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INVESTIGATION OF THE POSSIBILITY OF USING A DEFLECTING SYSTEM FOR MAGNETIC FIELDS IMPACT COMPENSATION DURING ELECTRON-BEAM WELDING

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The impact of magnetic fields caused by thermoelectric currents and residual magnetization of the welded parts on the accuracy of an electron beam positioning along the welded joints is a complicated scientific and technical problem to achieve high quality of welds in the aerospace industry, shipbuilding and power engineering. Presented in the article mathematical models of distribution of magnetic fields of interference in the space between the electron beam gun and the surface of a welding workpiece and also inside a workpiece allow to culculate the quantitative characteristics of the electron beam deflection from welded joints. The authors propose to use a deflection system for compensation of magnetic interference impact. The deflection system must be set to a certain height above the workpiece to be welded. The authors obtained a mathematical model of the magnetic field induction of the deflecting system distribution along its axis which coincides with the optical axis of the electron beam gun. The coordinates of installation of the deflection system concerning the surface of the parts to be welded are determined using the presented mathematical models. Calculations showed that the height of installation of deflection system depends on the thickness of the welded components. Using the deflection system installed at a certain height above the workpiece to be welded allows to eliminate the impact of magnetic fields caused by thermoelectric currents and residual magnetization of the welded parts on the quality of welded joints.

Keywords: electron-beam welding, magnetic field, deflection system, electron beam, compensating system.

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ИССЛЕДОВАНИЕ ВОЗМОЖНОСТИ ИСПОЛЬЗОВАНИЯ ОТКЛОНЯЮЩЕЙ СИСТЕМЫ ДЛЯ КОМПЕНСАЦИИ ВЛИЯНИЯ МАГНИТНЫХ ПОЛЕЙ ПРИ ЭЛЕКТРОННО-ЛУЧЕВОЙ СВАРКЕ

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Влияние магнитных полей, вызванных термоэлектрическими токами и остаточной намагниченностью свариваемых деталей, на точность позиционирования электронного пучка по стыку соединения является сложной научно-технической проблемой по достижению высокого качества сварных соединений в аэрокосмической отрасли, судостроении и энергетике. Представлены математические модели распределения магнитных полей помех в пространстве между электронно-лучевой пушкой и поверхностью свариваемого изделия, а также внутри изделия, которые позволяют рассчитать количественные характеристики отклонений пучка электронов от стыка соединения. Для компенсации влияния магнитных помех предлагается использовать отклоняющую систему, установленную на определенную высоту над свариваемым изделием. Авторами получена математическая модель распределения магнитной индукции поля отклоняющей системы вдоль ее оси, совпадающей с оптической осью электронно-лучевой пушки. С помощью представленных математических моделей определены координаты установки отклоняющей системы относительно поверхности свариваемых деталей. Расчеты показали, что высота установки отклоняющей системы зависит от толщины свариваемых деталей. Использование отклоняющей системы, установленной на определенной высоте над свариваемым изделием, позволяет устранить влияние на качество сварных соединений магнитных полей, вызванных термоэлектрическими токами и остаточной намагниченностью.

Ключевые слова: электронно-лучевая сварка, магнитное поле, отклоняющая система, электронный пучок, компенсирующая система.

Introduction. High demands on quality of welded joints in aerospace branch, shipbuilding, automotive industry, nuclear power engineering assume precise alignment of an electron beam with an interfacing surface at the electron beam welding (EBW). The magnetic fields occuring during dissimilar materials welding and products with a residual magnetization cause a deflection of an electron beam from an optical axis of the electron beam gun in an interval from the gun to the welded product and on the depth of weld penetration channel as well. If these deflections exceed 0.3 mm, then they lead to incomplete root penetration, especially at welding of thicker parts [1–7].

A more perspective way of electron beam protection against magnetic fields interference is their compensation in a welding zone. For this purpose a longitudinal in relation to a welded joint component of a magnetic field is measured in area the electron beam gun – the welded product, and carry out its compensations [8; 9].

The compensation of a longitudinal component of a magnetic field impact on an electron beam when welding dissimilar materials can be carried out by applying the welded parts of the local compensating magnetic field, parallel to the interfacing surface which is generated by electromagnetic coils [10], or introduction of compensating currents to the welded product which are counter-directed to thermoEMF currents [11; 12]. When welding products from ferromagnetic materials compensation of a longitudinal component of a residual magnetization magnetic field can be carried out by means of the electromagnet creating a compensating magnetic field in the welded product, counter an interference field [12; 13].

These methods of magnetic fields compensation assume a possibility of a contact supply of the compensating field in the welded product that in some cases complicates their technical realization. Therefore consideration of a possibility of an interference magnetic field compensation by means of the deflection system located in an interval between the electron beam gun and the welded product is relevant.

Magnetic field of interference. It is known that welding of products from dissimilar materials is followed by the magnetic fields caused by action of thermoelectric currents.

In the absence of external magnetic fields distribution of an induction of a longitudinal component of the field in the channel of weld penetration has almost linear character [14; 15]. The size of an induction of a magnetic field has the maximal values B_0 on a product surface, decreases to the center of the channel of weld penetration and is defined from the ratio:

$$B_n(z) = B_0\left(1 - \frac{2z}{\delta} + \frac{2l}{\delta}\right), \tag{1}$$

where B_0 – the size of a magnetic induction on a surface of the welded product near a joint; δ – thickness of the welded product; l – distance from the electron beam gun to a surface of the welded product.

Over the surface of welded parts in the space between a product and an electron beam gun a magnetic induction of a longitudinal component of the interference field decreases on dependence which is defined by expression [13]:

$$B_n(z) = B_0\frac{\delta/2}{\delta/2 + (l - z)}. \tag{2}$$

Thus, distribution of a longitudinal component magnetic induction of the interference field on the way of an electron beam will be as follows

$$B_n(z) = \begin{cases} B_0\dfrac{\delta/2}{\delta/2 + (l-z)}, & 0 \le z \le l; \\ B_0\left(1 - \dfrac{2z}{\delta} + \dfrac{2l}{\delta}\right), & l < z \le l + \delta. \end{cases} \tag{3}$$

The slope angle of an electron beam trajectory and amount of deflection of the beam from an axis of the electron beam gun can be estimated according to approximate formulas [8]:

$$\psi = \frac{e}{mV}\int_0^z B(z)dz; \tag{4}$$

$$x = \frac{e}{mV}\int_0^z\int_0^z B(z)dz, \tag{5}$$

where $e = 1{,}602\cdot10^{-19}$ – electron charge, Kl; V (m/s) – electron speed which can be calculated on the known accelerating voltage, U (B) [16]:

$$V = \frac{5{,}93\cdot10^5\sqrt{U\left(1 + 0{,}983\cdot10^{-6}U\right)}}{1 + 1{,}967\cdot10^{-6}U},$$

m – electron mass determined by a formula

$$m = \frac{m_0}{\sqrt{1 - \dfrac{V^2}{c^2}}},$$

where $m_0 = 9{,}109\cdot10^{-31}$ – rest mass of electron, kg; $c = 2{,}977\cdot10^8$ – light velocity, m/s; $B(z)$ – the distribution law of a longitudinal component of a magnetic field induction in the space between a gun and a welded product.

Substituting (3) in formulas (4) and (5) and integrating ranging from 0 to (l + δ/2), we will get

$$\psi_n = \frac{e}{mV}\int_0^z B_n(z)dz = \frac{e}{mV}B_0\frac{\delta}{2}\ln\frac{\delta + 2l}{\delta} + \frac{e}{mV}B_0\frac{\delta}{4}; \tag{6}$$

$$x_n = \frac{e}{mV}\int_0^z\int_0^z B_n(z)dz =$$

$$= \frac{e}{mV}B_0\frac{\delta}{2}\left(l + \frac{\delta^2}{2}\ln\frac{\delta}{\delta + 2l}\right) + \frac{e}{mV}B_0\frac{\delta^2}{12}. \tag{7}$$

Formulas (6) and (7) allow to define the slope angle and amount of deflection of an electron beam from an optical axis of the gun caused by action of magnetic interferences in the center of the channel of weld penetration.

The size of the circulating thermoelectric currents can reach 100 A [17] and the deflection of an electron beam caused by these currents from an optical axis of the gun on a surface of a product can make 1 mm and more. Substituting expression (2) in formula (5), integrating in the range from 0 to l, it is possible to receive a formula for the definition of an induction of a magnetic field on the surface of the welded product near a joint on the known deflection of an electron beam from an optical axis of the gun

$$B_0 = \frac{2xmV}{e \cdot \delta \left(l + \frac{\delta^2}{2} \ln \frac{\delta}{\delta + 2l} \right)}. \tag{8}$$

The values of magnetic induction calculated by formula (8) at various deflections of x beam from an optical axis of the gun for products of various thickness δ are presented in tab. 1.

Thus, distribution of a longitudinal component magnetic induction of a residual magnetization field on the way of an electron beam will appear as:

$$B_n(z) = \begin{cases} B_0 \dfrac{\delta/2}{\delta/2 + (l - z)}, & 0 \le z \le l; \\ B_0, \quad l < z \le l + \delta. \end{cases} \tag{9}$$

The compensating system. Compensation of the magnetic field rejecting an electron beam can be carried out in an interval between an electron beam gun and a welded product by means of compensating system representing electromagnetic coils placed in the metal cylinder made of a permalloy. The axis of the cylinder coincides with an optical axis of the electron beam gun (fig. 1).

In the vicinity of the compensating system center there is a zone of the homogeneous magnetic field. The size of an induction of a compensating system magnetic field in the arbitrary point with z coordinate on an axis of system can be described by the equation

$$B_c(z) = \frac{B_{\max} L^3}{2 \cdot 0.715} \times \left[\left(L^2 + \left(\frac{L}{2} + z \right)^2 \right)^{-\frac{3}{2}} + \left(L^2 + \left(\frac{L}{2} - z \right)^2 \right)^{-\frac{3}{2}} \right], \tag{10}$$

where $B_{\max}$ – the size of a magnetic induction in the center of the compensating system; L – the height of the compensating system (diameter of electromagnetic coils).

The normalized distribution of an induction of a magnetic field ($B_c(z)/B_{\max}$) of the compensating system on axis Z at $L = 25$ mm is presented in fig. 2.

Substituting (10) in formulas (4) and (5), considering that an origin of coordinates is ЭЛП (Electron Beam Gun), integrating ranging from 0 to z, we will get

$$\psi_c = \frac{e}{mV} \cdot \frac{B_{\max} \cdot L}{2 \cdot 0.715} \times \left[\frac{z - a + \frac{L}{2}}{\sqrt{L^2 + \left(\frac{L}{2} + z - a \right)^2}} - \frac{\frac{L}{2} - a}{\sqrt{L^2 + \left(\frac{L}{2} - a \right)^2}} \right] + \frac{e}{mV} \cdot \frac{B_{\max} \cdot L}{2 \cdot 0.715} \times \left[\frac{z - a - \frac{L}{2}}{\sqrt{L^2 + \left(\frac{L}{2} - z + a \right)^2}} + \frac{\frac{L}{2} + a}{\sqrt{L^2 + \left(\frac{L}{2} + a \right)^2}} \right], \tag{11}$$

$$x_c = \frac{e}{mV} \cdot \frac{B_{\max} \cdot L}{2 \cdot 0.715} \times \left[\sqrt{L^2 + \left(\frac{L}{2} + z - a \right)^2} - \sqrt{L^2 + \left(\frac{L}{2} - a \right)^2} \right] + \frac{e}{mV} \cdot \frac{B_{\max} \cdot L}{2 \cdot 0.715} \times \left[\sqrt{L^2 + \left(\frac{L}{2} - z + a \right)^2} - \sqrt{L^2 + \left(\frac{L}{2} + a \right)^2} \right] + \frac{e}{mV} \cdot \frac{B_{\max} \cdot L}{2 \cdot 0.715} \times \left[\frac{\left(\frac{L}{2} + a \right) z}{\sqrt{L^2 + \left(\frac{L}{2} + a \right)^2}} - \frac{\left(\frac{L}{2} - a \right) z}{\sqrt{L^2 + \left(\frac{L}{2} - a \right)^2}} \right]. \tag{12}$$

Operation of the compensating system has to be directed to elimination of a deflection of an electron beam from an optical axis of the gun and decrease of a tangent slope angle to a beam trajectory.

The system of equations

$$\begin{cases} \psi_n - \psi_c = 0, \\ x_n - x_c = 0, \end{cases} \tag{13}$$

allows to determine the size of a magnetic induction $B_{\max}$ necessary for elimination of a deflection of an electron beam from a gun axis, and distance of a where the compensating system concerning the gun has to be installed so that the beam trajectory slope angle was equal to zero in the center of the channel of weld penetration.

In fig. 3–5 schedules of dependence $\psi(a) = \psi_n - \psi_c$ a tangent slope angle to an electron beam trajectory from height of installation of the compensating system for the welded parts of various thickness made of dissimilar materials are submitted.

At a product thickness δ = 25 mm the center of the compensating system has to be at the height of 43.05 mm from a product surface, at δ = 50 mm – at the height of 36.98 mm, at δ = 100 mm – at the height of 16.95 mm.

Table 1

Values of a magnetic induction of the field caused by a current of thermoEMF

δ, mm	25	50	100
x, mm	B_0, мТл		
1	0.321	0.179	0.106
2.5	0.802	0.447	0.265
5	1,6	0.894	0.53

The analysis of the presented dependences shows: the size of a magnetic induction field caused by action of thermoelectric currents does not exert an impact on height of installation of the compensating system; if the distance from the gun to the welded product remains constant, then with the increase in thickness of a product up to some critical value the coordinate of the application of the compensating magnetic field approaches a product surface.

In tab. 2 the values of deflections of an electron beam are given in a root of penetration at compensation of the magnetic fields caused by thermoEMF currents for details of various thickness.

In fig. 6 schedules of dependence $\psi(a) = \psi_n - \psi_c$ a tangent slope angle to an electron beam trajectory from height of installation of the compensating system for the welded parts with a residual magnetization of various thickness are given.

At a product thickness δ = 25 mm the center of the compensating system has to be at the height of 34.56 mm from a product surface, at δ = 50 mm – at the height of 26.16 mm, at δ = 75 mm – at the height of 15.2 mm; at a product thickness δ = 100 mm technical realization of system of compensation of the considered design is impossible. It is necessary to apply a design of the compensating system with the magnetic tips used for concentration of a magnetic field. To use the considered compensating system it is necessary to limit acceptable magnetic fields of interference.

Let the center of the compensating system be located at the height of 17.5 mm from a product surface the thickness of which is equal to 100 mm. The solution of a system of equations

$$\begin{cases} x_n - x_c = 0, \\ x_{rn} - x_{rc} = 0.0003, \end{cases} \tag{14}$$

where 0.0003 – the maximum permissible deflection in a root of penetration, m; x_{rn} – the deflection in a root of penetration caused by action of the field of a residual magnetization; x_{rc} – the deflect in a root of penetration caused by action of a magnetic field of the compensating system; allows to determine the most admissible size of an induction of a magnetic field of a hindrance B_0 = 0.1257 мТл that corresponds to a magnetic intensity of 100 A/m.

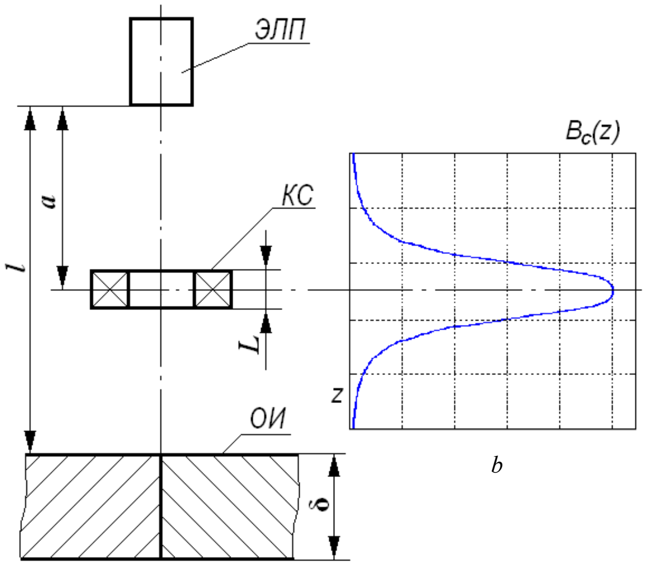
In tab. 3 values of deflections of an electron beam are given in a root of penetration at compensation of fields of a residual magnetization of parts of various thickness.

Thus, for most cases happening in practice it is possible to define the distance from a product surface to the center of the compensating system providing acceptable values of a beam deflection in the root of penetration. During thicker products welding when this distance is very small and does not allow to realize compensation of a residual magnetization fields technically, it is necessary to introduce restrictions on the size of a magnetic field of interference induction.

Conclusion:

1. With the use of the deflection system installed at a particular height over the welded product, it is possible to eliminate an impact on the quality of welded joints of magnetic fields caused by thermoelectric currents and a residual magnetization.

2. At electron beam welding of products of larger thickness with a residual magnetization it is necessary to limit acceptable magnetization for the purpose of exception of incomplete penetration.



b

a

Fig. 1. The scheme of ЭЛС (Electron Beam Welding) installation with the compensating system (*a*) and distribution of an induction of a magnetic field of the compensating system (*b*): ЭЛП – the electron beam gun; КС – the compensating system; ОИ – a workpiece

Рис. 1. Схема установки ЭЛС с компенсирующей системой (*а*) и распределение индукции магнитного поля компенсирующей системы (*б*): ЭЛП – электронно-лучевая пушка; КС – компенсирующая система; ОИ – обрабатываемое изделие

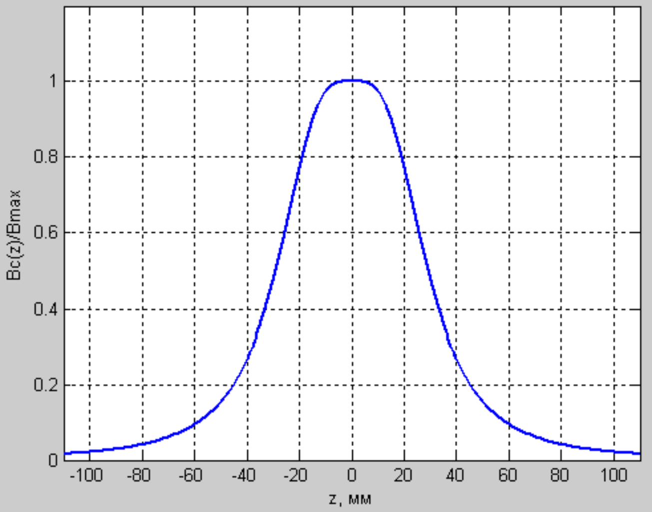


Fig. 2. Distribution of magnetic induction on axis *Z*

Рис. 2. Распределение магнитной индукции по оси *Z*

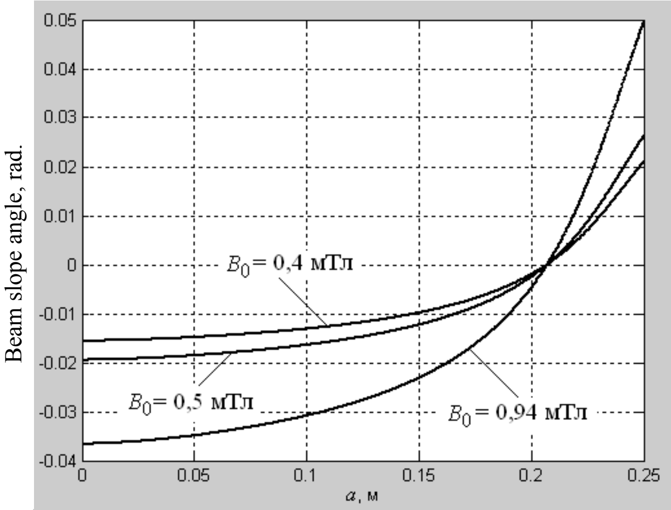


Fig. 3. Dependency $\psi(a)$ at $\delta = 25$ mm, $l = 250$ mm, $L = 25$ mm

Рис. 3. Зависимость $\psi(a)$ при $\delta = 25$ мм, $l = 250$ мм, $L = 25$ мм

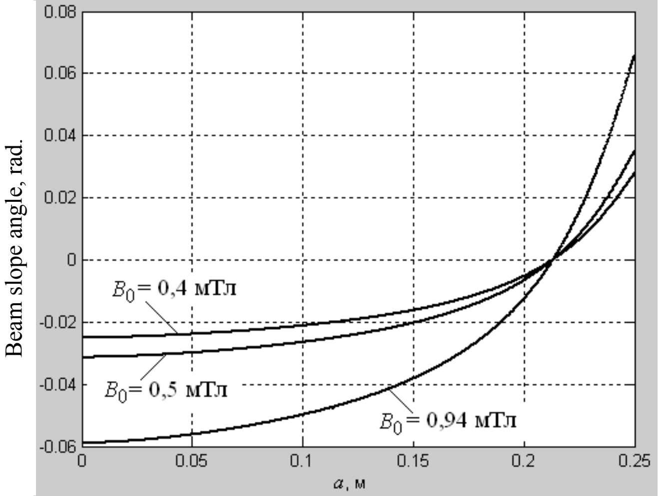


Fig. 4. Dependency $\psi(a)$ at $\delta = 50$ mm, $l = 250$ mm, $L = 25$ mm

Рис. 4. Зависимость $\psi(a)$ при $\delta = 50$ мм, $l = 250$ мм, $L = 25$ мм

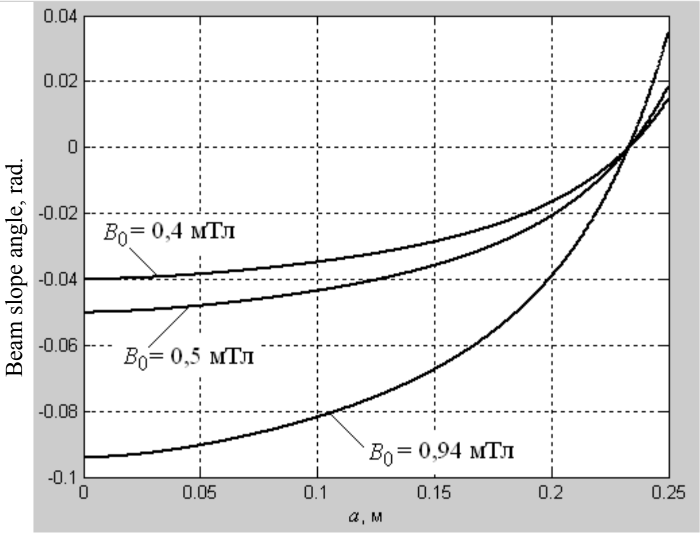


Fig. 5. Dependency $\psi(a)$ at δ = 100 mm, l = 250 mm, L = 25 mm

Рис. 5. Зависимость $\psi(a)$ при δ = 100 мм, l = 250 мм, L = 25 мм

Table 2

Deflections in a root of penetration at compensation of the magnetic fields caused by thermoelectric currents

δ, mm	25	50	100
B_0, мТл	Beam deflection in a root of penetration, mm		
0.94	0.0576	0.2306	0.9222
0.5	0.0307	0.1226	0.4905
0.4	0.0245	0.0981	0.3924
0.3	0.0184	0.0736	0.2943

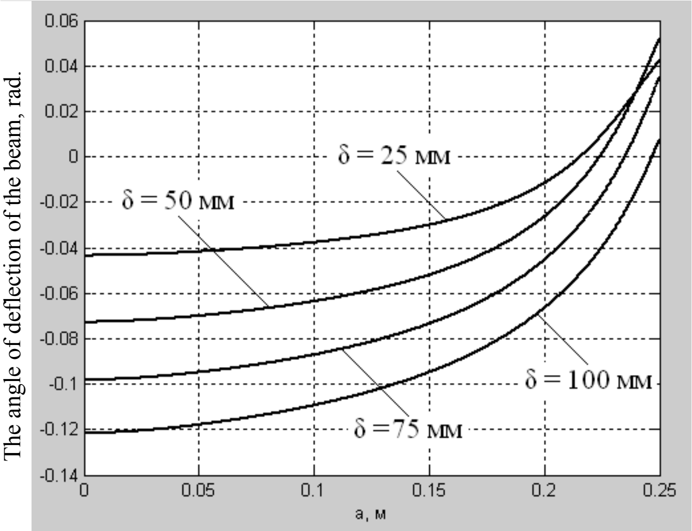


Fig. 6. Dependancy $\psi(a)$ at B_0 = 0,94 мТл, l = 250 mm, L = 25 mm

Рис. 6. Зависимость $\psi(a)$ при B_0 = 0,94 мТл, l = 250 мм, L = 25 мм

Table 3

Deflections in a root penetration at compensation of fields of a residual magnetization

δ, mm	25	50	75	100
B_0, мТл	Beam deflection in a root of penetration, mm			
0.94	0.0865	0.3458	0.7781	2.3
0.5	0.046	0.184	0.4139	1.2
0.4	0.0368	0.1472	0.3311	0.9593
0.2	0.0184	0.0736	0.1656	0.4797
0.125	0.0115	0.046	0.1035	0.2998

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