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ON THE ISSUE OF CALCULATING THE PARAMETERS OF THE EDGES DURING HIGH-FREQUENCY WELDING OF A PIPE BILLET FROM A FERROMAGNETIC MATERIAL

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Abstract: The article presents a method for calculating the parameters of weldable edges during high-frequency welding of pipe billets made from ferromagnetic material (low-carbon and low-alloy steels). It examines the features of current distribution under the influence of the skin effect, proximity effect, and magnetic circuits. An approach is proposed to account for the loss of magnetic properties in the heated zone, along with a correction coefficient for power and resistance of ferromagnetic edges compared to non-magnetic ones. Calculation dependencies and graphs are provided to optimize inductor parameters and welding regimes.

Key words: roll calibration, continuous pipe welding mills, high-frequency welding, pipe blank forming, single-radius calibration, double-radius calibration, oval calibration, edge pre-forming, corrugation, welded seam, electric-welded pipes.

Annotatsiya: Maqola ferromagnit materialdan (kam uglerodli va past qotishmali po‘latlardan) quvur tayyorlamasini yuqori chastotali payvandlashda payvandlanadigan chetlar parametrlarini hisoblash usulini taqdim etadi. Sirt effekti, yaqinlik effekti va magnit sxemalar ta’sirida tok taqsimlanishining xususiyatlari ko‘rib chiqiladi. Isitish zonasida materialning magnit xususiyatlarini yo‘qotishini hisobga olish usuli, shuningdek, nomagnit chetlar bilan solishtirganda ferromagnit chetlarning quvvati va qarshiligini tuzatish koeffitsiyenti taklif etiladi. Induktor parametrlari va payvandlash rejimlarini optimallashtirish uchun hisoblash bog‘lanishlari va grafiklari keltirilgan.

Kalit so‘zlar: valklarni kalibrlash, uzluksiz quvur payvandlash agregatlari, yuqori chastotali payvandlash, quvur tayyorlovini shakllantirish, bir radiusli kalibrlash, ikki radiusli kalibrlash, oval kalibrlash, chekka qismlarni shakllantirish, gofrirovka hosil bo‘lishi, payvand chok, elektropayvandlangan quvurlar.

Аннотация: Статья посвящена разработке метода расчёта параметров свариваемых кромок при высокочастотной сварке трубной заготовки из ферромагнитного материала (низкоуглеродистые и низколегированные стали). Рассматриваются особенности распределения тока под влиянием поверхностного эффекта, эффекта близости и магнитных контуров. Предложен подход к учёту потери магнитных свойств материала в зоне нагрева, а также коэффициент коррекции мощности и сопротивления для ферромагнитных кромок по сравнению с немагнитными. Приведены расчётные зависимости и графики, позволяющие оптимизировать параметры индуктора и режимы сварки.

Ключевые слова: калибровка валков, непрерывные трубосварочные агрегаты, высокочастотная сварка, формовка трубной заготовки, однорадиусная калибровка, двухрадиусная калибровка, овальная калибровка, проформовка кромок, гофрообразование, сварной шов, электросварные трубы.

INTRODUCTION

High-frequency welding is one of the most advanced and widely applied technologies in modern metalworking, particularly in the production of longitudinally welded steel pipes. This process is fundamentally based on the laws of electromagnetic induction and current flow, as well as a complex combination of physical phenomena, including the surface effect, proximity effect, ring and coil effects, and the influence of magnetic circuits and copper shields on current distribution. In addition, the welding process is significantly affected by temperature-dependent changes in the electrical and magnetic properties of metals, as well as by electromagnetic forces arising in high-frequency fields. The controlled interaction of these phenomena enables localized and efficient heating of the welded edges, ensuring high productivity, structural integrity of the joint, and stable geometric characteristics of the finished product.

Despite the extensive industrial application of high-frequency welding, the accurate analysis and optimization of electromagnetic and thermal processes in the welding zone remain a challenging scientific and engineering problem. The distribution of current density, the role of magnetic permeability variations, and the influence of auxiliary elements such as magnetic cores introduce significant complexity into both theoretical modeling and practical implementation. In particular, the behavior of ferromagnetic materials during heating, including the loss of magnetic properties near the welding temperature, necessitates refined analytical approaches and reliable calculation methods. Therefore, a detailed study of current distribution, power consumption, and heating efficiency in high-frequency welding is essential for improving process controllability, reducing energy losses, and enhancing the overall quality and reliability of welded pipe joints under modern industrial conditions.

REVIEW OF LITERATURE ON THE SUBJECT

The law of electromagnetic induction manifests itself in the fact that if the magnetic flux Φ passing through a surface bounded by a certain contour changes in time, an emf is induced (induced) in this contour, the instantaneous value of which e is determined by the formula:

$$e = \oint E_{ind} dl = -d\Phi / dt \quad (1)$$

where Eind is the vector of the electric field strength (induced); dl is a vector equal to the length of the contour section dl and directed tangentially to the contour in the direction of the bypass; dΦ - change in the magnetic flux through the surface bounded by the contour during the time dt [1].

Direction e. etc. with. is determined by the rule of the right-hand screw, while if the screw is tightened so that its tip moves in the direction of the magnetic forces with increasing flux, then the positive direction for the induced emf. coincides with the direction of rotation of the head of this screw. In fact, the induced emf at this moment has a negative direction, therefore, a minus sign is put in formula (1) [2].

The surface effect is manifested in the uneven distribution of alternating current over the cross section of the conductor. The highest current density is observed at the outer surface of the conductor. With increasing distance from the outer surface, the current density gradually decreases. The higher the frequency, the faster the current density decreases. At a very high frequency, the current flows only through the thin surface layer of the conductor. The surface effect significantly increases the resistance of the conductors, which greatly complicates the transmission of alternating current. However, the surface effect makes it possible to concentrate the release of energy in the surface layers of the heated product, which is important when carrying out the processes of hardening, high-frequency welding, etc. [3]

The proximity effect is manifested when an alternating current flows in the conductor system. Moreover, each of them is located not only in its own alternating magnetic field, but also in the field of other conductors. The effect of proximity is manifested the stronger, the smaller the distance between the conductors and the higher the frequency of the current. With induction heating, the currents in the inductor and the heated part are almost exactly in antiphase. Therefore, using the proximity effect, it is possible by selecting the appropriate shape of the inductor to concentrate the current on the parts of the product that need to be heated [4].

The effect of magnetic circuits on the current distribution in a conductor is that if a conductor through which a high-frequency current is passed is surrounded on three sides by a ferromagnetic material having a high electrical resistivity (ferrite or stratified iron), then the current distribution in the conductor will change dramatically ... It can be assumed with sufficient accuracy for practice that almost all the current will be pulled to the open edge [5].

RESEARCH METHODOLOGY

The research methodology of this study is based on analytical and computational approaches to investigate high-frequency welding processes of ferromagnetic and non-magnetic pipe billets. The initial data were obtained from established electromagnetic induction laws, theoretical models of surface and proximity effects, and experimentally measured material properties of steels used in pipe production. Model parameters, including current density distribution, magnetic permeability, and geometric characteristics of the welded edges, were determined using experimental measurements and reference data from prior studies. The analysis was carried out through mathematical modeling and the coupled contour method, allowing calculated values of current distribution, specific power, and welding power to be evaluated and compared under different welding conditions and configurations of magnetic circuits.

ANALYSIS AND RESULTS

When welding pipes, the material of the surfaces to be welded by the end of heating loses its magnetic properties to a depth of up to (2 ÷ 3) Δ in the middle of the edges and up to (3 ÷ 5) Δ at the corners. Approximately 80–85% of the length of the edges in the heating section have the surfaces to be welded, heated to the temperature of loss of magnetic properties to a depth equal to or greater than Δ. Therefore, the real edges can be reduced to the one shown in Fig. 1 system (Figure 1).

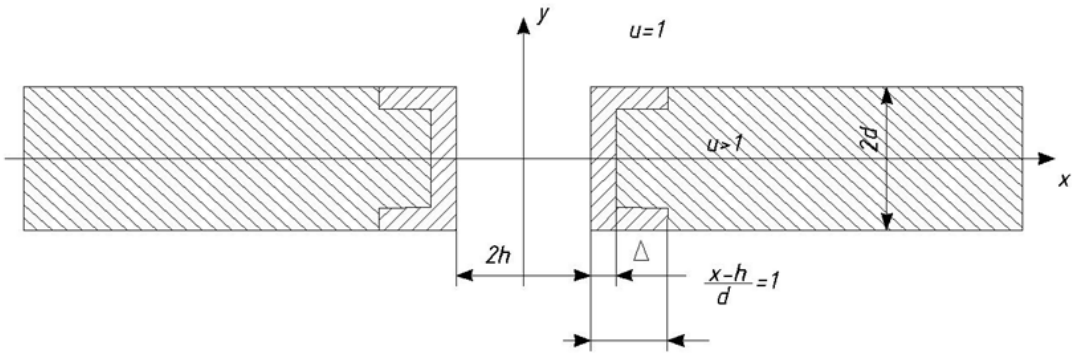

Figure 1. The flat system to which the weldable edges made of ferromagnetic material

Measurements have shown that the distribution of the surface current density on models made of ferromagnetic material, in which the surfaces to be welded to a depth of (1 ÷ 2) Δ are non-magnetic, the same as on models made of non-magnetic material (maximum discrepancy 12%).

Consequently, with the same distribution of the surface current density on the non-magnetic and ferromagnetic edges, the useful power is approximately the same. The total power on the ferromagnetic edges is somewhat higher, since on the lateral surfaces the magnetic permeability μ> 1 and the specific power is higher than at μ = 1.

The power required for welding and the resistance of ferromagnetic edges increase in comparison with the power and resistance of non-magnetic edges in proportion to the coefficient:

$$k_{\mu} = \frac{\int_{S_2} |\delta_S|^2 |dz| + 0,55 \int_{S_3} \sqrt{\mu_e} |\delta_S|^2 |dz|}{\int_{S} |\delta_S|^2 |dz|}, \quad (2)$$

where S2, and S3 are the contours of integration in the sections with μe = 1 and μe> 1 (μe is the relative magnetic permeability on the surface of the edges.

Using formula (2), the values of kμ for parallel edges were calculated, from which the average coefficients kμ cf for edges located at an angle were then obtained. The values of these coefficients for edges with different arrangement of magnetic circuits are shown in Fig. 2, from which it can be seen that kμ av depends on the welding current and the gaps between the edges, as well as the gaps between the magnetic cores and the edges (Figure 2).

1 – Iкр / 2d = 15·104 А/м; 2 – Iкр / 2d = 45·104 А/м; 3 – Iкр / 2d = 90·104 А/м

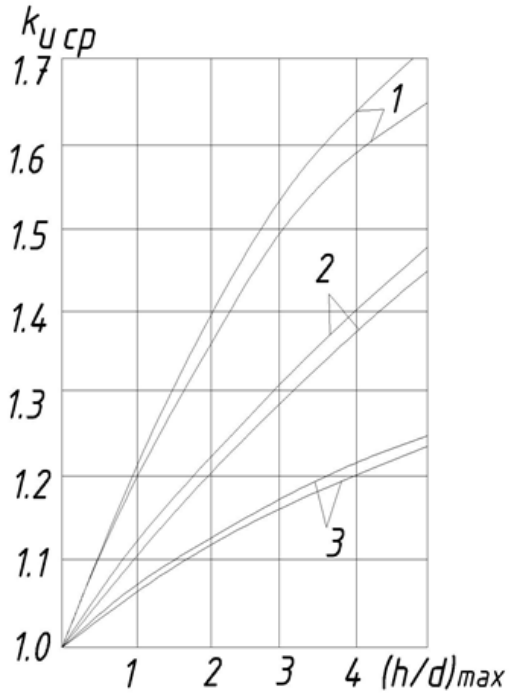

Figure 2. Values of the coefficients kμ cp for ferromagnetic edges located at an angle with and one magnetic core (b / d = 10 - solid lines, b / d = 6 - dashed lines)

The coupled contour method can be used to calculate the parameters of an inductor used to weld pipes made of ferromagnetic material without using magnetic cores. The system under study (inductor - pipe billet) is divided into elements isolated from one another. The cross-section of the conductors of each element is taken so small that the current density within the cross-section can be considered constant. Breaking the outer and inner surfaces of the pipe billet into elements, we obtain two circuits I and II (Fig. 3) with elementary currents: one is formed by currents flowing along the outer Inap and inner Iin surfaces of the pipe, and the second is formed by the current flowing along the inner surface of the pipe Iin, and the current passing along the welded edges Icr. In this case, the real spreading of the current over the surfaces of the pipe billet is replaced by the idealized one. The inductor also breaks down into elements (Figure 3).

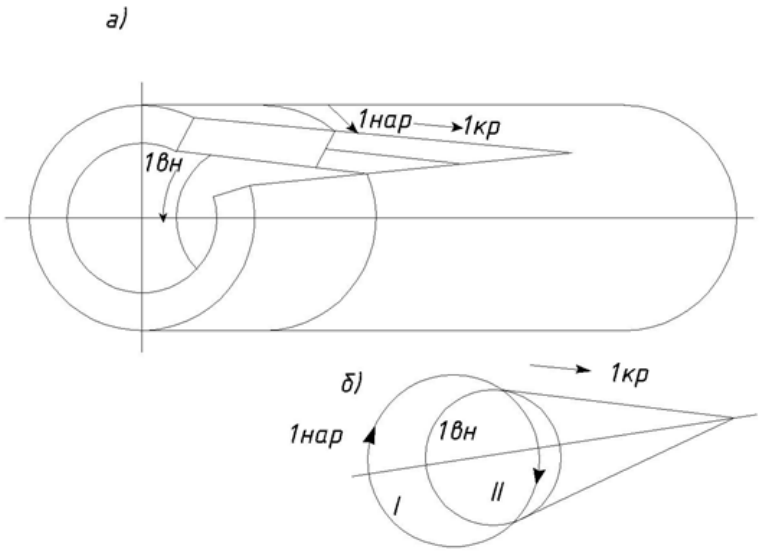

Figure 3. Idealized surface spreading pattern pipe billet and an element consisting of contours current with inductive current supply

The solution of the system of equations for the contours of the pipe billet and the inductor makes it possible to obtain the distribution of the current density and specific power on the surfaces of the pipe billet and the

inductor; equivalent active, inductive and impedance of the inductor and the welding power required to heat the edges to the welding temperature; choose the optimal dimensions of the inductor and its location.

CONCLUSIONS AND SUGGESTIONS

Research work on determining the influence of thermal deformation parameters during high-frequency welding on the quality of welded joints of longitudinal welded pipes of low-carbon and low alloy steels revealed that:

- with the same distribution of the surface current density on the non-magnetic and ferromagnetic edges, the useful power is approximately the same;

- the power required for welding and the active resistance of edges made of ferromagnetic material are increased compared to the power and active resistance of edges made of non-magnetic material.

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