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CONTENTS

EFFECT OF PROCESS PARAMETERS AND BRAKING DYNAMICS IN FRICTION WELDING ON STRUCTURE AND PROPERTIES OF JOINTS BETWEEN COPPER AND ALUMINIUM

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The technology for friction welding with a regulated braking has been developed. It provides joints with high strength and ductility values, containing no intermetallic layer. The use of the new technology allows technological capabilities of standard friction welding equipment to be expanded.

Key words: *friction welding, technology, dissimilar joints, process parameters, conventional friction welding, inertia completion of the process, heating and forging pressure, rotation frequency, upsetting, heating, forging and braking time, intermetallic layer, quality of joint, equipment*

The main difficulty in optimisation of friction welding conditions is associated with a large number of variable parameters. Thus, parameters which are set in conventional friction welding are rotation speed, heating pressure, heating time (or allowance) and forging pressure. To chose the optimum combination of the process parameters, it is necessary to conduct a large number of experiments, each of which involves mechanical tests, metallography, durometry and other investigations.

The need to allow for a number of other factors which affect the quality of welded joints adds to the complexity of the task of optimisation of parameters for welding dissimilar metals, especially those which enter into chemical interaction during heating. These factors include chemical composition of materials, state in which they were received and their heat treatment history [1, 2], quality of preparation of surfaces to be welded [2–6], and dynamic characteristics of a rotation drive of the welding equipment, which determine the time of interruption of relative rotation at the final stage of the process [2, 4, 7]. For example, according to the data given in [2], the quality friction welded joints between copper and aluminium were produced at a braking time of not less than 0.07 s, whereas in [4] forging was performed with a delayed switch-on of the rotation drive.

Analysis of the data on friction welding of copper to aluminium [1–5] reveals substantial differences in specific values of the recommended process parameters given by different investigators. In addition, the data available in literature concern conventional friction welding, which provides for a rapid forced interruption of rotation by applying the forging force. The effect of the braking dynamics on conditions of formation of the joints has been insufficiently studied, although reportedly the inertia completion of the friction welding process allowed thermal-deformation conditions of formation of the joints between dissimilar materials to be optimised in many cases [6–11].

The task of this study is to determine the effect of the process parameters, such as heating time, heating and forging pressure, braking time and their combinations, on the quality of the joints between copper and aluminium, and optimise on this basis the conditions for friction welding of copper-aluminium transition pieces.

Base materials, i.e. copper M1 (99.9 % Cu) and commercial purity aluminium (99.5 % Al), were studied on billets with a diameter of 25 mm. Copper billets were annealed (650 °C, 0.5 h), and the mating surfaces prior to welding were machined using a lathe and degreased with acetone. Experiments were conducted using the upgraded friction welding unit ST-120, which allows the braking dynamics to be varied and the rotation braking time at the final welding stage to be programmed. Programming of the welding cycle was done on the basis of the heating time t_h, and the moment of application of the forging pressure coincided with the beginning of braking. The N145 oscillograph recorded the following welding parameters: rotation frequency n, heating and forging pressure P_h and P_f, upsetting (shortening) of billets in welding L, heating, forging and braking time t_h, t_f and t_b. To substantially reduce the amount of experiments, the studies were conducted using the methods of mathematical experimental design [12–14]. The second-order polynomial of a parameter being optimised, characterising the quality of a joint, was selected as the mathematical model: $Y = b_0 + b_1X_1 + \ldots + b_nX_n + b_{(n-1)}X_{(n-1)}X_n$, where Y is the responsible function; $b_0, \ldots, b_n$ are the regression coefficients; and $X_1 + \ldots + X_n$ are the factors to be studied (welding parameters).

Heating pressure P_h (X_1), heating time t_h (X_2), forging pressure P_f (X_3) and braking time t_b (X_4) were selected as the optimisation parameters. Identification of the variation range for the parameters to be studied, i.e. selection of the baseline (zero) level and ranges of variations of the factors, was done so

Table 1. Levels and ranges of variations of the investigated factors

Optimisation parameter	Factor	Level			Variation range J
		−1	0	+1	
Heating pressure P_h, MPa	X_1	20	40	60	20
Heating time t_h, s	X_2	0.4	1.7	3.0	1.3
Forging pressure P_f, MPa	X_3	100	150	200	50
Braking time t_b, s	X_4	0.1	0.4	0.7	0.3

that it covers mostly the entire range of the recommended welding parameters [1–5]. Values of the coded variables, i.e. −1, 0 and +1, which determine, respectively, the lower, baseline and upper levels of the studied factors are given in Table 1. The rotation frequency n, selected on the basis of preliminary investigations, allowing for conclusions of studies [2, 7], was n = 1460 rpm, which corresponded to a linear speed on the periphery of samples — v_{per} = 1.9 m/s. The forging time in all the experiments was t_f = 6 s. Figure 1 shows a typical oscillogram of the welding process.

As standard tensile and static bending tests fail to provide a satisfactory control of the quality of dissimilar welded joints, the bending angle α was assumed to be the responsible function Y in impact bending tests of a full-scale welded joint (after flash removal). This method is widely applied by many investigators for assessment of the quality of friction welding [2, 15, 16], although it fails to provide a comprehensive quantitative estimation of mechanical properties, as the major part of deformation occurs in the base metal of a less strong billet [15]. To make the test conditions more stringent and localise deformation in the joining zone, the billets tested were clamped in the zone of an aluminium part, at a distance from the joining line equal to diameter of the billets joined. Metallography (optical microscope «Neophot-32»), electron microscopy (scanning electron microscope JSM-T200), X-ray microanalysis (Cameca SX-50 microanalyser with a probe diameter of about 1 μm) and X-ray diffraction analysis (DRON-UM-1 unit) were conducted to determine relationship between mechanical properties of the joints and their structure. Angle lap microsections [7], which were studied in a non-etched condition, were made for visual enlargement of the joining zone.

The experimental design matrix and results are given in Table 2. Variance of the entire experimental criterion at each point of the design was determined on the basis of two parallel experiments. Homogeneity of variances was checked using the Cochran test. Values of the regression coefficients of the model developed (adequate at a significance level of 5 %), determined by the least-squares method, are as follows:

Table 2. Experimental design matrix and results

Joint No.	X_1	X_2	X_3	X_4	Bending angle α, deg
1	−	−	−	−	0
2	−	−	−	+	90
3	−	−	+	−	4
4	−	−	+	+	90
5	−	+	−	−	0
6	−	+	−	+	2
7	−	+	+	−	6
8	−	+	+	+	35
9	+	−	−	−	0
10	+	−	−	+	90
11	+	−	+	−	90
12	+	−	+	+	90
13	+	+	−	−	0
14	+	+	−	+	3
15	+	+	+	−	3
16	+	+	+	+	4

b_0 — 31.69, b_1 — 3.31, b_2 — −19.43, b_3 — 8.56, b_4 — 18.81, b_{12} — −7.44, b_{13} — 3.18, b_{14} — −7.06, b_{23} — 3.19, b_{24} — −14.44 and b_{34} — −4.3.

Therefore, the regression equation, allowing for interaction of the factors, including X_4 — braking time (X_1X_4, X_2X_4, X_3X_4), has the following form:

$$Y = 31.68 + 3.31X_1 - 19.43X_2 + 8.56X_3 + 18.81X_4 - 7.06X_1X_4 - 14.44X_2X_4 - 4.3X_3X_4.$$

According to [12], $X_i = (x_i - x_0)/J$, where X_i is the coded value of the factor; x_i and x_0 are the natural values of the factor and baseline level; and J is the variation range. After substitution of X_i to the regression equation, the model which adequately describes the value of bending angle α in impact bending tests of the friction welded joints between copper and aluminium, produced within the indicated range of variations of the process parameters, will have

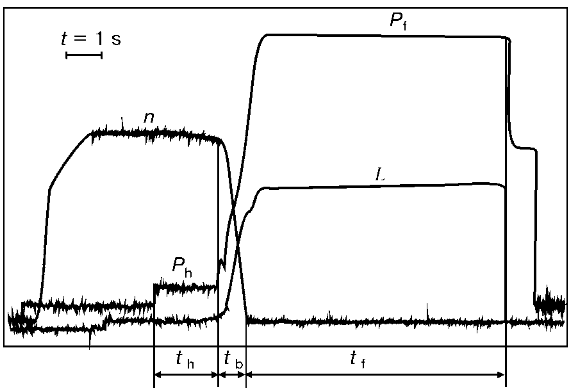

Figure 1. Typical oscillogram of the friction welding process: P_h and P_f — heating and forging pressures, respectively; n — rotation frequency; L — upsetting of the billets; t_h, t_b and t_f — time of heating, braking and forging, respectively

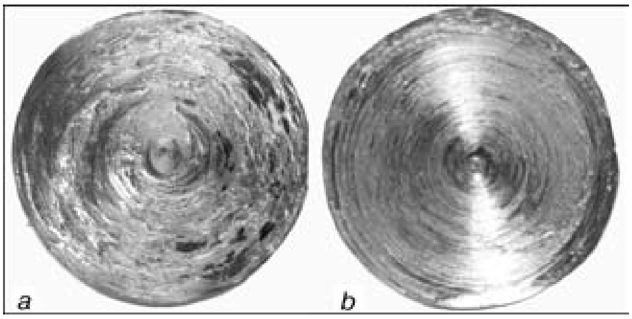

Figure 2. Fracture surfaces of welded joints produced at different values of the heating and braking time: a — $t_h = 0.4$ and $t_b = 0.1$; b — $t_h = 3.0$ and $t_b = 0.1$ s

$$\alpha = 31.68 + 3.31(P_h - 40)/20 - 19.43(t_h - 1.7)/1.3 + 8.56(P_f - 150)/50 + 18.81(t_b - 0.4)/0.3 - 7.06(P_h - 40)(t_b - 0.4)/6 - 14.44(t_h - 1.7)(t_b - 0.4)/0.39 - 4.3(P_f - 150)(t_b - 0.4)/15.$$

Positive values of the regression coefficients were obtained for the heating and forging pressures and braking time, while the negative values were obtained for the heating time. Significance of the coefficients with decrease in their numerical values is as follows: heating time (−19.43), braking time (18.81), forging pressure (8.56) and heating pressure (3.31). As increase in the responsible function Y corresponds to decrease in factors which have a negative regression coefficient and increase in factors with a positive coefficient, the results obtained allow the following conclusions.

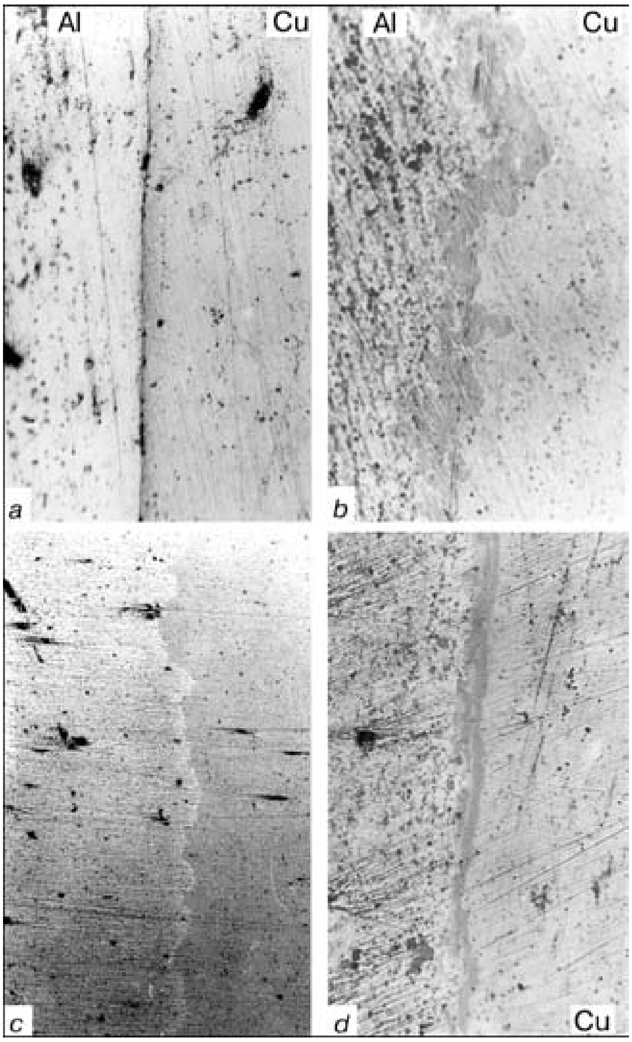

Figure 3. Microstructure of the copper to aluminium joining zone: a — ×200; b, c — ×400; d — ×625

To optimise the heating stage parameters, it is necessary to increase pressure and reduce time. The heating time, which determines the thermal welding cycle and, thus, initiation and growth of the intermetallic phase, has a higher impact on the quality of the joints. The positive effect of the heating pressure P_h on the quality of the joints is likely to consists in the following: increase in P_h provides a more rapid growth of temperature and its levelling across the sections of the billets, the maximum contact temperature is decreased to some extent [7], and the fitting duration, i.e. the initial phase of heating, which is not accompanied by a marked pressing of the heated metal from the welded joint zone, is reduced. This is indicative of the fact that increase in pressure P_h within the range investigated has a positive effect on thermal-deformation processes occurring in the welded joint at the heating stage.

The forging stage parameters, i.e. pressure P_f (coefficient 8.56) and braking time t_b (18.81), exert a substantial impact on the process of formation of welded joints. The important role of the forging pressure is noted by the majority of investigators [1–4], as increase in P_f leads to decrease in thickness of the brittle layer containing intermetallic compounds.

Analysis of the effect of the braking time t_b on the quality of the welded joints shows that at the lower level of its value the joints fracture by the brittle mechanism over the contact surface at the bending angle values close to zero, even with maximum values of the heating and forging pressures. The character of fractures and microstructure of the joints produced at different values of the heating time t_h are substantially different. At the lower level of the t_b and t_h values the fractures contain individual sticking regions (see Figure 2, a), and the fracture surface on the copper billet side has a characteristic copper tint. Metallography reveals individual adhesion regions in a peripheral part of the section and absence of adhesion in the central part (Figure 3, a), which is a result of an insufficient heating of the contact zone.

At the upper level of t_h and lower one of t_b the character of fractures changes, i.e. almost all the surface of the copper billet is covered by a thin layer of metal of a light-grey colour (see Figure 2, b). According to the data of X-ray diffraction analysis (Figure 4), the phase corresponding to compound CuAl is found on the fracture surface on the copper billet side.

As established by metallography, the shape of the interface in the welded joint varies with the heating pressure and time from almost straight-lined to that with a complex relief, containing the wave-formation regions (Figure 3, b). An interlayer with thickness

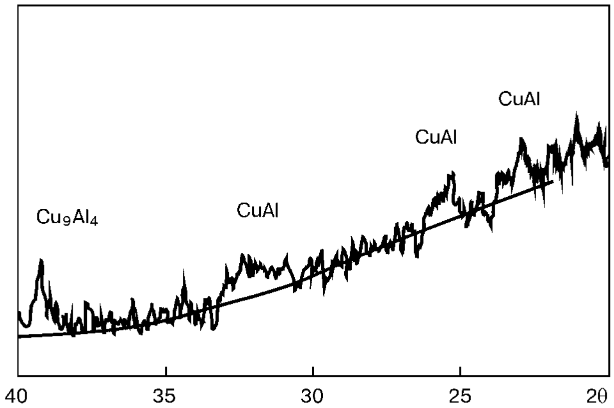

Figure 4. Results of X-ray diffraction analysis of fracture on the copper billet side

increasing with a transition from the centre to the periphery of sections of the billets is revealed within the joining zone. Maximum thickness of the interlayer decreases with increase in the heating pressure.

Identification of phases in the joining zone by X-ray microanalysis (Figure 5, *a, b*) showed intermetallic compounds with a composition close to that of the $CuAl_2$, CuAl and Cu_9Al_4 phases. Mass fraction of copper in different regions of the transition zone varies from 40 to 90 %, which is associated with formation of different compositions of phases. As in pressure welding the joining zone is formed in the presence of a high concentration gradient across the contact zone and under conditions of intensive stirring of minor particles without a change in the concentration of chemical elements, phase composition of the formed intermetallic compounds may not be in full correspondence to the constitutional diagram of Cu–Al derived for the equilibrium state [17].

Therefore, the transition layer has a laminated structure, the $CuAl_2$ phase being dominant on the aluminium side and the CuAl and Cu_9Al_4 phases — on the copper side. Properties of welded joints between dissimilar metals with a limited mutual solubility are known to depend upon the properties of the diffusion zones formed in the contact zone [18]. X-ray diffraction analysis of fracture surfaces of the joints shows that fracture of the joints in mechanical tests occurs primarily along the interface between the $CuAl_2$ and CuAl phases.

Joints produced at the upper level of the braking time t_b have higher mechanical properties. However, only the joints which were produced at a minimum value of t_h withstood bending to 90° without fracture (Figure 6). No intermetallic phase was found in the interlayers in joints No.2, 4, 10 and 12, according to the metallography (see Figure 3, *c*) and X-ray microanalysis (Figure 5, *c*) data. Diffusion of copper into aluminium to a depth of 3–5 μm was found in the contact zone, which is indicative of a change in the concentration of copper with distance to the contact boundary (on the aluminium side). Minimum values of the above range correspond to the central part of the section, and maximum values correspond to the peripheral part. Formation of metastable solid

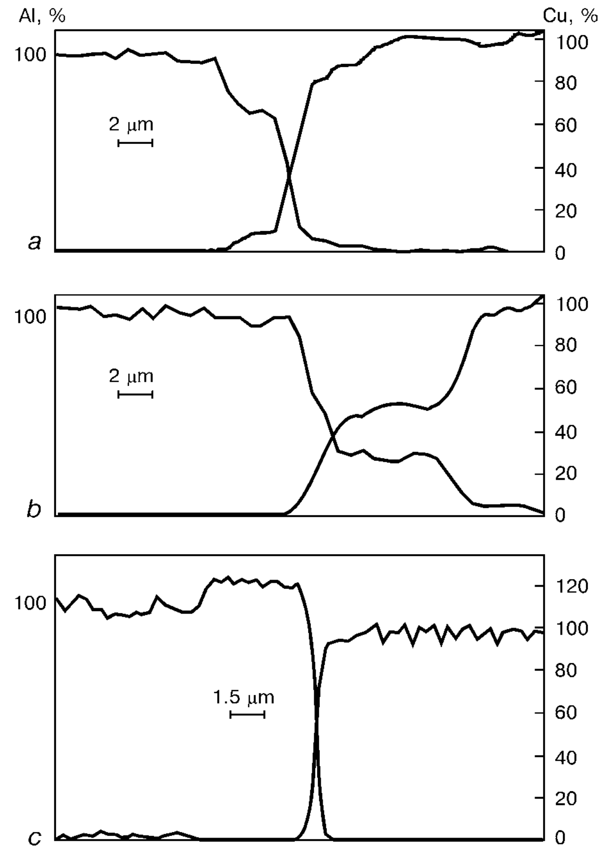

Figure 5. Distribution of copper and aluminium across the joining zone at different values of the heating and braking time: *a, b* — t_h = 3.0 and t_b = 0.1 s at the centre of the section (*b*) and on the periphery (*a*); *c* — t_h = 0.4 and t_b = 0.7 s on the periphery of the section

solutions of copper in aluminium, having a variable composition, is characteristic of structure of the transition zone. Formation of the intermetallic phase can be fixed at the initial stage until a solid layer is formed.

At the upper level of t_b and t_h all the joints fractured by a brittle mechanism. Metallography (Figure 3, *d*) and analysis of fracture surfaces of samples that fractured show the presence of the 3.5–5.0 μm

Figure 6. Welded joints (P_h = 40–60 MPa, P_f = 200 MPa, t_h = = 0.4 s, t_b = 0.7 s) after impact bending tests

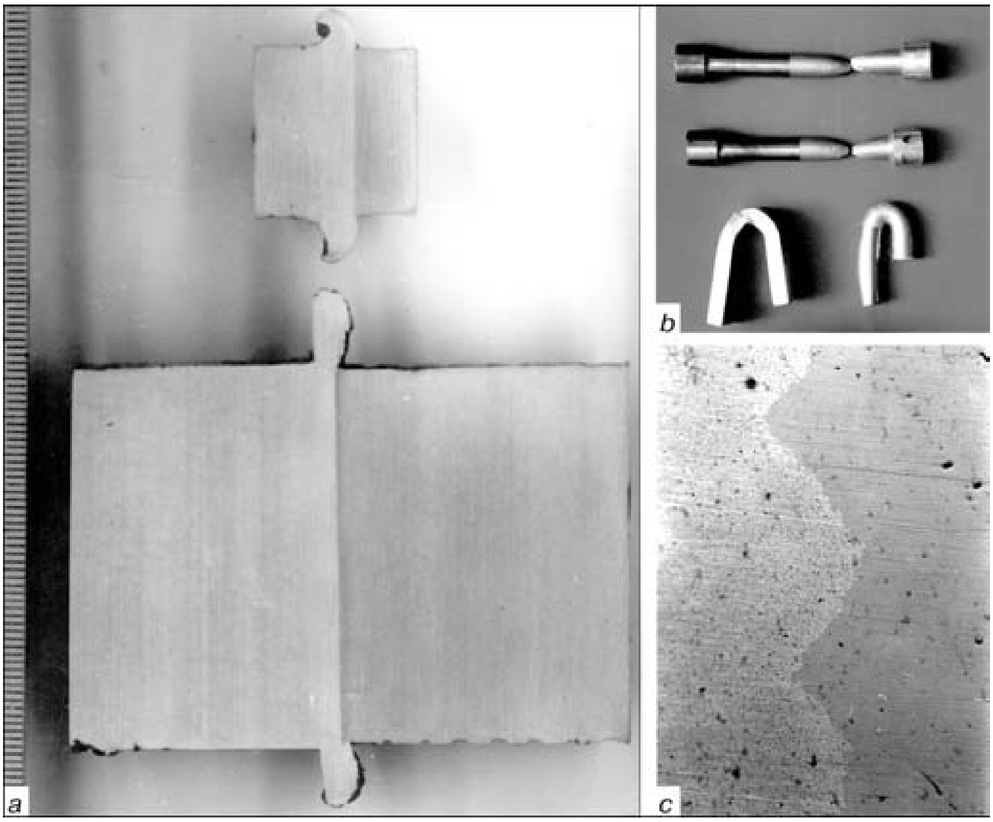

Figure 7. Friction welded joints between copper and aluminium produced at the regulated braking dynamics: *a* — macrosections of the joining zone; *b* — specimens after mechanical tests; *c* — microstructure of the joining zone (×2000)

thick interlayer containing intermetallics (which is much smaller compared with joints produced at a high rotation braking). A considerable decrease in thickness of the intermetallic layer is noted in the case of increase in the forging pressure. However, the attempts aimed at decreasing thickness of this layer to values at which the high ductile properties of the joints can be provided fail even with the upper values of P_f and t_b within the investigated range of their variations. Therefore, to optimise welding parameters, it is necessary to decrease the heating time and increase the rest of the programmed process parameters.

The optimal welding conditions determined on the basis of the data obtained are as follows: P_h = 60 MPa, t_h = 0.4 s, P_f = 200 MPa, t_b = 0.7 s, t_f = 6 s and v = = 1.9 m/s. A series of the joints was welded under these conditions. In testing the specimens to static and impact bending, all the joints withstood bending to an angle of 90° without fracture, while in counter-bending the specimens fractured in aluminium.

Analysis of interaction of factors X_1X_4, X_2X_4 and X_3X_4 allows a conclusion that within the range investigated the heating time and heating and forging pressures can be decreased due to increasing the braking time, with no deterioration of the quality of the welded joints. The X_3X_4 interaction is of the highest practical importance, as decrease in the forging pressure allows the range of sections welded by the same unit to be substantially widened.

To study the possibility of decreasing the forging pressure and effect of the scale factor on conditions of producing the quality welded joints, an experimental batch of billets with a diameter of 15, 20, 30, 40 and 55 mm was welded using the upgraded units MST-2001 and ST-120 with a maximum axial force of 20 and 12 t, respectively. The range of variation of the braking time was 0.5–1.5 s. Welded copper-aluminium transition pieces were tested to tension, static and impact bending. Results of mechanical tests showed no fractures in the welding zone with a decrease in the forging pressure to 70–90 MPa for different diameters of the billets. In this case, conclusions made in analysis of the derived regression equation were valid for the entire range of the diameters. As increase in the diameter of the billets was accompanied by a drastic increase in the friction moment in the joints (especially at the initial stage of the process), setting the value of the heating pressure in welding of large-diameter billets should be done with allowance for reliability of the clamping mechanisms and rigidity of the force chord of the welding equipment.

Macrosections of joints in samples with a diameter of 25 and 55 mm are shown in Figure 7, *a*. Insignificant width of the thermo-mechanicaly affected zone is indicative of localisation of deformation within the contact zone. Mechanical tests of the specimens cut from different parts of the sections (Figure 7, *b*) showed high strength and ductility properties of the joints. Microstructure of the joints was studied on non-etched angle lap sections [7] cut at an angle of 11.5°. Thickness of the joining zone in this case was visually increased by a factor of 5. Metallography of the joints at a maximum magnification provided by the «Neophot-32» microscope revealed no transition layer containing intermetallic phases (Figure 7, *c*).

Therefore, application of the forging pressure with a gradually decreased rotation frequency, i.e. the combined effect of axial and tangential deformation components on the plastisised metal at the stage of forging, provides formation of the quality welded joints at a lower pressure. However, this effect can be achieved only on the condition of setting the heating time at which the thermal welding cycle is not in excess of the time-temperature parameters of formation of the intermetallic interlayer. In this case the thermal-deformation parameters of formation of the joints are identical to those of the inertia friction welding.

The technology for welding with a regulated braking has been developed on the basis of the results obtained. The technology is characterised by a minimum duration of the heating stage and programmable decrease of the rotation frequency at the forging stage. To realise the technology using the standard friction welding equipment, the latter was upgraded with a purpose to create the possibility of programming the rotation braking dynamics at the final stage of the welding process. The upgraded welding units have high technological capabilities, compared with the standard friction welding equipment. For example, the commercial machine MST-2001 can provide the quality joints between copper and aluminium on billets with a diameter of up to 35 mm (forging pressure of not less than 200 MPa). Subjected to appropriate upgrading, this machine provides the quality copper-aluminium transition pieces with diameters in a range of 16 to 55 mm.

CONCLUSIONS

1. The braking time at the final stage of the process plays a considerable role in formation of structure, phase composition and mechanical properties of friction welded joints between copper and aluminium.

2. Within the investigated range of variations of the process parameters, the joints produced at a minimum value of the heating time and maximum values of the braking time and heating and forging pressures are characterised by the best mechanical properties.

3. The possibility of a substantial decrease in the forging pressure, compared with the conventional friction welding process, is provided by optimising the braking time.

4. The new technology for friction welding with a regulated braking has been developed. It provides joints without the intermetallic layer, characterised by high strength and ductility properties.

5. The use of the new technology allows widening of the technological capabilities of the standard friction welding equipment.

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MODIFYING, REFINING AND ALLOYING WITH YTTRIUM IN WELDING OF STEELS

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Refining, modifying and alloying effect of yttrium in cast steel 30 was substantiated using advanced procedures. Mechanism of yttrium effect on cold resistance of pearlitic steels and their welded joints is specified.

Key words: *rare-earth metals, modifying, alloying, refining, steel, cold resistance, internal friction of lattice, dislocations, substructure, Mössbaurer spectra, lattice pitch*

It is well-known that the adding of microadditions of rare-earth metals (REM) into composition of Fe–C alloys, including also welding consumables, increases the resistance of the latter against the transition to brittle state and reduces the critical brittle temperature [1, 2]. However, there is no single opinion as to the nature of REM effect on physical-mechanical properties of steel, in particular on weld metal. It is stated in some publications that the modifying effect of REM, providing a heterogeneous crystallization from the melt, is the main factor of improving service properties of the metal [3, 4]. At the same time the fine-grained structure can be produced by adding other known modificators into the steel composition, for example, nitrides, carbides, oxides, but here it is not managed to increase significantly the low-temperature toughness of metal.

The low-temperature embrittlement of metal is due to a dislocation structure. When examining the medium-alloyed metal of electroslag remelting, produced under flux, containing REM oxides, the authors of [2] revealed a clear interrelation of plastic characteristics and toughness with peculiarities of a fine structure, sizes and nature of distribution of non-metallic inclusions (NMI). Here, the mode of metal fracture under the effect of REM was changed from quasi-brittle to tough transcrystallite.

The cause of increase in cold resistance of low-alloyed and low-carbon steels, microalloyed with cerium, is explained in [5] by decrease in density of dislocations and Patch–Hall factor which characterizes the degree of their locking. It should be noted here that cerium does not change parameters of the crystalline lattice, i.e. it does not alloy the solid solution.

Decrease in dislocation density was mentioned also by authors of [6], who examined the high-chromium steel, being microalloyed with REM (cerium, lanthanum, niobium). However, they described another scheme of effect: REM, interacting with impurities in metal, show a barrier effect and arrest the movement of dislocations.

The obtained data prove a contradiction of some statements of hypotheses and require additional studies.

The present work was aimed at integrated estimation of REM effect on low-temperature behaviour of metal. Results of investigations make it possible to clarify many unclear moments and to simplify approaches to the problem of REM application in steel welding. It is difficult to obtain the reliable results in fine procedures of investigation of metal of welded joints because of specifics of its producing. Improving the experiment validity and taking into account the similarity of processes of solidification of castings and welds [7, 8], the cast St.30, which is close to carbon and low-alloyed structural steels in carbon content, was taken as a model for investigations. Yttrium, showing the greatest effect on weld metal, was added to steel in the form of microadditions. Chemical composition of the steel variants investigated is presented in the Table.

At the second stage the weld metal made by electrodes, having microalloyed cast metal in cores, was investigated. Results of investigations will be given in next publications devoted to this problem.

Change in substructure of metal under the effect of yttrium additions was examined using the method of internal friction (IF), which makes it possible to record the dissipation of energy of mechanical oscillations [9].

Temperature and amplitude relations of IF were studied in a relaxometer of «reverse torsion pendulum» type at frequency of free torsional oscillations of 1 Hz order. Measurement was made in a longitudinal magnetic field of 24 A/m intensity. Cylindrical samples of 230 mm length and 8 mm diameter were used. The length of a working part of 3 mm diameter samples was 50 mm.

Metal structure was examined using optical and electron microscopy. Size of a ferrite grain was revealed by the method of random secants. Lattice pitch was determined in line [310] on roentgenograms made by a method of a back-reflection X-ray photography in cobalt radiation. Silver was used as a reference. In parallel with a photographic method a record of a profile of interference maxima in DRON-2 unit in iron radiation was used. The record was made by points. Lines [211] and [220] were recorded. The scanning pitch was 0.05°.

The examinations showed that yttrium addition to steel up to 0.084 % leads to reduction of IF background (Figure 1, *a*). The further increase in yttrium content increases the IF background (Figure 1, *a*, curve *4*).

The IF background decrease in bcc-metals testifies about formation of stabilized structures that is, prob-

Chemical composition of experimental steels

Conditional designation of steel	Elements, wt.%						
	C	Mn	Si	Al	P	S	Y
1	0.30	0.51	0.25	0.027	0.022	0.033	–
2	0.30	0.52	0.28	0.024	0.022	0.028	0.025
3	0.31	0.52	0.27	0.025	0.022	0.027	0.045
4	0.29	0.53	0.27	0.028	0.011	0.025	0.084
5	0.29	0.52	0.28	0.030	0.018	0.021	0.120
6	0.31	0.52	0.26	0.031	0.020	0.021	0.160
7	0.30	0.53	0.28	0.030	0.020	0.007	0.210
8	0.30	0.52	0.30	0.029	0.016	0.006	0.400
9	0.29	0.52	0.28	0.032	0.018	0.006	1.600

ably, due to increase in Peierls–Nabarro force (lattice friction) with a total decrease in amount of dislocations and stronger their locking with interstitial atoms. The latter factor can result both from increase in number of anchored points due to increase in a number of interstitial atoms and also to the growth of energy of interstitial atoms binding with dislocations. According to data of [2], density of dislocation in steels with REM is decreased and their clustering is eliminated.

As to the lattice friction it is known that the small amounts of impurities, dissolving by the type of substitution (yttrium is dissolved in iron by the substitution type) can effect noticeably on the binding forces between iron atoms, thus increasing or decreasing the Peierls–Nabarro barrier.

Thus, the examinations confirm that yttrium adding to steel leads to locking of dislocations. In accordance with data of [9] the critical amplitude γ_{cr}, characterizing the moment of dislocation separation from their impurities of locking, are calculated by formula

$$\gamma_{cr} = \frac{U}{Gb^3} C_0 \exp\left(-\frac{U}{kT}\right),$$

where U is the energy of interstitial atoms binding with dislocations; G is the shear modulus; b is the Burger's vector; C_0 is the mean concentration of impurities in a solid solution.

It follows from formula that the critical amplitude depends linearly on the concentration of impurities and on energy of their interaction with dislocations exponentially. The latter factor plays a main role in locking of dislocations and increase in energy of their separation from their impurities of locking.

The fact of dislocations locking in microalloying of steel with yttrium is confirmed also by decrease in angle of inclination of branch α of amplitude-dependent IF (see Figure 1, *a*). Here, it should be noted that the minimum value of IF background and tg α is recorded at yttrium content 0.084 % — 0.5, and in steel without yttrium, from 0.045 and 0.16 % yttrium — 1.48, 0.58 and 0.76, respectively.

One of the most sensitive factors characterizing the change in level of dislocation locking is a thermal stability of the metal crystalline structure. The study of the temperature relation of IF background of steels with different content of yttrium showed that the

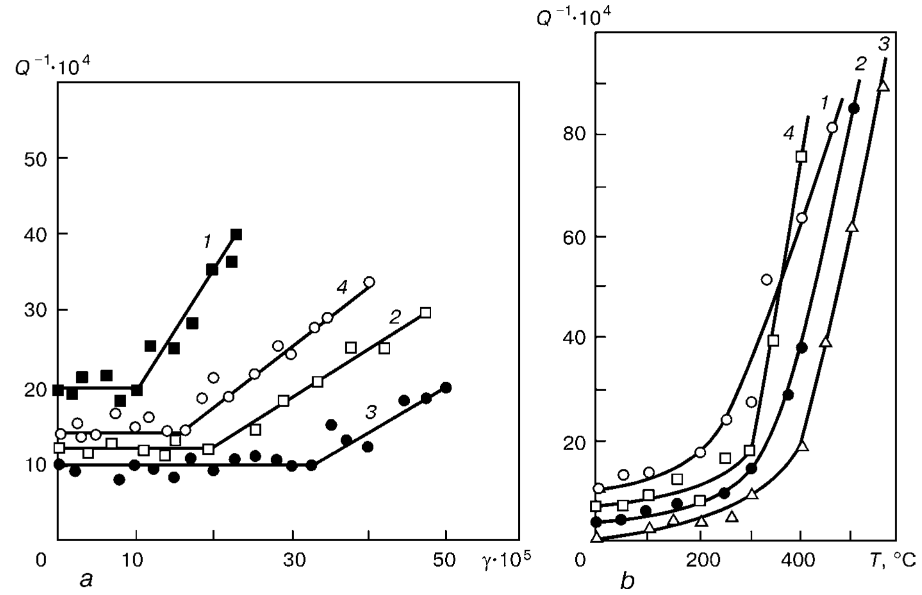

Figure 1. Amplitude (*a*) and temperature (*b*) relationships of internal friction background: *1* — steel without yttrium; *2–4* — with a mass share of yttrium 0.045, 0.084 and 0.16 %, respectively

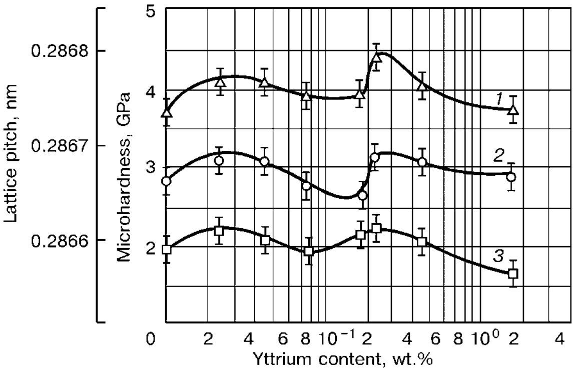

Figure 2. Change in a pitch of α-phase lattice (*1*), microhardness of pearlite (*2*) and ferrite (*3*) depending on yttrium content in steel

lowest IF background in the given case is in steel, containing 0.084 % Y (see Figure 1, *b*, curve *3*). At yttrium content up to 0.084 % in steel the thermal stability threshold is increased, i.e. the increase in temperature of beginning of intensive separation of dislocation is occurred. In steel with 0.084 wt.% Y this temperature lies in the range of 400 °C, while this threshold in steel without yttrium is observed in the 280–300 °C range. The further increase in yttrium content (in our case 0.16 wt.% Y in steel) leads to the increase in IF background and, respectively, to the reduction of temperature of dislocation separation (see Figure 1, *b*, curve *4*). It follows from above-mentioned that when yttrium up to 0.084 % is added to steel the tendency of increasing the structure stabilizing was revealed, while at 0.084 % Y content its maximum stability is provided.

Main factors, influencing increase in energy of interatomic bonds, can be as follows: dissolution of yttrium in solid solution, i.e. at metal alloying, and clustering of interstitial atoms around imperfections of crystalline lattice. The effect of metal refining by yttrium, leading to neutralizing of surface-active elements (sulphur, oxygen, carbon), decreasing the energy of interatomic bonds, is not excluded. The latter factor represents a special interest, because the weld metal during welding undergoes the high-temperature treatment and REM in metal, having high thermodynamic activity, are consumed mainly for metal refining.

Yttrium additions in steel influence adequately on the change in pitch of α-phase lattice and microhardness of ferrite and pearlite (Figure 2). At yttrium content approximately up to 0.045 % the maxima on curves are observed. The further increase in yttrium up to 0.16 % causes the decrease in the mentioned parameters and then the growth in lattice pitch (maximum at 0.21 % Y) is observed again.

This complex change in lattice parameter is explained by a simultaneous effect of several factors. From the data of several authors the yttrium in small amounts is dissolved in iron that leads to the growth in the lattice pitch. In parallel with dissolution in iron its interaction with oxygen and other elements providing steel refining is occurred. In boundary regions the submicroscopic precipitations of yttrium with horophile impurities are formed that leads to depletion of solid solution with yttrium and, respectively, to the decrease in the lattice pitch (0.045–0.16 % range of concentrations) [10]. Increase in mass share of yttrium up to 0.21 % leads again to the growth in lattice pitch, even to larger growth than that at the initial stage. From data of [11] the REM atoms are dissolved again in the boundary zones after binding all impurities which fill the grain boundaries.

The change in lattice pitch has a good correlation with a shape of curve of pearlite and ferrite microhardness (Figure 2, curves *2*, *3*). Decrease in microhardness of structural constituents at mass share of yttrium of more than 0.2 % is explained by decrease in its content in α-solution due to formation, as was shown earlier [12], of high-yttrium phases and also by decrease in carbon content in ferrite due to formation of yttrium carbides in the boundary regions.

The increase in energy of interatomic and intercrystalline bonds, i.e. change in distribution of electrons on external shells under the REM effect, contributed greatly to the change of metal properties, in particular in increase in energy of low-temperature fracture. State of solid solution and carbide phase were studied using the method of a nuclear gamma-resonance which is known as Mössbauer effect. To obtain spectrograms ^{57}Co in palladium of 20 mCi activity was used as source of γ-quanta. Fine structure of Mössbauer spectra of absorption was analyzed, thus making it possible to judge about electronic structure of metal; value of quadrupole splitting, carrying information about formation of chemical compounds of a non-stoichiometric composition; change in width and intensity of spectrum lines, associated with atomic imperfection and amount of substance analyzed; isomeric shear, giving information about changing radiating and absorbing nuclei in a local chemical environment.

Analysis of Mössbauer spectra of steels with different yttrium content, obtained as a result of experiment, did not reveal their noticeable difference. They represent six lines of absorption corresponding to Zeeman splitting and typical of α-iron.

At a comprehensive analysis of dependence of width of most intensive (first and sixth) lines of spectrum on the yttrium content, their widening is first observed, and then their width begins to decrease in the region of concentrations by ≈ 0.045–0.084 % and reaches a peak of narrowing at yttrium mass share 0.084–0.1 % (Figure 3). The further increase in yttrium content leads to the widening of lines.

Coming from results obtained, it is possible to state that minimum degree of crystalline lattice distortion is provided at mass share of yttrium in steel in the 0.084 % range and associated with a solid solution refining, change in energy of interaction of interstitial impurities with dislocation in dissolution with given IF changes (see Figure 1). Analyzing the shape of curve *1* in Figure 3 it should be noted that at mass share of yttrium of about 0.045 % the isomeric shear changes sign for opposite. Such change proves about the decrease in density of *s*-electrons on a resonance nucleus [13] and increase in amount of *3d*-electrons in α-iron that is equivalent to increase of degree of bond covalence [14].

In study of spectra of carbide deposits, precipitated by electrolytic etching from steels of initial variant

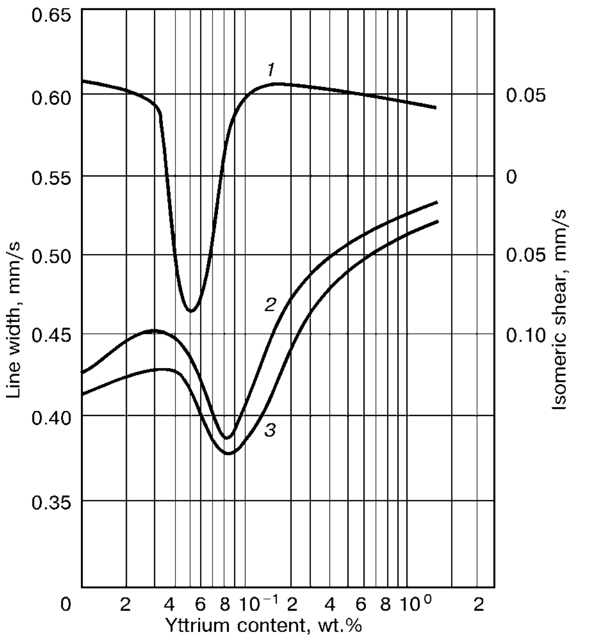

Figure 3. Isomeric shear (*1*) and width of first (*2*) and sixth (*3*) lines of absorption spectrum depending on yttrium content in alloy

and containing yttrium, a quadrupole splitting (Figure 4) was revealed whose value is changed depending on the yttrium amount (see curve *3* in Figure 4). The presence of the quadrupole splitting proves about non-symmetry of environment of iron resonance nucleus in cementite.

Decrease in quadrupole splitting at mass share of yttrium up to 0.045 % is a result of increase in symmetry of fields effecting the resonance nucleus. At yttrium concentration above 0.045 % the changes in quadrupole splitting are caused, probably, by a starting formation of yttrium compounds with carbon and iron. The significant positive isomeric shear of cementite is caused by the higher density of *s*-electrons in iron of cementite than in a pure iron. Correlation

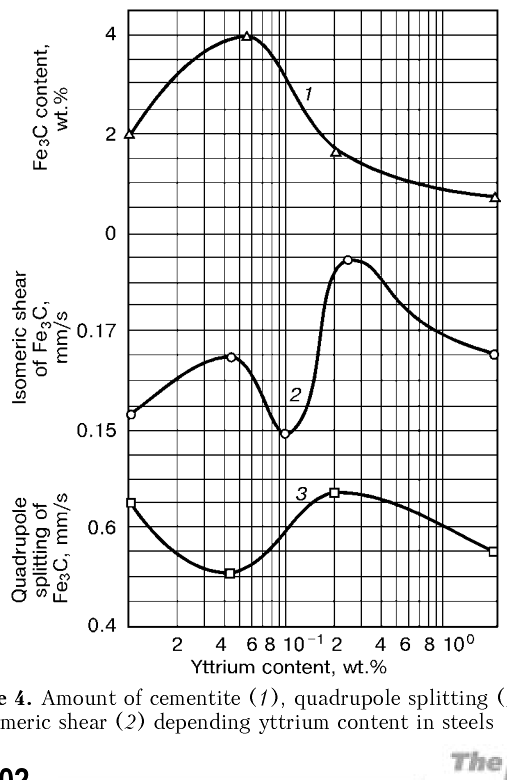

Figure 4. Amount of cementite (*1*), quadrupole splitting (*3*) and its isomeric shear (*2*) depending yttrium content in steels

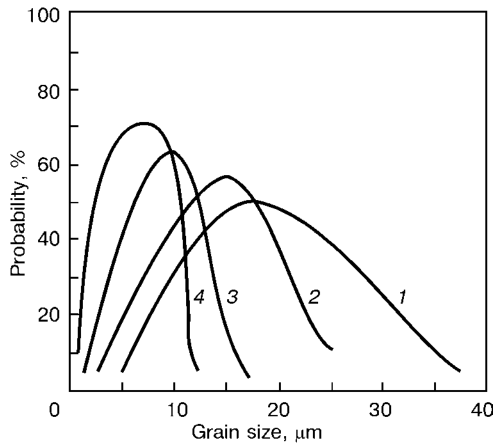

Figure 5. Distribution of grains by sizes in St.30: *1* — without yttrium; *2–4* — with a mass share of yttrium 0.084, 0.21 and 0.4 %, respectively

between the cementite amount and isomeric shear proves about changes in stoichiometric composition occurring under the yttrium influence.

Yttrium adding has a great influence on the structure dispersity. With grain refining their scattering in size is reduced (Figure 5). Size of grain in steel without yttrium is from 5 to 40 μm. In steel with 0.4 % Y 70 % of grains has a size of about 6 μm at scattering from 2 to 12 μm. Ratio of structural constituents, ferrite and pearlite, is also changed (Figure 6). Increase in yttrium content up to 0.1 % leads to the growth of a pearlitic constituent which reaches 80 % at the given concentration. The further increase in yttrium content leads to the decrease in pearlite content and increase in ferrite. The modifying effect of steel structure is at the microlevel. Structure of pearlite is greatly changed: cementite plates lose orientation within the pearlite colony, they are crushed and acquire round shape (Figure 7). At yttrium mass share starting from 0.084 % the pearlitic regions acquire structure similar to a grained structure. Then, when yttrium begins to display itself as ferritizer the pearlitic regions become laminated with a high degree of dispersity.

Results of experimental investigations can make the following conclusions.

Mass share of yttrium 0.02–0.045 % in steel causes the growth in pitch of α-phase lattice that indicates its dissolution in a solid solution. This leads to the

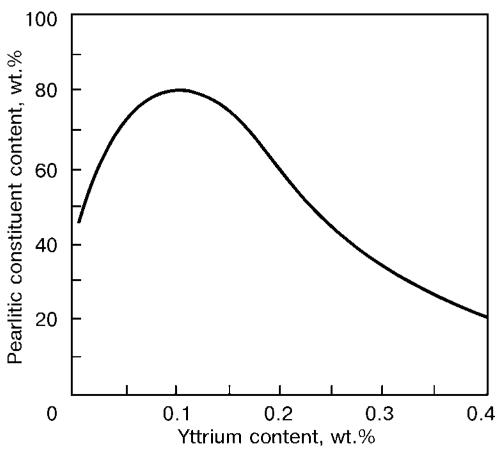

Figure 6. Change in amount of pearlite in yttrium adding to steel

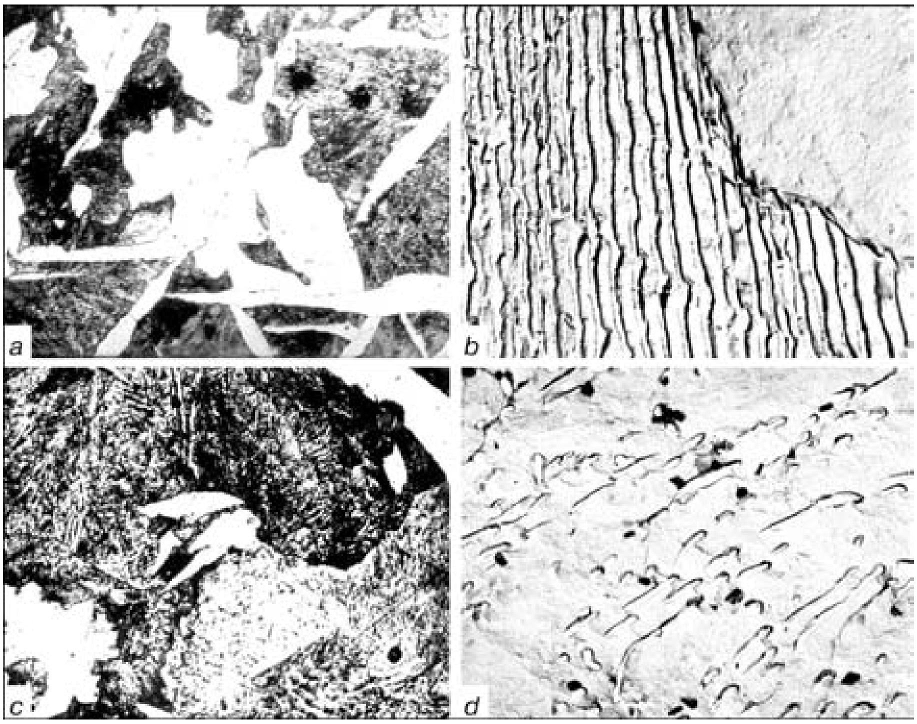

Figure 7. Structure of a pearlitic constituent in steel without yttrium (*a, b*) and with 0.084 % yttrium (*c, d*) (*a, c* — ×500; *b, d* — ×10000)

increase in energy of atoms binding in crystalline lattice that is proved by changing a sign of isomeric shear characterizing the increase in degree of bond covalence. The intensive growth of a pearlitic constituent is also noted.

The increase in mass share of yttrium from 0.045 to 0.084–0.1 % intensifies the process of refining solid solution, leads to formation of a stabilized structure, decrease in density of dislocation with a simultaneous increase in degree of their locking by interstitial atoms, decrease in a pitch of α-phase lattice. The total share of a pearlitic constituent in steel containing 0.084 % Y reaches 80 % at a simultaneous strong modifying of pearlitic colonies and change of their shape. Grain size is decreased.

The further growth of yttrium mass share up to 0.16 % and higher leads to the decrease in a pearlitic constituent up to 20–25 % with simultaneous formation of phases, highly-enriched with yttrium, in the boundary regions. The mentioned changes have a good correlation with results of nuclear gamma-resonance examinations, from which the increase in quadrupole splitting and isomeric shear proves about formation of complex compounds of yttrium with iron and carbon. Strong modifying effect ia appeared, structure stability is reduced, which is confirmed by increase in IF background.

Results of investigations show adequately the complex dependence of change in metal properties on the amount of yttrium added. Mechanisms of yttrium effect on metal, i.e. alloying, refining, modifying, are closely interrelated. The data obtained can serve an important criteria in study of the nature of a positive REM effect on cold resistance of steel and weld metal.

Thus, in parallel with modifying and refining effect the yttrium in certain concentrations shows an alloying effect on steel, increases the forces of interatomic bonds in crystalline lattice, increases degree of locking dislocations at simultaneous decrease in their density and stabilizes the structure.

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WELDED JOINTS OF AUSTENITIC STEEL 25Cr–20Ni–2Si IN AUGMENTED TURBOPISTON ENGINES

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Experimental data are given on prevention of hot cracks in dissimilar welded joints of high-silicon 25Cr–20Ni–2Si steel with 10Kh18N10T steel and KhN65MTYu nickel alloy. It is shown that alloying of weld metal with boron in the amount of 0.45–0.80 % improves the technological strength of welds.

Key words: *austenitic weld, hot cracks, microstructure, second primary phase, welded joints*

Working temperature of gas in augmented turbopiston engines [1, 2] may rise up to 800–1000 °C. The main requirements made of the material of the parts operating at such a temperature are strength and resistance to high-temperature gas corrosion. In keeping with these requirements high-temperature and heat-resistant steels and alloys of 25Cr–20Ni–2Si type, where the silicon weight fraction may be up to 2–4 %, are used in the augmented turbopiston engines developed by the Kharkiv Engine Design Bureau (KhEDB). Casting steel 20Kh25N19S2L (EI 283) is applied for fabrication of welded structure of discharge manifold, and wrought steel 20Kh25N20S2 is used for the combustion chamber parts.

It is known [3, 4] that the problem of welding austenitic steels and alloys with silicon is particularly complicated. Silicon pertains to elements formed on the crystallite boundaries in the weld metal in the liquid phase interlayer, which induce hot cracks. This is specifically manifested, if the weld metal has a higher content of nickel. In this case the elements with liquation capabilities, have a lower solubility and there exists a higher probability of formation of liquid eutectic interlayers. Single-phase austenitic welds of the type of 25Cr–20Ni, 25Cr–20Ni–2Si and 25Cr–35Ni–2Si are so highly susceptible to hot cracking in welding of items that this has become a classical example of cracking in welding (Figure 1, *a*). A characteristic lowering of the critical deformation rate and increase of the susceptibility to hot solidification cracking with the increase of silicon weight fraction is known for welds of the type of 20Cr–32Ni [4] and 15Cr–35Ni [5] (Figure 1, *b*).

To reduce the cracking susceptibility of weld metal in welding of the above steels and alloys, welding modes are sometimes used, providing a lowering of the share of base metal and of silicon, contributed to the weld pool, respectively. No significant increase of the cracking resistance is found, however, as even a small share of silicon in single-phase welds leads to formation of liquid eutectic interlayers.

The structure of cast austenitic steels of Kh25N20S2 type contains two primary phases, namely austenite and silicon eutectic. This guarantees good weldability of these steels and absence of near-weld cracks. Problem of welding such steels consists in achieving a weld metal composition providing cracking resistance. By analogy with the HAZ the weld cracking resistance may also be provided by a two-phase primary structure of its metal, for instance, austenitic-ferritic structure [3]. It is found [3, 6] that in order to prevent hot cracks in welding of steels and alloys exposed to elevated and high temperatures in service, it is rational to use boride eutectic as the second primary phase in the weld metal. Among the

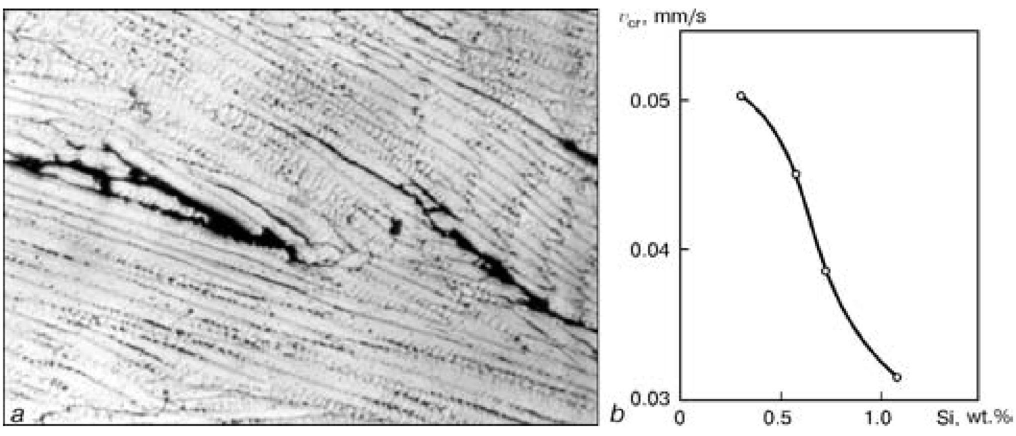

Figure 1. Susceptibility to solidification cracking in single-phase austenitic welds: *a* — hot solidification cracks in the weld metal of an item on 20Kh25N20S2 steel (×100); *b* — silicon influence on critical deformation rate v_{cr} of deposited 21Cr–32Ni–Nb metal [4]

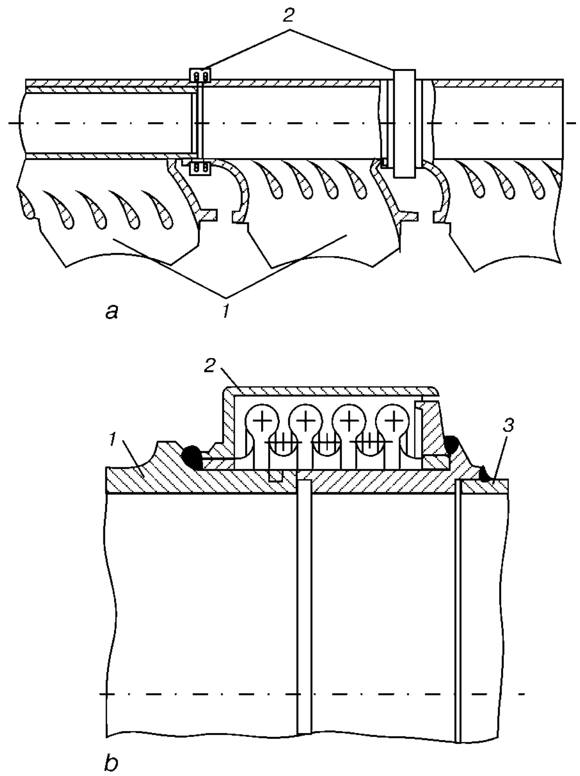

Figure 2. Design of a welded header of a turbine: *a* — schematic of a joint of parts in the header (*1* — cast nozzles; *2* — intermediate compensator); *b* — schematic of joining parts in a nozzele–compensator weldment in front of turbine entrance (*1* — nozzle of cast steel 20Kh25N19S2L; *2* — protective sleeve of bellows of 10Kh18N10T steel; *3* — turbine entrance)

studied with this purpose alloys of iron, chromium and nickel, containing elements, which form eutectics (phosphorus, sulphur, chromium, boron) [3], boron has an advantage. Carbon is inferior to it, as during ageing the carbides undergo transformations and such a structure is unstable. The chief advantage of boron, compared to the above elements, is stability of the structure and properties of deposited metal, alloyed with boron, no susceptibility to embrittlement and high long-term ductility of welds.

Being an active raiser of hot cracks in welds at its low content (hundred fractions of a percent), in large amounts (more than 0.3 % for Fe-based austenitic welds and more than 0.2 % for Ni-based welds), boron prevents their formation. At a sufficient content of the eutectic liquid, it encloses the crystallites and promotes relaxation of welding stresses. This results in a greater resistance of welds to hot cracking.

Table 1. Influence of boron content (wt.%) on critical deformation rate v_{cr} (solidification cracking susceptibility) in austenitic welds [5]

Weld metal type	*Si*	*B*	v_{cr}, *mm/min*
Kh14N18VM	0.51	–	0
	0.29	0.28	3.26
	0.48	0.28	3.14
Kh14N18VMTYu	0.36	–	0
	0.69	–	0
	0.34	0.32	3.55
	0.56	0.36	3.55
Kh15N35VMT	0.35	–	0
	0.76	–	0
	0.37	0.33	1.54
	0.59	0.39	3.03

The data of [5] are indicative of an increase of the critical deformation rate and reduced hot solidification cracking in alloying of austenitic welds of 15Cr–35Ni type (Table 1) and nickel welds of KhN67MVTYu type [7] with boron. Increase of cracking resistance of welds is also found in boron alloying of nickel welds of the type of Ni–Cr and Ni–Cr–Mo [5].

The PWI developed a number of austenite-boride welding consumables, which provide a higher resistance to cracking of welds [5, 8]. In particular, EP 532 (08Kh25N20S3R1) welding wire has been developed for welding 25Cr–20Ni–2Si steel [9]. This wire has been used in industry already starting from 1970s in welding muffles of carburizers, thermal furnace rolls, repair welding of nozzle diaphragms and blades of gas pumping unit turbines and gas turbine blades [5, 7, 10–13].

This paper gives the data on application of austenite-boride wire EP 532 for welding gas turbine

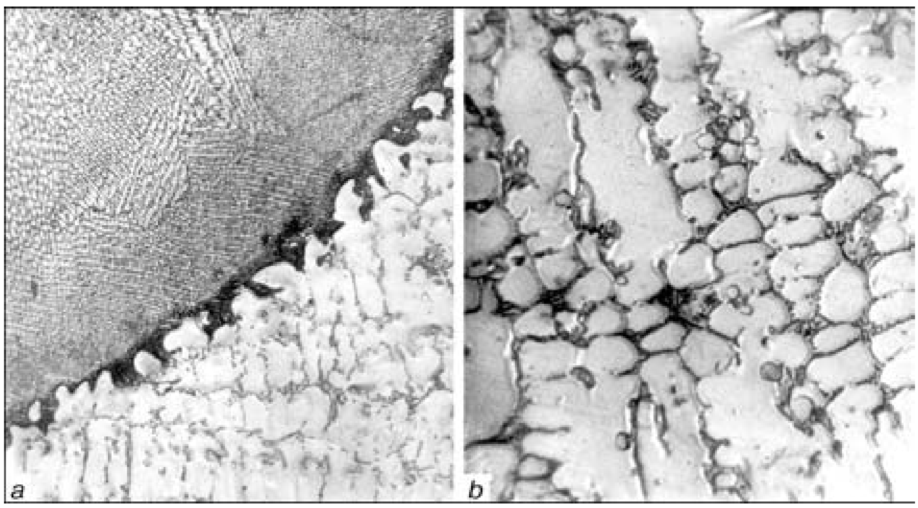

Figure 3. Microstructure of a nozzle-compensator welded joint of the header from the nozzle side (*a* — ×200; *b* — ×100)

Table 2. Content of chemical elements (wt.%) in the weld metal, base metal and EP 532 wire of nozzle–compensator welded joint of the header

Object of study	*C*	*Mn*	*Si*	*Cr*	*Ni*	*B*	*S*	*P*
Weld metal	0.09	1.05	2.3	22.10	17.3	0.55	0.014	0.021
Base metal (EI 283 steel)	0.16	1.10	3.3	25.2	19.0	–	0.014	0.019
EP 532 wire (to specification requirements)	≤ 0.10	≤ 1.50	2.5–3.0	24.0–27.0	18.0–21.0	0.50–0.80	≤ 0.020	≤ 0.030

headers in augmented turbopiston engines*, which are batch- produced by PA «Malyshev Plant» (Kharkiv).

Turbopiston engines with a higher level of forcing, developed by KhEDB, are fitted with high-speed outlet headers, made in the form of two asymmetrical ejectors. The purpose of the headers is feeding the flows of discharge gases to the power turbine. The gas temperature and pressure in the headers vary from 300 up to 900 °C and from 150 to 400 kPa over a 300 s period, respectively. Headers consist of individual nozzles produced by precision casting from heat-resistant EI 283 steel with an outer diameter of 120 mm and wall thickness of 4 mm. Temperature deformation compensators are located between the nozzles (Figure 2). The latter are made of austenitic steel 10Kh18N10T and insulated from the direct impact of the hot gas.

A dissimilar joint of the nozzle of Si-containing EI 283 steel and compensator of 10Kh18N10T steel is made by manual tungsten electrode argon-arc welding with EP 532 austenitic filler wire alloyed with boron. In this case weld metal is produced with a two-phase primary structure (Figure 3), namely γ-solid solution of alloying elements in iron and boride eutectic of γ + (Cr)B or (Cr, Si, Fe, Ni)$_n$B$_m$. Alloying element content in the weld metal of the nozzle–compensator welded joint of the header is shown in Table 2. Technology used in header manufacturing provides sound welded joints with a high service reliability.

In EP 532 welding wire the silicon eutectic is a component of the overall boride-silicon eutectic [5]. Simultaneous addition of boron and silicon in the selected ratio (0.5–0.8 % B and 2.5–3.0 % Si) ensures weld metal resistance to cracking and increases the level of oxidation resistance at high temperatures (Table 3). Scale resistance of the metal of austenite-boride welds, made with EP 532 wire at the temperature of 900 °C corresponds to the level of EI 283 steel (testing was conducted for 1000 h, testing data are provided by I.I. Polzunov Central Boiler-Turbine Institute). By the levels of short-time rupture and long-time strength welded joints of EI 283 steel, made with EP 532 wire are equivalent to the base metal [5] (Fi-gure 4). The well-known problem of embrittlement of single-phase welds of the type of Fe–Cr–Ni at thermal ageing [3, 12] is practically absent in two-phase austenitic-boride welds. Welds of this type are not subject to embrittlement at long-term service under the conditions of elevated and high temperatures. Values of impact toughness of carburizer muffles of steel EI 283 after long-term service at 930 °C for 14000 h are higher than after welding and annealing (Table 4).

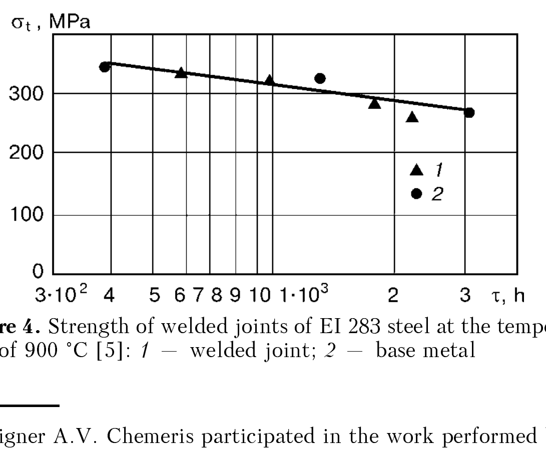

Figure 4. Strength of welded joints of EI 283 steel at the temperature of 900 °C [5]: *1* — welded joint; *2* — base metal

Evaluation of mechanical properties of the header welded joints was performed on samples of rigid welded joints simulating the nozzle–compensator joint. Butt welding of samples of steel EI 283 (cast plate) and 10Kh18N10T (wrought plate steel) 10 mm thick was performed in argon with non-consumable tungsten electrode with EP 532 filler wire. As shown by the testing result, as to the level of short-time strength at room and high temperatures, the welded joints simulating the nozzle–compensator joint, are close to the level of strength of EI 283 steel (Table 5).

In scientific and practical terms the results of experimental work conducted at KhEDB with the PWI participation are also of interest: a cover plate of wrought Si-containing steel Kh25N20S2 is welded to fasteners of a heat-resistant nickel alloy EI 893

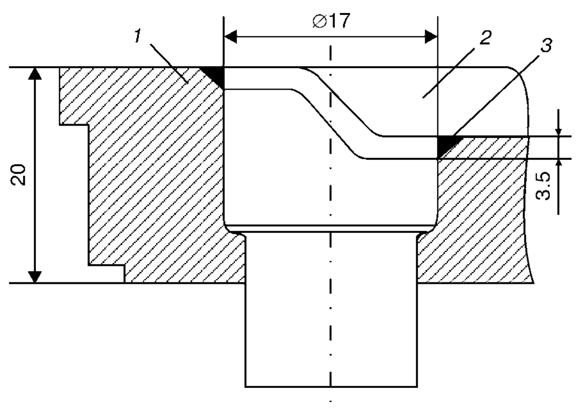

Figure 5. Schematic of a joint of parts of the combustion chamber: *1* — cover plate of 20Kh25N20S2 steel; *2* — fastener of EI 893 alloy; *3* — weld

*Designer A.V. Chemeris participated in the work performed by KhEDB on header welding.

Table 3. Scale resistance of base metal and weld metal made with EP 532 wire at the temperature of 1100 °C [5]

Object of study	*Weight fraction of elements, %*			*Increase in weight, $g/(m^2\cdot h)$*
	Cr	*Si*	*B*	
EI 283 steel	25.9	1.70	–	0.236
Weld metal	25.7	2.56	0.50	0.271

(Kh65VMTYu)*. When the above dissimilar joint is made (Figure 5), a nickel weld should be produced, proceeding from the conditions of its strength. As was noted above, boron alloying to prevent formation of welding cracks is also effective for nickel welds [5, 7, 13]. So, study [7] shows that the critical deformation rate v_{cr} and cracking resistance of deposited nickel metal of the type of KhN67MVTYu are increased at boron content above 0.3 %.

Dissimilar rigid welded joints of plates of EI 283 steel and EI 893 nickel alloy 20 mm thick made at the PWI by manual arc welding into a V-shaped circular groove 4 mm deep (edge bevel angle of 20–25°), demonstrated the effectiveness of applying nickel boride electrodes EZh-6, which provide the deposited metal alloying with boron within 0.45–0.75 %. Investigations were conducted on macro- and microsections. Weld metal microstructure contains two primary phases, namely γ-solid solution of elements (Cr, Mo, Fe) in nickel and boride eutectic ($\gamma + (Ni)_3B$ or γ + (Ni, Cr, Fe, Si, Mo)$_n$B$_m$ type. Presence of the second primary phase, namely an eutectic, promotes increased resistance of weld metal to hot solidification cracking. The above rigid samples did not have any cracks, either after welding or after post-weld heat treatment (heating at 950 °C for 30 min, cooling in air).

Thermographic analysis by differential thermal analysis (DTA) method shows that the metal of

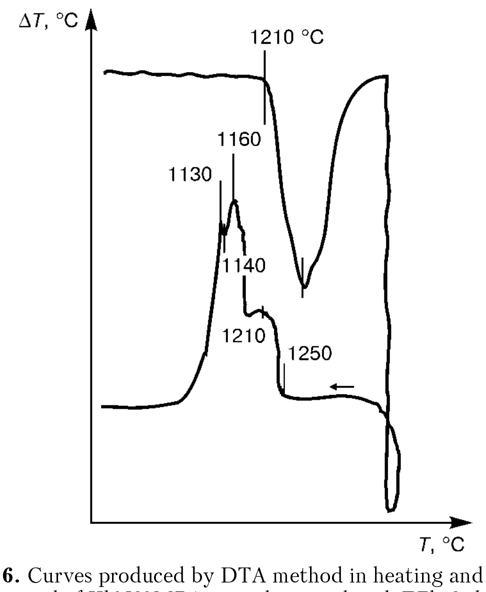

Figure 6. Curves produced by DTA method in heating and cooling of weld metal of KhN60MR1 type, deposited with EZh-6 electrodes

Table 4. Mechanical properties of welded joints of steel EI 283 made with EP 532 wire, before and after service at room temperature

Object of study	*Condition*	σ_t, *MPa*	a_n, J/cm^2
Welded joint	After welding and annealing	460*	19**
	After service	420*	30**
Base metal (EI 283 steel)	Before service	456	140
	After service	420	125

*Fracture in the base metal.
**Notch across the weld.

KhN60MR1 type deposited with nickel boride electrodes EZh-6 has a relatively narrow temperature interval of solidification (about 40 °C) (Figure 6). Solidification starts with precipitation of solid solution crystals. As they grow, the liquid phase is enriched with boron and other segregating elements.

Solidification results in formation of a eutectic, taking up a considerable part of the deposited metal volume. In an alloyed nickel alloy KhN60MR1 the temperature of boron eutectic is higher than in a binary Ni–B alloy (1140 °C) and is about 1210 °C. The above dissimilar joints were welded under the conditions of KhEDB pilot production on experimental parts of engines. Two variants of the technology were tired out, namely argon-arc welding with nickel filler wire KhN60M (EP 367) and arc welding with EZh-6 type coated electrodes (deposited metal of KhN60MR1 type). In the case of a single-phase nickel weld produced in argon-arc welding with EP 367 filler wire, hot cracks were found in the weld metal (Figure 7). Under the conditions of production and a higher rigidity of dissimilar joints on full-scale parts of 20Kh25N20S2 steel and high-temperature nickel alloy EI 893 a sound joint without cracks was produced only in welding with a two-phase nickel weld made with EZh-6 electrodes (Figure 7, *b*). Comparison of the results of welding with the data on weld metal composition (Table 6) shows that in a single-phase nickel weld (EP 367 filler wire) hot cracks form at silicon content of 0.72–0.98 %. In a two-phase boride weld with a high cracking resistance (EZh-6

Table 5. Mechanical properties of welded joints simulating the header nozzle–compensator joint of EI 283 and 10Kh18N10T steels made with EP 532 wire

Object of study	*T*, °*C*	σ_y, *MPa*	σ_t, *MPa*	δ, *%*	ψ, *%*	a_n, J/cm^2
Weld metal	20	310	530	14.2	18.2	22
	900	108	130	29.5	34.7	38
Welded joint	20	–	442*	–	–	–
	900	–	102*	–	–	–
EI 283 steel	20	270	460	18.0	24.2	140
	900	72	98	28.4	36.3	–

*Fracture runs in steel 10Kh18N10T.

*Designer V.A. Bornoenko participated in KhEDB work on welding the cover plate–fastener assembly.

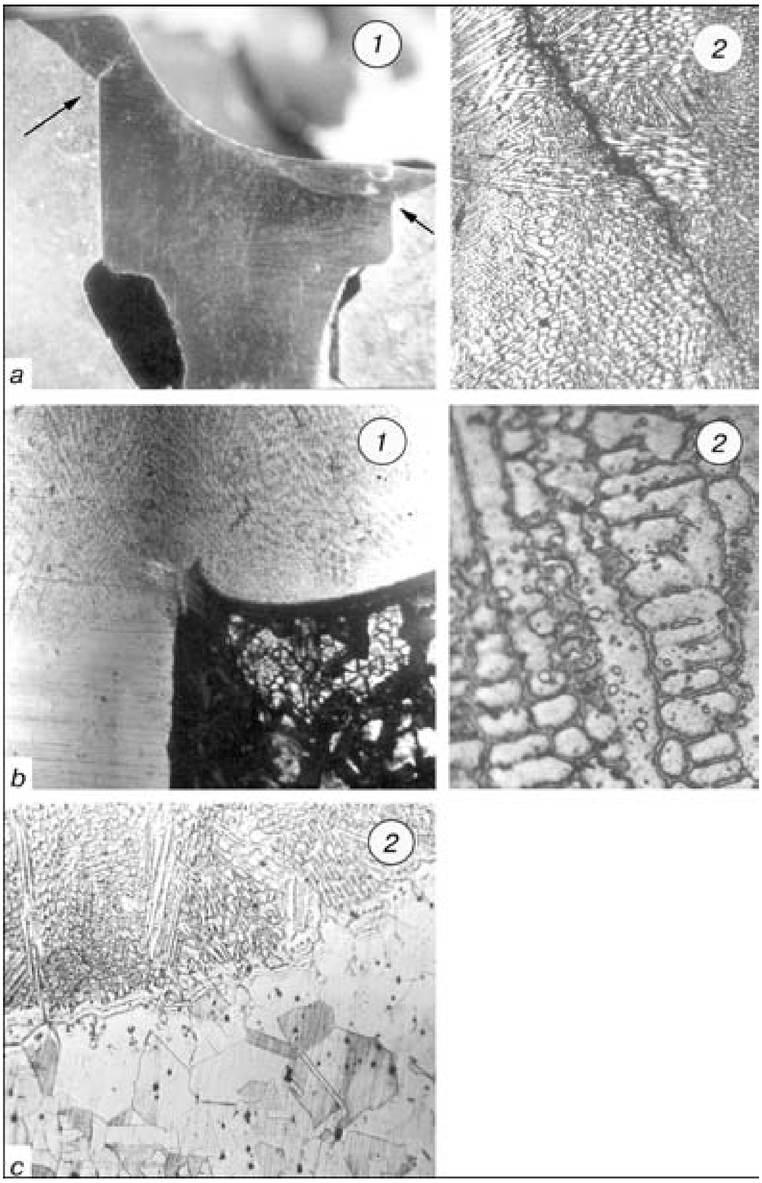

Figure 7. Macro- (*1*) and microstructure (*2*) of a welded joint of a cover plate–fastener in an experimental assembly of the combustion chamber: *a* — hot solidification cracks in the metal of a single-phase weld (*1* — ×2; *2* — ×100); *b* — two-phase weld, no cracks (*1* — ×20; *2* — ×200); *c* — near-weld zone of a two-phase weld from the side of the fastener of KhN65VMTYu alloy, no cracks (*2* — ×100)

Table 6. Content of chemical elements (wt.%) in dissimilar welded joints of cover plate–fastener of 20Kh25N20S2 steel and EI 893 nickel alloy

Object of study	*Filler (electrode)*	*C*	*Si*	*Mn*	*Cr*	*Ni*	*Mo*	*W*	*B*	*Fe*	*Al*	*Ti*
Weld metal	EP 367*	0.11	0.63	0.40	16.6	Base	11.3	0.9	–	9.0	0.10	0.20
		0.10	0.78	0.33	17.0	Same	10.6	0.8	–	11.0	0.07	0.18
	EZh-6**	0.10	1.22	0.43	19.0	»	14.5	1.0	0.58	10.5	0	0.20
20Kh25N20S2 steel	–	0.16	2.26	1.00	23.5	19.1	–	–	–	Base	–	–
EI 893 alloy	–	0.06	0.29	0.42	15.9	Base	4.0	9.4	–	2.0	1.50	1.50

*In argon-arc welding in the following mode: U_a = 220 V, I_w = 60–75 A.
**In arc welding at I_w = 90–140 A.

electrodes) silicon content is higher and equal to 1.22 %.

Thus, the results of studying dissimilar welded joints of austenitic steel and high-temperature nickel alloy with high-silicon austenitic steels 20Kh25N19S2L (EI 283) and 20Kh25N20S2 of headers and experimental parts of the chamber demonstrate a higher resistance of two-phase austenitic-boride Fe–Cr–Ni and nickel welds to hot cracking. Austenite-boride welding consumables are promising materials for welded structures of high-temperature steels and alloys.

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STRUCTURE AND PROPERTIES OF NICKEL-BASED ALLOY DEPOSITED BY LASER-POWDER METHOD

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Structure and properties of Ni-based deposited layer produced by a laser-powder surfacing were examined. It was established that it possible to produce coatings with a microcrystalline, amorphous-crystalline or amorphous structure depending on the surfacing technological conditions. Tests on corrosion resistance and wear were performed. It was found that it is rational to use the deposited layers with amorphous-crystalline structure for the parts operating in aggressive media and in the conditions of abrasive wear.

Key words: *laser surfacing, nickel-based alloys, structure, corrosion resistance, wear resistance*

Laser beam (as a highly-concentrated energy source) possesses great technological capabilities in fulfilment of welding and surfacing jobs. A special interest in laser surfacing consists of a feasibility of producing metal of amorphous or microcrystalline structures as a result of melting and subsequent superfast cooling in a thin surface layer. The produced two-phase (amorphous phase + crystalline) or microcrystalline (one or several phases with a very small size of grain) deposited layers can have a high corrosion resistance, wear resistance, magnetic properties, increased hardness, etc. [1–3].

The aim of the present work is to reveal the regularities of effect of technological conditions of surfacing Ni-based alloys on properties of the deposited layers.

The initial powder had the following composition, wt.%: Ni — base; Fe — 40.0; B — 4.0; Cr ≤ 1.0; Al ≤ 0.5; C ≤ 0.2; Si ≤ 1.0. Surfacing of the material was performed in a shielding gas using continuous CO_2-laser with a generation of infrared radiation and 10.6 μm wave length. Basic experimental equipment was a laser technological complex «Kometa-2M» of 1 kW rated power. Heat source was moving at 4–10 mm/s rate providing deposited beads of 0.5–1.5 mm width and up to 1 mm height. To focus the radiation, a lens with a focal distance F = 300 mm was used. Surfacing was made on a flat surface of the St.3 (C — 0.14–0.22; Mn — 0.3–0.6 wt.%; Fe —

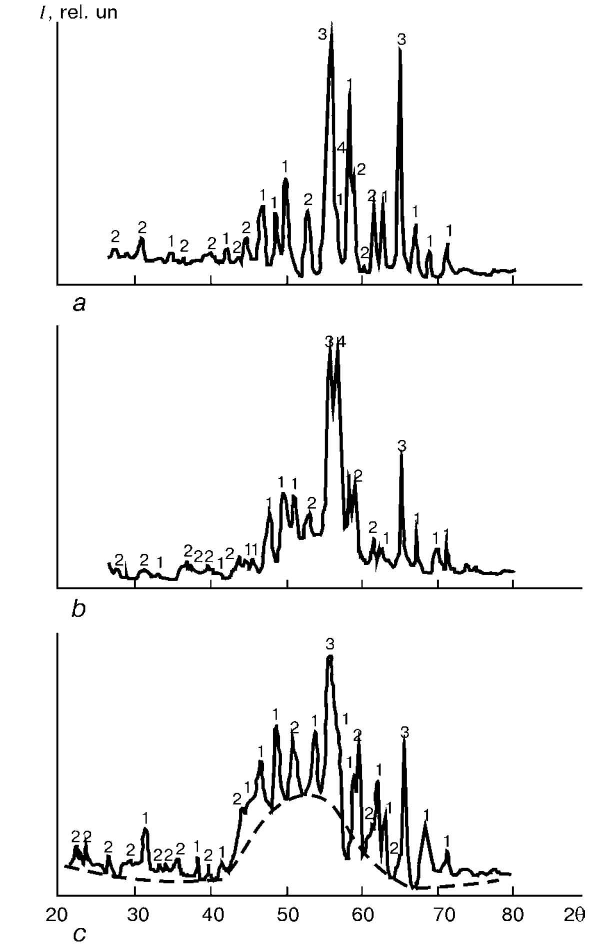

Figure 1. Roentgenograms of deposited layers from alloy of Fe–Ni–B system of microcrystalline (powder consumption Q = = 0.25 g/s, rate of surfacing v = 5 mm/s) (a), amorphous-crystalline (Q = 0.25 g/s, v = 8 mm/s) (b) and amorphous structure (Q = 0.15 g/s, v = 6 mm/s) (c): *1* — Me_3B (rhombic packing of atoms); *2* — Me_3B (tetragonal); *3* — γ-Fe; *4* — γ-Fe

balance) specimen, cleaned preliminary from scale in an abrasive tool. The depositing powder was fed under the 45° angle following the specimen movement.

Structural-phase examinations were performed in a DRON-3 diffractometer, corrosion resistance of deposited specimens was determined using an electron potentiostat P-5848M. Non-working surface of specimens was isolated by acid- and alkali-resistant varnishes. Tests were made in a slightly-acid, neutral and slightly-alkaline (pH 4.5–9.0) media.

The wear resistance was investigated in a friction machine of IPL design in accordance with standards 23.201–78, 23.204–87, 23.205–79 and 23.216–84 during sliding friction without lubricant. Cylindrical specimens with 10^{-4} m^2 contact area were tested by moving them along a mating body at 20 mm/s rate. Load on specimen was changed within 5–16 MPa. Steel U8 was used for the mating body.

Figure 1 shows fragments of roentgenograms of scattering intensity I in the interval of angles 2θ = = 0–80° (θ — angle of Wulff–Bragg). Analysis shows that the deposited layer structure depends on the laser surfacing conditions. Layers produced in consumption of 0.25 g/s powder and 5 mm/s surfacing rate (Figure 1, a) have a crystalline structure and consist of

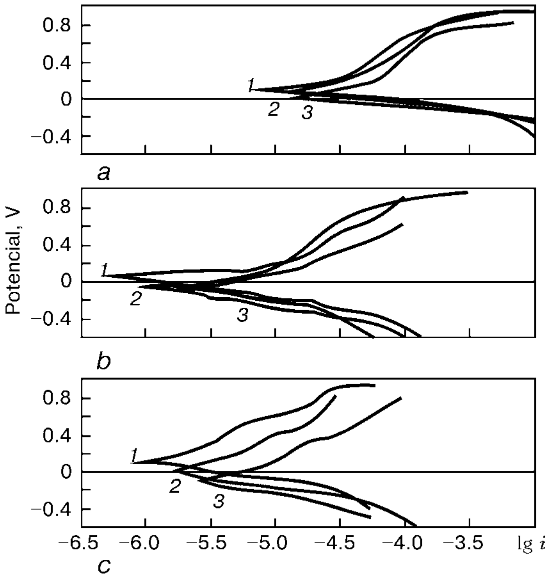

Figure 2. Electrochemical characteristics of deposited layers from alloy of Fe–Ni–B system at pH 4.5 (a), 7.0 (b) and 9.0 (c): *1* — amorphous; *2* — amorphous-crystalline; *3* — crystalline structure (i — corrosion current density, A/cm^2)

a solid solution of (α + γ)-Fe–Ni alloy and borides $(Fe, Ni)_3B$ with tetragonal (a = 0.863, c = 0.437 nm) and rhombic (a = 0.441, b = 0.522, c = 0.662 nm) packing of atoms. At 0.25 g/s powder consumption and surfacing rate above 6 mm/s (Figure 1, b) metastable phases Me_3B, γ-Fe are observed, however, there is no a clearly expressed amorphous halo. Thus, it can be stated that both amorphous and crystalline structural constituents are present in the deposited layer.

The deposited layers produced in 0.15 g/s powder consumption and surfacing rate above 5 mm/s, have mainly the amorphous structure in the surface layer (Figure 1, c). It can be assumed on the basis of the structural analysis that during surfacing of one bead at the mentioned condition the deposited layer has an amorphous structure which after surfacing of the neighboring bead undergoes transition into a crystalline state. This occurs due to the fact that a tetragonal boride, but not an orthorhombic boride, which is more spherically symmetrical (a = 0.441, b = 0.522, c =

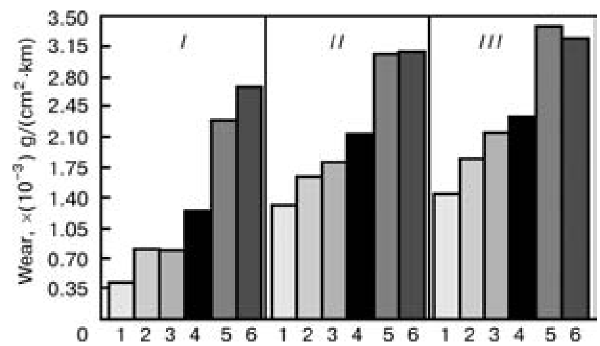

Figure 3. Total wear of the deposited layer from alloy of Fe–Ni–B system under load of 5 (I), 10.2 (II) and 15.3 (III) MPa; microcrystalline structure: *1* — Q = 0.25 g/s, v = 4 mm/s; *2* — Q = = 0.25 g/s, v = 5 mm/s; amorphous-crystalline structure: *3* — Q = 0.25 g/s, v = 6 mm/s; *4* — Q = 0.15 g/s, v = 6 mm/s; amorphous structure: *5* — Q = 0.15 g/s, v = 5 mm/s; *6* — Q = = 0.15 g/s, v = 6 mm/s

Table 1. Results of measurement of corrosion emf in deposited layers from alloy of Fe–Ni–B system in different media

Structure of deposited layer	*Corrosion emf, A/cm²*					
	pH 9.0	*pH 8.0*	*pH 7.0*	*pH 6.0*	*pH 5.0*	*pH 4.0*
Amorphous	0.048	0.050	0.045	0.041	0.038	0.036
Amorphous-crystalline	0.035	0.039	0.033	0.028	0.027	0.020
Microcrystalline	0.027	0.031	0.024	0.021	0.017	0.014

Table 2. Corrosion resistance of deposited layer from alloy of Fe–Ni–B system

Structure of deposited layer	*Corrosion current density, A/cm²*		
	pH 4.5	*pH 7.0*	*pH 9.0*
Amorphous	$6.3\cdot10^{-6}$	$5.6\cdot10^{-7}$	$1.3\cdot10^{-6}$
Amorphous-crystalline	$7.9\cdot10^{-6}$	$7.9\cdot10^{-7}$	$1.8\cdot10^{-6}$
Microcrystalline	$11.4\cdot10^{-6}$	$17.7\cdot10^{-7}$	$3.2\cdot10^{-6}$

0.662 nm), is produced at the deposited layer surface, i.e. crystallization is proceeding not from the melt, but from the amorphous state.

Analysis of polarization curves (Figure 2) showed that the examined deposited layers behave almost identically in a wide interval of potentials. At anodic polarization the current in an active zone depends linearly on the potential, and at further increase in potential the saturation current is reached and current value is changed negligibly.

The deposited layers possess a high corrosion resistance. However, if they are almost equal in corrosion potential (Table 1), then a great difference is observed in corrosion current density (Table 2). Thus, for example, the corrosion current density in neutral medium for a layer with an amorphous structure is $5.6\cdot10^{-7}$, amorphous-crystalline — $7.9\cdot10^{-7}$, microcrystalline — $17.7\cdot10^{-7}$ A/cm^2, while in a weak-alkaline medium it is increased by 2–3 times, in acid — by 10 times.

The high corrosion resistance of microcrystalline deposited layers is explained as follows. It is known that grain boundaries in crystalline alloys are subjected to the greatest degree to corrosion. Crystalline coatings produced as a result of a rapid cooling consist of very small crystallites. Therefore, the specific surface of boundaries in them is large. However, during fast cooling the fluctuations in the chemical composition are not observed. Therefore, alloys produced by a fast cooling of liquid, have no chemical inhomogeneity at the boundaries of crystallites, though being crystalline, thus providing high corrosion resistance.

Tests on wear resistance of deposited specimens in sliding friction of metal without lubricant were performed. The total wear after 8 hour-tests of the deposited layer of alloy of Fe–Ni–B system is given in Figure 3. As is seen, the specimens with a microcrystalline structure possess 1.5–2 higher wear resistance than the specimens with amorphous structure.

High tribotechnical characteristics have layers with amourphous-crystalline, which were deposited at change of the powder consumption from 0.15 to 0.25 g/s and 5–6 mm/s rate of surfacing. These conditions provide formation of a high-strength and comparatively ductile amorphous matrix with uniformly distributed dispersed particles of strengthening phases. The presence of microcrystalline inclusions in the amorphous matrix increases the hardness and improves greatly the tribotechnical characteristics of the specimens. Layers with amorphous-crystalline structure have a sufficiently high wear resistance which is higher with larger dispersity of boride particles and uniformity of their distribution in the volume of the deposited layer.

Thus, the corrosion- and wear-resistant properties of deposited layers from alloys of Fe–Ni–B system depend on the structure. Important factor which makes it possible to control the structure and properties is the selection of technological conditions of surfacing. Depending on the amount of the powder, being fed, and surfacing rate it is possible to produce amorphous, amorphous-crystalline and microcrystalline structures. Maximum wear resistance is observed in deposited layers with a microcrystalline structure, and high corrosion properties are observed in layers with an amorphous structure. To work in the conditions of an abrasive wear and corrosion media it is rational to use deposited layers from alloy of Fe–Ni–B system with amorphous-crystalline structure having high corrosion- and wear-resistant properties.

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NUMERICAL MODELLING OF THE PROCESS OF FORMATION OF A MOLTEN METAL DROP AT THE TIP OF A CONSUMABLE ELECTRODE

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The paper describes a numerical method of determination of the weight and mean temperature of the drop at the tip of a consumable electrode in arc welding. Changes in thermophysical characteristics of a material, availability of phase transitions and programmed change of arc current are taken into account. Calculation data for drops of copper, titanium, and aluminium coincide with the experiment with the accuracy commensurate with experimental error. Programmed variation of arc current widens the capability of adjustment of temperature and weight of the molten metal drops.

Key words: *drops, consumable electrode, arc, numerical method, modelling, calculation, experiment, accuracy, identity*

Development of precision processes of welding, surfacing, brazing by a single drop of molten metal of a controlled weight and heat content [1], required construction of a calculation model of the process to determine the basic parameters of the drop, using modern calculation methods and a computer.

This paper gives the results of studying the process of formation of a metal drop from a section of a consumable electrode, cooled by a massive heat-removing nozzle for the case of large drops ($d_d > d_e$, where d_d and d_e are the drop and electrode diameters, respectively). Such a variant is characteristic of the modes of heating by a low-amperage arc and is convenient to conduct experimental studies and measurements, which is required to identify the calculation and experimental data.

The essence of the numerical method consists in that the electrode stick-out is divided into a number of elements and for each element and each time interval the laws of energy conservation, Joule–Lenz, Fourier heat conductivity, Newton heat exchange and Stefan–Boltzmann radiation laws are written and used for calculations. Heat balance equation is set up for each element and its temperature increment is determined at each moment of time.

Calculations are conducted taking into account the change of thermophysical characteristics of the electrode material, depending on temperature and phase transformations, including melting. In addition, changes of the shape and dimensions of the electrode and the drops are taken into account for different stages of the process. Calculation can be performed with any degree of accuracy. Process parameters and characteristics are determined at all the stages. Introducing acceptable simplifications of the process, in modern computers calculations are performed in a short time.

The process of drop formation for an electrode section (Figure 1) may be divided into the following three stages:

• first stage — electrode heating in the solid state up to formation at the electrode tip of a small zone of molten metal;

• second stage — development of a melting zone of much larger dimensions, when the drop diameter is greater than that of the electrode;

• third stage — complete melting of the electrode stick-out and further keeping a drop of maximal dimensions at the nozzle tip.

Thermal design of the first stage is reduced to calculation of the temperature field of a rod of finite length heated by an arc at one tip with preservation of ambient temperature at the other (at the nozzle). The second stage is characterised by a continuous change of the dimensions of the drop and the electrode, this significantly complicating the calculation (non-stationary problem of heat conductivity of a system of bodies of varying dimensions). In this connection we assume that temperature T along electrode radius does not change and is a function of two variables $T = f(x, t)$, where x is the co-ordinate along

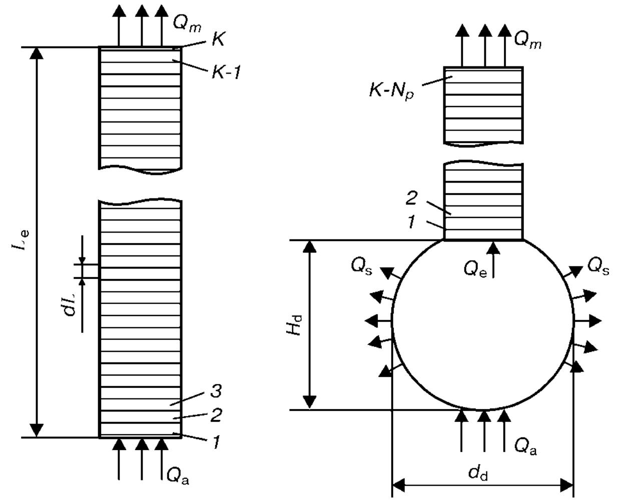

Figure 1. Schematic for thermal calculation of the process of formation of a molten electrode metal drop

the electrode axis. We will consider the drop as an object of a spherical shape with an averaged temperature. Such assumptions allow reducing the scope of calculations to an acceptable level.

Equation of heat conductivity for the case of electrode heating by an arc with the assumption of a one-dimensional thermal field, according to [2], becomes

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{dx^2} + \frac{i^2 \rho}{c\gamma}, \quad (1)$$

where α is the coefficient of thermal conductivity; c is the heat capacity; γ is the density; ρ is the specific electric resistance of electrode material; i is the current density.

Let us divide the electrode stick-out into a number of the same elements of thickness δ_c. The total number of elements k is selected to be equal to 100. The temperature of each element after an interval of time Δt (interval number is $n+1$) is equal to the temperature in the previous interval plus temperature increment:

$$T_{k,\, n+1} = T_{k,\, n} + \Delta T d_{k,\, n}. \quad (2)$$

To determine $\Delta T_{k,\, n}$ we will use equation (1) and boundary conditions. Temperature increment in the inner elements of the electrode over time Δt is equal to

$$\Delta T_{k,\, n} = \frac{\Delta t \alpha}{\delta^2} (T_{k+1,\, n} + T_{k-1,\, n} - 2T_{k,\, n}) + \frac{i^2 \rho \Delta t}{c\gamma}, \quad (3)$$

and for an element ($k = 1$) heated by the arc

$$\Delta T_{1,\, n} = \frac{q}{c\gamma\delta}\Delta t + \frac{\Delta t \alpha}{\delta^2} (T_{k+1,\, n} - T_{k,\, n}) + \frac{i^2 \rho \Delta t}{c\gamma}. \quad (4)$$

For an element, coinciding with the nozzle tip ($k = 100$), the temperature remains unchanged ($T_{100} = 20$ °C), due to a considerable removal of heat Q_m into the nozzle.

The power of the arc evolved on the electrode

$$q = U_a I_a \eta_e, \quad (5)$$

where U_a is the arc voltage; I_a is the arc current; η_e is the effective efficiency of electrode heating by an arc (for an DCRP arc in argon $\eta_e = 0.4$). Current density in the electrode $i = I_a / F_e$, in the drop $i = I_a / F_d$, where F_e and F_d are the cross-sectional areas of the electrode and the drop, respectively.

Time interval Δt meeting the condition of stability of the difference scheme [3]

$$\Delta t \le \frac{\delta c \gamma}{2\lambda} \quad (6)$$

is taken to be equal to 0.0001 s.

Characteristics of electrode material, depending on temperature, are determined using a separate program. For this purpose values c, λ, ρ, which are temperature dependent and taken from [4, 5], are presented in the form of piecewise-linear functions based on recommendations of [6].

Influence of phase transformation heat Q_{PT} (also in melting) on the heating process is taken into account in calculations by a temporary interruption of temperature rise for a given element when it has reached the temperature of phase transition. We will use expressions (3), (4) to calculate and sum up temperature increment ΔT, comparing it with value $\Delta T_{PT} = Q_{PT} / c\gamma$ (ΔT_{PT} is conditional temperature increment to carry out the phase transformation). Further rise of element temperature is calculated only at $\alpha \Delta T > \Delta T_{PT}$.

After one or more elements have melted in the electrode, calculation is performed for molten drop–electrode system.

Equation of heat balance for a drop

$$\Delta Q = Q_a + Q_J - Q_s - Q_e, \quad (7)$$

where ΔQ is the energy consumed in increasing the heat content of the drop; Q_a is the arc energy; Q_J is the Joule heat; Q_s is the heat consumption from the drop outer surface as a result of radiation and convective heat exchange; Q_e is the heat consumption in the electrode, equal to

$$Q_e = \lambda_{l.m} \frac{F_e \Delta T_d \Delta t}{\delta_l}, \quad (8)$$

where ΔT_d is the drop overheating equal to $T_d - T_m$; δ_l is the height of a layer of liquid equal to half of drop height; $\lambda_{l.m}$ is the heat conductivity of liquid metal, taking into account the mixing; T_m is the melting temperature. Heat Q_e is applied to the first solid element of the electrode, adjacent to the drop.

When Q_e is calculated, we assume that the drop surface has mean temperature T_d, and the surface shape is spherical. Then,

$$Q_s = a(T_d - T_a)S\Delta t + \sigma(T_d^4 - T_a^4)S\Delta t, \quad (9)$$

where a, σ are the coefficients of convective heat exchange and radiation heat exchange, respectively; T_a is the ambient temperature; S is the drop surface area.

Increment of the drop temperature after time interval Δt will be

$$\Delta T_{d,\, n} = \frac{\Delta Q}{m_d c \gamma}. \quad (10)$$

For practical purposes it is important to determine the drop weight m_d and average temperature of the drop, T_d, as these values largely determine the welding process and characteristics of the produced joints.

Drop weight is calculated by the weight of molten elements, and value T_d for any time interval by expression:

$$T_d = T_{d,\, n+1} = T_{d,\, n} + \Delta T_{d,\, n}, \quad (11)$$

where $T_{d,\, n}$ is the drop temperature in the previous interval.

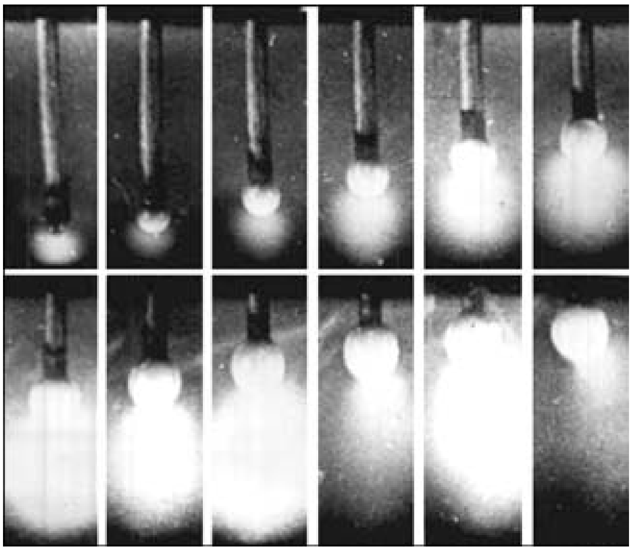

Figure 2. Film frames of melting process of an electrode of M1 copper: d_e = 1 mm, L_e = 9.5 mm, I_a = 30 A, t_a = 0.3 s

Calculations were performed in the computer with subsequent use of expressions (1) – (11). Calculated values of L_e and m_d are presented in the visual form similar to process film frames, which is convenient for analysis and comparison with the filming data (see Figure 2).

Figure 2 shows film frames of the process of melting of an electrode of M1 copper, produced by high-speed filming, and Figure 3 gives the respective stages of the melting process obtained by calculation in the same modes. Calculations correspond to odd film frames. Comparison of filming results and modelling data demonstrates a complete identity of the processes. Images of the actual and simulated processes coincide with the accuracy commensurate with the error of experimental measurements of electrode length and drop diameter.

Let us consider the data of m_d and T_d calculation for commercial titanium alloy VT-1 and compare them with experimental data.

Analysis of calculation dependencies showed that value m_d first grows linearly, then its growth is slowed down and stops completely at a certain value t_a (Figure 4).

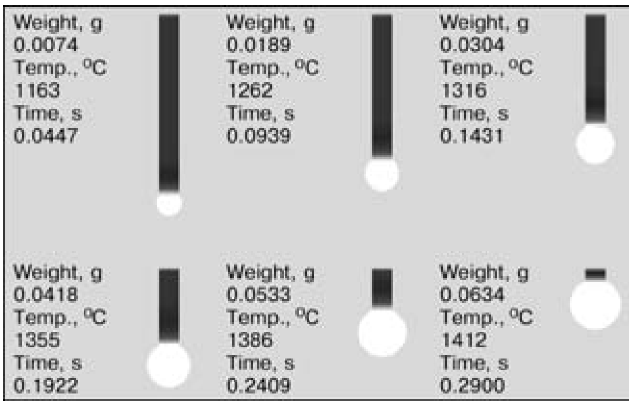

Figure 3. Images of the drop on the electrode produced by computer modelling

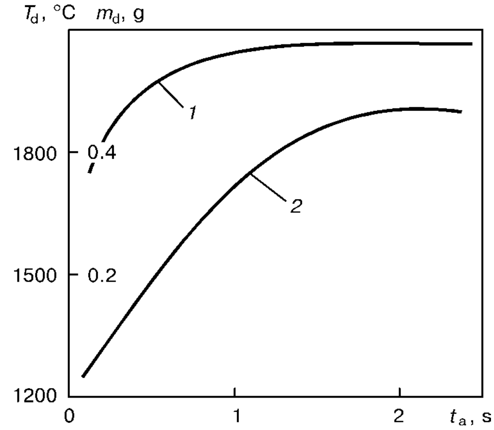

Figure 4. Dependence of m_d (*1*) and T_d (*2*) on arcing time in the case of an arc on alloy VT-1 (d_e = 3 mm)

Drop temperature at the initial moment of its formation rises fast, then slows down and at the final stage of formation T_d reaches a steady-state value (Figure 4). T_d rises with the increase of arc current. A greater value of the drop weight corresponds to a higher T_d value at the same arc current. Overheating of drops of alloy VT-1 is equal to 400–550 °C, depending on I_a and m_d.

When operating in standard modes ($I_a \approx$ const) m_d and T_d increase with time. Qualitatively different results are obtained at programmed adjustment of current. For instance, at stepped decrease of arc current to 40 A at the final stage of the process (at t_a = = 1.2 s, Figure 5) the nature of $T_d = f(t)$ and m_d = = $f(t)$ dependencies changes significantly. At t_d > > 1.2 s the drop temperature decreases, and its weight increases further. This enables a more flexible control of the drop formation process, allowing achievement of the required values of m_d and T_d and controlling the process of the joint formation and their characteristics. Calculation results were compared with experimental data. During experimental studies the molten metal weight was measured at different I_a and t_a, for which purpose the molten metal of the electrode was forced to separate from the electrode at a certain moment of time, using a special device, and was weighed after cooling. Results of m_d measurement

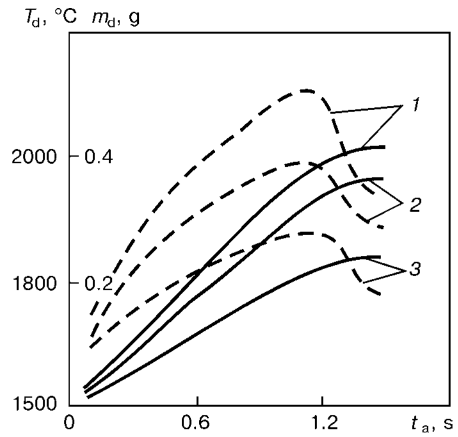

Figure 5. Dependence of m_d (solid curve) and T_d (dashed curve) on time for different values of I_a at current decrease at the end of the cycle: *1* — I_a = 160; *2* — I_a = 140; *3* — I_a = 120 A (VT-1 alloy, d_e = 3 mm)

Controlling the process of formation of drops of alloy VT-1 at d_e = 3 and L_e = 16 mm

I_a, A	t_a, s	Drop weight, mg	
		Calculation	Experiment
82	1.3	319	317
120	0.75	282	280
120	0.9	338	335

coincided with the calculation results with an accuracy of up to 5 % in a broad range of I_a and t_a (see the Table).

Drop temperature was also measured by briefly inserting a tungsten-rhenium thermocouple into the liquid drop volume. Thermoelectromotive force was in this case measured by an electronic oscillograph by taking photos of the screen image. Drop temperature was determined by thermoelectromotive force, using a graduation table. The calculated mean temperature of the drop for VT-1 was 2091 °C, and that measured at the same values of I_a and t_a was equal to 2040 °C.

Performed calculations and experiments for a wide range of electrode materials (silver, copper, bronze, steels, titanium and aluminium alloys) demonstrated a good agreement of the results. A database of thermophysical characteristics, required for calculations, was put together for the above materials. For each material the database provides more precise values of power of the near-electrode region, assigned by coefficient η_e, as well as heat conductivity of the liquid drop material, taking into account mixing $\lambda_{l.m}$. Taking these values to be the same for all the materials leads to a greater calculation and experimental error.

Thus, the considered method of m_d and T_d calculation provides a high accuracy. It allows obtaining valid data without resorting to sophisticated labour-consuming experiments. Particularly valuable are the data on temperature cycles of the drop at different diagrams of arc current, heat content of the drop at different moments of time, this allowing to purposefully solve the practical problems of producing high-quality joints.

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TENDENCIES IN DEVELOPMENT OF LASER-ARC WELDING (REVIEW)

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Dynamics and subject-oriented nature of scientific publications on hybrid and combined laser-arc processes and methods to develop them, based on current promising welding technologies, are described. Comparison of laser-arc and laser welding is made. Selection of the area of further research is substantiated.

Key words: *laser-arc welding, development tendencies, process schematics, comparison of the modes, advantages, applications*

Laser-arc welding processes were developed in the second half of 1970s in Great Britain [1]. Investigations in this field were conducted by experts in many research institutes [2–20], including the PWI [18]. Materials presented in [21, 22] give an idea of the physical processes proceeding during welding by the above procedures and contain a range of experimental data, from which the authors proceeded in their attempt at estimating the prospects for further technological development of combined laser-arc processes and selecting the areas of their own research.

The terms of «hybrid» and «combined» welding process are used in publications. Further on the hybrid welding process will mean such a welding process, where the laser radiation and the electric arc are simultaneously applied to the same point, and the physical essence of such an action differs from the action of each of the components. The notion of «combined» will denote a welding process, where the laser radiation and the arc form a common thermal cycle of the process, while the physical essence of the impact of each of the components remains unchanged.

We have analysed 92 publications, dealing with laser-arc welding and allied processes (Figures 1 and 2). If they are chronologically arranged (Figure 1), the following picture is formed. From 1978 to 1981 investigations were performed by researchers of the scientific school of Prof. Steen [1–5]. After their results became accessible for the world scientific community, they were subjected to a critical study. This, probably, explains the absence of publications in 1982. After that a higher interest to investigations in this field is observed (see the peaks in 1983–1986 and 1988–1991 in Figure 1). A short pause in 1992–1993 is followed by a gradual increase. If in the next year or two the same increase of the number of investigations is observed, it will be possible to speak about a tendency of further development of laser-arc technologies.

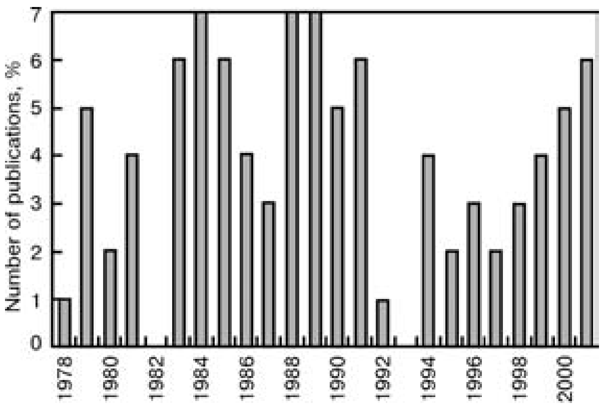

Figure 1. Chronology of intensity of investigations of laser-arc processes of material treatment

According to [21, 22] five main areas of investigations may be singled out, namely welding of sheet metals; welding of plate metals; surfacing and heat treatment; physical studies; other (advanced equipment and technologies of welding, cutting, etc.). Having grouped the studies by areas and arranged them in the chronological order, we have the situation shown in Figure 2.

Predomination of experimental studies and increase of interest to patenting all possible processing methods and apparatuses for their implementation has

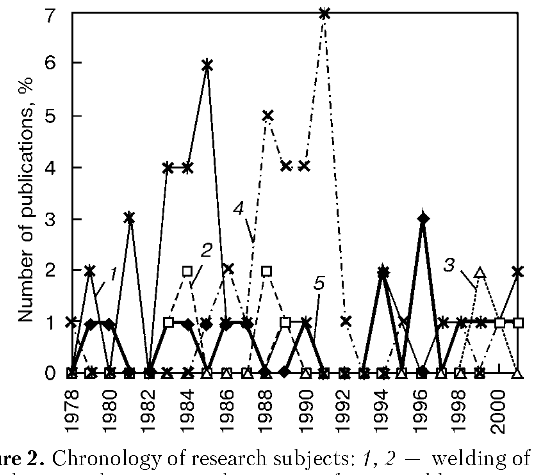

Figure 2. Chronology of research subjects: *1, 2* — welding of sheet and plate metals, respectively; *3* — surfacing and heat treatment; *4* — physical studies; *5* — other areas (for instance, development of novel equipment, technology of welding, cutting, etc.)

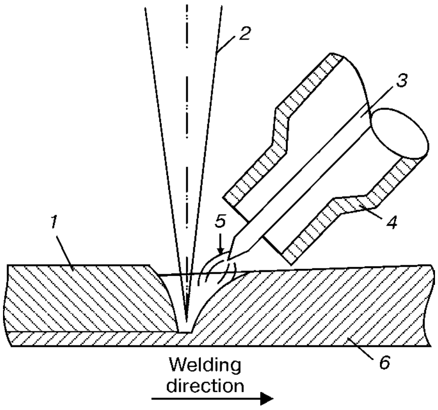

Figure 3. Schematic of the process of laser-arc welding, when a non-consumable electrode arc is used [10]: *1* — weld; *2* — laser beam; *3* — non-consumable electrode; *4* — nozzle; *5* — arc; *6* — time

been observed from the time of appearance of laser arc processes up to 1985. Then, probably, after sufficient factual material has been accumulated (1988–1991) research in the area of process physics became more intensive. Against this background the issues of welding plate and sheet metals were studied between 1978 and 1990 in a rather systematic manner. Beginning from 1994 and up to now a parity has been achieved in all the areas of research in the above field. This is indicative of a systemic approach to solution of the arising problems, as well as widening of the range of research.

Such a steady performance of subject-oriented work suggests that the hybrid and combined processes may take up the same place in science and technology as their component processes (laser and arc technologies). Note that despite a relatively stable interest of researchers to welding sheet and plate metals, in 1984 and 1988 the efforts were still focused on welding plate metals, and in 1994 and 1996 on welding sheets metals.

Analysis of [1–22] gives rise to the following comments. So-called synergetic effect [6] from combined use of laser radiation and electric arc (effect of disturbance of additivity of thermal impact of the laser beam and arc plasma on the item) is caused by transition from heat-conductivity mode of welding to that of keyhole (deep) penetration. When comparatively low-power laser and arc sources were used separately, it was determined that none of them has sufficient power density to achieve a through-thickness penetration of the metal (usually, sheet metal). In the case of their combination, the arc, according to a mechanism, described in [17], is also «tied up» to the point of laser radiation impact on the item (anode). The arc is constricted within the plume of laser plasma, thus eliminating the effect of anode spot erring [1–3]. Additional energy input of the arc stabilised by laser radiation, as well as increased absorptance of overheated metal results in the penetration mode changing from heat-conductivity to keyhole mode. A characteristic for laser welding vapour-dynamic channel is formed, where the anode region of the constricted arc column is lowered, following the laser radiation and the plasma, formed by it from the metal vapours. As soon as the threshold between heat conductivity and keyhole penetration modes is overcome, the volume of remelted metal is abruptly increased, this allowing increase of penetration depth or welding speed by 1.5 to 2 times [12].

Transition to deep penetration mode is an advantage of the hybrid laser-arc welding process. Therefore, use of this process is justified in welding of sheet metals [2, 8, 9–12], requiring comparatively small laser powers (up to 1–1.5 kW for CO_2-laser or 300–1000 W for YAG:Nd laser) and an arc of about 1 kW power, capable of making an impact equivalent to 1 kW increase of laser radiation power. Another important moment also is application of small and medium currents of the arc. At more than 300 A currents the effect of «tying up» the anode region of arc discharge to laser heating spot was not observed in the above publication [2]. Schematic of such hybrid welding is similar to that shown in Figure 3.

Various techniques may be applied in welding thick metal. One of these methods may be laser-arc welding, using a consumable electrode arc (Figure 4). Edge preparation is made so that welding up of the root weld and groove filling with the consumable electrode metal were performed using laser radiation [10, 20]. Varying distance *a* between the zones of impact of laser radiation and arc, allows selection of such a common thermal cycle of welding, when the negative consequences of laser welding are eliminated. So, for instance, in butt welding of steel plates 20 mm thick with a V-shaped groove a thermal cycle of welding was selected, in which the root weld was normalised, and hardness distribution between the base and weld metal was uniform. In this case the following welding mode was used: laser power — 6.3 kW; arc power — 18.55 kW; welding speed — 0.6 m/min; distance between laser and arc sources — 30 mm [7].

Let us analyse the modes of hybrid and combined welding to determine the optimal parameters, that is such parameters at which a maximal area of remelted

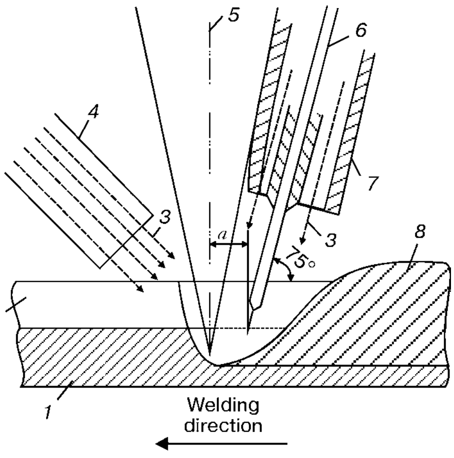

Figure 4. Schematic of the process of laser-arc welding, using a consumable electrode arc [10]: *1* — item; *2* — groove; *3* — shielding gas; *4*, *7* — nozzles; *5* — laser beam; *6* — electrode wire; *8* — weld (*a* — distance between the heat sources)

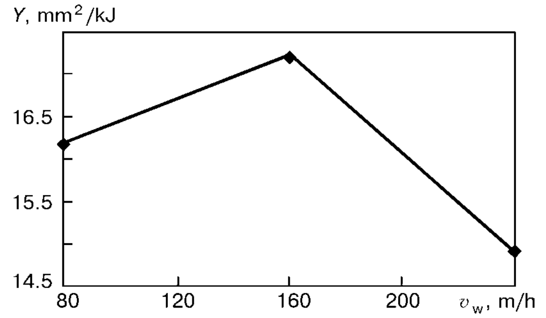

Figure 5. Dependence of welding rate of aluminum alloy 5052 on welding speed by the schematic in Figure 3 at combination of low-power welding sources (power of laser radiation of 600 W, I_a = 30–70 A) [11]

metal (greatest depth of penetration at a given speed) is achieved with minimal energy consumption. For this purpose let us use a complex quantity, namely welding rate [23]. It is a product of penetration depth h (mm) and welding speed v_w (mm/s), referred to the welding source power. In our case, welding rate Y may be written as

$$hv_w/(P_l + P_a)\ [\mathrm{mm}^2/\mathrm{kJ}],$$

where P_l is the laser radiation power, kW; P_a is the arc power, kW. Results of [10, 11, 20] were used to calculate the rates of hybrid and combined welding for different process speeds and plot graphic dependencies presented in Figures 5–7.

The data shown in Figures 5 and 6 cannot be compared, because of the difference of the materials being welded. They do not allow making a conclusion about the effectiveness of applying welding sources of a high and low power. However, as according to [2, 3] the effect of anode spot tying up to the item is observed at currents of up to 300 A, a hybrid laser-arc process runs in the cases shown in Figures 5 and 6. This leads to the conclusion that for metal preheating by a non-consumable electrode arc and subsequent simultaneous impact of the arc and laser radiation the optimal values of welding rate are achieved at v_w = 160–180 m/h. From Figures 6 and 7 it can be seen that at the same welding speeds the effectiveness of application of the above technological procedures (see Fi-gures 3 and 4) is about the same. However, the available data are insufficient to determine the optimal welding speed by the schematic in Figure 4 (Fi-gure 7).

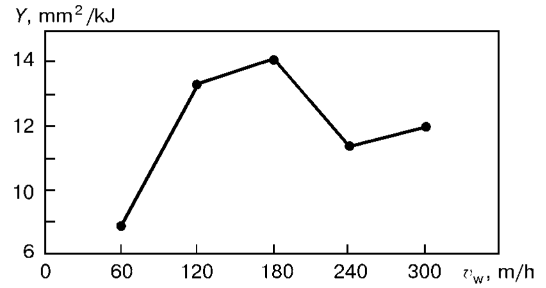

Figure 6. Dependence of welding rate of carbon structural steel on welding speed by the schematic in Figure 3 at combinations of powerful welding sources (laser radiation power of 1–5 kW, I_a = = 100–300 A) [10]

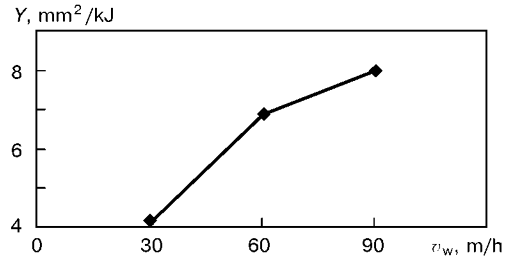

Figure 7. Dependence of welding rate of steel on welding speed by the schematic in Figure 4 (laser radiation power of 3–5.7 kW, I_a = 350–370 A) [20]

A curve of dependence of laser welding rate on its speed was plotted by the data of [10] for comparison (Figure 8). From the Figure it is seen that welding speed of 180 m/h is optimal to conduct such a process, and Y = 25 mm^2/kJ, this being higher than the values of a similar quantity in the hybrid process (Figure 6). Comparison of two welding processes (Figures 6 and 8) demonstrates that laser welding requires less power consumption than the hybrid process, to achieve an equal area of the remelted weld metal (similar penetration depth). Thus, laser welding is preferable to laser-arc welding.

The issue of arc plasma influence on laser radiation is interesting. During our investigations of welding by CO_2-laser radiation, combined with a tungsten electrode arc, the known effect was manifested, namely screening of laser radiation by argon plasma. This was eliminated by using helium as plasma gas. Helium was used to conduct the combined process, probably, for the same reason [10]. In [1–5] argon was fed to the tungsten electrode in welding, and the zone of laser radiation impact was protected by helium. Screening of laser radiation with different wave lengths by plasma of the column of an argon arc of different power was studied in [16]. It was proved that the screening effect becomes weaker with the decrease of the wave length. Hence, the evident conclusion on the rationality of applying the radiation of YAG:Nd laser for welding by the schematic in Figure 3. As an example [13] considers joining aluminium alloy sheets about 3 mm thick by YAG:Nd laser of 360 W power combined with non-consumable electrode arc welding at 50 A current. On the other hand, for welding by the schematic in Figure 4, it is desirable to use a powerful CO_2-laser [7, 10, 20]. Results of those investigations are interesting, where CO_2 was used for shielding the arc instead of argon or helium.

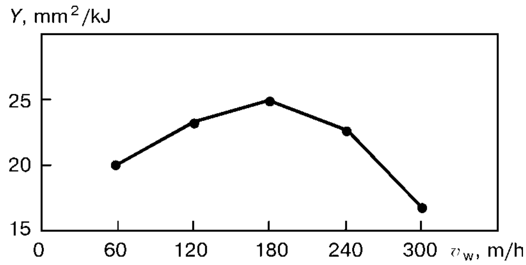

Figure 8. Dependence of welding rate on the speed of laser welding of carbon structural steel at the power of laser radiation of 5 kW [10]

Authors of [19, 21, 22] suggested applying additional focusing of laser radiation in the plasma of a hybrid discharge, when using special laser-arc plasmatrons, as well as controlling the plasma lens, which should promote higher efficiency of the processes of welding, cutting, heat treatment and coating application. All the above said, however, needs a thorough experimental verification, as the so-far known effects of laser radiation refocusing by the screening plasma result in deterioration of the focusing conditions [24].

Laser welding of metal sheets is currently used (for instance, in fabrication of blanks for stamping the car body elements) not only to improve the efficiency, but also to produce a high quality narrow weld with a minimal HAZ. As shown in some works (for instance, [15]), in hybrid and combined welding the produced welds are narrower than those in arc welding, but wider than those in laser welding. In this case their HAZ is larger than in the case of laser welding. A slight «sagging» of laser welds, which is mentioned in these studies, can be eliminated by selection of welding modes [25]. The advantages of hybrid welding processes in terms of speed [14] are very relative, as increment of radiation power in laser welding promotes a linear increase of speed, and increment of the power of the laser and the arc in laser-arc welding may eliminate the stability of the effect of constriction of the arc anode region and, hence, result in a loss of the increase in penetration depth [10, 11] or deterioration of the cut quality in hybrid cutting [3]. Therefore, ousting of laser welding by the combined technologies, described in [14], is unlikely.

CONCLUSIONS

1. For high-speed welding of sheets of different metallic materials it is rational to apply a combination of YAG:Nd laser radiation with a non-consumable electrode arc. In this case there is no need to use powerful laser units or helium as shielding gas. Weld metal with the required structure and improved degassing of the weld pool can be produced.

2. Various techniques may be used in welding sheets of different metals or thick-walled items. One of them is the production technology, when the root weld is welded by CO_2-laser with simultaneous welding up of the groove by a consumable electrode arc. Porosity may be reduced by changing the optimal parameters of the thermal cycle, controlled by the simultaneous action of the laser radiation and the arc.

3. Quality of welds produced by hybrid laser-arc welding, in some cases is close to that of welds made by laser welding at a lower cost of one linear meter in terms of capital investments into equipment (for instance, when going over from the jointly acting heat sources to the deep penetration mode, when an arc of about 1 kW power is capable of producing an impact equivalent to increasing the power of laser radiation by 1 kW). This fact is interesting for introducing laser-arc welding in the countries, where the economy is in the period of transition, including Ukraine and other CIS countries, in view of the absence of expensive powerful laser units.

4. Available publications lead to the conclusion, that in case of a combination of laser radiation and an arc running from a non-consumable electrode, the optimal mode is such, in which the maximal penetration depth is achieved at the speed of 160–180 m/h with energy consumption, corresponding to the welding rate range of 17–20 mm^2/kJ. There is not enough data for analysis of the technological modes of combined welding with a consumable electrode arc.

5. Dynamics and subjects of the current scientific publications suggest further advance of investigations of hybrid and combined laser-arc processes and development of promising technologies on their basis.

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CLASSIFICATION OF FLUXES FOR ARC WELDING BY METALLURGICAL AND TECHNOLOGICAL PROPERTIES*

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Updated classification of welding fluxes by metallurgical and technological properties, kind of welding current and other features, is offered. The comprehensive system of flux coding with allowance for different characteristics is described.

Key words: *classification of fluxes, metallurgical properties, polarity of welding current, technological properties, graphical system*

Variety of national standards for welding consumables has led to the need in creation of unified international standards within the scope of the International Institute of Welding (IIW), and later on — International Standards Organization (ISO). Below, proposals of the authors are considered for updating classification of fluxes for arc welding by metallurgical and technological properties.

Classification of fluxes by metallurgical properties. In document [1] the metallurgical properties of each of the flux classes mentioned in it are considered from the point of view of transition of alloying elements from flux to the deposited metal. Taking into account the flux-wire combination, recommended by standard ISO 14171, the transition of alloying elements is evaluated by the difference between chemical compositions of the deposited metal and electrode (wire). All the fluxes are divided into 9 classes, not depending on the composition. Classes No.1–4 represent a group of fluxes at use of which in welding and hardfacing the burn-out of alloying elements from 0.7 (No.1) to 0.1–0.3 wt.% (No.4) is occurred. Fluxes of class No.5 belong to neutral fluxes which do not provide an increment of alloying element ±(0–0.1) wt.%, while classes No.6–9 give an increment of alloying element in the deposited metal from 0.1–0.3 (No.6) to more than 0.7 (No.9) wt.%.

Oxidizing or alloying abilities of fluxes are evaluated for each class separately. For fluxes of class No.1 the transition of silicon and manganese is only considered, while for class No.2 — the transition of elements, different from silicon and manganese, for example, chromium, for class No.3 — only transition of alloying elements from flux, for example, carbon and chromium. Standard envisages the feasibility of alternative evaluation of metallurgical properties of fluxes which is given in accompanying documents for the flux batch. These documents include the procedure of manufacture of samples for experimental determination of elements transition into the weld metal and also technology of depositing experimental beads. Standard IIW-A-8–74 envisages another procedure of evaluating metallurgical properties of flux by their basicity index (BI) [2]. For example, calcium-silicate flux CS, having $BI < 0.45$, is defined as very acid, while fluoride-basic FB ($BI > 2.5$) is defined as basic. Flux is considered neutral if $1 < BI < 1.5$. With increase in basicity its oxidizing ability is decreased, and weld formation, as a rule, is deteriorated. It is possible to create fluxes mainly on the base of CaO, MnO and CaF_2 (systems FB) whose basicity is more than 4.

It should be noted that there are fluxes which do not practically contain oxides (halogenide systems) for which $BI \to \infty$. These are mainly non-oxidizing fluxes being neutral as regards to oxygen.

In addition, the above-mentioned standard evaluates the alloying ability of flux, due to which the fluxes are distinguished as neutral (as to alloying) and active. Neutral fluxes do not contain active additions unlike the active fluxes whose composition consists of powders of appropriate metals and alloys (ferrosilicon, ferromanganese, silicomanganese, etc.). The term «neutral flux» in the same standard has also another meaning which denotes the transition of silicon and manganese into the deposited metal when the fluxes, not containing active alloying additions, are used. For these initially neutral fluxes the index of neutrality $N = 100\ ([\Delta Si] + [\Delta Mn])$ is introduced additionally [2].

Flux is considered neutral when $N \to 0$. This index, as is seen, belongs to class No.5 of standard [1], reflecting the nature of alloying elements transition to the weld metal.

It is known that fluxes, containing the large amount of oxides of alloying elements, alloy metal by a reaction of recovery [3] (a generalized reaction

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is given as a summed process of dissociation of oxides and description of metal):

$$(MeO) + [Fe] = [Me] + (FeO).$$

Alloying is possible by using a reaction of recovery even with such active element as titanium [4], and also chromium, tungsten and vanadium [5].

To ensure this reaction proceeding from left to right it is necessary to keep, except sufficient amount of (MeO) in flux, two more conditions: the content of [Me] in electrode wire should be much lower than equilibrium, and welding flux should not contain (FeO) in any noticeable amounts. Thus, the alloying ability of the neutral flux can be determined if to consider its composition in combination with the electrode wire composition. It is reasonable to recommend flux in the pair with an electrode wire.

It should be noted that the weld alloying by element recovery from flux oxide can be considered promising, because, according to law of distribution, (MeO) is dissolved partially in weld metal [MeO]. This dissolution is intensified with increase in temperature. At a rapid cooling the generalized common reaction in metal pool is completed and MeO in the form of oxide inclusions is remained in weld metal. By the same reason FeO is also remained in metal being dissolved in it, thus deteriorating its quality.

It is evident that there is no clear distinction between conceptions of active and neutral fluxes in existing versions of standards IIW and ISO for welding fluxes. Moreover, there is no full conception about all the complex of metallurgical properties of fluxes. Actually, we are only speaking about the oxygen reaction: flux can be either oxidizing ($BI < 1$) or slightly oxidizing, neutral ($1 < BI < 1.5$) or non-oxidizing ($BI > 1.5$).

To have an objective evaluation of metallurgical properties of flux it is necessary to take into account also the reactions of other elements — «participants» of the metallurgical process (sulphur, phosphorous, nitrogen and hydrogen). Unfortunately, the above-mentioned standards of IIW and ISO do not take this into account, except hydrogen.

Thus, the most objective characteristics of flux properties as to the reaction with oxygen, as well as to its alloying abilities is its basicity BI and presence of alloying elements in an active form in it.

This, in our opinion, makes it possible to classify fluxes by basicity as follows:

- very acid flux (oxidizing) — $BI < 0.45$;
- acid flux — $0.45 < BI < 1$;
- neutral flux — $1 < BI < 1.5$;
- semi-basic flux — $1.5 < BI < 2.5$;
- basic flux — $BI > 2.5$.

By content of alloying elements in an active form the fluxes are classified as those containing alloying elements in an active form (A) and also without them (NA).

As to the content of diffusion hydrogen in the deposited metal, then the document [1] takes into account its role as a whole. The attempt to standardize the temperature-time conditions of drying by using calcination in the technological process of fluxes production with allowance for composition of initial components, method of production and final flux composition is under discussions. It is, probably, rational not to standardize them, but to specify in technical specifications of production of definite grades of the fluxes.

In our opinion, fluxes can be divided into five groups depending on hydrogen content in the deposited metal, $cm^3/100$ g:

- ultralow — $H < 3$;
- low — $H < 5$;
- medium — $5 < H < 10$;
- increased — $10 < H < 14$;
- high — $H > 14$.

Classification of fluxes by content of nitrogen (symbol N) in weld metal, by nature of transition of sulphur (symbol SI) into weld metal, phosphorus (PI) into weld metal is to be developed.

Classification of fluxes by the kind of welding current. According to authors of document [1] it is possible to classify fluxes by the above-mentioned feature as those suitable only for DC welding (category DC) and for AC (also DC) welding (category AC).

Statement of the fact that fluxes of category AC should be tested using current sources with open-circuit voltage $U_{o.-c} \leq 70$ V is under discussion. Firstly, in welding under flux of category DC the current sources with $U_{o.-c} > 70$ V should not be used. Secondly, in study (testing) of any technological property of the flux (stability of exciting, burning stability, quality of formation of deposited bead and so on) the used type of a welding head should be specified: with a self-adjusting arc (wire feed speed is constant) or with automatic arc adjustment (by current, by voltage, with influence on wire feed speed or on voltage at the power source or on impedance of welding circuit, etc.). In many cases of SAW the heads with a self-adjustment and power sources with a rigid or steep-falling volt-ampere characteristic are used. Here, $U_{o.-c}$ cannot exceed much the arc voltage which is 28–30 V in welding at low currents (100–200 A). Moreover, lower arc voltage should correspond to lower welding current and vice versa. Therefore, the power sources designed for welding at high currents (1000 A and more) and having $U_{o.-c} = 70$ V can occur to be not suitable for welding at low currents. The limiting value of voltage 70 V is probably designed from the point of view of electrical safety and is hardly appropriate in the standard for flux.

As to the flux ability to withstand high current, then the compilers of standard [1] are right that the above-mentioned characteristics do not belong to features by which the flux should be standardized. Nevertheless, it seems that the range of diameters of electrode wires designed for SAW is shifted greatly towards the small diameters. We know the technology of SAW with use of the electrode wire of not less than 0.1 mm diameter. At the same time the diameter of 4 mm cannot be too high. In practice the wire of 5 mm diameter is widely used. Successful attempts were made to perform SAW with 8 mm diameter wire [6]. Coming from our experience the range of wire diameters for submerged-arc welding (hardfacing) from 1.6 to 8.0 mm can be recommended.

Classification of fluxes by technological properties. Both versions of standards (IIW and ISO) classify types of fluxes (MS, CS, etc.) by chemical composition. Classification by technological properties is given for each type of the flux, but in descriptive form. However, any properties, quality, characteristics are taken as such if they are expressed in numerical form. As to the technological properties of fluxes we suggest to standardize them and to define the scale of numerical values for each of them. In our vision and taking into account the above-considered standards of IIW and ISO the technological properties of welding fluxes can include:

- resistance to hot crack formation in weld (*1*);
- resistance to pore formation (*2*);
- resistance to cold crack formation in weld (*3*);
- quality of weld bead formation (*4*);
- depth of penetration (*5*);
- feasibility of welding at high speed (*6*);
- feasibility of welding of horizontal welds on inclined and vertical surfaces (*7*);
- removal of slag crust (*8*);
- hygroscopicity (it is presented in a reverse value as anti-hygroscopicity, i.e. with increase in index the hygroscopicity is decreased) (*9*);
- mechanical resistance of grains in flux feeding (*10*);
- hygienic characteristics (*11*).

To reduce the numerous estimates of technological properties of fluxes (their quantity may increase) to a common denominator it is convenient to express these properties in 5-mark system:

- mark 5, symbol «++» (excellent) — quality which can be accepted as reference (perfect);
- mark 4, symbol «+» (good) — acceptable level of quality in engineering and esthetic aspect;
- mark 3, symbol «0» (satisfactory) — acceptable level of quality in engineering aspect;
- mark 2, symbol «–» (bad) — unacceptable quality, whose level can be increased by an appropriate repair;
- mark 1, symbol «– –» (very bad) — quality which is not acceptable at any conditions, i.e. unrepairable rejection.

Technological properties (*1*), (*2*), (*5*), (*6*), (*9*), (*11*) can be expressed in physical values and to be converted into marks. For example, resistance to pore formation can be expressed by a quantity of pores per weld length unit (and also by mode of their location):

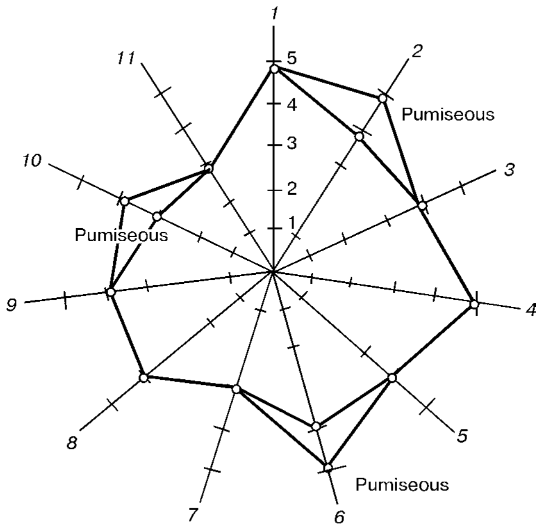
- absence of pores — mark 5;
- single pores in amount *n* per 1 m linear length of weld — mark 4;
- single pores, located non-uniformly, being admissible for structure of the given type (for example, operating at positive temperatures and static load) — mark 3;
- chain or a local clustering of pores (weld is repairable) — mark 2;
- continuous clusters and/or chain of pores — mark 1, etc.

For flux properties which are difficult today to express in physical values (for example, slag crust removal) it is possible to apply an expert estimate (let us call extreme values): mark 5 if the crust is self-removable; mark 1 if it is impossible to remove the crust in large pieces, not using special crushing tool.

Undoubtedly, technological properties of fluxes should be determined in combination with recommended electrode wires, on standard samples and under standard technological conditions of welding (spatial position, temperature, welding condition parameters, etc.).

Technological properties of fluxes can be presented in more visual form in many-coordinate (many-ray) graphical system of coordinates where an appropriate estimate of either property is plotted by corresponding point on each axis (ray) in 5-mark scale. Figure gives a graphical presentation of technological properties of fluxes of system MS (for example, glassy AN-348A and pumiseous AN-60). Graph has two variants: for fluxes with pumiseous grains (properties are distinguished in axes *2, 6, 10* and marked by a word «pumiseous») and glassy (without marks). Flux of MS system is characterized by the following properties of the highest level: resistance to formation of hot cracks in weld (coordinate axis — «ray» *1*); resistance to formation of pores («ray» *2* for pumiseous); formation of weld (*4*); feasibility of welding at high speed («ray» *6* for pumiseous). Hygienic characteristics and mechanical resistance in flux feeding and also the feasibility of welding horizontal welds on inclined and vertical planes are worst for this flux. As a whole this is not a bad flux, and it could be recommended for welding a rather wide range of steels and alloy if he did not possess low metallurgical properties (BI < < 1). Low-carbon and low-alloyed Si–Mn steels can be welded by flux of this type with pumiseous grains at very high speeds.

And finally, we shall give an example of conditional designation of fluxes in accordance with updated system of classification which is offered by us. Two variants are given: full (it is also optional) and



Many-coordinate system of graphical presentation of technological properties of flux: *1*–*11* — axes of system of coordinates corresponding to technological properties of fluxes; 1–5 — estimate marks shortened (obligatory). In case of a full coding of fluxes the numeration of code is as follows:

1 — by the method of application;

2 — by the method of manufacture;

3 — by the chemical composition;

4 — by the type of metals and alloys, for welding or surfacing of which the flux is used;

5 — by metallurgical properties:

5.1 — by flux basicity;

5.2 — by content of alloying elements in active form;

5.3 — by content of diffusive hydrogen in deposited metal;

5.4–5.6 — by content of nitrogen, sulphur and phosphorous in weld metal, respectively;

6 — by kind of welding current;

7 — by technological properties. In 7 (7.1–7.11) the marks are indicated using a hyphen.

Let us take the above flux of MS system, for example, AN-348A (glassy) [3]. Thus, the first variant, 7-numbered: Welding flux ISO 14174 — 1.S; 2F; 3.MS; 4.F-St. (n, l)-Cu; 5.1 BI 0.7; 5.2. NA; 5.3. H10; 5.4. N; 5.5. SI; 5.6. PI; 6. AC; 7.1-5; 7.2-4; 7.3-4; 7.4-5; 7.5-4; 7.6-4; 7.7-3; 7.8-4; 7.9-4; 7.10-4; 7.11-3.

This code is decoded as follows: welding flux by standard ISO 14174 for SAW (code category 1), fused (2), manganese-silicon (3), for welding low-carbon and low-alloyed steels and also copper (4);

its metallurgical properties (category 5): acid, BI 0.7 (5.1), not containing active alloying additions (5.2), diffusive hydrogen in weld metal is not more than 10 $cm^3/100$ g (5.3), nitrogen in weld metal is to be determined (5.4), indices of desulphurization and phosphorous transfer is to be determined (5.5 and 5.6), suitable for DC and AC welding (6);

its technological properties (7): excellent resistance to formation of hot cracks in weld (*1*), good resistance to pore formation (*2*), the same — resistance to formation of cold cracks in weld (*3*), excellent weld formation (*4*), good penetration of parent metal (*5*), good feasibility to increase the welding speed (*6*), satisfactory feasibility to weld horizontal welds on inclined and vertical surfaces (*7*), good removal of slag crust (*8*), good storage in air (not very hygroscopic) (*9*), good mechanical resistance of grains in flux feeding (*10*), bad hygienic characteristics (mainly due to evolution of fluorides and manganese compounds, as well as aerosols in welding) (*11*).

The second variant of conditional designation of flux (shortened) is obligatory: Welding flux ISO 14174 — S.F.MS.F-St. (m, l)-Cu. BI 0.7.H10.AC.

CONCLUSIONS

1. It is rational to widen the classification of fluxes by metallurgical properties. Except taking into account the basicity of flux BI and hydrogen content in the deposited metal H it is necessary to introduce symbols as regards to content of alloying elements in flux in active form (those containing them are designated with symbol A, those not containing them — by symbol NA); content of nitrogen in weld metal (symbol N similar to H — for hydrogen); refining properties with respect to sulphur — symbol SI, while BI — for oxygen, PI — for phosphorous.

2. Classification of fluxes by the following technological properties is useful: ability to prevent the crystalline cracks, to prevent pores in weld, to provide resistance to formation of cold cracks in weld; quality weld formation; depth of parent metal penetration; feasibility of welding at high speeds; feasibility of welding of horizontal welds on inclined and vertical planes; removal of slag crust; hygroscopicity; mechanical resistance in flux feeding; hygienic characteristics.

3. There are no fluxes which satisfy all requirements in a similar way by metallurgical and technological properties. However, there is feasibility to provide their optimum ratios, if to make the purposeful combinations, for example, flux + gas, flux + flux, flux + wire (including flux-cored wire) and so on.

4. The offered method of a graphical presentation of technological properties of fluxes not only specifies and widens the information, giving it in a visualized numerical form, but also allows quick finding of their desirable combinations, providing required ratio of properties using the method of superposition.

5. Submerged-arc welding is the progressing trend among the welding technologies. It is possible to predict the widening of range of grades of metals and alloys which are welded by this method; widening of technological possibilities of SAW, for example, when multi-pass welding is realized into a narrow gap; increase in quality of welded joints by optimum alloying and modifying of weld metal; increase in ecological safety of SAW, in particular, the decrease in intensity of evolution of harmful substances (gases, aerosols) into atmosphere; elimination of flux rejections in the form of slag crust (waste-free production); increase in welding production efficiency by utilization and regeneration of welding slags and wastes of welding production. It is possible to predict the appearance of new grades of fluxes, and also methods of welding connected with their application. It would be perfect, from the point of view of the welded joint quality, if the fluxes were manufactured by individual orders for definite grade of steel (alloy) to be welded and, respectively, grade of wire and planned volume of welding. The most optimum composition of the flux is such at which there are no exchange reactions between the flux melt (slag) and metal melt.

6. Feasibilities of improvement of metallurgical properties of fluxes, as well as their technological characteristics are not far exhausted. Works in this aspect are very challenging.

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EXPERIENCE OF USING GUNS WITH PLASMA CATHODES FOR ELECTRON BEAM WELDING OF NUCLEAR POWER STATION FUEL ELEMENTS

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Data are given on commercial application of electron beam guns with plasma cathodes for welding zirconium and aluminium alloys. Design peculiarities of plasma sources of electrons and their advantages are considered. Many-year experience accumulated in the field of sealing the nuclear power station fuel elements by EBW shows a promising future of using the plasma-cathode electron guns for these purposes. The guns are simple in service and reliable in operation under complicated vacuum conditions.

Key words: *electron beam welding, plasma-cathode gun, fuel element*

In fuel elements (FE) of nuclear power stations the nuclear fuel is placed in a sealed thin-walled metal shell, the vacuum-tightness of which is the basic requirement for performance of FE during its operation in a reactor. The FE shell should retain its integrity for the entire service life, which can amount to several years, depending upon the type of FE and its service conditions.

The FE shells are made primarily from zirconium or aluminium alloys, and their vacuum tightness is ensured by welding. Zirconium and its alloys at high temperatures exhibit high reactivity for oxygen, nitrogen and hydrogen. In this connection, to seal FE, it is necessary to ensure good shielding of the welding zone when welding zirconium in vacuum at a pressure of not higher than $1 \cdot 10^{-3}$ Pa. Welding of aluminium alloys can be performed at a higher pressure of residual gas in the vacuum chamber, which is determined mainly by requirements of the available technology and capabilities of equipment for EBW.

As a rule, the weld on the FE shell has a relatively short length. However, because of substantial volumes of production of FE, the total length of the welds made during a year may amount to several tens of kilometres. Production of a large volume of duplicate parts can be achieved only under conditions of automated mass production, where the equipment involved should meet the increased requirements for operational reliability and consistency. Welding lines include, as a rule, specialised units with a continuous feed of workpieces to the welding zone, as well as lock chambers and devices. The high productivity level and balance of such lines tolerate interruption of operation of some pieces of the equipment only for a short period of time. Repair, adjustment and replacement of some assemblies of the welding equipment lead to extra downtimes, which is caused by the need to maintain performance of the unit and ensure the quality of welded joints meeting the established standards (by welding witness samples and their subsequent testing).

Electron guns with hot cathode assemblies, which were used some time ago in welding units for sealing the FE, for certain reasons failed to meet all the requirements of mass production. This led to the use of electron guns with plasma cathodes [1–3].

Based on the available operational experience, the Open Joints Stock Company «Novosibirsk Factory for Chemical Concentrates» (NFCC) has recently completed the work on development of a new design of the discharge chamber for the gun with a plasma cathode. A simple and reliable design of the gun with a power of up to 5 kW has been developed. It includes cermet assemblies, the vacuum-tightness and mechanical strength of which are provided by EBW.

The plasma-cathode electron gun comprises a gas-discharge device which generates plasma and creates conditions for entry of electrodes into vacuum or low-pressure atmosphere [1]. The low-voltage reflection discharge with a hollow cathode is used to generate plasma [4]. This discharge is excited in the electrode system containing three «cold» electrodes: hollow cathode (Figure 1), anode and additional electrode, which in the majority of cases has potential of the hollow cathode. The hollow cathode and anode have cylindrical shape, while the additional cathode located in front of the hollow cathode has a flat shape. Coaxial magnetic field is generated in the discharge chamber. The discharge exists at a gas pressure in the discharge chamber equal to about 1–5 Pa and voltage of 350–450 V. The emission channel through which the electrons are emitted is made in the additional electrode (emitting cathode). The emission channel is located on the axis of the discharge chamber in the region of a maximum concentration of plasma. The high concentration of plasma provides the required electron gun current at small sizes of the emission

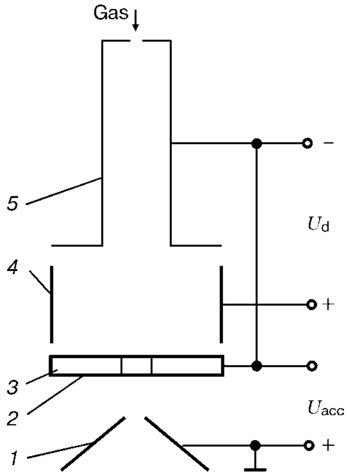

Figure 1. Electrode system of the discharge chamber: *1* — accelerating electrode; *2* — emission channel; *3* — emitting cathode; *4* — anode; *5* — hollow cathode

channel, the diameter of which does not exceed 1.8 mm.

To ensure emission and accelerate electrons, a voltage of up to 50 kV is applied between the emitting cathode and accelerating electrode. Electrons emitted by plasma are formed into a beam and focused by the magnetic field of the focusing system.

Design of the discharge chamber is shown in Figure 2. The core of the discharge chamber and the gun as a whole is a welded cermet assembly, which consists of high-voltage ceramic insulator *1*, as well as ring *2* and anode unit *6* welded to its collars. The anode unit comprises supporting cermet insulators *3* welded to the anode of discharge chamber *7*. Removable hollow cathode *5* is installed on the central supporting insulator. The rest of the insulators are intended for fixing removable cooling radiator *10* of the cathode with an emission hole and the cathode electric insulation.

Removable emitting cathode *9* comprises a channel for escape of electrons from the discharge chamber into vacuum. It is installed on the radiator, whose annular space is connected to the space of the oil-filled source.

The anode unit houses removable magnet *8*, which creates magnetic field with induction of about 0.01 T

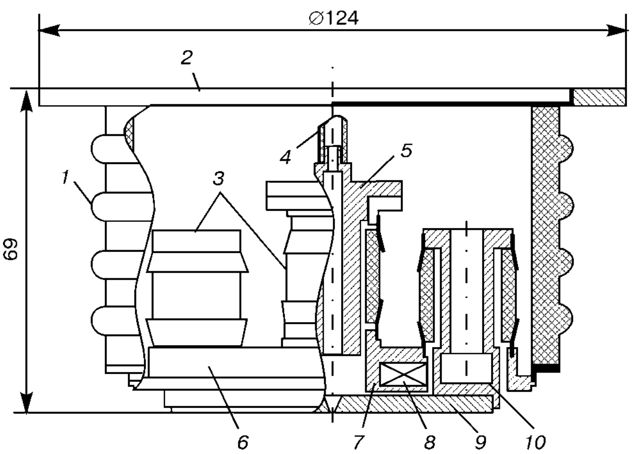

Figure 2. Design of the discharge chamber (see designations in the text)

in the discharge chamber. The discharge chamber with the high-voltage insulator is installed in the gun casing. Transformer oil is poured into the space confined by the casing and the high-voltage insulator. The radiator is immersed into oil to provide extra cooling of the discharge chamber electrodes. The radiator is a copper tube through which the running water is drawn.

The gun includes a system for portioned gas feeding. A working gas is fed through the leak which regulates the leak-in to the discharge chamber via dielectric tube *4* through the hollow cathode channel.

At NFCC the plasma-cathode electron guns are used as part of the upgraded power systems of the U-250, ELA-50/5 and ELA-15 types. Equipment initially designed for the hot-cathode gun was upgraded to be combined with the electron gun. The discharge power unit was introduced to the equipment instead of the filament and bias unit. A special welding cycle programming device, intended for automatic start up of the electron gun from an external signal, variation of the beam current following the assigned law and control of the electron beam focusing and scanning, was additionally developed and interfaced with the equipment.

Figure 3 shows the typical beam current variation law set by the programming device. The welding cycle is divided into five successively performed stages: switch on of the beam current — t_0–t_1, sample preheating — t_1–t_2, increase in current to achieve an amplitude set by the welding conditions — t_2–t_3, welding — t_3–t_4 and current switch off — t_4–t_5. Duration of each of these stages can be regulated from 0.1 to 10 s with an increment of 0.1 s. Amplitude values of the currents in the preheating and welding stages are set at an increment of 1 mA. Upon completing the welding cycles, a command is sent to turn the manipulator, and welding of the next sample is performed. At individual stages of the welding cycle the programming device can give commands to switch over the focusing current or change the shape, radius and frequency of the electron beam scanning.

Service life of the gun is limited by erosion of electrodes in discharge, which leads to changes in their geometrical sizes and dusting of the discharge chamber with a cathode material. Fracture of a narrow emission channel with fast ions from the accelerating gap and particles from the discharge may also play a substantial role. However, erosion processes are relatively slow, while deposits are periodically removed by cleaning the electrodes during a scheduled preven-

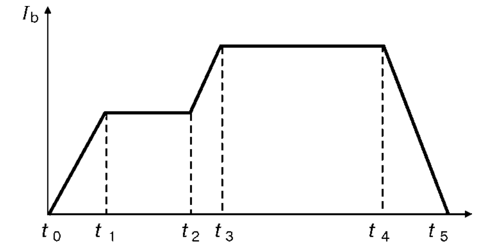

Figure 3. The welding current variation law

tive maintenance of the units, this ensuring a long-time performance of the gun.

To restore performance of the gun, it is enough to replace worn out components, which are bodies of revolution and can be made using a versatile lathe equipment. Conventional, widely applied steels are normally used as the electrode material. At the same time, the life of the gun can be extended approximately by a factor of 1.5, if the electrodes are made from materials resistant to ion bombardment. As a result, optimisation of design of the discharge chamber and use of a light plasma gas (helium) provided an extension of the life of the gun electrodes to 16,000 weldings for FE with the zirconium alloy shells and to 80,000 weldings for FE with the aluminium alloy shells. This makes it possible to carry out systematic preventive maintenance, including periodic preventive inspection between the maintenance cycles and removal of erosion products from the discharge chamber.

Therefore, experience of operation of the plasma-cathode guns under conditions of automated welding production lines showed that such guns have the following advantages:

• absence of heating components to high temperatures;

• low sensitivity to the level of vacuum and its fluctuations;

• high reliability and extended service life, including under conditions of intensive evaporation from the weld pool;

• fast response and simplicity in operation.

These advantages determine the promising future of applying the plasma-cathode guns for mass production of the nuclear power station fuel elements.

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MECHANIZED EQUIPMENT FOR WELDING, HARDFACING AND CUTTING IN THE FIELD CONDITIONS

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Feasibility of use of the arc mechanized processes in the field conditions is considered. It was found that welding units with internal combustion engines can be used in this case as arc supply sources for the semi-automatic machines. Accumulators with a series-parallel connection are offered as a stable power source for supply of the electric circuit elements. Diagram of connection of the power source for the semi-automatic machine systems with a definite algorithm of accumulators switching (for their charging and service in devices of the mechanized arc equipment) has been developed.

Key words: *mechanized arc equipment, supply systems, accumulators, service conditions, electrical supply systems*

The mechanized arc processes of welding and hardfacing using consumable electrode wire are widely spread in different branches of industry, construction, agriculture and repair workshops [1].

During recent years a greater attention is paid to the mechanized arc equipment in which the self-shielding electrode wires are used for the processes of welding, hardfacing [2] and cutting [3]. Development of different types and kinds of these wires makes it possible to realize most arc processes at the higher level in various conditions, including site conditions where the use of gas-shielded semi-automatic machines is impossible.

However, in spite of advantages of self-shielding flux-cored electrode wires the application of existing designs of the semi-automatic machines for the needs of the agricultural complex is not always possible, in particular in the field conditions, i.e. when there is no networks of industrial or local (mobile electric stations) electricity supply. In shops and in the site conditions the networks of industrial electricity supply are, as a rule, used, and static converters of level and kind of voltage (rectifiers), and, in some cases, the welding generator–driven electric motor systems are mainly used as arc supply sources.

In the field conditions the use of the above-mentioned arc supply systems is impossible. For these purposes the welding units, i.e. generators with benzine ADB or diesel ADD driven engines, are used. These autonomous systems of arc supply are widely used in creation of stations of manual rod electrode arc welding.

The use of available designs of the mechanized arc equipment in a set with welding units is almost impossible because of several reasons, among which the following ones can be distinguished:

• absence of quality power sources for systems of control of semi-automatic machines which are designed for realization of different arc technological processes using self-shielding flux-cored electrode wires (semi-automatic machines of A765, PDG-508 types, etc.);

• impossibility of use of voltage from arc supply sources of welding generators for supply of control systems of the semi-automatic machines (semi-automatic machines of A547Um, A825M, PSh107V types, etc.) due to high values of output open-circuit voltages, which are typical of power sources of this type, and also quality of this voltage, whose spectrum has collector switching overvoltages.

Equipment for the mechanized arc processes with use of consumable electrode in the form of self-shielding flux-cored wires, which was designed for operation in the field conditions, can find application in many areas of agriculture: in repair of agricultural, military, road-construction machinery directly at the sites of its use using technologies of welding, hardfacing and cutting; in utilization cutting of steel structures and also structures of copper and aluminium alloys, eliminating the use of industrial networks of electricity supply (ships directly on shelf, objects of agricultural and military machinery directly in the field conditions, etc.). The semi-automatic machines can be used in the field conditions for realizing shielded-gas welding (temporary rooms, special tents, shields). Here, the problems of increasing efficiency, improving quality and labour conditions of operators and reduction of material and energy consumption are solved.

This problem is especially actual for the branches of industry connected with construction of new and repair of different-purpose pipelines being in service under the field conditions, where a rod electrode welding until now is the main technological process. Welding units are usually used as arc supply sources. In non-stationary conditions this problem can be solved by several methods, for example, by using mobile electric stations of a required power and voltage. In addition, the welding station can be equipped with power sources of different types including the widely used static converters (rectifiers). However, in this case the cost of welding station equipment is abruptly increased, its mobility and manoeuvrability are decreased. A local power source, based on DC or AC, generator with a drive from internal combustion engine of a sufficiently low power for supply only systems of control and adjustment of the mechanized arc equipment can be added to the welding unit. But in this case additional expenses will also be required at low reliability of the whole complex.

Design Bureau of the E.O. Paton Electric Welding Institute came to the conclusion that the problem of a wide application of the semi-automatic machines in the field conditions, in particular in construction and repair of the pipelines, utilization of metal structures, can be solved by using a gained experience and technical developments of mechanized arc equipment of a multi-variant application of a basic model of a modular design [4]. This design provides an adjustable transistor electric drive which admits the use of DC power sources of almost any shape of voltage for its supply. Power sources with high values of open-circuit voltage (more than 60 V) and also those having high-voltage constituents in output voltage are an exception.

Thus, the main task in the design of the semi-automatic machine for use in different mechanized arc processes is the selection of a system of supply of the electric drive and control circuit. The effectiveness of this task solution is defined by a simplicity, low cost of the new equipment, easy maintenance and repair as well as by the reliability characteristics. All this will allow wide implementation of the arc mechanized welding, hardfacing and cutting of metals with a consumable electrode in the technologies used in the field conditions, in particular in construction and repair of the different-purpose pipelines.

During development, designing and testing of different variants of organizing the system for supply of the different-purpose mechanized arc equipment the final conclusion was made about impossibility of use of voltage of welding generator using simple technical and design solutions.

Variant of use of the auxiliary voltage source which is included into welding units and designed for charging storage batteries providing the start of a driven internal combustion engine was also studied. Direct application of the above-mentioned power source was also impossible by two main reasons: due to a low level of output voltage and presence of high-voltage constituents in the output voltage, though its use for charging a starting accumulator in the system of mechanized arc equipment supply is admissible.

To create a system of continuous and quality supply of the electric drive and circuit for control of different-purpose semi-automatic machines at their operation in the field conditions in a set with welding units it was suggested [5] to furnish the available energy accumulator with an auxiliary accumulator and to realize the supply of the mechanized arc equipment from the system of two accumulators providing 24 V voltage which is designed for electric equipment of the semi-automatic machine.

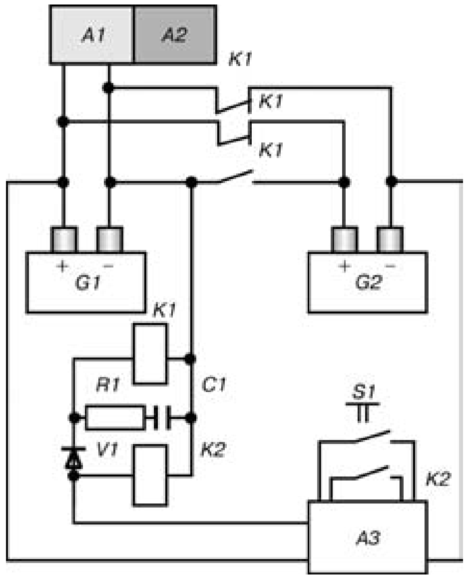
Variant of electrical elementary diagram of the semi-automatic machine with a new system of its supply in the field conditions is given in the Figure.

As is seen from the diagram, the design of the new system is quite simple and can be easily realized in any conditions. It includes mainly an auxiliary accumulator *G2* and operation condition switch (relay *K1* in our case) which realizes an automatic selection of the operation condition of the main *G1* and auxiliary

G2 accumulators as follows. If the relay *K1* is not switched on (there is no command from the system of the semi-automatic machine control about the operation start), then both accumulators *G1* and *G2* are connected in parallel and charged from the charging device *A1*. When the semi-automatic machine is switched on the command is entered from its circuit from relay *K1* for switching the accumulators *G1* and *G2* into series connection and connection to the supply circuit of the semi-automatic machine. In this operation condition the main accumulator *G1* is charged again from the charging device *A1* of the welding unit. The supply of switching relay *K1* is realized from the main accumulator *G1*. Besides relay *K1*, the relay *K2* is also switched on which controls the operation of electric drive for the electrode feed mechanism and also other elements included into the operational cycle of the automatic machine *A3*. After completion of the arc process cycle the relay *K2* is first switched off, then other elements participating in the working cycle of the semi-automatic machine are switched off. Relay *K1* is switched off at a some delay provided by circuit *C1*, *R1* and isolating diode *V1*. This delay is necessary to make the conditions of recomutation of accumulators *G1* and *G2* easier. All the auxiliary elements of the station for mechanized processes are arranged in a separate module directly on a welding unit (panel of instruments and controls of the unit).

The offered variant of supply system of the different-purpose mechanized arc equipment for service in the field conditions was realized in a serially-produced semi-automatic machine PSh107V type for welding and hardfacing using self-shielding flux-cored electrode wires. In the supply system 12-volt accumulators of 65ST type were used. Such design of the semi-automatic machine was tested by emergency services of enterprise «Vodokanal» in repair welding and cutting with self-shielding flux-cored electrode wires of water supply pipes of a different assortment. Specialists recognized the high quality and minimum terms of works fulfillment, and, especially, mobility and simplicity of the semi-automatic machine having a new supply system.

During the experimental service of the semi-automatic machine the possible duration of operation without additional charging of accumulators was defined, that at presence of two preliminary charged and series-connected accumulators of 65ST type the supply systems guarantees the serviceability of semi-automatic machines of PSh107V type at 40 % duty cycle during 2–3 shifts. In some cases the above-men-



Elementary electrical diagram of the semi-automatic machine for welding, hardfacing and cutting in the field conditions

tioned semi-automatic machine with an accumulating system of supply using storage batteries can operate also without devices for charging accumulators.

It should be noted that the offered development of the energy-accumulating system of supply can be used also with other types of the semi-automatic machines. Here, the obligatory requirement is the presence in its design of DC electric drive for the electrode wire feed mechanism and also an adjustable transistor electric drive or simplest resistive controllers in circuits of electric motor like the type of semi-automatic machines A547Um, A825M. It is required additionally that voltage used for supply of electric drive and control circuit was 24 V or divisible by 12 V (most widely spread types of accumulators).

The advantages of the offered supply system make it possible to state that the sphere of spreading this equipment can be widened significantly.

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ABOUT EFFECT OF ELECTRIC FIELD FLUCTUATIONS IN ARC COLUMN ON ARC WELDING PROCESS STABILITY

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A sufficient condition has been obtained guaranteeing the asymptotic stability of the consumable electrode arc welding process in the case when the electric field intensity in the arc column varies within certain known limits.

Key words: *arc welding, consumable electrode, electric field, stability of welding process*

Stability of the consumable electrode arc welding is analyzed usually coming from the assumption that the parameters of the process considered are constant. Actually, some of them (in particular, electric field intensity in arc column) are significantly changed with time. What is the effect of these changes on the welding process stability? Judging from the available publications the above-mentioned question is little studied until now.

In the present article the conditions, specified at the limits of changing electric field intensity in the arc column which guarantee the asymptotic stability of the arc welding process, were obtained.

Let us consider the differential second-order equation

$$\ddot{\lambda} + \alpha (t, \lambda) \dot{\lambda} + \beta (t, \lambda) \lambda = 0, \tag{1}$$

describing a dynamic process relative to some variable λ. The stability of this process is judged from coefficients $\alpha(t, \lambda)$ and $\beta(t, \lambda)$. According to [1] the function $\alpha(t, \lambda)$ can be interpreted as non-linear, time-dependent t, generalized coefficient of damping, while function $\beta(t, \lambda)$ can be interpreted as non-linear, clearly t-dependent, generalized rigidity of the process.

At any, but constant and positive values of coefficients α and β the process (1) is asymptotically stable relative to variable λ. However, if the values of these coefficients, being positive, are changed, then the process will become instable at certain conditions. As the law of changing functions $\alpha(t, \lambda)$ and $\beta(t, \lambda)$ is often not defined and only the limits of their changes

$$a \le \alpha (t, \lambda) \le A, \quad b \le \beta (t, \lambda) \le B \tag{2}$$

are known, then it is interesting to define conditions specified for positive numbers a, A, b, B at the fulfilment of which the steady process will be stable asymptotically.

In [1] the sufficient conditions, guaranteeing asymptotic stability of the process (1), were obtained using a Lyapunov's direct method and Silvester's generalized inequalities. These conditions have a form

$$\begin{gathered}\sqrt{B} - \sqrt{b} < 2\sqrt{a_1(a - a_1)}, \\ 2\sqrt{b} > \sqrt{a_1(A - a_1)} - \sqrt{a_1(a - a_1)}.\end{gathered} \tag{3}$$

Number a_1 in expressions (3) is selected arbitrary in the range of $0 < a_1 < a$.

The result obtained will be used for finding conditions of a consumable electrode arc welding process stability at electric field fluctuations in arc column, i.e. for the case when the electric field intensity is not a constant value, but it is changed in the preset known ranges.

According to [2] the transition process in a welding circuit is described quite satisfactorily by equation (1) in which the generalized coefficient of damping

$$\alpha (t, \lambda) = \frac{R_*}{L}, \tag{4}$$

and generalized rigidity of the process

$$\beta (t, \lambda) = \frac{EM}{L}. \tag{5}$$

In these ratios

$$R_* = R + S_a - S_s, \tag{6}$$

where R is the total resistance of supplying wires and a sliding contact in a torch nozzle; S_a, S_s are the steepness of volt-ampere characteristics of arc and welding current source at rated value of current i_0, respectively; L is the welding circuit inductance; E is the electric field intensity in arc column; M is the steepness of characteristic of electrode melting at a rated value of welding current i_0 and preset electrode stickout h_0; $\lambda = l - l_\infty$ is the deviation of arc length l from its steady value l_∞.

Let us assume that the damping coefficient $\alpha = R_*/L$ has a constant value, and the electric field intensity E, included into ratios (5), depends on time t, where inf $E(t) \le$ sup $E(t) \le E(t)$. In this case, according to (2), $\alpha = a = A$ and second condition (3) is fulfilled automatically. In the first condition (3) we assume that $a_1 = a/2$ (here, $a_1(a - a_1)$ reaches maximum). Then, the first condition (3) can be reduced to a simple form

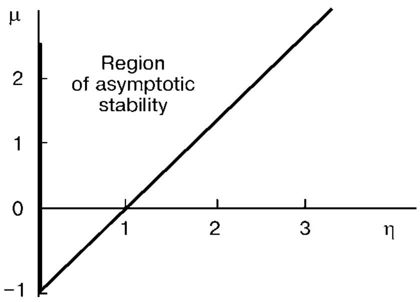

Figure 1. Boundaries of asymptotic stability region

$$\sqrt{B} - \sqrt{b} < \alpha, \tag{7}$$

where

$$B = \frac{M}{L}\sup E(t), \quad b = \frac{M}{L}\inf E(t). \tag{8}$$

Inequality (7) with allowance for (4), (6), (8) and designations $E_s = \sup E(t)$, $E_i = \inf E(t)$ will be written in the final form

$$\sqrt{E_s} - \sqrt{E_i} < \frac{S_a - S_s + R}{\sqrt{ML}}. \tag{9}$$

Thus, the following fact was established: if the condition (9) is fulfilled, then the consumable electrode arc welding process with changing electric field intensity in the mentioned ranges E_s and E_i is asymptotically stable.

Inequality (9) can be presented also in some different form:

$$\mu > -1 + \eta, \tag{10}$$

where

$$\mu = \frac{S_a - S_s}{R}, \quad \eta = \frac{\sqrt{ML}}{R}(\sqrt{E_s} - \sqrt{E_i}). \tag{11}$$

The sufficient condition of an asymptotic stability (10) is differed from required and sufficient condition

$$\mu > -1,$$

obtained in work [2] for case $E = \text{const}$, only by an additive term η characterizing the effect of changes

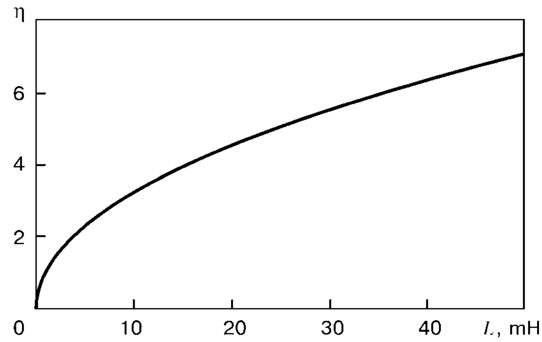

Figure 2. Curve of relationship $\eta = \eta(L)$

of electric field E in arc column on the stability of processes proceeding in welding circuit.

Figure 1 shows the region of stability in the plane of dimensionless parameters μ and η, plotted by formula (10). Coming from this Figure and expression (10) it can be concluded that with increase in η the stability region is narrowed.

It comes from the second ratio (11) that the values η are increased with increase in difference between values $\sqrt{E_s}$ and $\sqrt{E_i}$ and inductance L. Figure 2 gives a curve of relationship $\eta = \eta(L)$, plotted by formula (11) at E_s = 4 V/mm, E_i = 1 V/mm, M = = 0.4 mm/(A·s), R = 0.02 Ohm. It is seen from the Figure that at small (up to 1 mH) values L the values η remain within unity. It means that the effect of electric field fluctuations in arc column on the stability of process proceeding in the welding circuit is so small that it can be neglected. However, at high values L (tens of millihenry) the values η are increased ($\eta > 3$). Moreover, as is seen from Figure 1, the region of stability is significantly narrowed.

Thus, the effect of the mentioned fluctuations on the process stability at large values is high, therefore, the steepness of the volt-ampere characteristic of the welding current source S_s should be selected taking into account the criterion (9) to provide the condition $S_s < S_a + R - \sqrt{ML}\,(\sqrt{E_s} - \sqrt{E_i})$.

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INTERNATIONAL EXHIBITION «WELDING — UKRAINE'2002»

The 4th Specialised Exhibition with international participation, which was held in Kyiv in April 22–26, 2002, became a marked event in the life of scientists, developers, designers, manufacturers and users of welding equipment and facilities for testing, protection of welders and environment. It is worthy of note that the Exhibition coincided in time with the 10th anniversary of the Welding Society of Ukraine. More than 70 companies of Ukraine, CIS and other foreign countries demonstrated their achievements and future capabilities. While welding does have the future and, as said Prof. B.E. Paton at the opening ceremony, welding and related technologies will maintain their position in the XXI century, and equipment will be continuously upgraded and quality of the technological processes will be improved.

In general, the Exhibition demonstrated widely applied types of welding equipment, the equipment for manual arc welding and surfacing, power units for manual stick electrode and semiautomatic welding of steels in the first place being the dominant exhibits.

Consideration was given to welding consumables, such as high-quality and special electrodes, different types of electrode wires, including flux-cored self-shielded ones and others. Along with foreign manufacturers, worthy of note are also the Ukrainian manufacturers of high-quality electrode products, such as a new Company «Arksel» (Donetsk), Research and Production Company «Elna» (Kyiv) and others.

Considerable increase was noted in the number of companies involved in solving environmental problems of the welding industry, including manufacture, delivery and assembly of facilities for removal and cleaning of welding aerosols. Noteworthy among developments in this area are small-size local means for individual protection of welders with forced feed of purified air, produced by the «Sizod» Company (St.-Petersburg). Very good in this respect are filter-ventilation devices, a joint development of the R&D Centre «Temp» and the E.O. Paton Electric Welding Institute. Among the exhibits were reliable and very efficient means for removal of welding aerosols, combined with hose holders («Binzel» Company), which showed themselves to advantage. Evidently, the area of development and manufacture of welder's and environment protection facilities shows a marked progress taking place in the last years.

Companies involved in production of welding accessories have increased in number, and their products are of a high quality, wide diversity and good design. One cannot but note the Ilnitsk Mechanical Pilot Plant for welding equipment, which achieved a substantial improvement in quality of its hose holders for gas-shielded welding. As reported by representatives of the Plant, its target is to upgrade hose holders to make them fit for operation with flux-cored electrode wires, the Plant being the only manufacturer of them in Ukraine. Of a pleasant surprise were exhibits of the PWI Pilot Plant for Welding Equipment, which developed and is commercially producing a wide range of hose holders characterised by a modern design and high technological perfection. The Kakhovka Plant for Electric Welding Equipment (KPEWE) developed and is manufacturing a number of hose holders. Most probably, the national manufacturers will retain the main market of application of the hose holders.

The current trend now is that some manufacturers of mechanised arc equipment in Ukraine complete their products with hose holders produced by foreign companies, for example, «Binzel». As to other components and accessories for the arc equipment, such as stick electrode holders, return welding wire clamps, etc., certain advances have been achieved in this area as well. Of special notice is the problem of gas shutoff devices, which is very topical for manufacturers and users of mechanised arc equipment. Until recently the use was made of all-industry valves or in-house shut-off devices (semiautomatic devices A547Um, A825M). This problem was solved by KPEWE, which arranged production of gas shutoff devices of a good design and sufficiently high quality. Manufacture of electric motors and electrode wire feed mechanisms, based on the above gas shutoff devices, is developed by the Company «Artyom-Kontakt». It is not enough however, as the main manufacturers of arc welding equipment employ other developments of mechanisms and other electric motors. It is our opinion that manufacture of electric motors and electrode wire feed mechanisms is very topical and promising for Ukraine, and should be expanded in terms of ranges (flux-cored and aluminium electrode wire feed mechanisms and mechanisms with a pulsed character of wire feed), allowing for developments available in this field, including at the PWI Design Bureau.

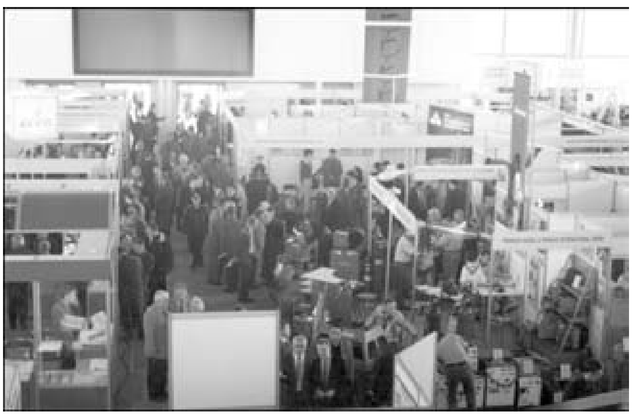
Let us dwell on such an important piece of equipment for arc welding processes as arc power supplies. Along with maintaining output of sufficiently simple transformers and rectifiers, including the regulated (thyristorised) ones for mechanised welding processes, there is an increase in developments that use inverter technologies. Different modifications of the inverter-type arc power supplies were exhibited by a number of foreign companies, such as CEMONT S.R.L., which demonstrated its equipment for the first time, as well as «Fronius-Fakel», «Lincoln Electric», etc. A number of Ukrainian companies also demonstrated rather attractive facilities based on foreign components and assemblies. These companies include the Simferopol Motor Factory, which exhibited a number of power supplies for manual arc welding and small-size semiautomatic devices for welding using thin steel solid electrode wire. The absolute leader in manufacture of home inverter-type facilities for manual arc welding and, during the last years, for mechanised processes is the Production Association «Kommunar» (Kharkiv), which manufactures single- and three-phase power units for manual arc, mechanised and tungsten-electrode welding. It should be noted that the three-phase power units produced by this Company have built-in devices for decreasing open-circuit voltage, which makes it possible to use them under especially critical conditions and save power. These technical solutions realised in commercial equipment are new and beneficial, and should be assessed by customers.

By analysing the exhibits, we see the recent growth of the number of developments of the inverter-type facilities and increase in their output. However, proceeding from the expert poll, there is no such growth under industrial conditions. As shown by analysis, such facilities are expensive so far and too sophisticated for commercial customers in Ukraine, and, what is most important, it is our opinion, they do not use those technical advantages which can be provided by algorithms of the welding process control, e.g. the mass transfer control (electrode metal transfer), which are realised in the inverter technologies, as it is done, e.g. in realisation of the synergic control with the KEMPPI equipment (this equipment was not demonstrated at this Exhibition), or in the SST technology with the «Lincoln Electric» equipment. Apparently, the weight-dimension indicators, the advantages of which are provided by the use of the inverter technologies, are not enough to master the market of welding and related technologies. It is even more evident against developments of the resonance-type arc power supplies made by the PWI. These units have small sizes, they are highly efficient and provide the improved welding properties. In addition, the resonance-type units are characterised by a very low

interference level, which is not typical for other types of welding equipment. In our opinion, these units have high potential and excellent future both inside and outside Ukraine.

Above we have already mentioned the equipment and accessories for manual and mechanised arc welding methods. However, the characteristic peculiarity of this Exhibition is a relative growth of the number of developments for automatic welding using automated processes. Here we have to note the tractor-type equipment exhibited by three companies: PWI Design and Production Association (PWI DPA) (small-size tractors), KPEWE (several models of welding tractors) and SELMA, Simferopol (welding tractor). Now we have equipment of the type of automatic devices and units, which could hardly be seen at our previous exhibitions. Thus, in addition to traditional automatic devices with the tactile-type tracking systems produced by KPEWE, demonstrated were also developments of assemblies of the automatic devices with seam tracking systems of the laser type (PWI DPA). The «Fronius-Fakel» for the first time demonstrated its automatic device for orbital position butt welding of pipes and automatic welding carriage for making fillet welds.

Special consideration should be given to growth of the number of exhibits for automated processes involving microprocessor facilities (in principle, these are the fully mechatronic systems), i.e. advanced programmable controllers. Here we have to note developments of the PWI DPA associated with the control systems for welding automatic devices with a tracking function, which were made on the basis of the pro-



grammed controller. This development uses another highly promising design, i.e. equipping all systems for movement of the welding automatic device with regulated AC electric drives which, as proved by research and experience, are much more reliable than the DC drives with commutator motors.

Note that, in addition to the above-said, the microprocessor-controlled systems demonstrated at the Exhibition included also the control systems for flash butt welding machines produced by the KPEWE, as well as systems for automated location and spacing of metal blanks presented by companies «Zont» (Odessa) and «Messer MGM».

The major expositions at the Exhibition were presented by the Scientific- and-Technical Complex «The E.O. Paton Electric Welding Institute» (STC «PWI»), KPEWE and SELMA. Let us dwell on exhibits of these organisations in view of their importance and effect on the welding equipment and technology. Some developments of STC «PWI» have been already noted above.

Therefore, here we will note equipment manufactured by the PWI Pilot Plant for Welding Equipment. The Plant demonstrated a number of welding and surfacing semiautomatic devices designed on different power characteristics basis, as well as power supplies for manual arc welding. Equipment of the Plant involves some ingenious concepts. First of all it is orientation to a specific customer. The Plant selected enterprises where operation of welding equipment is characterised by the most severe conditions, and is manufacturing part of its equipment intended particularly for such customers. In addition, the automatic welding devices produced by the Plant incorporate technical solutions which allow the weakest points (electronics) to be separated in an original design and thus the reliability characteristics to be improved. Unlike the majority of other manufacturers, semiautomatic devices of the Plant are equipped with the in- house hose holders and use the in-house electrode wire feed mechanisms. The Plant demonstrated the advanced unit for welding plastic pipes.

In booths of the PWI DPA one could see really new and ingenious developments of power- and material-saving equipment, e.g. a new design of the semiautomatic devices for welding steels and aluminium with pulsed electrode wire feed, as well as the «Triplet» type unit for welding and surfacing of steels and aluminium with a simultaneous and alternate electrode wire feed. Note that almost nothing was offered at the Exhibition for mechanised welding of aluminium and its alloys, except for the semiautomatic device with the pulsed electrode wire feed, whereas the quality welding of aluminium in power generation, metallurgy and transport remains a very pressing problem not only in Ukraine but also abroad. It is worthwhile to draw attention of welding equipment manufacturers to this problem.

KPEWE presented the widest range of equipment for different types of welding and different technologies. This is in full agreement with the characterisation of the Plant which was made by Prof. B.E. Paton at the Exhibition opening ceremony, when he called the Plant the largest enterprise of Ukraine, producing and exporting welding equipment. Indeed, one could see everything in the Plant booths, starting from in-house components (gas shutoff devices and heaters, hose holders) to automatic welding units and flash butt welding machines (for rail, seam and spot welding, etc.).What is the distinctive feature of the KPEWE equipment? First of all, it is robustness, forethought and relying on the in-house production of the majority of components (hose holders, electrode wire feed mechanisms, gas shutoff devices, etc.). In our opinion, KPEWE has all the conditions to be among the world leaders in manufacture of welding equipment, including the arc welding equipment. However, it lacks new technical solutions to realise advanced technologies, and misses some types of welding, including mechanised welding of aluminium. Willingness of the Plant to meet the current needs of customers (e.g. upgraded modification of A547Um, current sources for operation under severe conditions) helps it to solve the today's economical problems, but yields nothing for the future.

The SELMA Company booth was of interest. It concerns primarily widening of the range of the equipment produced, including welding tractors, which were demonstrated for the first time at the Exhibition. Products which are traditional for the Company, i.e. power units for manual arc welding and semiautomatic welding devices, have been subjected to substantial qualitative changes during the last years. They include now digital systems for measuring the arc welding process parameters, new developments of four-roll gear feed mechanisms for semiautomatic devices, etc. SELMA demonstrated its new development, i.e. the advanced model of semiautomatic welding device using the inverter technologies and synergic algorithms for the electrode metal transfer control. Demonstration of a multi-station system for mechanised welding using the muslti-station arc power supply and a special converter of output voltage of this unit into a level required to realise the welding process, with the unit located at a substantial distance (tens of meters) from the workpiece, is an ingenious design of the Company which attracts attention of specialists. The converter may have different programmable pulse control algorithms. The level and quality of the basic types of the SELMA welding equipment are such that, as reported by the Company managers, they allow export of up to 65 % of the entire output.

Summarising description of the diversity of the exhibits of welding equipment, the majority of which naturally are the devices for manual and mechanised arc welding processes, it can be stated that at the given stage even the major manufacturers of this equipment in Ukraine cannot meet in full and within the short terms the increasing demand of various customers. We believe that this is caused by the absence of developments to allow problems of the welding industry, associated with repair of machine and mechanism parts and units, to be solved quickly and at minimum costs for potential customers. The way out from this situation was offered by PWI DPA, which exhibited in its booths the certified method for modular design and manufacture of mechanised and automated arc welding equipment incorporating multifunctional baseline assemblies, units and systems.

In parallel with the Exhibition, on 24–25 April STC «PWI» hosted the International Conference «Welding and Related Technologies'2002» (history, achievements, prospects, Benardos readings). The Conference was sponsored by STC «PWI», the Welding Society of Ukraine, Ministry for Industrial Policy of Ukraine, Institute of History of Ukraine of the NAS of Ukraine, G.M. Dobrov Centre for Productive Forces and History of Science of Ukraine and Centre for Monuments History of the NAS of Ukraine. The Conference was dedicated to N.N. Benardos, the inventor of electric arc welding.

The Conference was attended by more than 100 scientists and specialists in the field of welding and related processes from Austria, Belarus, Russian Federation and Ukraine. The Conference was opened by Prof. L.M. Lobanov, Deputy Director of the E.O. Paton Electric Welding Institute. The Conference program included about 70 papers and presentations. Considering the importance of the knowledge of history of technology, and the welding science and technology in particular, for prestige of the country and prestige of the welding discipline, the Conference included several plenary presentations on the technology and natural history. High consideration to this issue was given in his days by Evgeny O. Paton, the founder of the Electric Welding Institute. At the beginning of the XX century, being a dean of the Engineering Department of the Kyiv Polytechnic Institute, Evgeny Paton headed at the same time the Engineering Museum of the Institute. While he was the Director of the Museum, he managed to arrange its work and substantially replenish its exposition. In 1995 the Engineering Museum of the Kyiv Polytechnic Institute was transformed into the State Polytechnic Museum. The President of the NAS of Ukraine, Director of the E.O.Paton Electric Welding Institute Prof. B.E. Paton has expressed high interest in history of technology and advocacy of priorities and advances of our scientists in the field of welding. This problem is topical for all industrialised countries. It is enough to say that in the USA there are about 16 universities and institutes that deal with historical studies in the field of technology.

Papers presented at the Conference were dedicated to the following subjects:

• technology and natural history, role of technical museums in study of the history of science and technology;

• investigation of the processes of arc welding, using mathematical modelling for investigation of the arc welding processes, new generation of arc welding equipment, welding consumables and fusion arc welding technology; study of underwater arc welding and cutting processes;

• development of combined welding processes and investigation of their technological capabilities (laser and plasma welding, arc and plasma welding, etc.);

• technology and equipment for different pressure joining methods, development of technology for resistance welding of multilayer materials;

• technology and equipment for deposition of coatings, new high-productivity methods for deposition of different-purpose coatings (wear-resistant, protective, decorative, current-conducting, etc.);

• technology and equipment for high-productivity manufacturing and repair surfacing methods, new sparsely-alloyed different-purpose surfacing consumables;

• high-productivity methods for cutting metals and alloys;

• new types of welded structures, application of advanced structural materials, automated design of welded structures;

• strength of welded joints and structures, investigation and methods for regulation of welding stresses and strains, peculiarities of fabrication and operation of welded structures at low climatic temperatures;

• estimation of residual life of welded structures, methods for improvement of their reliability and fabrication quality;

• technical diagnostics and non-destructive testing;

• standardisation and certification of welding industry products, training and qualification of welding industry specialists, including using the training programs in compliance with requirements of the European Welding Federation.

Summarising the Conference, Prof. L.M. Lobanov highly estimated the level of the majority of the presentations and wished the Conference participants further success in their scientific and business activities. Abstracts of the Conference were included in the book «Welding and Related Technologies'2002» published by STC «PWI».

During the Conference, its participants had the possibility to see exposition of the already traditional Exhibition «Welding — Ukraine'2002».

V.A. Lebedev and I.A. Ryabtsev
The PWI Press Group

V.K. Lebedev is 80

June 6, 2002 marked 80th birthday anniversary of Vladimir K. Lebedev, prominent scientist in the field of welding technology and equipment, Dr. of Science (Eng.), Professor, Honoured Scientist, winner of the Lenin Prize, State Prizes of the USSR and Ukr. SSR, of Evgeny Paton Prize, academician of the National Academy of Sciences of Ukraine.

After graduation from the Moscow Institute of Energy in 1945 V.K. Lebedev became actively involved in research, aimed at development of advanced welding equipment, which was conducted at the E.O. Paton Electric Welding Institute. The start of engineering and scientific activity of V.K. Lebedev coincided with a complicated and difficult period of restoration of the national economy, destroyed by the Great Patriotic War. Working continuously at the PWI for more than half a century now, V.K. Lebedev has covered the path from junior staff scientist to head of a major scientific division and Deputy Director on Research. His first scientific search was devoted to investigation of the features and development of methods for designing welding transformers with complex leakage fields, which was reflected in his Candidate's thesis, defended in 1948. In 1959 V.K. Lebedev was granted the degree of Doctor of Science (Eng.) for his work, which was a major contribution into the theory and practice of modern transformer construction.

V.K. Lebedev is one of the leading experts in the field of electrothermics and conversion of electric energy. The most prominent work of this scientist deals with studying the means of conversion of electric energy into thermal energy and development of dozens of types of new power sources for various variants of electroslag, resistance, electron beam and laser welding and for special electrometallurgy. These current sources have found wide application in different industries. Developments by V.K. Lebedev and his name are widely known not only in Ukraine and CIS countries, but also far beyond them.

In 1964 V.K. Lebedev was elected the Corresponding Member of the NAS of Ukraine, and in 1972 he became academician of the NASU.

The results of V.K. Lebedev's investigations and his inventions formed the basis of a fundamentally new technology and novel equipment for flash-butt welding of items with a large cross-section of the parts being joined. Owing to its high productivity, this technology became widely accepted in construction of railways, for which V.K. Lebedev, as a member of the author's team, was granted the title of winner of the Lenin Prize in 1966. Further advance of investigations in this area led to development of processing systems with in-pipe machines for flash-butt welding of large-diameter pipes. V.K. Lebedev has also made a great contribution to development, fabrication and introduction of equipment for multiposition flash-butt welding of the heads of locomotive engine blocks and heat exchangers of power transformers. This work was rewarded by the State Prize of the Ukr. SSR (1976).

In 1980 the scientist conducted a series of investigations, which were highly important for science and technology, in particular in the field of flash-butt welding of load-carrying elements of flying vehicles, rewarded in 1986 by the USSR State Prize.

V.K. Lebedev is the author of more than 450 scientific publications, including 11 monographs, and more than 200 inventions on advanced welding processes and equipment. Most of the inventions are protected by patents.

Vladimir K. Lebedev combines intensive creative work with the ability of not only feeling the needs of industry, but also determining the promising and priority areas of the progress of science and technology. Creative activity of Vladimir K. Lebedev is characterized by a broad range of scientific interests and strong determination to achieve practical application of the results of the conducted research.

A vivid proof of that is Prof. Lebedev's involvement over the last decade in a new field for welding scientists and specialists, namely development of bioelectric technology, which allowed producing for the first time sound welded joints in damaged live tissues. Uniting the efforts of specialists of engineering and medical profile, V.K. Lebedev became the principal investigator of the «Welding of Live Tissues» Project, fulfilled within the framework of International Association «Welding». His development of the theoretical fundamentals of the process of joining live tissues at the molecular level and of the principles of automatic self-adjustment of the process of producing a sound joint allowed creating for the first time in the world practice the medical equipment and welding medical instruments to perform surgery to restore the physiological functions of damaged human organs. New welding medical technology created by V.K. Lebedev has been successfully applied in clinics.

In 2001 V.K. Lebedev was awarded the Evgeny Paton Prize for a series of developments on welding and allied technologies.

V.K. Lebedev currently is a consultant of the PWI Management and Head of the Research Department of Electric Processes. He actively pursues scientific-organizational and public activity: he is Deputy Editor-in-Chief of the «Avtomaticheskaya Svarka» journal, Deputy Chairman of the Specialized Council for defending the theses of candidate and doctor of science, and Chairman of the Ukrainian Welders Certification Committee.

V.K. Lebedev readily and generously shares his extensive experience and knowledge with his pupils, colleagues and young scientists. He has trained 10 doctors and 42 candidates of science in engineering.

Many years of V.K. Lebedev's creative work have been rewarded by state prizes.

All those who work and communicate with Vladimir K. Lebedev unanimously note his exceptional respectableness, kindness, goodwill and intelligence.

We would like to convey to Vladimir K. Lebedev our heartfelt greetings and sincere wishes of good health, personal happiness and great success in implementation of his new creative ideas.

The E.O. Paton Electric Welding Institute
Society of Welders of Ukraine
Editorial Board of «Avtomaticheskaya Svarka»