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INCREASING THE EFFICIENCY OF THE SURFACE-MOUNTED ULTRASONIC ELECTROMAGNETIC-ACOUSTIC TRANSDUCER ON ACCOUNT OF THE MAGNETIC FIELD SOURCE

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Model studies were carried out using the COMSOL Multiphysics package, aimed at ensuring the forming of a permanent magnet magnetic field at a considerable distance to a ferromagnetic product from its pole, which is necessary to create efficient portable ultrasonic electromagnetic-acoustic transducers of thickness gauges and testing and diagnostic devices. It is theoretically shown and experimentally confirmed that for portable measuring ultrasonic devices it is expedient to set the height of the permanent magnet at about 60 mm and the cross section of the magnet pole 50x50 mm^2. At the same time, with a gap between the magnet pole and the product of about 30 mm, the value of the normal component of the magnetic field induction near the surface of the object is about 0.3...0.4 T, which is sufficient for thickness gauging or diagnostics of ferromagnetic products using the ultrasonic pitch-and-catch method. References 19, figures 8.

Key words: measurements, testing, diagnostics, electromagnetic-acoustic transducer, gap, magnetic field, permanent magnet, magnetic field induction, ultrasonic pulses, ferromagnetic product.

Introduction

Electromagnetic-acoustic (EMA) transducers are increasingly used for ultrasonic testing and diagnostics of products made of ferromagnetic material with dielectric coatings or deposits on the surface [1-13]. The thickness of coatings can reach 2-5 mm, and deposits up to 20 mm or more, especially on the inner surfaces of pipelines for various purposes. Cleaning such deposits before control requires significant financial and material costs [14-15].

There is an opinion among non-destructive testing specialists that electromagnetic-acoustic transducers (EMATs) have a low efficiency of converting electromagnetic energy into ultrasonic energy and vice versa (double EMA conversion) [2, 7]. A contradiction arises. On the one hand, it is necessary to diagnose products with coatings and deposits of significant thickness without expensive cleaning [7, 14-15], and on the other hand, in this case, low efficiency of EMA conversion is declared.

According to known works [2-3, 5, 7, 16], the efficiency of EMAT is estimated by the coefficient η of the double EMA conversion, which can be represented as:

$$\eta = k \cdot I \cdot B^2 \cdot \exp(-h/R),$$

where k is a coefficient that depends on the electrical, magnetic and elastic characteristics of the material tested; I is the strength of the high-frequency current in the EMAT inductance coil, *A*; B is the value of the normal induction component of a permanent polarizing magnetic field in the surface layer of the object of control (OC), *T*; h is the distance from EMAT to surface of OC, mm; R is the average size of the high-frequency inductor of the transducer, mm.

Direct combined overhead EMATs are most often used for portable devices that allow exciting and receiving shear ultrasonic pulses, which are characterized by increased sensitivity when detecting defects [7, 16]. For these devices, it is necessary to ensure the maximum possible induction of the magnetic field at a considerable distance (5 - 60 mm) from the surface of the ferromagnetic OC to the source of the magnetic field.

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To increase the EMAT efficiency, research and development is being carried out aimed at increasing the current *I* in the high-frequency coil [17], and at increasing the value of the normal component of the induction of the magnetic field in the surface layer of the OC [2, 7, 10, 18]. It should be considered that when using combined EMATs, the efficiency depends to a greater extent on the magnitude of the induction *B* of the magnetic field than on the high-frequency current *I* [2, 7]. This makes it necessary to increase the induction of a permanent magnetic field in the surface layer of the OC, which is especially relevant at significant distances *h* from its source, made on the basis of a highly coercive permanent magnet.

The aim of the work is to increase the effectiveness of the overhead ultrasonic EMAT by increasing the ratio of the amplitude of the first reflected ultrasonic pulse to the noise amplitude by selecting the geometric parameters of the magnetic field source located at significant distances from the surface of the ferromagnetic control object.

Consider EMAT for portable ultrasonic devices, which are used mainly for thickness measurement or diagnostics of products with equidistant surfaces: sheet, tube, shell, etc.

Basic provisions for modeling:

– consider the ferromagnetic material half-plane product as the OC.

– use a *NeFeB* ceramics-based permanent magnet in the form of vertically arranged sections, each of which has a rectangular shape in the vertical section, and a square shape in the horizontal section as a source of the magnetic field

– use a magnetic wire located above the sections of the permanent magnet to increase the induction of the magnetic field in the near-surface layer of the OC.

Also consider the magnetic field *B* in the plane (*z*0*x*) crossing the middle of a magnet with a square section of a pole with side *a*, Fig. 1, using the COMSOL Multiphysics application program package [19].

When conducting experimental research, the normal component of magnetic field *B* induction was measured by a Hall sensor in the active zone – under the pole of the magnetic system at a height of 0.5 mm above the surface of the OC. This is necessary for verification of simulation results and experimental measurements.

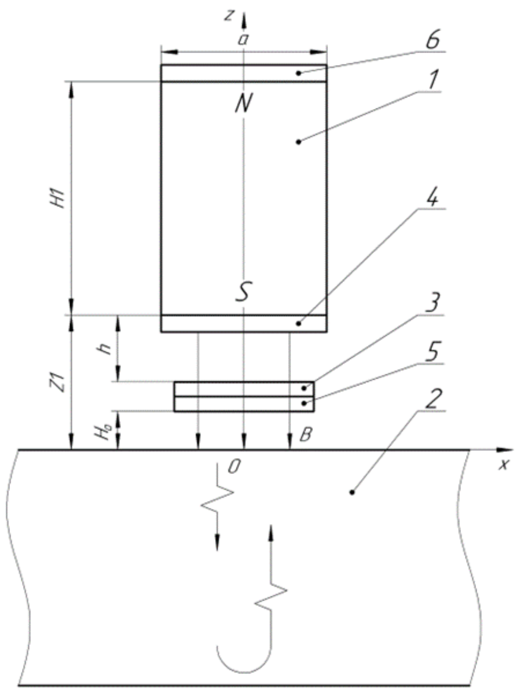


Fig. 1

A simplified physical model of a combined EMAT located above the surface of a ferromagnetic OC with plane-parallel planes (a variant of thickness measurement) is shown in Fig. 1, which shows: *1* is the permanent magnet; *2* is the OC; *3* is the high-frequency inductor; *4* is an electromagnetic screen designed to protect against excitation of coherent pulsed ultrasonic interference in the magnet; *5* is a protector designed to protect the transducer from mechanical damage; *6* is the magnetic screen; *Z*1 is the distance between the magnet pole and the product (hereinafter the gap); H_0 is the thickness of the dielectric coating (deposit) on the OC surface; *H*1 the height of the permanent magnet; *a* is the side of the square pole of the permanent magnet; *B* is the normal component of induction of the permanent magnetic field. Arrows in the OC volume show the directions of ultrasonic pulse propagation.

The following provisions are considered during modeling. The thicknesses of the electromagnetic shield, the high-frequency inductor and the protector are included at a distance of *Z*1 from the magnet pole to the OC surface. A certain (technological) distance *h* is required between the high-frequency inductor and the end of the permanent magnet. This is due to the fact that in a permanent magnet, even in the presence of an electromagnetic shield, coherent ultrasonic pulse interference can be excited. Thus, for example, with the thickness H_0 of the dielectric gap between EMAT and OC up to 20 mm, the thickness of the protector 1 mm, the thickness of the high-frequency inductor up to 1.5 mm, the thickness of the electromagnetic screen up to 0.6 mm and the distance between the high-frequency inductor and the end of the magnet up to 8 mm, the total distance *Z*1 between the lower end of the permanent magnet and the surface of the product being measured can be 30 mm or more.

Considering the influence of the height $H1$ of the permanent magnet on the value of the induction normal component of the magnetic field in the active zone of the OC, a permanent magnet with a pole cross section of 50x50 mm as the maximum size was chosen, which is determined based on the ability of the operator of the portable device to physically scan the ferromagnetic metal product being diagnosed. One example of modeling for a magnet height of 60 mm and changes in the distance from the pole of the magnetic field source to the OC in the range of 5...60 mm is shown in Fig. 2. These are the results of comparative experimental studies, for an air gap of 5.5 mm, position 1 (19.5 mm total gap from the magnet pole to the OC) and 15.5 mm, position *2* (29.5 mm total gap from the magnet pole to the OC). The distance from the magnet pole center is calculated along the surface of the OC.

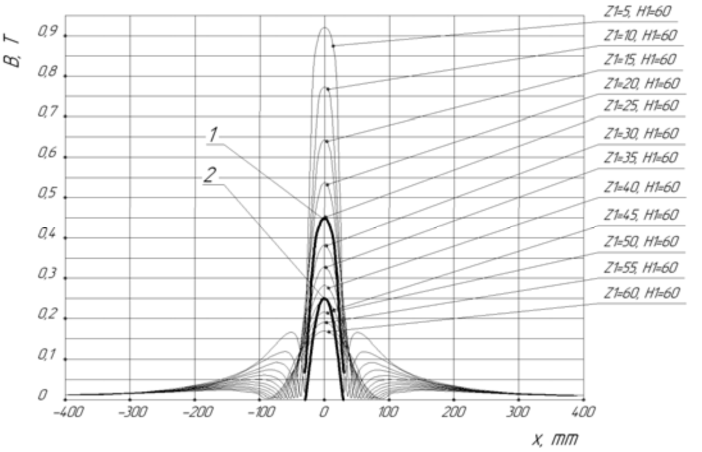


Fig. 2

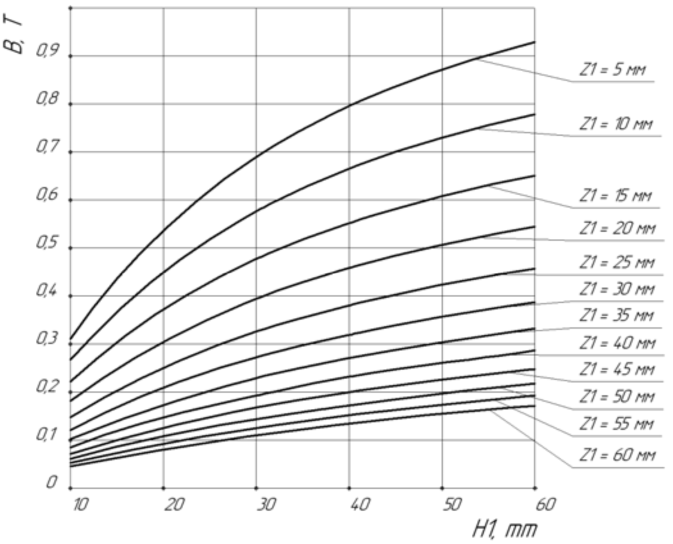


Fig. 3

Fig. 3 shows the generalized simulation results for the normal component of magnetic field induction for magnets of different heights $H1$ at different values of the distance $Z1$ from the pole of the magnetic field source to the surface of the OC. Analysis of the data shown in Fig. 2 and Fig. 3 allows us to draw the following conclusions:

– to obtain a value of the normal component of magnetic field induction sufficient for EMAT operation (at least 0.35 T) [19] at a distance between the permanent magnet pole and OC $Z1$ = 30 mm, the height of the magnet should be selected $H1$ = 50 mm.

– with an increase in the height of the $H1$ magnet, the normal component of the magnetic field induction in the active zone near the surface of the ferromagnetic OC increases nonlinearly with a slowdown in its growth rate;

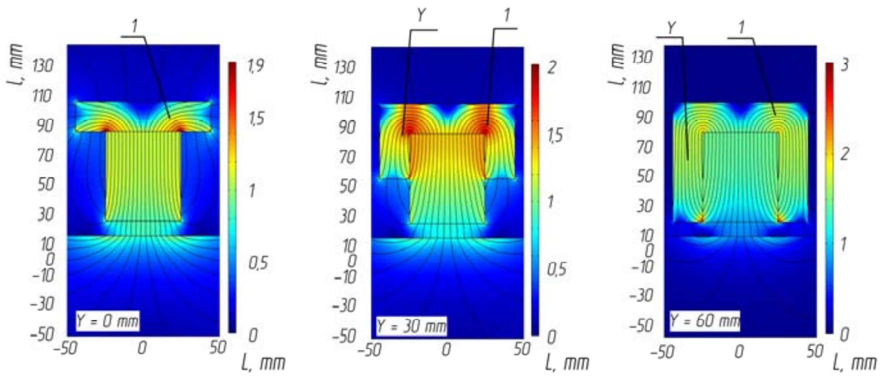
– the value of the normal component of the magnetic field B induction within ± 10 mm from the center of the magnet pole (the EMAT active zone) does not change by more than 10%, which is sufficient [10-11] for the formation of the directional diagram of the ultrasonic field during reception and emission in the OC pulses of ultrasonic vibrations;

– when the gap increases, the width of the dependence of the normal component of the magnetic field induction on the border of its maximum value also increases, which makes it possible to form a sharper directional diagram of the ultrasonic field, other things being equal;

– for the conditions established during modeling, the value of the normal component of the magnetic field induction at a gap of about 30 mm, determined earlier, reaches 0.3...0.4 T, which is sufficient [4-5] to ensure the performance of the EMAT.

An increase in the normal component of magnetic field induction is also possible due to the use of a magnetic (ferromagnetic) screen [7, 16]. Consider the EMAT magnetic system wi*th a magnetic shield* (position *1* in Fig. 4), which covers the permanent magnet from above (Fig. 4, *a*), partially (Fig. 4, *b*) and completely (Fig. 4, *c*) from its sides. During modeling, the height Y of the side sections of the magnetic screen varied in the range of 0...65 mm. In the given example, the gap $Z1$ = 10 mm.

The influence of the height Y of the side sections of the magnetic screen on the value of the normal component V of the magnetic field induction in the center of the magnet pole is shown in Fig. 5. The analysis of the data shown in Fig. 4 and Fig. 5 shows that the greatest increase in the normal component of the induction of the magnetic field is provided by the location of the magnetic screen on the upper part of the pole of the permanent magnet. Comparing the generalized simulation data shown in Fig. 3 and Fig. 5, it



a *b* *c*

Fig. 4

should be noted that with a significant gap between the permanent magnet and the OC due to the ferromagnetic screen on the upper part of the magnet pole, the addition of magnetic field induction is about 0.1 T, which with a significant gap can be significant (25...30%). In addition, the magnetic shield can be the basis for fastening a permanent magnet in the EMAT case. This allows you to suspend the magnetic system in the EMAT housing and protect it from destruction in the event of a collision with a ferromagnetic OC.

Let us consider the influence of the size of the magnet end (parameter *a*, Fig. 1) on the value of the normal component of the magnetic field *B* induction. Based on the practical experience of operating the EMAT [5], the minimum size of the permanent magnet end is chosen as *a*x*a* = 30x30 mm. This ensures the formation of an acceptable magnitude of the of the magnetic field *B* induction at relatively small distances to the OC. The maximum acceptable pole size is defined as 50x50 mm, based on the operator's physical ability to scan the diagnosed metal product. The maximum size of the magnet pole is set at 100x100 mm, as acceptable for use in mechanized or automatic systems of ultrasonic measurement, control and diagnostics.

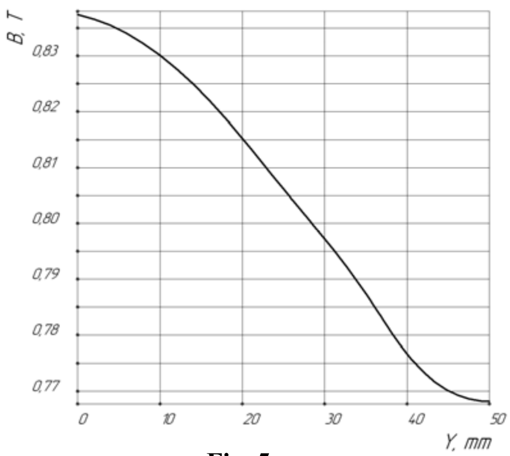


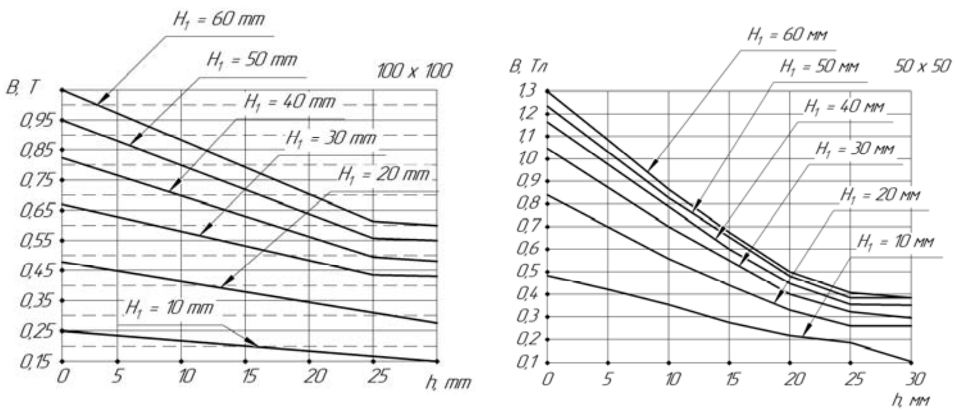
Fig. 5

The influence of the end size of the pole permanent magnet on the value of the normal component of the of the magnetic field *B* induction at different values of the height of the magnet and different sizes of the gaps between the magnet and the OC are shown in Fig. 6.

The analysis of the results regarding modeling of the influence of the pole ends sizes in the range of 30x30...100x100 mm^2 allows us to draw the following conclusions:

– with all considered sizes of pole ends and gaps greater than 20 mm, the increase in the value of the normal component *B* of the magnetic field induction does not exceed 0.1 T, which is not significant.

– with smaller pole end sizes and a magnet height of about 60 mm, it is possible to obtain larger values of the normal component of the magnetic field induction with gaps between the magnet and the OC up to 5 mm.



a *b*

Fig. 6

Based on the obtained theoretical results and experimental studies, an EMAT model with a permanent magnet based on NeFeB ceramics with a height of *H*1=60 mm and a pole end size of 50x50 mm was made. A magnetic shield 6 (Fig. 1) made of grade 3 steel with a thickness of 10 mm is attached to the

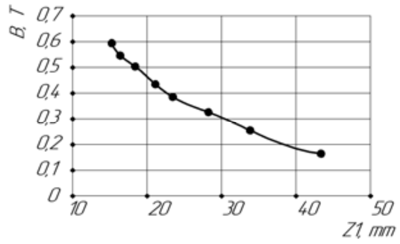


Fig. 7

upper pole of the magnet. Experimental verification of the normal component of induction of a constant magnetic field showed compliance with the results of model studies, Fig. 7. Its value reaches 0.25...0.3 T, which, according to [4–5], is sufficient to obtain the necessary amplitude of ultrasonic pulses during double EMA transformation. This assumption was tested on a special stand for OC – a sheet sample made of 09G2S steel 40 mm thick. Time sweep of the sequence of ultrasonic pulses reflected in the volume of the OC on the screen of a digital oscilloscope, obtained using the developed EMAT on the sample with a gap between the transducer protector and the metal surface of 20.1 mm (the distance from the pole end of the magnet to the metal surface is 33.6 mm) shown in Fig. 8.

From the data shown in Fig. 8, it can be concluded that the ratio of the amplitude of the first reflected ultrasonic pulse and the noise amplitude is approximately 5/1, while according to [7] this ratio should be approximately 3/1. Therefore, the developed transducer with a modernized magnetic system has a higher efficiency compared to known ones. Thus, the obtained experimental results show the increased efficiency of the developed EMAT, which uses an improved magnetic field source.

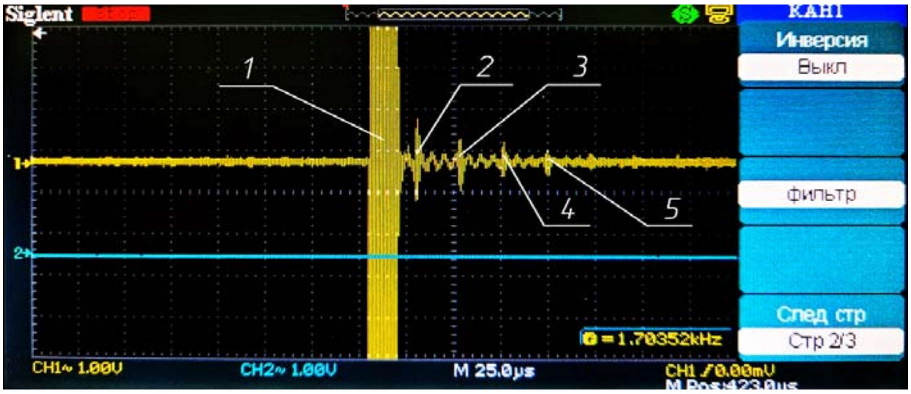


Fig. 8

Conclusions.

1. As a result of calculation and experimental studies, it was established that in order to ensure a sufficient value for the measurement of the normal component of the magnetic field induction, at significant distances from the EMAT permanent magnet to the ferromagnetic OC, it is necessary to increase the height of the indicated magnet and the width of its poles.

2. For portable measuring ultrasonic devices, it is advisable to set the height of the magnet to about 60 mm and the cross-section of the magnet pole to 50x50 mm^2. Thus, with a gap of about 30 mm, the value of the normal component of magnetic field induction is about 0.3...0.4 T, which is sufficient for thickness measurement or diagnostics by the ultrasonic mirror-shadow method.

3. With large gaps, an increase of approximately 0.1 T in the normal component of the magnetic field induction is proposed to use a magnetic screen with a thickness of about 10 mm, located on the upper pole of the magnet.

1. Suchkov G.M., Migushchenko R.P., Kropachek O.Iu. Portable surface-mounted direct combined electromagnetic-acoustic transducer for ultrasonic testing through dielectric layers of up to 20 mm thickness in ferromagnetic products. *Defektoskopiia*. 2022. No 5. Pp. 13-23. (Rus)

2. Petrov K.V., Muraveva O.V., Myshkin Y.V., Basharova A.F. Modeling Magnetic, Electric, and Acoustic Fields of a Pass-Through Transducer When Testing Cylindrical Objects. *Russ J Nondestruct Test*. 2019. No 55. Pp. 102-110. DOI: https://doi.org/10.1134/S1061830919020062. (Rus)

3. Migushchenko R.P., Suchkov G.M., Petrishchev O.N. Information-measurement electromechanical transducers for quality assessment of ferromagnetic product surface via ultrasonic Rayleigh waves. *Tekhnichna elektrodynamika.* 2017. No 2. Pp. 70-76. DOI: https://doi.org/10.15407/techned2017.02.070.

4. Migushchenko R.P., Suchkov G.M., Radev Kh.K., Petrishchev O.N., Desiatnichenko A.V. Electromagnetic-acoustic transducer for ultrasonic thickness-gauging of ferromagnetic products without removal of dielectric coating. *Tekhnichna elektrodynamika*. 2016. No 2. Pp. 78-82. DOI: https://doi.org/10.15407/techned2016.02.078. (Rus)

5. Migushchenko R.P., Suchkov G.M., Petrishchev O.N., Desiatnichenko A.V. Theory and practice of electromagnetic-acoustic testing. Part 5. Peculiarities of design and practical application of EMA ultrasonic testing devices of metal products: monograph. Kharkiv: TOV Planeta-print, 2016. 230 p. (Rus)

6. Pliesnetsov S.Yu. Development of methods and tools of electromagnetic-acoustic testing of rod-shape, pipe-

shaped and sheet metal products. ScD diss. autoref. Kharkiv, National Technical University Kharkiv Polytechnic Institute. 2021. 40 p. (Ukr)

7. Non-destructive testing. Vol. 3: Ultrasonic testing. Moskva: Mashinostroenie, 2008. 864 p. (Rus)

8. Willems H., Jaskolla B., Sickinger T., Barbian A.A., Nies F. Advanced possibilities for corrosion inspection of gas pipelines using EMAT technology. X European Conference on *Non-Destructive Testing* (*ECNDT-2010*). Moscow, Russia, June 7-11, 2010. URL: http://www.ndt.net/article/ecndt2010/reports/1_11_16.pdf (accessed at 25.09.2022).

9. Tolipov K.B. Possibilities for Increasing the Efficiency of Contactless Emitters of Acoustic Waves. *Russ J Nondestruct Test*. 2017. No 53. Pp. 304–307. DOI: https://doi.org/10.1134/S106183091704009X.

10. Desyatnichenko A.V. Electromagnetic-acoustic thickness gauge for dielectric-coated metal product thickness gauging. PhD diss.: 05.11.13. National Technical University Kharkiv Polytechnic Institute. Kharkiv. 2015. 172 p. (Rus)

11. Myshkin A.V. Influence of constructive parameters of multi-element phased transducers on formation of acoustic fields. PhD diss. Federal State Budgetary Educational Institution of Higher Professional Education "Izhevsk State Technical University named after M.T. Kalashnikov. Izhevsk. 2015.175 p. (Rus)

12. Jianpeng He, Steve Dixon, Samuel Hill, Ke Xu. A New Electromagnetic Acoustic Transducer Design for Generating and Receiving S0 Lamb Waves in Ferromagnetic Steel Plate. *Sensors*. 2017. Vol. 17(5). Pp. 10-23. DOI: https://doi.org/10.3390/s17051023.

13. Mikhailov A.V. Highly effective scanning systems for electromagnetic-acoustic flaw detection in elongated ferromagnetic objects with thick walls. PhD diss. Federal State Budgetary Institution of Science Institute of Physics of Metals named after M.N. Mikheev. Ural Branch of the Russian Academy. Sankt-Peterburg. 2019. 141 p. (Rus)

14. Sudakova K.V., Kazyukevich I.L. On increasing of metallurgic product quality testing efficacy. *V mire nerazrushayushchego kontrolya*. 2004. No 3. Pp. 8-10. (Rus)

15. Semerenko A.V. Using EMAT for testing of corrosion and erosion in steam heaters of boiler systems. *Territoriya NDT*. 2014. No 1. Pp. 42-43. (Rus)

16. Suchkov G.M., Plesnetsov S.Yu., Meshcheryakov S.Yu., Yudanova N.N. New developments of electromagnetic-acoustic transducers (overview). *Tekhnicheskaya diagnostika i nerazrushayushchii kontrol*. 2018. No 3. Pp. 27-34. (Rus). DOI: https://doi.org/10.15407/tdnk2018.03.03.

17. Suchkov G.M., Mygushchenko R.P., Plesnetsov S.Yu. Powerful Sources for High Frequency Electromagnetic Transducers for Measurement, Monitoring and Diagnostics. *Russian Journal of Nondestructive Testing.* 2017. Vol. 53. No 12. Pp. 850-855. DOI: https://doi.org/10.1134/S1061830917120063.

18. Bussi Salam. Electromagnetic-acoustic transducers for ultrasonic testing of metal products: author's abstract of PhD diss.: 05.11.13. National Technical University Kharkiv Polytechnic Institute. Kharkiv. 2020. 22 p. (Ukr)

19. Simulate real-world designs, devices, and processes with multiphysics software from COMSOL. URL: http://www.comsol.com (accessed at 15.10.2022).

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ НАКЛАДНОГО УЛЬТРАЗВУКОВОГО ЕЛЕКТРОМАГНІТНО-АКУСТИЧНОГО ПЕРЕТВОРЮВАЧА ЗА РАХУНОК ДЖЕРЕЛА МАГНІТНОГО ПОЛЯ

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За допомогою пакету COMSOL Multiphysics виконано модельні дослідження спрямовані на забезпечення формування магнітного поля постійного магніту на значній відстані від його полюса до феромагнітного виробу, що необхідно задля створення ефективних портативних ультразвукових електромагнітно-акустичних перетворювачів товщиномірів і приладів контролю та діагностики. Теоретично показано та експериментально підтверджено, що для портативних вимірювальних ультразвукових приладів висоту постійного магніту доцільно встановлювати близько 60 мм та переріз полюса магніту – 50х50 мм^2*. При цьому у разі зазору між полюсом магніту і виробом близько 30 мм величина нормальної компоненти індукції магнітного поля біля поверхні об'єкта становить близько 0,3...0,4 Тл, що є достатнім для проведення товщинометрії чи діагностики феромагнітних виробів ультразвуковим дзеркально-тіньовим методом.* Бібл. 19, рис. 8.

Ключові слова: вимірювання, контроль, діагностика, електромагнітно-акустичний перетворювач, зазор, магнітне поле, постійний магніт, індукція магнітного поля, ультразвукові імпульси, феромагнітний виріб.

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