до 50 dB.

Ключевые слова: магнитное поле; электромагнитное поле; электропроводный материал; ферро-магнитный материал; ультразвуковые колебания; электромагнитно-акустический преобразователь.

Introduction

One of the promising directions of ap-plication in measurements, non-destructive quality testing and diagnostics of electrically conductive and ferromagnetic materials and products is the method of ultrasonic pulses excitation and reception using magnetic and high-frequency electromagnetic fields [1].

It is traditionally considered for elec-tromagnetic-acoustic method (EMA) to have low sensitivity [2]. At the same time it's safe to assume the modern possibilities of polar-izing magnetic field and high-frequency electromagnetic field forming to allow reali-zation of EMA advantages [3] in compari-son to traditional approaches, like, for ex-ample, using piezoelectric transducers [1-2].

Main part

Let us consider the mechanisms of elec-tromagnetic energy into high-frequency ul-trasonic and ultra-sonic into electrical trans-formation in the surface layers of electro-conductive, electro-conductive and ferro-magnetic or ferromagnetic materials.

Ultrasonic pulse excitation. Place the high-frequency current $I_1 = I_0 e^{j\omega t}$ conductor 3 above a flat surface of the sample 1 on a small height *h*, as suggested by fig. 1.

High-frequency current I_1 generates magnetic field strength $|H|$. Due to $|H|$ activity the sample's surface skin-layer receives the I_2 eddy current of the same frequency ω, $j = \sqrt{-1}$. Next affect the skin-layer current I_2 with polarizing

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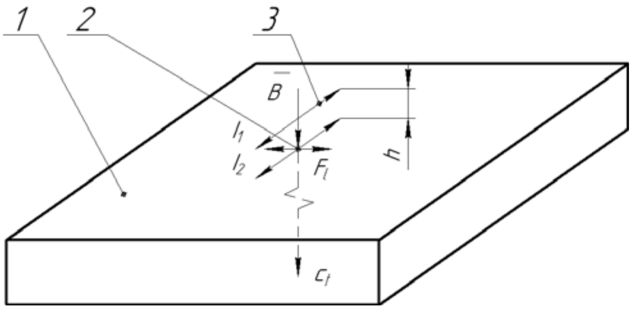


Fig.1. For the explanation of ultrasonic wave excita-tion via affecting the conductive ferromagnetic ma-terial with magnetic and high-frequency electromag-netic fields.

magnetic field of $\overline{B} = \overline{x}_0 B_x + \overline{y}_0 B_y$ induction. In case the sample is electrically conductive the organized electron flow of I_2 current will be affected by variable Lorentz force F_l. As a result, the sample skin-layer will receive tangential voltage variables 2 [2]. In other words, the electrodynamic mechanism is in action:

$$T_{xy} = I_2 B_x e^{-jk_t x}, \tag{1}$$

where k is the wave number for ultra-sonic fluctuations.

Accordingly the normal mechanical stress will be as follows:

$$T_{xx} = I_f B_y e^{-jk_t x} \tag{2}$$

С учетом объемного распространение вихревых токов электродинамические напряжения, создаваемые силами Лоренца F_l, можно записать

$$T_{xx}^E = HB_x \frac{1}{1 - j\beta_t^2} e^{-jk_t x} \tag{3}$$

where β is the generalized parameter equal to the relation of wave numbers for ultrasonic and electromagnetic waves $\beta_t^2 = \varpi / \left(c_t^2 \mu_0 \mu \sigma\right)$;

H is the alternating magnetic field strength;

μ_0 is the magnetic constant $4\pi \cdot 10^{-7}$ H/m;

μ is the relative permeability;

c_t is the velocity of propagation of high-frequency elastic shear perturbation in the sample material;

ω is the actual frequency of high-frequency elastic oscillations, coinciding with the frequency of high-frequency cur-rent in the induction coil of the EMA trans-ducer;

σ – specific electrical conductivity of the sample material.

As a result of the variable voltages ac-tion, ultrasonic volume waves C_t, which propagate deeper inside the sample are ex-cited. In this case, the transverse waves C_t arise only as a result of the electrodynamic effect. In the case of longitudinal waves C_l excitation the other electromagnetic field effects should be taken into account.

The second way of stress forming is based off the magnetic interaction between the conductor 3 and eddy current I_2 created by it within the sample.

$$T_{xx}^M = -HB_y \frac{\mu - 1}{\mu} e^{-jk_t x}. \tag{4}$$

Variable forces action direction is de-fined as follows. If the density of the magnetic field force lines increases (the field H coincides with the direction of B_y), the forces of conductors repulsion from the solid body act, and if the force lines density decreases, the conductors and the solid body are attracted. Movement direction T_{xx}^M will be opposite to T_{xx}^E.

The third mechanism of stress formation is due to the effect of magnetostriction

$$T_{xx}^C = \alpha HB \frac{j\beta_l^2}{1 - j\beta_l^2}, \tag{5}$$

where $\beta_l^2 = \varpi / \left(c_l^2 \mu_0 \mu \sigma\right)$;

$\alpha = \mu$-1 is applicable for paramagnetics;

$\alpha = a/H_0$ is applicable for non-paramagnetics;

a is the magnetostriction constant;

If $\beta_l^2 << 1$, which is generally true form metals

$$T_{xx} = -j\alpha\beta_l HB_y e^{-jkx}. \tag{6}$$

In summary for (3), (4) и (6) (act of all three mechanisms) we get the expression for stresses appearing within the ferromagnets

$$\left|T_{xx}\right| = \left|T_{xx}^E + T_{xx}^M + T_{xx}^C\right| = HB_y \left|1 - \frac{\mu - 1}{\mu} - j\alpha\beta_l^2\right|. \tag{7}$$

If an electric coil is placed between the pole of the polarizing magnetic field source and the sample surface, where there is only one normal or tangential induction compo-nent, then high-frequency longitudinal or transverse waves can be excited separately. For example, under the poles of the magnet, the normal field component ($B = B_x$) pre-dominates, therefore a coil located directly below the pole will excite transverse waves. Between the poles of the horseshoe magnet the field is directed along the surface ($B = B_y$), so the coil above this section will excite longitudinal waves.

Analysis of the expression (7) and literature sources [1-2, 4] shows that mechanical variable stresses value and, consequently, the excited ultrasonic oscillations displacements amplitude is mainly dependent on the induction value of polarizing magnetic field and magnitude of current in the inductor. When diagnosing ferromagnetic materials, it is very difficult to formulate the value of magnetic field induction in the excitation zone of high-frequency mechanical oscillations of more than 1 Tl, especially in case of portable EMA converters (EMAT). The impulse current in the EMAT inductance coil can theoretically be increased without spe-cial restrictions up to tens of kA. Therefore, it is necessary to create an optimal converter design that will allow exciting the necessary type of ultrasonic oscillations, with the max-imum induction of the polarizing magnetic field and the maximum current in the EMAT coil.

EMAT ultrasonic oscillations reception. The system for reception is presented on fig. 2.

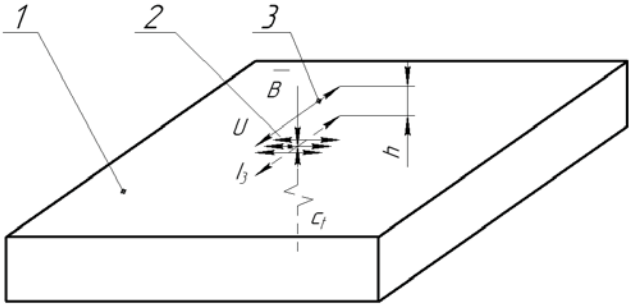


Fig.2. To an explanation of the EMA method-based ultrasonic oscillations reception from electrically conductive sample mechanism.

Let us place a conductor above the sample flat surface 1 at a small distance *h*. Suppose a linearly polarized high-frequency ultrasonic wave C_t is falling from the volume of the metal 1 to its surface under the conductor 3 so that the oscillations of the two metal particles occur perpendicular to the conductor 3 projection on the sample surface. Let us apply a polarizing magnetic field with induction *B* to the area. Displacements of the metal surface layer in magnetic field will lead to appearance of EMF, and, consequently, to appearance of a high-frequency eddy current I_3, which forms a high-frequency electromagnetic field above the surface of the sample. In conductor 3, EMF *U* is induced, the frequency of which will be the same as the frequency of ultrasonic oscillations in the sample. The magnitude of the EMF *U* induced will be proportional to the ultrasonic vibrations displacements 2 magnitude, which allows to gather information about the properties of material researched.

Thus, it follows from the foregoing that it is possible to use a single EMAT to perform both excitation and reception of ultra-sonic oscillations.

With EMAT combined implementation, the coefficient η of electromagnetic into ultrasonic and back energy convertion with-in the radiation / reception cycle can be writ-ten as follows

$$\eta = k_1 I B^2 \cdot \exp(-\alpha h) \qquad (8)$$

where k_1 is the coefficient taking into ac-count the magnetic field source shape;
I is the current in the high-frequency coil of the converter when excited;
B is the induction of a polarizing magnetic field;
h is the gap between high-frequency converter coil and sample surface;
α is the coefficient taking into account the transducer high-frequency coil.

A schematic representation of a com-bined EMAT for the diagnosis of metal products is shown in Fig. 3.

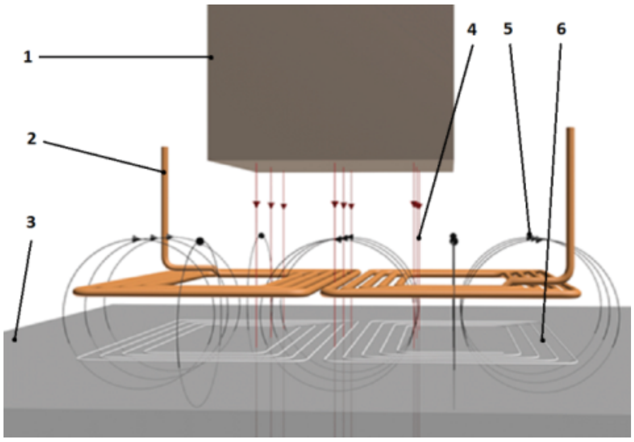
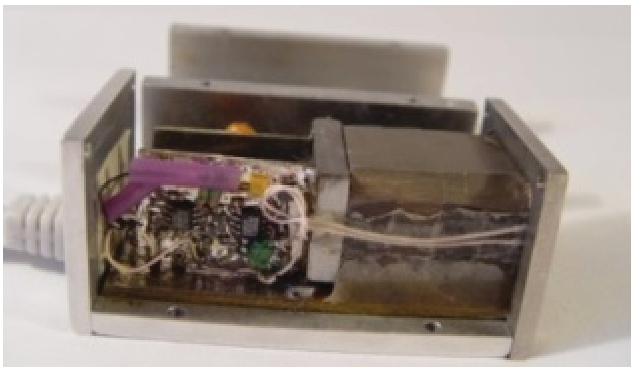


Fig.3. Schematic design of the EMAT, allowing to excite and receive pulses of volumetric shear ultra-sonic vibrations in an electrically conductive ferro-magnetic product.

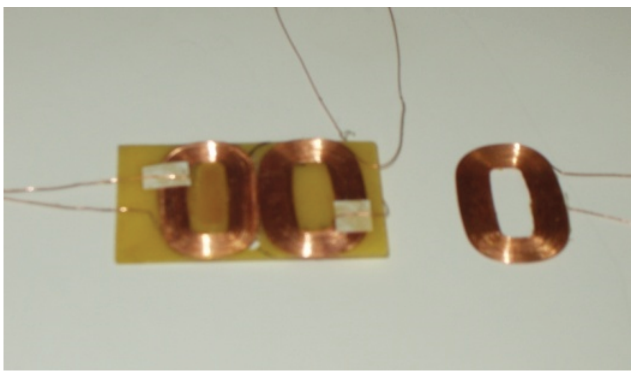
For combined EMAT: 1 - source of a constant magnetic field based on, for example, NeFeB ceramics; 2 - flat high-frequency inductivity coil, for example, from a 0.2 mm conductor containing 5 ... 30 turns; 3 - sample; 4 - lines of polarizing magnetic field induction; 5 - lines of high-frequency electromagnetic field intensity; 6 - eddy current in the sample skin layer.

The EMAT high-frequency coil working part is its middle, in the zone of which a polarizing magnetic field is formed.

Figure 4 shows a combined EMAT model, which is designed to excite and receive shear ultrasonic vibrations normally to the sample surface.



a



b

Fig.4. The combined EMAT model (a) and its induction coil (b)

Figure 5 shows the time development of a pulse taken from the steel 45 sample 45 mm thick. In the high-frequency EMAT coil, a 120 A peak amplitude current with a dura-tion of 6 2.5 MHz frequency periods was excited by a special generator [5]. The polar-izing magnetic field induction in the gap between the converter and the sample was of 0.8 Tl.

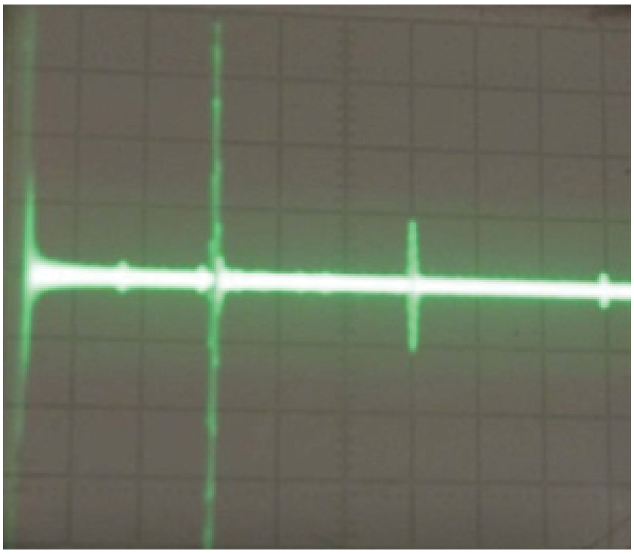


Fig.5. Time sweep with the received signal, obtained using EMAT presented on Fig.3 (vertically - 10 mV / div, horizontally 10 μs)

Studies of various materials have shown that the ultrasonic pulse amplitude ratio forf the received from sample to the noise ampli-tude in frequency range 1 ... 5 MHz, for aluminum alloys or ferromagnetic steels, can reach 40..50 dB.

Conclusions

1. The influence of factors determining the efficiency of electromagnetic into ultra-sonic energy conversion and vice versa is estimated. It is shown that the main contribu-tion is made by the converter high-frequency coil current and the polarizing magnetic field induction magnitude.

2. A variant of a combined direct elec-tromagnetic-acoustic transducer allowing information signal obtaining with an ampli-tude of up to 40 ... 50 dB in relation to noise, which is sufficient for diagnostics of ferro-magnetic materials and aluminum alloys is developed.

References

1. И.Н. Ермолов, Ю.В. Ланге. Неразру-шающий контроль: Справочник: В 7 т. Под общ. ред. В.В. Клюева. Т.3: Ультра-звуковой контроль, Машиностроение, М. (2008), 864 с.
2. И. Н. Ермолов. Теория и практика уль-тразвукового контроля. Машиностое-ние, М. (1981), 240 с.
3. К.В. Судакова, И.Л. Казюкевич. О по-вышении эффективности контроля каче-ства металлургической продукции. В: В мире неразрушающего контроля. № 3 (2004), с. 8-10.
4. Г.М. Сучков. Современные возможно-сти ЭМА дефектоскопии. В: Дефектос-копия. № 12 (2005), с. 24-39.
5. G.M. Suchkov, O.N. Petrishchev, I.V. Cherednichenko, V.V. Fedorov, A.V. Desyatnichenko, S.V. Khashchina, M.S. Maslova. A Generator of Probing Puls-es for EMA Flaw Detectors. In: Russian Journal of Nondestructive Testing, Vol.48, No.9 (2012), p. 537–540.