UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 9, No. 4, 2023

Volodymyr Biloborodchenko[1], Stanislav Biloborodchenko[2]

[1] Department of Oil and Gas Engineering and Welding,
Lviv Polytechnic National University, 12, S. Bandery str., Lviv, Ukraine,
e-mail: volodymyr.i.biloborodchenko@lpnu.ua,
ORCID 0000-0002-0827-2321;
[2] Department of Oil and Gas Engineering and Welding,
Lviv Polytechnic National University, 12, S. Bandery str., Lviv, Ukraine,
e-mail: stanislav.biloborodchenko@lpnu.ua

STUDY OF THE WELDABILITY OF MOLYBDENUM TUBULAR FITTINGS OF THERMAL CONVERTERS

Received: November 23, 2023 / Revised: November 26, 2023 / Accepted: December 4, 2023

https://doi.org/10.23939/ujmems2023.04.001

Abstract. The purpose of the work is to optimize the technological solution for the production of molybdenum tubular fittings of heat exchangers (TCs) that work at high temperatures and external mechanical load on calculated and practical modes of electron beam welding. The results of welding largely depend on the degree of contamination of the material, and the combined calculation of EBW parameters according to a set of existing methods does not give an unambiguous solution, but allows to outline the range of their acceptable values for further experimental clarification. The proposed methods of testing welded fittings according to mechanical parameters and resistance to crack formation with simultaneous simulated application of operating temperature load (500–1200 ^{0}C) initiate the detection of cracks and provide information on the actual strength and plasticity of the metal of the welding zone in real conditions of operation of the fittings.

Key words: fittings of heat exchangers; electron beam welding; setting parameters of the welding mode; welded joints of molybdenum fittings; welding defects; testing of welded joints; simulation of working temperature loads; mechanical characteristics of a welded joint.

Introduction

Assessment of the thermal stress state of environments and objects in engineering and industry is in many cases carried out using metrologically standardized thermoelectric converters (TC) [1, 2].

In the design of submersible TPs (Fig. 1), which are used to measure a wide range of temperatures of liquid and gaseous media, the presence of protective fittings for thermoelectrodes is provided. It is made of various materials – metals, alloys, ceramics, as well as their combinations using welding and related technologies.

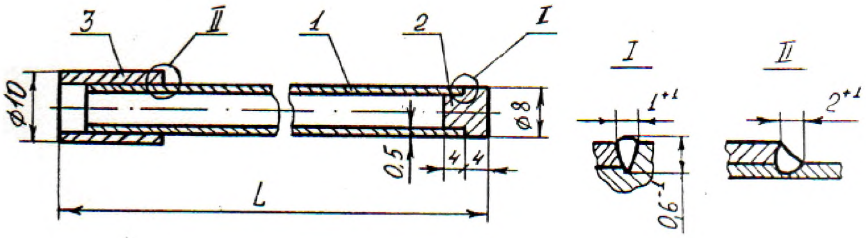


Fig. 1. Combined TC armature: 1– molybdenum tube;
2– molybdenum metal; 3– adapter (X18NT9 steel); I, II – welding zones

Such a wide range of structural materials: highly alloyed steels, iron alloys alloyed with nickel, chromium, manganese, aluminum, silicon with high corrosion and heat resistance, heat resistance, refractory materials and alloys based on them, silicide – graphite, corundum, etc. is due to the need to ensure operational conditions armature work. They should include physical-mechanical, thermal-physical, metallurgical, chemical, radiation, electrical, metrological, and resource indicators.

This, at the very beginning, should be understood as ensuring the specified operational resource of the product under conditions of shock thermal, mechanical, and other physical loads of the measured environment by the mechanical strength of the armature material in a wide temperature range, its high resistance to structural and phase transformations in heating and cooling cycles, the minimal influence of its own thermophysical parameters on the metrological reliability and inertia of temperature measurements, minimal chemical and radiation reactivity to the environment, insensitivity to the chemical composition of the thermoelectric insulation, a given level of electrical conductivity if the armature is used as one of the thermoelectrodes, and, conversely, high insulating electrical resistance to them branches, tightness.

Molybdenum and alloys based on it serve as an acceptable structural material for TC fittings for the temperature range higher than 1000 ^{0}C. Technically pure molybdenum for the manufacture of welded tubular fittings with a typical wall thickness of $1–20\cdot10^{-4}$ m is not used due to its high reactivity to the controlled environment at elevated temperatures, which is accompanied by its saturation with products of interaction with gases (perceptible starting from the range of 371–538 ^{0}C and above) [5, 7].

Technological processing of such materials, especially with the involvement of thermal welding processes, which to a certain extent reproduce the thermo-deformation load cycle during real measuring work of the TC, is critical for the final results of the product manufacturing. The latter requires strict consideration of both the choice of the welding method and the technological methods of its implementation.

An indicator of the optimality of the welding technology for such materials is the mechanical characteristics of the joint zone at a given temperature of the transition to plastic-brittle failure of the structure.

Object and subject of research

The purpose of the work is to optimize the technological solution for the production of welded molybdenum tubular fittings of heat exchangers (TC) by electron beam welding (EBW) and those that work at high temperatures and internal pressure, ensuring the necessary level of density of the material of the welding zone and its mechanical characteristics.

The main tasks of the work should include:

– the effect of the initial state of the material on the defectiveness of the welded joint;

– the influence of the setting parameters of the EBW mode on the mechanical properties of the welding zone;

– calculation justification for the selection of the area of acceptable welding modes with the determination of the most influential on the connection indicators;

– substantiation and selection of test methods of welded joints of fittings for crack resistance and tightness;

– the effect of simulated temperature loads on the degree of cold fracture (fragility) of welded joints of fittings on their mechanical indicators.

Purpose and objectives of the study

The object of research is the welded joints of tubular elements of fittings made of molybdenum МЧ microstructures obtained by electron beam welding (EBW) technology.

The subject of work research is the compliance of welded joints with certain requirements for resource operation of tubular fittings in terms of mechanical and hermetic parameters.

The practical significance of the obtained results

As a result of the work, data were obtained on the sensitivity of the EBW results, with strict maintenance of its parameters, to the structural purity of the input material in terms of the formation of hot and cold cracks and negative changes in the mechanical characteristics of the metal of the welding zone.

Calculation approaches to establishing the region of optimal values of the setting parameters of the welding mode are demonstrated.

Proposed methods of testing the mechanical properties of welded tubular fittings with simultaneous simulation, relative to the operating cycle, temperature load, and its effect on the crack resistance of the product.

Analysis of literary sources

The assessment of the suitability of the use of the material in the structure according to certain indicators of its performance, provided that such material is subjected to welding technologies in the process of manufacturing the product, is weldability. The latter represents a comprehensive indicator of ensuring a given level of functionality of the TP, as well as the degree of technological damage to the material of the armature during its manufacture.

Weldability can be considered both physical and technological. Taking into account the crystalline structure and the level of interatomic bonding, molybdenum fully meets all the criteria for good physical weldability.

However, ensuring acceptable technological weldability – the density of the material of the welding zone with a certain level of transition to the elastic-plastic state (low-temperature plasticity) is quite a difficult task. The difficulty lies in the need to take into account the initial state of the material (structural and metallurgical features, the presence of impurities, previous processing technologies, etc.), the relationship between the grain structure, the crystallographic structure and mechanical properties, the change (degradation) of the above parameters under the influence of the thermo-deformation cycle of welding [10, 11].

Due to the special physical properties of molybdenum (high melting point, high thermal conductivity, and volumetric heat content, etc.), the latter is an acceptable structural material for TC fittings. However, when welding technologies are applied to it, it requires locally concentrated welding heating sources and maximum protection of the welding zone from the surrounding metal-active environment [8, 9, 11–14].

The main problem of ensuring the given resource performance of products is insufficient plasticity of the material of the welding zone, which is caused by the delamination of the base metal in the fusion zone, fragility due to saturation of the liquid metal of the welding bath with impurities above their solubility limit, high sensitivity to grain growth, gas saturation even at temperatures lower than the melting temperature (the rate of oxidation of molybdenum increases sharply at temperatures higher than 816 ^{0}C), the formation of hot and cold cracks.

An increase in the content of rooting impurities contributes to a continuous increase in the temperature of the plastic-brittle transition (cold brittleness) [2, 3, 8–10].

An increase in the oxygen content in molybdenum alloys can cause welding defects such as seam leakage (pores and hot cracks at an oxygen content of more than 0.009 % by mass), as well as a sharp increase in the temperature threshold of brittle failure. The latter is explained by the increased concentration of oxygen in the fusion zone with the release of molybdenum oxides along the grain boundaries [6, 10].

Molybdenum does not create stable hydrides, that is, welded joints are not prone to hydrogen embrittlement, but excessive saturation of the liquid metal of the weld leads to the development of the process of pore formation [1].

An increase in the nitrogen content in the metal from 0.002 to 0.055 % by mass increases the threshold of the plastic-brittle transition from 310 K to 350 K. Like oxygen, nitrogen segregates along grain boundaries [6].

This mechanism of the negative influence of oxygen and nitrogen is explained by their high adsorption capacity and significant energy of connection with grain boundary surfaces. The maximum allowable values of oxygen and nitrogen content are 0.002 % by mass and 0.005 % by mass, respectively.

The effect of carbon on low-temperature plasticity (plastic-brittle transition) is estimated in different ways: molybdenum carbides are located in the form of a continuous intercrystalline layer or film along the grain boundaries and sharply crumble the weld metal, even more intensively than oxygen; the expected reduction of the cold fracture threshold is ensured only with a maximum carbon content of no more than 0.01 % by mass [10].

On the other hand, with a carbon content of up to 0.06 % by mass, such carbides are formed in the form of a fine intergranular phase and in the grains themselves in the form of localized small clusters without breaking the bond between the grains themselves. Positive carbon content is also noted for inhibiting the beginning of the metal recrystallization process at high temperatures [2].

The structural state of the source metal significantly affects the properties of welded joints due to the crystallographic heredity of the texture of the heat-affected zone and the base metal and their reactivity to temperature changes: when working in high-temperature zones, recrystallization processes are observed in fittings made of molybdenum alloy МЧВП.

The latter, due to the thermal inertia of the material, has a directed direction from the surface to the depth of the wall thickness. In this way, an uneven grain-size structure is formed, which causes a significant mechanical deformation state of the tubular shell, which also contributes to the redistribution of impurities along the cross-section of the pipe wall and brittle failure [2].

Results and discussion

When choosing a welding method, the following is taken as a basis: a) locality and intensity of heat input; b) reliability of protection of the welding zone from active gases; c) spatial minimization of the zone of residual welding stresses and deformations; d) given seam geometry; e) indicators of mechanical deformability (flattening), as estimates of joint plasticity and tightness of the product as a whole.

These requirements are met by electron beam, laser, and argon arc welding (EBW, LW, TIG). The first two methods, as surface sources of heat release, provide high intensity and concentration of heat input, which allows for an increase in the welding speed and thereby reduces the time of existence of a small volume of the welding bath [11–14].

A positive thing is the reduction of the zone of thermal influence, the size of the crystals with a change in the crystallization scheme of the weld metal (planar crystallization). All other things being equal, the LZ of molybdenum alloys requires an additional technological arrangement for comprehensive protection of the welding zone from the air. EBW is carried out in a vacuum at a residual pressure of no more than 0.013 Pa, which removes the problem of saturation of the seam with rooting impurities. In the process of welding in a high vacuum, the metal of the welding zone is partially refined from gas impurities, which contributes to the quality of the welded joint.

The geometric dimensions of the seam with EBW in comparison with TIG unequivocally indicate its positive side, despite the complexity of the technology and equipment (Table 1).

Welding was carried out on the UELS-925M unit, modernized for welding tubular fittings. Parts before welding consist of a minimum permissible gap (no more than 5 % of the wall thickness) and an axial eccentricity of no more than 2 % of the wall thickness; practical for wall thicknesses up to 3 mm, gaps and eccentricities are not acceptable. The welding is continuous without filler wire, the formation of the seam is only due to the melting of the base metal with complete penetration of the wall thickness. An inflow of the root of the seam no more than 5 % of the wall thickness was considered acceptable.

Researched materials: rods and reinforcing tubes with a diameter of 8 mm made of molybdenum with a wall thickness of 0.5–3 mm. The rod was threaded under the inner diameter of the tube as a dowel.

All recommendations for the selection of welding mode parameters are based on the need for optimization experimentation specific to each case, although there are certain general methodological approaches that are based on the thermophysical and geometric parameters of the material and weld, as well as the dynamics of changes in thermal processes with some assumptions [3, 10, 14, 15].

Table 1

Linear dimensions of structural sections of welded joints (pipe wall thickness lp = 0.003 m)

Method of welding	The maximum width of the welding zone is 10^{-3} m		The width of the zone of structural transformations
	seam	zone of thermal influence	
TIG	4.2	2.1	8.4
EBW	1.5	0.8	3.1

The research was carried out on the material molybdenum МЧ – a tube with a diameter of 8 mm and a wall thickness of 1–3 mm; according to the recommendations for tubular materials made of molybdenum, the edges of the pipes should not have deviations greater than $\pm 5\cdot 10^{-5}$ m [10].

Preparation of parts for welding is standard: cleaning and degreasing followed by chemical etching.

Molybdenum welding: in the process of mode optimization, a significant tendency of the material to form cracks in the welding zone is confirmed (Fig. 2, *a*, *b*). Hot cracks are oriented along the axis of the seam and can be considered to be due to the increased content of oxygen in the source material, or the insufficient degree of chamber vacuuming.

a

b

Fig. 2. Hot cracks in the welded connected tube of the armature with the bottom:
a – the development of a crack with the opening of the banks from the fusion zone to the base metal;
b – axial crack (X200)

Cold cracks are formed both in the weld metal and in the heat-affected zone (Fig. 3); the orientation of the cracks is normal to the axis of the seam with growth towards the base metal. The typical reason for the formation of such cracks is the knowledge of the stresses of the pressing technological arrangement, and they can also appear during the aging process in a free state under normal conditions. The formation of cold cracks in this case is caused by a high level of residual tangential (along the axis of the seam) welding stresses, which are formed due to, other things being equal, asymmetric heat removal of parts (butt-tube).

Fig. 3. Opening of a cold crack in the heat-affected zone (tube wall X200)

The formation of cracks, even with optimal welding modes, is facilitated by the unsatisfactory condition of the rod material and the production of parts: delamination of the material, the presence of structural defects such as local discontinuity (Fig. 4).

Fig. 4. Stratification of the metal rod

According to the above results, a conclusion was made about the unsatisfactory condition of the material of the rod, and further work with parts from it was not carried out.

The results of welding of rebar tubes made of molybdenum МЧ with a butt in the area of optimal setting parameters: accelerating voltage 18–22 kV, beam current 70–250 mA (Fig. 5) demonstrate defect-free seams with a small melting zone.

Further annealing of welded joints in a vacuum (1373–1600 K, duration 1 hour) helps to remove internal residual stresses.

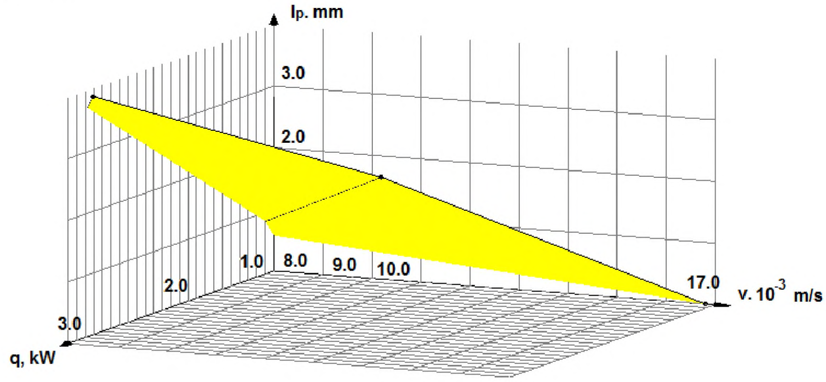


Fig. 5. The response surface is the penetration depth l_P from the setting parameters of the process: the thermal efficiency of the beam ($q = U \cdot I \cdot \eta_e$) and the speed of the beam movement (v)

The study of the effect of each setting parameter of the mode on the depth of penetration of the reinforcing pipe wall (Fig. 6–9) allows to establish the most acceptable range of high-quality welding modes for a wall thickness of $1^{-0.5}$–3 mm.

The following conclusions can be drawn from the obtained results, for all options for changing the value of the setting parameters of the EBW mode, there is a mostly hyperbolic dependence with the depth of penetration with a high level of correlation ($R^2 \geq 0.989$–0.998), which allows normalization by setting the coefficients of the hyperbola of the predicted value of penetration.

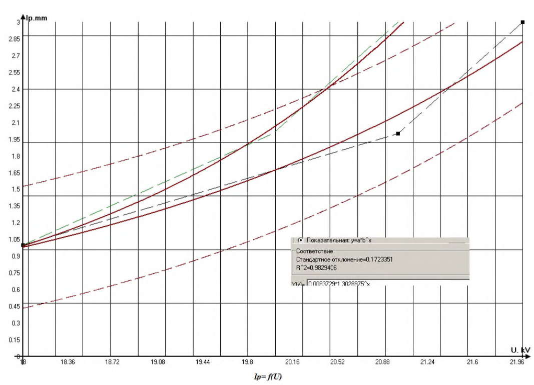


Fig. 6. Dependence of penetration depth on acceleration voltage

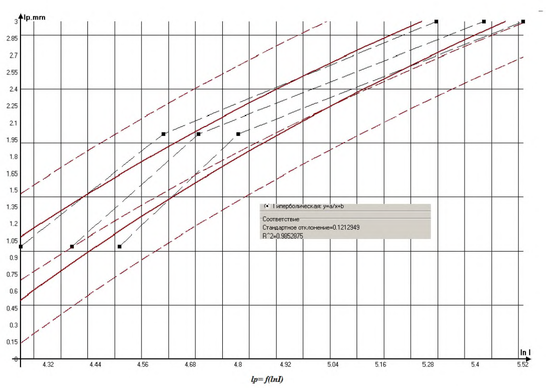


Fig. 7. Dependence of the penetration depth on the beam current

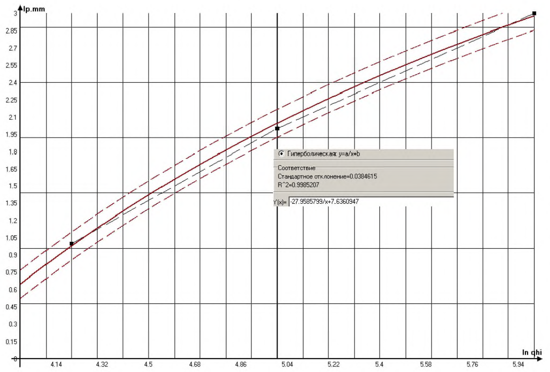


Fig. 8. Dependence of the penetration depth on the linear welding energy

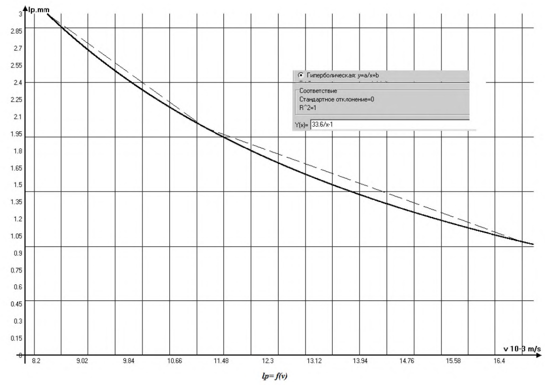


Fig. 9. Dependence of the penetration depth on the speed of the beam movement

The most acceptable mode adjustment parameter can be considered the acceleration voltage, which must be strictly maintained at a given level, and the beam current should be kept at the selected level, since any of its changes lead to the need to adjust the diameter of the heating spot due to the focusing current, or change the focal length to maintain given heat input flux density.

An increase in the welding speed clearly reduces the penetration depth and cross-section of the seam; the temperature criterion of cold brittleness decreases.

The linear welding energy clearly increases the cross-sectional dimensions of the welding zone and the depth of penetration. Since the linear energy is directly proportional to the parameters that determine the power of heat input and inversely to the welding speed, there are prerequisites for deep correction by the selected welding mode.

To establish the area of adjustment of the setting parameters of the EBW mode of the tubular armature, a calculation method is applied with a preliminary setting of the seam geometry: seam width 1+1 mm, penetration depth, corresponding to the thickness of the armature wall from 0.5 mm.

The solutions were found by a compatible consideration of the equations with respect to the basic condition – the characteristics of the melting zone during 1 second of the action of the heat source of the beam for a unit volume of molten metal [14, 15]

$$U \cdot I \cdot \eta_e \cdot \eta_T = \rho \cdot v \cdot F \cdot (cT_m + L_m), \tag{1}$$

where U is the acceleration voltage; I – beam current; η_e= 0.727 [12] – the effective efficiency coefficient of the radiant heat input process; η_T – the thermal efficiency coefficient of the process of transferring the material to another aggregate state; ρ = 10.1· 10^3 kg/m^3; v – speed of beam movement; F – cross-sectional area of the seam; c = 0.462 kJ/kg·K [7]; = 2890 K; T_m – melting temperature; L_m = 210 kJ/kg – specific amount of heat of phase transformation.

Then for (1) according to the setting parameters of the regime,

$$l_P = b\frac{a}{v}\left(\frac{U \cdot I \cdot \eta_e}{\lambda \cdot T_m}\sqrt{\frac{v}{a \cdot d_s}}\right)^n = \frac{q_{hi} \cdot d_s \cdot \eta_T}{(\pi \cdot B^2/4) \cdot \rho \cdot (c \cdot T_m + L_m)} \tag{2}$$

from condition B, the penetration width is at the level of 1/e (Fig. 10), and on the other hand

$$d_s = \frac{4q_e}{\pi \cdot l_P \cdot H_b \cdot v}; \; B = \sqrt{\frac{4 \cdot d_s \cdot q_e}{\pi \cdot H_b \cdot l_P} \cdot \eta_T}\;, \tag{3}$$

where b = 9.5·10^{-2}; n = 1.82 – coefficients; λ =82 W/m·K ; a – thermal conductivity; d_s – the diameter of the heating spot; q_{hi} – linear welding energy; B – is the width of the penetration zone at the level of 1/e (Fig. 10); H_b= 34.78 kJ/mol – heat content of boiling metal.

When refining the obtained values of the setting parameters of the mode, the coefficients of the completeness of the seam and the shape of the seam μ_{cs} were additionally taken into account K_{ss}

$$\mu_{cs} = F / B \cdot l_P;\ K_{ss} = l_P / B. \quad (4)$$

Since the initial shape of the seam is not known: so for dagger penetration – hard welding mode – μ_{cs} = 0.5–0.7, $K_{ss} \geq 1$, and for soft mode the corresponding μ_{cs} = 0.6–0.9, $K_{ss} < 1$ [16] their data set was tested for homogeneity of groups according to the Wilcoxon test [16]

$$u_z = z_n \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}};\ 2\Phi_0(z_n) = 1 - \alpha;\ \alpha = 0.05;\ u_z = 32 \geq u_{tabl} = 19, \quad (5)$$

which does not confirm group homogeneity, which forced to accept the range of setting values of the setting parameters of the mode: beam current 10–20 mA; welding speed 5–10 m/h, acceleration voltage 20 kV.

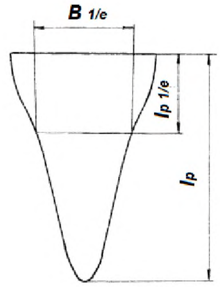
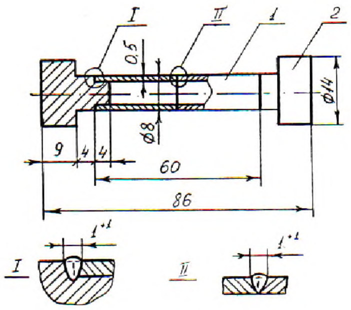


Fig. 10. Geometry of the melting zone during EBW



1– molybdenum tube; 2– molybdenum adapter

Fig. 11. Sample for tensile tests

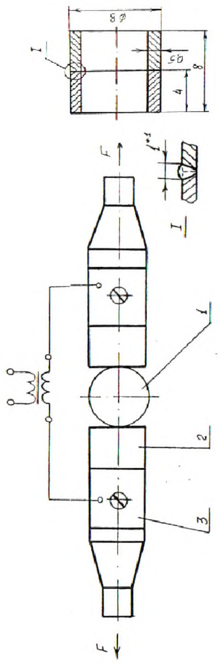
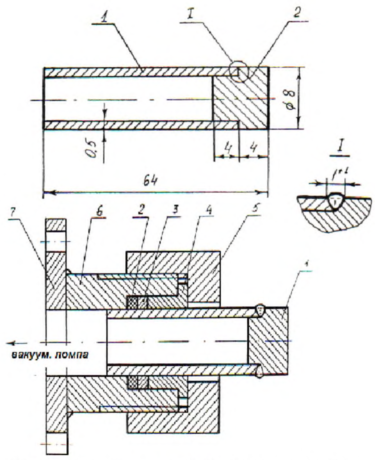


Fig. 12. The scheme of flattening tests: 1– sample; 2– holder; 3– current supply



Sample: 1– molybdenum tube; 2– low molybdenum

Fig. 13. Leakage test scheme: 1 – sample; 2 – sealing ring; 3– puck; 4– sleeve; 5 – nut; 6 – adapter body; 7 – flange

The results of EBW fittings were evaluated according to three types of tests: tensile (Fig. 11), flattening (Fig. 12) and tightness (Fig. 13) at temperatures of 20, 500 and 1200 ^{0}C.

The last temperature, which is reached during the minimum heating time of the welded armature, is practically an imitation of thermal shock, close to the operation of the TC armature in real conditions.

The IMASH -20-78 installation, on which the tests were carried out, allows the heating of samples in a vacuum of 0.02Pa to a temperature of 1800 ^{0}C (stabilization accuracy ±10 ^{0}C).

The dimensions of the samples are chosen according to the working course of the holders of the installation. Flattening tests are normalized for tubes with a diameter of more than 20 mm [8].

However, since welded joints of molybdenum and alloys, unlike most technical materials, are prone to crack formation and destruction along the seam, the calculated amount of flattening h before the appearance of cracks is accepted as an additional criterion for the mechanical properties of the welded joint.

Tests for tension to failure (tear) and flattening were carried out while simulating the working load of the armature with a limit temperature of 1200 ^{0}C, which was reached in 60 and 30 seconds. The heating speed (20–40^0/s) is limited by the pumping speed, gas release of the chamber walls during heating and intensive heat removal on the holder, which is cooled through bellows to avoid loss of vacuum in the installation chamber.

Airtightness tests were carried out using the helium flow detector method on full-scale samples; sensitivity of control equipment – $5.6 \cdot 10^{-7}$ liter· mm· Hg.

Testing for mechanical parameters (strength limit and elongation) of pipe fittings made of molybdenum of the МЧ brand in the state after deformation, and the main material itself is prone to delamination, and even more so after welding.

The fracture welding zone is characterized by the coarse structure of the weld metal and the thermally affected zone. Such a structure is typical for welded joints made with large values of linear energy. A typical defect appears in welding options with low linear energy – not welding the root of the seam. The negative influence of the welding temperature cycle on the properties of welded joints is caused by the grain size and the purity of the source metal. The zone of thermal influence is characterized by developed grain sizes and considerable length.

Welded tubular fittings made of this material are characterized by cracks that are oriented normal to the axis of the seam and enter the base metal through the heat-affected zone. In addition, the formation of cracks was noted during the cooling of the welding zone, as well as after a certain time after the complete cooling of the entire product.

An unambiguously established way to avoid cold cracks is careful correction of welding modes, mainly reducing the beam current with a simultaneous increase in the speed of its movement.

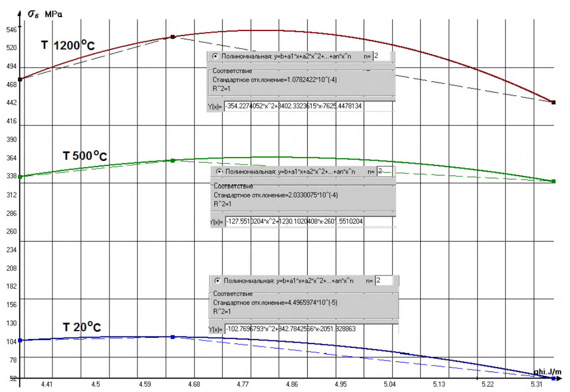


Fig. 14. Dependence of the strength limit of the Mo+Mo welded joint on the test temperature and the continuous welding energy

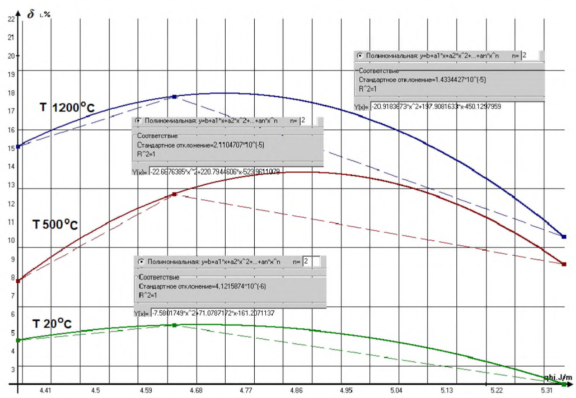


Fig. 15. Dependence of the elongation of the Mo+Mo welded joint on the temperature of the tests and the continuous welding energy

For welded joints subjected to tensile tests, the destruction strictly along the seam is indicative, regardless of the test temperature. An increase in the test temperature leads to a natural decrease in the strength limit and an increase in the plasticity of the welded joint.

However, the maximum temperature of the tests (1200 ^{0}C) demonstrates both a decrease in strength and plastic elongation of the metal of the welding zone. This can be explained by the specifics of the heating of the samples by the flow current – most of the thermal work of the current is concentrated directly on the seam, which leads to a significant temperature gradient between the seam zone and the ends of the sample wound in the clamp (Fig. 14–17).

In this case, the total elongation of the tubular fittings is largely not due to the base metal (the typical temperature value for it is 500 ^{0}C), and the greatest deformation occurs in the welding zone, mainly in the seam. The weld metal has a lower resistance to tearing due to the structure of the cast metal changed by crystallization.

The results of tests of reinforcing tubes for flattening (Fig. 18–20) show a slight difference in the depth of crumpling h for different welding modes when there is no test temperature factor (T^0 = 20 ^{0}C). Here, all the samples, regardless of the variation of the parameters of the welding mode in the optimal region, were destroyed at h = 6 mm, that is, the deformation did not exceed 1 mm.

At the test temperature of 500 ^{0}C, the effect of the mode parameters on plasticity is sharply revealed (beam current 20^{-5} mA, welding speed 5m/h) – the deformation reaches 2.8 mm. Destruction occurs in the heat-affected zone along grain boundaries.

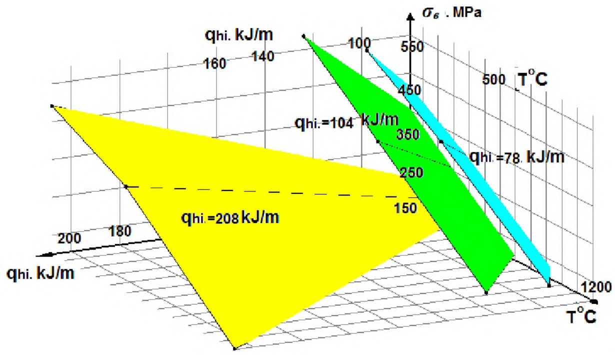


Fig. 16. The response surface of the change in the strength limit of the Mo+Mo welded joint depending on the linear welding energy and the test temperature

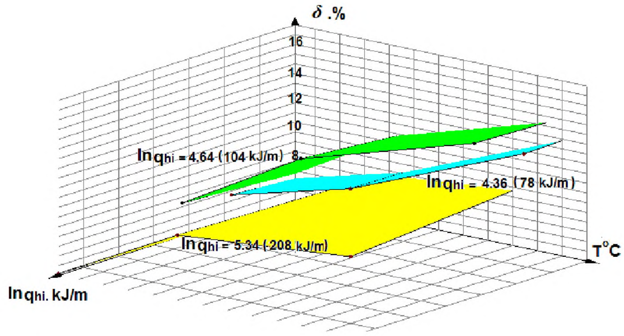


Fig. 17. The response surface of the change in the elongation of the Mo+Mo welded joint as a function of the linear welding energy and the test temperature

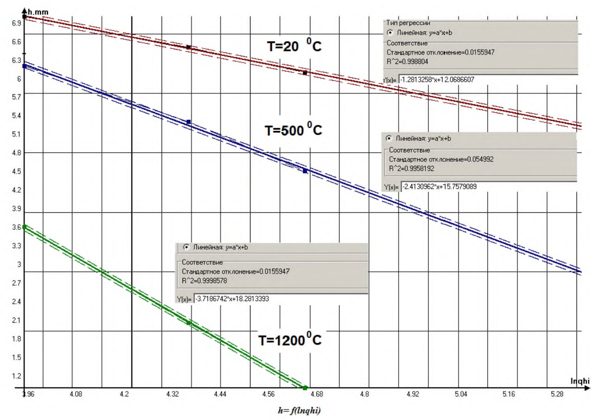


Fig. 18. Dependence of the amount of crumpling on the driving energy of the regime at different test temperatures

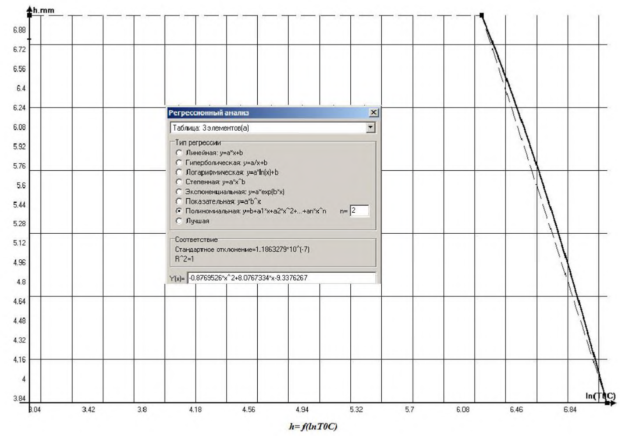


Fig. 19. Dependence of the amount of crumpling on the temperature of the tests at a driving energy of 208 kJ/m

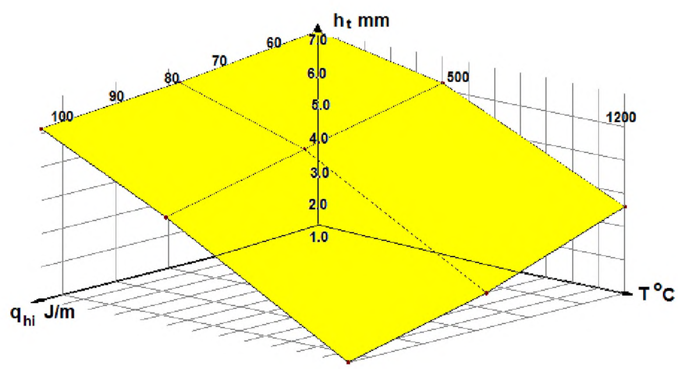


Fig. 20. Dependence of the amount of wrinkling on the temperature of the tests and the continuous welding energy

The test temperature of 1200 ^{0}C is the most indicative of the influence of the welding mode on the flattening results – with a beam current of 10–20 mA and a speed of its movement of 5–10 m/h, the value of h = 3.2–4 mm, that is, the samples were deformed without the appearance of cracks up to 3 mm in size.

Reducing the current of the beam with a simultaneous increase in its speed, the amount of deformation without the appearance of a crack reaches 7 mm.

High values of crumpling of the samples, the welding of which took place at a speed of 10 m/h and higher, demonstrate destruction either by the base metal or by the fusion zone. Here, the optimal setting parameters should be taken: acceleration voltage 20 kV, beam current 20 mA, speed 10^{+2} m/h.

In this case, at a high value of the strength limit of 580 MPa, the plasticity of the welded joint reaches 5.4 % due to the symmetrical elongation of the base metal from the seam.

Reducing the welding speed to 5 m/h at the same current values provides a soft welding mode with a seam width of up to 4 mm.

Leakage tests for the selected optimal EBW modes give a negative result – the welding zone has no leaks.

Conclusions

Despite the advantages of electron beam welding (EBW), even with optimal technological parameters of the formation of the welded joint, the metal of the latter remains extremely sensitive to the structurally contaminated state of the input material.

The main parameters of the regime when welding tubular molybdenum fittings are the beam current (10–15 mA) and the speed of its movement (5 m/h) with the condition of strictly maintaining the acceleration voltage of 20 kV. The joint calculation of EBW parameters using a set of existing methods does not give an unambiguous solution, but allows to outline the range of their acceptable values for further experimental refinement.

The proposed methods of testing welded fittings according to mechanical parameters and resistance to crack formation with simultaneous simulated application of operating temperature load (500–1200 ^{0}C) initiate the detection of cracks and provide information on the actual strength and plasticity of the metal of the welding zone in real conditions of operation of the fittings.

References

[1] https://aqteck.com.ua/ua/news/termoelektrychni-peretvorjuvachi-owen Thermoelectric converters ARIES. May 14, 2020.

[2]. Kisla G. P., Loboda P. I. Materials Science of Refractory Metals and Compounds K.: KNU Center for educational literature, 2019. 320 p.

[3] https:/Krohne.com/ Armature of thermometers with a thermocouple.

[4] https:/www td-etalon.com/Fittings for temperature sensors

[5] https:/books google..com. ua/ Protective pipe materials (armature)

[6] Kisla G. P. Materials science of refractory metals and compounds: a study guide for university students / H. P. Kisla, P. I. Loboda, V. E. Fedorchuk, M. O. Sysoev. K.: Center of Educational Literature, 2017. 320 p.

[7] Special alloys, RZM and precious metals: study guide / Kutsova V. Z., Nosko O. A., Kovzel M. A. Dnipropetrovsk: NMetAU, 2007. 163 p.

[8] Demenko V. Mechanical testing of structural materials. National aerospace university "Kharkiv aviation institute". Kharkiv, 2012. 51 p.

[9] Field Foster P. The mechanical testing of metals and alloys. Cousens Press, March 1. 2007. 308 p.

[10] Gurevich S. M. Reference book on welding of non-ferrous metals. K.: Science Dumka, 2010. 512 p.

[11] Weldability of molybdeum and its alloy sheet// https:/inis.iaea.org/ Sheet welding molybdenum and its alloys

[12] https:/ www.total material. com/ Welding of reactive and refractory materials

[13] https:/ebindustries.com/laser-welding molybdeum

[14] Kvasnytsky V. V. Special methods of welding. Mykolaiv, UDMTU, 2008. 437 p.

[15] Lebedev B. D., Peremytko V. V. Calculation methods in fusion welding. Dneprodzerzh State Technical University, 2008. 285 p.

[16] Volodarskyi E. T., Kosheva L. O. Statistical data processing: education. manual. K.: NAU, 2008. 308 p.