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ON THE ISSUE OF STUDYING THE FORMATION OF A WELDED JOINT DURING HIGH-FREQUENCY WELDING

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Abstract: The article proposes a methodology for calculating the power required to heat the edges of a pipe billet to welding temperature during high-frequency welding of longitudinally welded pipes made from low-carbon and low-alloy steels. Both contact and induction methods of energy supply are considered, and the influence of the distance from the inductor (or contacts) to the edge convergence point, as well as the configuration of magnetic cores, on energy consumption and welding speed is analyzed.

The authors introduce power increase coefficients k_P1 (maximum) and k_P2 (minimum), which account for the uneven distribution of surface current density along the edges, including cases of sharp and rounded edges, and the presence of one or two magnetic cores. A formula is proposed for determining the average coefficient k_P as the half-sum of the extreme values, as well as for calculating the required power P_кр, taking into account the variation of specific power along the heating zone.

It has been established that the gap between the edges (and, accordingly, the angle of their convergence) significantly affects the consumed power. It is shown that placing internal and external magnetic cores allows reducing the power at minimal convergence angles of the edges; however, their effectiveness decreases in the zone of very small gaps.

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: Maqolada kam uglerodli va kam legirlangan po‘latlardan yasalgan to‘g‘ri chokli quvurlarni yuqori chastotali payvandlashda quvur tayyorlovchisining qirralarini payvandlash haroratigacha isitish uchun zarur bo‘lgan quvvatni hisoblash metodikasi taklif etilgan. Energiyani uzatishning kontakt va induksion usullari ko‘rib chiqilgan hamda induktor (yoki kontaktlar)dan qirralar yig‘ilish nuqtasigacha bo‘lgan masofa, shuningdek magnit o‘tkazgichlar konfiguratsiyasining energiya sarfi va payvandlash tezligiga ta’siri tahlil qilingan.

Mualliflar tomonidan qirralarda yuzaki tok zichligining notekis taqsimlanishini hisobga olgan holda quvvat oshish koeffitsiyentlari k_P1 (maksimal) va k_P2 (minimal) kiritilgan bo‘lib, bular o‘tkir va yumaloq qirralar, bitta yoki ikkita magnit o‘tkazgich mavjud bo‘lgan holatlarni qamrab oladi. O‘rtacha k_P koeffitsiyentini ikki chekka qiymat yig‘indisining yarmiga teng deb aniqlash formulasi, shuningdek isitish zonasi bo‘ylab o‘zgaruvchan maxsus quvvatni hisobga olgan holda zarur quvvat P_kr ni hisoblash taklif etilgan.

Qirralar orasidagi bo‘shliq (va shunga mos ravishda ularning yig‘ilish burchagi) sarflanadigan quvvatga sezilarli ta’sir ko‘rsatishi aniqlangan. Quvur tayyorlovchisi ichida va tashqarisida magnit o‘tkazgichlarni joylashtirish qirralar yig‘ilishining minimal burchaklarida quvvatni kamaytirish imkonini berishi ko‘rsatilgan, biroq ularning samaradorligi juda kichik bo‘shliqlar zonasida pasayadi.

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: В статье предложена методика расчёта мощности, необходимой для нагрева кромок трубной заготовки до температуры сварки при высокочастотной сварке труб с продольным швом из низкоуглеродистых и низколегированных сталей. Рассмотрены контактный и индукционный способы подвода энергии, проанализировано влияние расстояния от индуктора (или контактов) до точки схождения кромок, а также конфигурации магнитопроводов на энергозатраты и скорость сварки.

Авторами введены коэффициенты увеличения мощности k_P1 (максимальный) и k_P2 (минимальный), учитывающие неравномерность распределения плотности поверхностного тока по кромкам, включая случаи острых и скруглённых кромок, наличия одного или двух магнитопроводов. Предложена формула для определения среднего коэффициента k_P как полусуммы крайних значений, а также расчёт требуемой мощности P_кр с учётом изменения удельной мощности вдоль зоны нагрева.

Установлено значительное влияние зазора между кромками (и, соответственно, угла их схождения) на потребляемую мощность. Показано, что применение внутренних и внешних магнитопроводов позволяет снизить мощность при минимальных углах схождения кромок, однако их эффективность падает в зоне очень малых зазоров.

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

INTRODUCTION

High-frequency welding of metals is based on the use of the laws of electromagnetic induction and full current, as well as the following phenomena: surface effect, proximity effect, ring or coil effect, the influence of magnetic circuits and copper screens on the distribution of current in the conductor, changes in the properties of metals with changes in temperature and voltage ness of the magnetic field, the occurrence of electromagnetic forces

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 change in time, an emf is induced (induced) in this circuit, the instantaneous value of which e is determined by the formula

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

where E_{ind} is the electric field strength vector (induced); dl is a vector equal to the length of the contour section dl and directed tangentially to the contour towards the bypass; dΦ is the change in the magnetic flux through the surface bounded by the contour during the time dt [1]. Welding with high frequency currents (HF) up to 500 kHz is used for the production of pipes with a diameter of 6–529 mm with a wall thickness of 0.5–10 mm. The main advantages of this method are: the possibility of a significant increase in the welding speed of pipes (up to 120 m/min) from carbon and alloy steels, non-ferrous metals; obtaining pipes with a high-quality seam from hot-rolled non-etched tape, a significant reduction in electricity consumption per ton of finished pipes; implementation of welding of pipes from various metals on one welding equipment. [1-3]. This made it expedient to transfer a large number of existing electric pipe welding mills to welding with high frequency currents. Most of the newly commissioned pipe welding plants have high-frequency welding equipment. The use of a current with a frequency of 450–500 kHz for pipe welding is based on the fact that the current at this frequency follows the path of not the least ohmic resistance, but the least inductive resistance. To increase the inductance of the workpiece perimeter circuit in order to concentrate the current in the edges of the workpiece, a ferromagnetic (ferrite) core is introduced into the workpiece [4–5].

REVIEW OF LITERATURE ON THE SUBJECT

The formation of a welded joint during high-frequency welding has been widely investigated due to its decisive role in determining the mechanical integrity and service performance of welded products, particularly in pipe manufacturing. Classical studies explain that the joint formation mechanism in high-frequency welding is governed by electromagnetic induction, skin effect, and proximity effect, which together ensure intensive surface heating of the strip edges prior to forging. These fundamental principles are consistently emphasized in technical analyses of high-frequency welding processes used in industrial practice.

K. Ravikiran, Peng Xu, and Liang Li provide a comprehensive and systematic review of high-frequency electric-resistance welding applied to steel line pipes. Their research demonstrates that welded joint formation is not a purely thermal phenomenon but a complex interaction of electrical current concentration, temperature gradients, mechanical squeezing force, and metallurgical transformations at the bond line. According to Ravikiran and co-authors, insufficient control of these parameters leads to incomplete bonding, oxide entrapment, or excessive grain growth in the weld zone, directly affecting toughness and fatigue resistance.

The influence of technological parameters on joint formation has been further explored by Darko Rogale and Stjepan F. Rogale, who analyze the role of welding current, frequency, heating time, and contact pressure in high-frequency welding. Their findings indicate that stable joint formation requires a precise balance between energy input and forging pressure, as excessive heat promotes grain coarsening while insufficient heat prevents full metallurgical bonding. Rogale's work highlights that welded joint quality is highly sensitive to even minor deviations in process parameters.

Geometrical aspects of joint formation have been addressed by Mohammad Ghaffarpour and Mohammad Akbari, who studied the effect of joint configuration in high-frequency induction welding of pipes. Their research confirms that edge preparation, alignment accuracy, and V-angle geometry significantly influence the temperature distribution and metal flow in the weld zone. Ghaffarpour and Akbari show that improper joint geometry results in asymmetric heating and unstable expulsion of molten material, which weakens the weld seam.

Post-weld performance of high-frequency welded joints has also been investigated in relation to corrosion and structural stability. Studies on low-alloy steels demonstrate that the microstructural state formed during high-frequency welding directly affects stress-corrosion resistance. These investigations reveal that the characteristics of the welded joint formed during the welding stage largely determine the long-term durability of welded components in aggressive operating environments.

Overall, existing studies by Ravikiran, Rogale, Ghaffarpour, and other researchers confirm that welded joint formation during high-frequency welding is controlled by a combination of electromagnetic, thermal, mechanical, and geometrical factors. Effective management of these interacting parameters remains a key scientific and technological challenge for improving weld quality and ensuring reliable industrial application of high-frequency welding processes.

RESEARCH METHODOLOGY

The study is based on experimental and analytical data obtained from high-frequency welding trials conducted under controlled industrial conditions. Process parameters, thermal regimes, and joint characteristics were recorded using electrical and metallographic measurements. The collected data were analyzed through comparative evaluation, microstructural examination, and correlation analysis to identify relationships between welding conditions and welded joint formation quality.

ANALYSIS AND RESULTS

Based on the current distribution pattern, it can be argued that during high-frequency welding with flashing, the deposit occurs under current. Consequently, the conditions for the formation of a welded joint and the removal of molten metal from the weld zone are even more facilitated and improved. Precipitation under current favors the processes of recrystallization and the formation of common grains, which increases the ductility of the welded joint [5]. This is clearly seen in the microstructure of a welded joint made of low-carbon steel, shown in figure 1 (Figure 1).

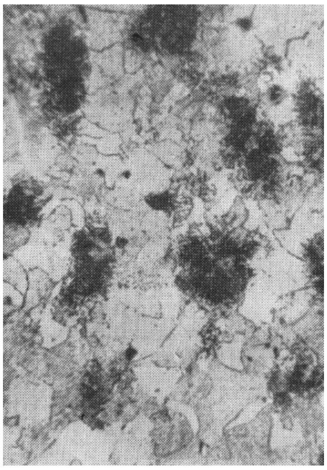

Figure 1. Microstructure of a welded joint made of steel 08 (X300). The thickness of the edges to be welded is 0,4 mm, vcv = 40m/min, voc≈700 mm/s, f=440 kHz

The upsetting current is sufficient for almost complete recrystallization of the weld zone. Places of welding are allocated only with a flash. The microstructures of the weld, transition zone and base metal are identical. Standard test methods did not reveal any differences in the ductility of the weld and the parent metal. Consider the second main parameter - draft Δos. For a symmetric system, it is determined

$$D_{oc} = (F_{в} + F_{н})/ 2s \qquad (2)$$

where $F_{в}$ and $F_{н}$ are the areas of the inner and outer burrs.

On figure 2 shows a draft diagram. Measurements of the values of F_b and F_h were carried out during welding with heating by a current of 440 kHz frequency of straight-seam pipes made of various materials, followed by the manufacture of microsections (Figure 2).

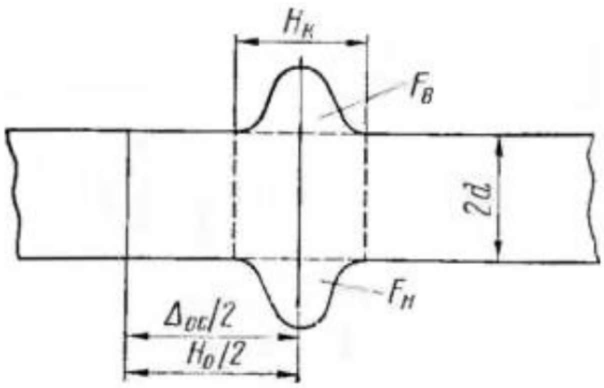

Figure 2. Scheme for determining draft

For comparison, in figure 3 shows the dependence of settlement Δ_{os} on thickness 2d for steel strips in continuous flash welding (Figure 3).

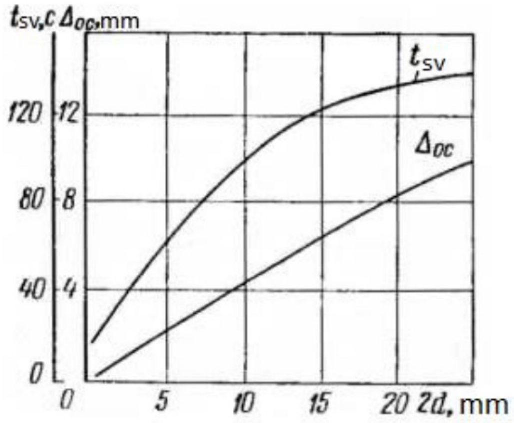

Figure 3. Dependence of settlement Δ_{oc} and welding time on the thickness of welded strips 2s

The curve indicates that in high-frequency flash welding, the deposit is an order of magnitude smaller than in conventional flash butt welding. In butt welding of metals and alloys with high thermal conductivity, flashing is carried out at a very high speed, as a result of which deep craters are formed on the welded surfaces [5]. In addition, it is assumed that it is difficult to obtain a uniform layer of liquid metal at the ends, and therefore it is necessary to mechanically destroy the hard films on the solid metal. All this leads to large deformations, essentially the same as in resistance welding. If we apply this hypothesis to the process we are considering and assume that as a result of the current flow along the edges, their uniform monotonous heating and melting occur, then the formation of craters is excluded. This may be the reason for the small value of Δos. However, during high-frequency flash welding, uneven heating of the elements to be welded due to disturbances is possible. When studying the nature of the disturbances and their influence on the temperature regime of the heated elements and Δoc, it was found that the disturbances are associated with the instability of the energy regime of the power source, the operation of the mechanisms for preparing and upsetting the elements to be welded, and the quality of the workpiece. Excessive upsetting leads to distortion of the fibers and, as a rule, to a deterioration in ductility and a decrease in toughness (Figure 4).

Figure 4. Fiber distortion due to excessive upset

The most typical and significant are the disturbances caused by the presence of a variable component at the output of the rectifier that feeds the lamp generator, and the associated periodic changes in the active power released in the welded elements (the case of welding at radio frequencies). The third parameter, which depends on the previous two, is the precipitation pressure Poc. As is known, with an increase in the rate of upsetting, the resistance to deformation increases and, as a result, Poc increases. This phenomenon in highfrequency flash welding was analyzed in [2], where it is proposed to estimate the average strain rate wcp of welded edges according to the formula

$W_{cp} = (1/ t_{oc})\ln(H_o/H_k)$ (3)

where toc is the settling time; H_0, H_k are the initial and final widths of the edge deformation zone (figure 5). The edge deformation rates calculated by formula (3) in straight-seam pipe welding are 300–450 1/s, which exceeds the rates. It is known that pressure welding processes without flashing in the absence of a reducing medium can provide satisfactory joint quality only in a narrow temperature range and with deformations sufficient to destroy oxide films. For low-carbon steels, this condition corresponds to the interval 150–200° C and Δ_{oc} = 1,5÷2,0 mm, and for aluminum alloys – 40–50 ° C and Δ_{oc} = 1,2÷1,4 mm. Let's imagine two metal bars 2, located tightly end to end and placed in the magnetic field of the inductor 1 (Figure 5).

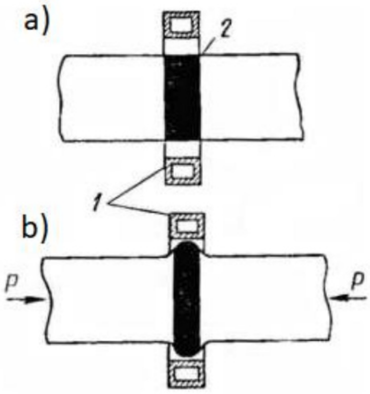

Figure 5. Scheme of welding without flashing: a - heating; b – sediment

If the width of the inductive wire is sufficiently small (5–10 mm), then the temperature gradient along the axis of the bars is quite large. In this case, the width of the heating zone and the steepness of the front of the temperature curve weakly depend on the frequency of the current of the power source. For the process of weld formation during upsetting, such a distribution of the temperature field should be considered favorable, since plastic deformation is concentrated in a narrow zone and a minimum burr is formed. The distribution of the temperature field along the radius of the rod is always sharply uneven. A temperature difference acceptable for the conditions of weldability can be achieved only with sufficiently small sections of the workpiece to be welded, a heating time calculated in seconds or tens of seconds, and a low frequency of the power source current (Figure 6).

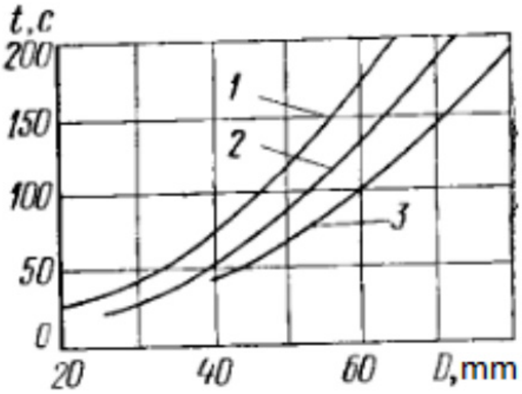

Figure 6. Steel heating time at different power supply current frequencies: 1 - 1000 Hz; 2 - 2500 Hz; 3 - 10000 Hz

Such conditions for the distribution of the temperature field over the cross section of the welded rod and the heating conditions as a whole should be considered unfavorable for the welding process. From consideration of the heating circuit, it is easy to conclude that with the smallest temperature difference over the cross section and along the generatrix, a cylindrical hollow body with a wall thickness of 2d≤Δк can be heated. Therefore, this method has limited application - for butt welding of thin-walled pipes. Obviously, in order to achieve a narrow heating zone, the inductor can only be single-turn, but in such an inductor it is difficult to obtain a symmetrical field and, consequently, a symmetrical temperature distribution along the perimeter of the heated product. In addition, an additional non-uniformity of the temperature field along the perimeter is introduced by the difference in wall thickness of the pipe billet. This makes it difficult to heat the welded pipes in a narrow temperature range. Therefore, this method is used in butt welding of pipes made of low-carbon steels. The heating rate does not exceed 400 ºC/s. Significant difficulties are associated with the destruction and removal of oxides during precipitation. For their complete destruction, it is necessary to fulfill the condition Δос = 1,5÷2,0 mm. It is feasible only for large gaps in the inductor–pipe system, but in this case the temperature field gradient along the tube axis decreases and even larger deformations are required. Attempts have been made to overcome this difficulty in the following ways. 1. Increasing the heating temperature above the melting point of FeO (for its melting). In this case, although it is possible to completely remove molten oxides from the zone of the welded joint, however, grain growth occurs and a widmannstate structure is formed. In addition, partial melting of the grain boundaries occurs, and sedimentary looseness appears during crystallization. 2. Application of gas shielding or fluxes. When heated to T = 1200÷1250°C, it is possible to obtain a high-quality welded joint and a satisfactory microstructure of the near-weld zone. The protective environment must be restorative. Severe welding temperature limits and the need for a protective environment limit the application of this method.

CONCLUSIONS AND SUGGESTIONS

The conducted research on the formation of welded joints during high-frequency welding of longitudinally welded pipes made from low-carbon and low-alloy steels has revealed the following key findings:

The proposed methodology allows for accurate calculation of the power required to heat the pipe billet edges to welding temperature, taking into account both contact and induction methods of energy supply. The introduced power increase coefficients k_P1 (maximum), k_P2 (minimum), and the average k_P enable accounting for the uneven distribution of surface current density along the edges, depending on edge sharpness, rounding, and the presence of one or two magnetic cores.

The distance from the inductor (or contacts) to the edge convergence point, as well as the configuration of magnetic cores, significantly influences energy consumption and welding speed. The gap between the edges and the corresponding convergence angle have a substantial impact on the consumed power.

Placement of internal and external magnetic cores effectively reduces the required power at minimal edge convergence angles, with their efficiency increasing as the gap between the cores and the edges decreases. However, in the zone of very small gaps near the convergence point, the influence of magnetic cores becomes insignificant, and their placement in this area is not recommended.

The obtained results can be applied in the design, modernization, and optimization of high-frequency welding equipment at pipe electric welding mills to improve energy efficiency, increase welding speed, and enhance the quality of welded joints.

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