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CONTENTS

THE THEORETICAL FOUNDATIONS OF APPLYING TAX INCENTIVES FOR INVESTMENTS DIRECTED TOWARD HUMAN CAPITAL	14
Quliyev Begimqul Melikovich	
ECONOMETRIC MODELS OF CASHLESS SETTLEMENTS AMONG ECONOMIC ENTITIES.....	21
Ruzimuradov Shukhrat Khusanovich	
PROSPECTS FOR THE DEVELOPMENT OF TOURISM BRAND MARKETING IN MODERN CONDITIONS (UAE: DUBAI ON THE EXAMPLE OF A CITY).....	26
Ibodova Dilsora Ibodovna	
CREDIT DEFAULT SWAPS AS A WAY TO HEDGE AGAINST FORTHCOMING FUTURE UNCERTAINTIES IN THE DEBT MARKET OF UZBEKISTAN	31
Abduganiev Abdulaziz Alisher o'g'li	
SHOULD THE REGULATION OF THE E-COMMERCE MARKET IN THE REPUBLIC OF UZBEKISTAN BE CARRIED OUT BY THE NATIONAL AGENCY FOR PERSPECTIVE PROJECTS OR THE CENTRAL BANK?	39
Sadikov Aziz Mirsharapovich	
MECHANISM FOR IMPLEMENTING ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN THE OPERATIONS OF COMMERCIAL BANKS IN UZBEKISTAN.....	46
Bakhriddin Berdiyarov	
INNOVATIVE APPROACHES OF SMALL BUSINESSES IN THE INDUSTRY AND CONSTRUCTION SECTORS AND THEIR IMPACT ON EMPLOYMENT.....	53
Ergasheva Nigora Abdigapparovna	
AI-BASED NORMALIZATION METHODOLOGY FOR COLLECTING AND PROCESSING KPI INDICATORS.....	56
Shuhratov Mamurjon Shuhrat o'g'li	
REFORMS AND PROSPECTS FOR THE DEVELOPMENT OF THE PARTICIPATORY BUDGETING INITIATIVE IN UZBEKISTAN	63
Khamidov Khabibullo Hikmatulla ugli	
PROBLEMS OF THE INWARD PROCESSING CUSTOMS REGIME AND WAYS TO ELIMINATE THEM.....	70
Abdullaev Shakhzodbek	
FINANCIAL ANALYSIS OF SMALL BUSINESS AND PRIVATE ENTREPRENEURSHIP IN CONSTRUCTION	74
Musayeva Shoirazimovna	
MEASURES TO ENHANCE THE ROLE AND EFFECTIVENESS OF SMALL BUSINESS IN REGIONAL ECONOMIC DEVELOPMENT.....	80
Ergashev Jamshid Jamoliddinovich	
THEORETICAL AND METHODOLOGICAL FOUNDATIONS FOR IMPLEMENTING INNOVATIVE TECHNOLOGIES IN EDUCATION.....	84
Alijonova Marjonabonu Jaxongir qizi	
INDIA'S EXPERIENCE IN ENHANCING PUBLIC WELFARE THROUGH THE DEVELOPMENT OF ENTREPRENEURIAL ACTIVITY	88
Aripov Oybek Abdullayevich	
GREEN STRUCTURAL TRANSFORMATION IN UZBEKISTAN: GREEN FINANCE AND ECO-INNOVATION FOR SUSTAINABLE INDUSTRIAL AND AGRICULTURAL DEVELOPMENT.....	93
Egamberdiev Khumoyun	
AGRICULTURAL MANAGEMENT BASED ON INNOVATIVE TECHNOLOGIES AT THE INTERNATIONAL LEVEL: THE EXAMPLE OF UZBEKISTAN.....	101
Bustonov Komiljon Kumakovich	
ANALYSIS OF THE FINANCIAL CONDITION OF ENTERPRISES: ASSESSMENT OF EQUITY EFFICIENCY	110
Umurkul Shukhratovich Fayziev	

IMPROVING THE QUALITY OF ECONOMIC GROWTH THROUGH THE TRANSITION TO THE DIGITAL ECONOMY.....	118
Mamadaliyev Akmaljon	
МЕТОДЫ И МЕХАНИЗМЫ ИССЛЕДОВАНИЯ ПОТРЕБИТЕЛЬСКОГО ПОВЕДЕНИЯ НА ТУРИСТСКОМ РЫНКЕ.....	124
Нурматова Ситора Шавкатовна	
ANALYSIS OF INNOVATION ACTIVITIES.....	133
Alieva Elnara Ametovna	
METHODS AND MECHANISMS FOR STUDYING CONSUMER BEHAVIOR IN THE TOURISM MARKET.....	139
Nurmatova Sitora Shavkatovna	
ALGORITHMS AND METHODS FOR CALCULATING THE AREA OF A GASTRIC ULCER DEFECT USING MODERN MATHEMATICAL TECHNIQUES.....	145
Yusupov Ibrohimbek XXX, Abdusamatova Munira Sultonbek qizi	
UTILIZATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN ENTERPRISE MARKETING ACTIVITIES.....	151
Sadikov Shohrux Shukhratovich	
ENSURING THE FINANCIAL SUSTAINABILITY OF HIGHER EDUCATION INSTITUTIONS: STRATEGIC DIRECTIONS, GLOBAL TRENDS, AND POLICY IMPLICATIONS.....	156
Inomiddin Imomov	
THEORETICAL FOUNDATIONS OF THE STRUCTURE OF THE NATIONAL ECONOMY.....	161
Bustonov Mansurjon Mardonakulovich	
IMPORTANT CHARACTERISTICS OF THE DEVELOPMENT OF E-COMMERCE SERVICES.....	169
Jurakulov Shohruh Bahtiyorovich	
AGRICULTURE PROMOTION AND DEVELOPMENT IN MOUNTAIN AND MOUNTAIN REGIONS.....	173
Abdulxayeva Gulshan Maxmudovna	
IMPROVING MECHANISMS FOR ENHANCING ECONOMIC EFFICIENCY IN SERVICE ENTERPRISES.....	178
Seytimbetov Kabul Serimbetovich	
INTEGRATION OF INTELLIGENT CONTROL IN DRYING SYSTEMS: PROCESS OPTIMIZATION THROUGH SENSORS, ARTIFICIAL INTELLIGENCE, AND MODULAR DRYING.....	184
Yangiboyeva Raxbaroy Mashrabboy qizi	
THEORETICAL MODELS AND CONCEPTS OF ECONOMIC DEVELOPMENT IN THE ENERGY SECTOR.....	190
Nigmatullaeva Gulchekhra Nurullaevna	
STATISTICAL ANALYSIS OF REGIONAL ECONOMIC POTENTIAL (A CASE STUDY OF NAMANGAN REGION).....	196
Tursinbayev Azizbek Nabijon o'g'li, Sirojiddinov Kamoliddin Ikromiddinovich	
DIRECTIONS FOR DEVELOPING INVESTMENT AND EXPORT IN REMOTE SERVICE ENTERPRISES.....	203
Uzakov Ortik Shaymardanovich	
SPECIFIC FEATURES OF ENTREPRENEURSHIP IN INCREASING THE INCOME OF THE POPULATION IN THE REGION.....	207
Kuldasheva Maftuna Musurmon kizi	
KEY FACTORS OF ATTRACTING INVESTMENT THROUGH SUBSIDIES AND INVESTMENTS TO INCREASE AGRICULTURAL CROP PRODUCTION IN UZBEKISTAN.....	211
Mamatkulova Nadira Makkamovna	
RAQAMLI MARKETING VA INNOVATSION TEXNOLOGIYALAR ASOSIDA EKOTIZIM SAMARADORLIGINI OSHIRISH USULLARI.....	216
Sobirov Azizbek Avazbekovich	
WAYS TO IMPROVE THE STATISTICAL ASSESSMENT OF FRUIT AND VEGETABLE PRODUCTION PROCESSES AND EXPORT POTENTIAL IN THE REPUBLIC OF UZBEKISTAN.....	223
Anorboeva Bakhtijamol Daniyar kizi	

THE IMPACT OF DEGRADATION ON THE OPERATIONAL CHARACTERISTICS OF PHOTOVOLTAIC MODULES UNDER SHARPLY CONTINENTAL CLIMATIC CONDITIONS	229
Qurbanov Yunus Murtaza o'g'li	
INTEGRATED NEW MEDIA OPERATION MODEL FOR INTELLIGENT TALENT ASSESSMENT PLATFORMS: THE PATH OF QR CODE ACTIVATION AND CONTENT-DRIVEN ENGAGEMENT.....	235
Wang Biao	
METHODOLOGICAL FOUNDATIONS FOR SHAPING THE CREATIVE ACTIVITY OF YOUNGER PUPILS IN SOLVING MATHEMATICAL PROBLEMS	239
Dzhurakulova Adolat Khalmuratovna	
SOLIDWORKS-BASED MODELING OF AN AIR-BLOWING SYSTEM TO ENSURE HIGH-QUALITY FIBER REMOVAL FROM SAW TEETH	247
Mirzakarimov Mirsharoffiddin Mirzaabdurahimovich	
THEORETICAL STUDY OF TEMPERATURE AND THERMAL PHENOMENA IN MECHANICAL CUTTING OF WHITE CAST IRON.....	256
Allanazarov Akmal Abdulxaqovich	
THEORETICAL AND METHODOLOGICAL FOUNDATIONS OF SUSTAINABLE DEVELOPMENT OF THE REGIONAL ECONOMY	262
Turdiyev Ulug'bek Qayumovich	
THE INTERRELATIONSHIP BETWEEN MIGRATION AND THE INDUSTRIAL ECONOMY	266
Khusanbek Begmatov	
THE IMPACT OF ESG PRINCIPLES ON THE HOTEL INDUSTRY	271
Khusenova Mekhrangiz	
CURRENT STATUS OF INDUSTRIAL PRODUCTION AND SERVICES MARKET IN KASHKADARYA REGION.....	276
Norov Murodjon Makhmudovich	
DEVELOPMENT OF AN ARTIFICIAL INTELLIGENCE-BASED CYBERSECURITY SYSTEM FOR THE AUTOMATIC DETECTION OF FAKE FINANCIAL RECEIPTS, PHISHING URLS, AND MALICIOUS APK FILES	284
Shermatov Axlidin Sharobiddin o'g'li	
WAYS TO INCREASE REVENUES IN COMMERCIAL BANK OPERATIONS	287
Ostonaqulova Gulchehraxon Muhammadyoqub qizi	
РОЛЬ СВОБОДНЫХ ЭКОНОМИЧЕСКИХ ЗОН В РЕГИОНАЛЬНОМ РАЗВИТИИ И ЗАРУБЕЖНЫЙ ОПЫТ	301
Файзиева Ширин Шодмоновна	
RAQAMLI IQTISODIYOTGA O'TISH SHAROITIDA IQTISODIY O'SISH OMILLARINING TA'SIRINI BAHOLASH METODOLOGIYASI.....	307
Bustonov Mansurjon Mardonakulovich	
FINTECH TRENDS: NEW TOOLS FOR ATTRACTING FINANCING IN THE CONTEXT OF DIGITAL TRANSFORMATION	313
Madjitova Lolakhon Lazizovna	
CHALLENGES AND PROSPECTS FOR THE DEVELOPMENT OF E-COMMERCE IN UZBEKISTAN.....	317
Toshpulatov Akhror Tukhtamurod ugli	
STRATEGIC DETERMINANTS OF FOREIGN DIRECT INVESTMENT IN UZBEKISTAN	326
Rustamov Foziljon	
TYPES AND MEANS OF ADVERTISING IN THE FIELD OF TOURISM	335
Bahriyeva Zarina Nasimovna	
INTELLECTUALIZATION OF TECHNICAL MEANS FOR CONTROLLING TECHNOLOGICAL REFINING PROCESSES.....	340
Ruziyev Umidjon Abdimajitovich	
NECESSITY OF ENSURING AND INCREASING THE COMPETITIVENESS OF PLACEMENT MEANS	349
Sherkulov Dilshod Jurakulovich	
YASHIL IQTISODIYOT VA MOLIYAVIY INKLYUZIYANING O'ZARO BOG'LIQLIK NAZARIYALARI.....	354
Adashaliyev Baxtiyorjon Valisher o'g'li	

THE IMPORTANCE OF THE AUDIT OF LEASING OPERATIONS ON FARMS OF THE REPUBLIC OF UZBEKISTAN	359
Tursunov Ulugbek Sativoldievich	
METHODOLOGY DEVELOPMENT RETAIL MARKETING AND TRADING SYSTEM.....	365
Makhmatkulov Golibjon Kholmuminovich	
NECESSITY OF ENSURING AND INCREASING THE COMPETITIVENESS OF PLACEMENT MEANS	369
Sherkulov Dilshod Jurakulovich	
ENVIRONMENTAL FISCAL POLICY AS A DRIVER OF GREEN GROWTH AND EMPLOYMENT IN CENTRAL ASIA: EMPIRICAL EVIDENCE	374
Rakhmatova Zilola Yurevna	
ON THE ISSUE OF CALCULATING THE POWER REQUIRED TO HEAT THE EDGES OF THE PIPE BILLET TO THE WELDING TEMPERATURE.....	379
Zairkulov Elyor Yoqubjon o'g'li	

ON THE ISSUE OF CALCULATING THE POWER REQUIRED TO HEAT THE EDGES OF THE PIPE BILLET TO THE WELDING TEMPERATURE



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Abstract: The article proposes a methodology for calculating the power required to heat the edges of a pipe billet to the welding temperature during high-frequency welding of longitudinally welded pipes made from low-carbon and low-alloy steels. The 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 factors 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 factor k_P as the half-sum of the extreme values, as well as for calculating the required power P_{kp} , 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.

The results of the work can be used in the design and optimization of equipment for high-frequency welding of pipes at pipe mills.

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 past uglerodli va past legirli po'latlardan yasalgan uzunchoq tikuvli 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, 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 koeffitsientlari k_{P1} (maksimal) va k_{P2} (minimal) kiritilgan, jumladan o'tkir va yumaloq qirralar, bitta yoki ikkita magnit o'tkazgich mavjud bo'lgan holatlar uchun. O'rtacha k_P koeffitsientini ikki chekka qiymatning yig'indisining yarmiga teng deb hisoblash formulasi, shuningdek isitish zonasi bo'ylab o'zgaruvchan maxsus quvvatni hisobga olgan holda zarur quvvat P_{kp} ni aniqlash 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, gofirovka 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, проформовка кромок, гофрообразование, сварной шов, электросварные трубы.

INTRODUCTION

In the Republic of Uzbekistan, the production of small-diameter steel pipes occupies a significant place within the metallurgical and machine-building sectors. One of the most efficient and widely implemented technologies in this field is high-frequency welding, which enables continuous, high-speed pipe formation while ensuring acceptable mechanical strength and geometric accuracy of the welded joint. The reliability and quality of the welded seam largely depend on the thermal regime established in the welding zone, particularly on the accurate determination of the power required to heat the edges of the pipe billet to the welding temperature.

In high-frequency pipe welding, energy is supplied to the edges being joined through electromagnetic processes that cause localized heating due to induced currents and resistive losses. At present, two principal methods of energy transfer to the welded edges are employed in industrial practice: contact welding and induction welding. Each of these methods is characterized by distinct physical mechanisms of heat generation, current distribution, and energy concentration, which directly affect heating efficiency, power consumption, and the stability of the welding process.

Contact welding provides direct current transfer through sliding contacts, offering relatively simple design solutions but introducing issues related to contact wear, surface contamination, and process instability at high production speeds. Induction welding, on the other hand, ensures non-contact energy transfer and higher operational reliability, though it requires more complex electromagnetic systems and precise control of process parameters. These differences necessitate a rigorous analytical approach to calculating the required heating power, taking into account material properties, billet geometry, welding speed, frequency of the current, and heat losses.

Therefore, the problem of accurately calculating the power required to heat the edges of a pipe billet to the welding temperature remains a key engineering and scientific task. Its solution is essential for optimizing welding equipment design, reducing energy consumption, improving seam quality, and enhancing the overall efficiency of pipe manufacturing processes under modern industrial conditions.

REVIEW OF LITERATURE ON THE SUBJECT

With the induction method, an annular inductor is installed at a distance of 30–300 mm from the point of convergence of the edges, covering the pipe billet. Under the action of the inductor field, a current is induced in the surface layer of the workpiece [1].

Due to the proximity effect, the largest part of the induced current flows along the edges and closes at the point of their convergence (useful current). Another part of the current is closed around the perimeter inside the workpiece tube (useless current). As with the contact method of supplying current, internal and external magnetic circuits are used to reduce the useless current. The length of the magnetic cores with the induction method should be longer by the length of the inductor than with the contact method [2].

The power consumption required for welding depends significantly on the distance between the inductor or contacts and the convergence of the edges. With an increase in this distance, the heating time increases and, consequently, the power loss due to heat transfer from the heated edges to the adjacent metal layers. This leads to a decrease in the welding speed [3].

With the induction method of supplying current, the power consumption is somewhat higher than with the contact method, since along with the edges, the body of the pipe billet is heated under the inductor. The energy utilization factor - the ratio of the energy spent on heating only the welded edges to the total energy absorbed by the workpiece - decreases with an increase in its diameter, since losses in the workpiece body increase, while the power for heating the edges remains practically constant. [4].

The advantage of the induction method is the exceptional simplicity and reliability of the inductors. [5].

RESEARCH METHODOLOGY

The study is based on analytical and computational methods. Initial data were obtained from theoretical models of high-frequency heating, material properties of steel pipe billets, and technological parameters of the welding process. The analysis was carried out by comparing calculated power values with thermal balance conditions and evaluating the influence of key parameters on heating efficiency.

ANALYSIS AND RESULTS

When calculating the power, the following assumptions were made: 1) heat losses due to heat transfer from the surface and along the edges are very small; 2) the energy released on the side surfaces of the edges that are not subject to welding does not affect the temperature of the surface to be welded.

Despite the assumptions, this calculation is very difficult, since at the corners of the edges, even when taking into account their rounding, the surface current density is much higher than in the middle of the edges. Therefore, one cannot neglect the heat flux from the corners to the middle of the edges, although it is rather difficult to strictly take into account the influence of this flux. In view of this, the calculation of the power was carried out for two extreme cases.

1. The heat flux from the corners to the middle of the edges is very small and does not affect the temperature distribution on the surfaces to be welded. In this case, the middle part of the edges heats up to the welding temperature, and their corners overheat. The useful power is determined from the condition that the surface current density on the surfaces to be welded is constant and equal to the current density in the middle of the edges. In this case, the useful power is equal to the total power released at the edges at $h/d = 0$ or $b/d = 0$, when the heat flux is directed along the normal to the surfaces to be welded. The ratio of the total power to the useful power is denoted by $k_P 1$ and is called the maximum power increase factor.

2. The heat flux from the corners to the middle of the edges is so great that despite the uneven distribution of the current on the surfaces to be welded, the temperature is leveled out due to thermal conductivity. In this case, all the energy released unevenly on the surfaces to be welded is useful. The ratio of the total power supplied to the edges to the power released on the surface to be welded will be called the minimum power increase factor $k_P 2$.

Obviously, the true value of the power increase factor k_P lies in the range from $k_P 1$ to $k_P 2$ and depends on the heating time, material properties, edge thickness, and other parameters, which are rather difficult to take into account. Therefore, this coefficient can be taken

$$k_P = (k_{P1} + k_{P2}) / 2.$$

(1)

Thus, the power P_{cr} required for welding is found by the formula

$$P_{\hat{\epsilon}\delta} = k_P p_0 2d 2l_{\hat{\epsilon}\delta}$$

(2)

where p_0 is the specific power determined by the method for a semi-infinite medium; l_{cr} is the length of the edges in the heating section.

This formula, strictly speaking, is applicable if p_0 does not change in the section from the contacts or inductor to the point of convergence of the edges. But in a real case, p_0 is not constant in the heating section. When welding products from a non-magnetic material, it grows according to a law close to linear. When welding products from a ferromagnetic material, it grows from zero to a maximum value, then decreases in the area of loss of magnetic properties and then grows again in the area up to the point of convergence of the edges. The error in calculating P_{kp} , if we neglect the change in p_0 in the heating section, does not exceed 10%.

Below are the formulas for calculating the power increase factors $k_P 1$ and $k_P 2$, obtained using the distribution of the surface current density for edges with sharp and rounded corners at different locations of the magnetic cores.

1. Edges with sharp corners and one magnetic circuit:

$$k_{P1} = \frac{2K - F(k, S) + K' - F(k, S_1)}{\frac{nt_0^2 - 1}{(t_0^2 - 1)(1 - k^2 t_0^2)} \int_1^{1/k} \frac{\sqrt{(t^2 - 1)(1 - k^2 t^2)}}{nt^2 - 1} dt};$$

(3)

$$k_{P2} = \left[2K - F(k, S) + K' - F(k, S_1) \right] / K'$$

(4)

2. Sharp edges without magnetic cores:

$$k_{P1} = \frac{K' + 2K - 2F(k, S)}{(1 + k^2)K' - 2E'};$$

(5)

$$k_{P2} = \left[K' + 2K - 2F(k, S) \right] / K'.$$

(6)

3. Sharp edges with two magnetic circuits:

$$k_{P1} = \frac{n(1 - k^2) K' + K - F(k, v)}{k^2(1 - n) K' - (n' k')};$$

(7)

$$k_{P2} = \left[K' + K - F(k, v) \right] / K'.$$

(8)

4. Edges with rounded corners without magnetic cores:

$$k_{P1} = \frac{C\sqrt{1 - k^2} + \sqrt{1 - k_1^2}}{d} \int_1^{t_1} \frac{dt}{\left(C\sqrt{1 - k^2 t^2} + \sqrt{1 - k_1^2 t^2} \right) \sqrt{t^2 - 1}};$$

(9)

$$k_{P2} = \frac{\int_1^{t_1} \frac{dt}{\left(C\sqrt{1 - k^2 t^2} + \sqrt{1 - k_1^2 t^2} \right) \sqrt{t^2 - 1}}}{\int_1^{1/k_1} \frac{dt}{\left(C\sqrt{1 - k^2 t^2} + \sqrt{1 - k_1^2 t^2} \right) \sqrt{t^2 - 1}}}.$$

(10)

Having calculated the coefficients kP 1 and kP 2, using formulas (3) - (10), we obtain by formula (66) the values of kP for parallel edges, which are shown in Fig. 1.

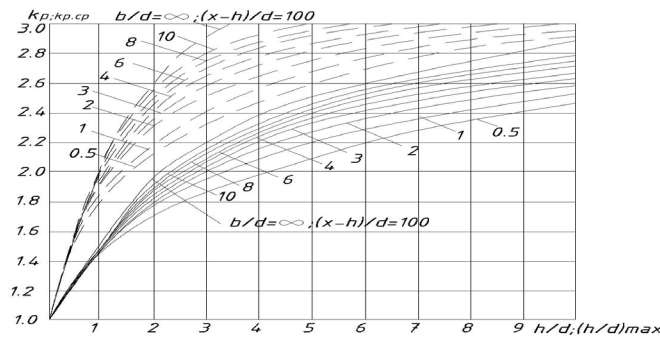


Figure 1. The values of the coefficients k_P and $k_{P_{av}}$ for edges with one magnetic core located in parallel (---) and at an angle (----)

The same figures show the values of the coefficient $k_{P_{cp}}$ for edges located at an angle, which were calculated by the formula

$$k_{P_{\tilde{h}\tilde{d}}} = \frac{1}{l_{\tilde{e}\tilde{d}}} \sum_{m=1}^{m=n} k_{Pm} \Delta l_m \tag{11}$$

where k_{Pm} is the coefficient for section m .

As can be seen from Fig. 1, the power required to heat the edges to the welding temperature depends significantly on the gap between the edges, and therefore on the angle of convergence of the edges.

For example, at $b/d = \infty$, a halving of the relative clearance (h/d) max allows the power to be reduced by about 25%. With a minimum angle between the edges, the power can be further reduced if magnetic cores are placed inside and outside the pipe billet, the effectiveness of which increases with a decrease in the gap between the magnetic cores and the edges. With very small gaps between the edges near their point of convergence, the influence of the magnetic cores is insignificant, and therefore they should not be placed in this zone.

The $k_P 1$, $k_P 2$, k_P and $k_{P_{av}}$ values calculated for edges with rounded corners are slightly less than the values obtained for $r = 0$. However, the difference is small and should be taken into account when calculating $k_P 1$, $k_P 2$ and k_P for $h/d \geq 2.5$ and when calculating $k_{P_{cp}}$ for $h/d \geq 2.5$.

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:

- at a minimum angle between the edges, the power can be reduced if magnetic cores are placed inside and outside the pipe billet, the effectiveness of which increases with a decrease in the gap between the magnetic cores and the edges;
- with very small gaps between the edges near their place of convergence, the influence of magnetic circuits is insignificant, and therefore they should not be placed in this zone.

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