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COMPUTER-AIDED DESIGN OF ADVANCED WELDING CONSUMABLES

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New approach to design of welding and surfacing consumables, based on modelling of physical-chemical processes occurring at all stages of formation of the weld and its interaction with environment, is described. Phenomenological model of non-equilibrium solidification of the weld pool has been developed, and system for computer-aided design of welding consumables has been built. Example of practical realisation of the new method for design of welding and surfacing consumables is given.

Keywords: welding consumables, electrode formula, computer-aided design, expert system, flux-cored wire, full-scale tests

Welding consumables perform their main function, i.e. providing of required strength characteristics and service properties of the weld metal, through their direct participation in the welding process characterised by complex physical-chemical interactions. Ignoring these interactions that ensure transformation of a welding consumable and base material into a deposited metal makes it impossible to describe structure, design, composition, functions and properties of welding consumables. The problem of development of welding consumables, including working out of the formulation of a particular consumable and technology for its manufacture, should be structured on the basis of a system approach. For this, it is necessary to analyse processes occurring in melting of a welding consumable and base material and formation of a weld drop and weld pool, processes of solidification of molten metal of the weld pool, interaction of deposited metal with the environment, and service properties of the deposited metal and welding consumable.

Modelling as a basis of the computer-aided design methodology. Basic conditions of a new conception [1, 2] were formulated as a result of application of the system approach and structural analysis for development of welding consumables. This conception is a logical sequence of interrelated stages of design of new welding consumables, such as analysis of environment, working medium and character of loading of the working medium; evaluation of the character of the environment–working medium interaction; determination of the required structure of the weld metal; calculation of the primary structure and chemical composition of the weld metal; and definition of the electrode formula for a specialised welding (surfacing) consumable.

Detailed analysis of basic postulates of the suggested conception [1–4] shows the need to develop appropriate models for main physical-chemical processes occurring at all stages of formation of the weld [5, 6] and its interaction with the environment. It is indicated in studies [1–4] that the efficient method for development of a new welding consumable is a solution to the inverse problem, which suggests finding formulation for this consumable as a function of service properties of the weld metal. The most important problem of the new methodology in terms of definition of the electrode formula for a new welding consumable is formation of an idea of the required structure of the weld metal under its service conditions and calculation of the primary structure and chemical composition of the deposited metal. Chemical composition of the weld metal depends upon the initial chemical compositions of the filler and base metals, as well as the character of physical-chemical processes of interaction between the metal and slag melts. Prediction of chemical composition of the deposited metal is based on the method of kinetic analysis of reactions occurring simultaneously in the diffusion mode between the metal and slag melts [7]. This should allow for a mutual effect of the reactions and diffusion of all reagents in metal and slag. As a result, for current and final compositions of the metal melt, according to study [8], it can be written down that

$$\left[E_i\right]^{\tau} = \frac{v_d \left[E_i\right]_d \tau + v_{bm} \left[E_i\right]_{bm} \tau + 100 M_{E_i} A_p \int_0^{\tau} v_{E_i} d\tau}{v_k \tau}, \quad (1)$$

where v_d and v_{bm} are the rates of feed of the electrode and base metals, respectively, to the weld pool; τ is the time of existence of the molten weld pool; $[E_i]_d$ and $[E_i]_{bm}$ are the contents of the i-th element in the electrode and base metals, respectively; M_{E_i} is the molar mass of the i-th element; A_p is the area of interaction between the phases; v_{E_i} is the rate of transition of the i-th element through the metal–slag interface; and v_k is the rate of solidification of the weld pool.

Therefore, the suggested method allows finding chemical composition of molten metal of the weld

pool, i.e. the weld metal. This chemical composition is an input parameter for determination of quantitative and qualitative compositions of the deposited metal phases. Further transformations of the metal melt are related to the processes of primary and secondary solidifications, i.e. phase transformations in a multicomponent alloy. Consider the process of primary solidification proceeding from chemical composition of molten metal of the weld pool. It is known from the theory of welding processes [5] that solidification of the weld pool occurs under extremely nonequilibrium conditions at the absence of convective stirring of metal in the tailing part of the weld pool, i.e. near the solidification front. That is why the process of distribution of components between the liquid and solid phases is «controlled» only by diffusion. Another important factor affecting the distribution of components is a concentration wave near the solidification front. These factors result in solidification overcooling, which, along with the thermal one, determines the cyclic character of solidification of the weld pool and chemical heterogeneity of the solidifying weld metal [5, 6, 9]. At any moment of solidification of the weld pool the amount of the i-th element that passed from the liquid phase to the solid one can be determined as follows [5, 9]:

$$E_i^{(s)} = E_i^0 \left[1 - (1 - K_{\text{ef}}) \exp\left(- \frac{L^t v_k}{D_i^{(l)}} \right) \right], \qquad (2)$$

where $E_i^{(s)}$ is the content of the i-th element in the solid phase at solidification time moment t; E_i^0 is the initial average concentration of the i-th element in the melt; K_{ef} is the effective distribution coefficient; L^t is the distance from the point of beginning of solidification (length of a crystalline grain at solidification time moment t); and $D_i^{(l)}$ is the coefficient of diffusion of the i-th element in the melt.

Determination of the content of the i-th element in the solid phase at solidification time moment t does not allow determination of its distribution between austenite and strengthening phases formed at the solidification moment. In the majority of cases we have one solid solution in the solidified weld metal, i.e. austenite and several phases of primary carbides. We must know the distribution of the i-th element between the solid solution and these phases. The factors that affect carbide formation can be subdivided into two groups: physical-chemical factors determining the nature of the carbide formation process proper, and technological factors affecting the carbide formation process through changing parameters of the first group. Principles of the carbide formation in an iron-carbon alloyed deposited metal are formulated in studies [10, 11] on the basis of a detailed physical-chemical analysis of the process of formation of primary carbides as compounds of carbon with d-metals, involving quantum-chemical notions of electron composition of d-metals and primary carbides. It is stated in these studies that the content of the i-th d-metal consumed for the formation of carbide is in direct proportion to atomic radius R_i of this metal and in inverse proportion to the quantity of electrons at d-sublevel d_i of this metal. This introduces the notion of the absolute carbide-forming ability of the i-th d-metal, Θ_i:

$$\Theta_i = \frac{R_i}{d_i}. \qquad (3)$$

As follows from expression (3), the carbide-forming ability grows in a series of iron, manganese, chromium, molybdenum, tungsten, niobium, vanadium, tantalum, titanium, zirconium and hafnium, which is in good agreement with the results of studies [12–15]. The distribution of alloying elements and carbon between the liquid and solid phases is determined by expression (2). Diffusion-free decomposition of the oversaturated solid solution into austenite and carbide phases takes place at the solidification moment. The amount of carbon fixed by some carbide-forming element is determined by stoichiometry of compound Me_xC_y, and can be found from the following expression:

$$E_{\text{C}_i}^{(c)} = E_i^{(c)} \frac{yA_{\text{C}}}{xA_i}, \qquad (4)$$

where x and y are the stoichiometric coefficients; A_{C} and A_i are the atomic masses of carbon and carbide-forming element, respectively; and $E_{\text{C}_i}^{(c)}$ is the content of the carbide-forming element in the carbide phase. Logically, it can be assumed that only that part of alloying elements and carbon which is not dissolved in austenite at a given temperature is consumed for the carbide formation:

$$E_{\text{C}}^{(c)t_k} = E_{\text{C}}^{(s)t_k} - E_{\text{C}}^{(\text{lim})t_k}, \qquad (5)$$

where $E_{\text{C}}^{(c)t_k}$ is the content of carbon non-dissolved in austenite; $E_{\text{C}}^{(s)t_k}$ is the content of carbon at the solidification time moment determined from expression (2); and $E_{\text{C}}^{(\text{lim})t_k}$ is the limit of solubility of carbon in austenite at a given solidification temperature at time moment t_k. In this case the distribution of carbon between the carbide phases in an alloy is proportional to the relative carbide-forming ability of a corresponding transition element, $\Theta_i / \sum_{i=1}^{n} \Theta_i$, and its atomic concentration a_i in the alloy. This shows that the proportionality coefficient for the i-th carbide-forming element is

$$\eta_i = \frac{1}{2} \left(\frac{a_i}{100} + \frac{\Theta_i}{\sum_{i=1}^{n} \Theta_i} \right). \qquad (6)$$

Then the content of the i-th carbide-forming element (here and below the content is given in wt.%) in this carbide phase by time moment t_k can be determined as

$$E_i^{(c)t_k} = \eta_i E_C^{(c)t_k} \frac{xA_i}{yA_C}. \quad (7)$$

Therefore, the content of the i-th carbide-forming element dissolved in austenite at time moment t_k is equal to

$$E_i^{(a)t_k} = E_i^{(s)t_k} - E_i^{(c)t_k}. \quad (8)$$

The content of carbides formed during time t_k is composed of a content of carbon and total content of carbide-forming elements consumed for the carbide formation:

$$Q_k^{t_k} = E_C^{(c)t_k} + \sum_{i=1}^{n} E_i^{(c)t_k}. \quad (9)$$

During the next time interval, t_{k+1}, austenite and carbide phases will change their composition. The calculation is repeated z times ($z = t_{rc} / t_k$, where t_{rc} is the time of cooling determined by the thermal-deformation welding cycle parameters depending upon the accepted process flow diagram [5, 6]). The total content of carbides by the end of the period of primary solidification, t_{rc}, is

$$Q^I = \sum_{k=1}^{z} Q_k^{t_k}. \quad (10)$$

Whereas the content of austenite is

$$S^{(a)} = 100\ \% - Q^I. \quad (11)$$

The average content of carbon and alloying elements in austenite can be found as

$$E_C^{(a)} = \frac{\sum_{k=1}^{z} E_C^{t_k}}{zS^{(a)}}\ 100\ \%, \quad E_i^{(a)} = \frac{\sum_{k=1}^{z} E_i^{t_k}}{zS^{(a)}}\ 100\ \%. \quad (12)$$

Therefore, the average chemical composition of austenite and quantitative and qualitative compositions of carbide phases in different zones of the weld become known by the end of the primary solidification process. Secondary solidification during the cooling process is accompanied by diffusion levelling of composition of the weld metal, to the extent of achieving the composition determined by expression (12), as well as by partial coagulation of primary carbides along the grain boundaries. Spinoidal decomposition of austenite and distribution of carbon between the carbide phases in proportion to the carbide-forming ability of a given carbide-forming element take place upon reaching the temperature of complete dissolution of carbon and alloying elements in austenite. In analogy with (7), it can be written down that

$$E_i^{(c)} = \sum_{j=1}^{k} w_j \eta_j E_C^{(d)} \frac{xA_i}{yA_C}, \quad (13)$$

where w_j is the content of carbon in the i-th carbide phase with respect to the total content of carbon consumed for the formation of carbides of the i-th alloying element; $E_C^{(d)}$ is the content of carbon in austenite decomposition products [10]; and η_i is the coefficient determined from expression (6). Then the content of the carbide-forming element and carbon dissolved in the matrix can be calculated as follows:

$$E_i^{(b)} = E_i^{(a)} - E_i^{(c)}, \quad (14)$$

$$E_C^{(b)} = E_C^{(a)} - \sum_{i=1}^{n} \sum_{j=1}^{k} w_j \eta_i E_i^{(c)} \frac{yA_C}{xA_i}. \quad (15)$$

The content of the carbide phases formed as a result of secondary solidification is

$$Q^{II} = E_C^{(a)} - E_C^{(b)} + \sum_{i=1}^{n} E_i^{(c)}, \quad (16)$$

and the total content of the carbide phases in the weld metal is

$$Q_{Hd} = Q^I + Q^{II}. \quad (17)$$

The matrix content of the deposited metal is

$$S^{(b)} = 100\ \% - Q_{Hd}. \quad (18)$$

The content of carbon and alloying elements in the matrix is equal to

$$E_C^b = \frac{E_C^{(b)}}{S^{(b)}}\ 100\ \%; \quad E_i^b = \frac{E_i^{(b)}}{S^{(b)}}\ 100\ \%. \quad (19)$$

The above expressions (1) through (19) present a phenomenological model of the process of non-equilibrium solidification of the weld pool and formation of the weld metal (deposited metal). This gives a phenomenological idea of the processes of non-equilibrium solidification of the weld metal with a wide range of alloying, thus allowing prediction of phase and structural composition of the deposited metal.

Development of the system for computer-aided design of new welding and surfacing consumables. The new analytical method for calculation of phase-structural composition of the weld metal was developed from equations (1) through (19) and formalised description of a new structural diagram of the deposited metal matrix [2, 16]. The developed analytical method for calculation of chemical and phase-structural composition of the weld metal serves as a basis for elaboration of the closed algorithm and system for computer-aided design of advanced welding and surfacing consumables. Such a system with an appropriate level of organisation and automation of design solutions can be made only on the basis of a system approach, the object of analysis of which is the design process proper. The system approach is no more than a tool for development of a methodology, i.e. a means for structuring a problem, establishing links, priorities, structuring data, etc. Based on this approach,

the methodology aimed at development of advanced welding and surfacing consumables is a closed system with a deep feedback coverage, which ensures structuring of a problem at a customer's request, its formulation on the basis of data packages, instructions and rules, as well as output in the form of statement of the problem for an expert system, solving the problem in the mode of dialog of a designer (expert) with the expert system, generation of a solution in the form of composition, structure and properties of the deposited metal, as well as an electrode formula for a welding consumable to ensure the predictable deposited metal and welding (surfacing) process parameters.

The design algorithm was formed on the basis of structural analysis and the developed analytical method. This algorithm presents a sequence of the design stages with a set of instructions and rules for each stage [1–4]. Automation of the design process was realised within the framework of building of a special system consisting of a package of means that include methodical, linguistic, mathematical, software, hardware, information and organisation support. The computer-aided design (CAD) system consists of several sub-systems that solve different problems. In our case the main system among them is the expert system that serves as a basic design tool. The developed CAD system for advanced welding consumables is an open system for individual use. It is controlled and supported directly by a developer of welding consumables [1–4]. Owing to its «openness», this system provides the possibility of continuously updating the knowledge and data bases as the knowledge of a design object and environment is generated and further improved, as well as upgrading the systems that control these bases. The system allows considerable reduction of time needed for development of welding and surfacing consumables for fabrication of sophisticated welded metal structures and multifunctional depositions.

Practical realisation of the conception of design of advanced welding consumables. The new approach was used to design a batch of flux-cored surfacing wires for hard-facing of walls of a loading device hopper of steel 1501 Gr. 161-400, 151-400 (BS United Kingdom), operating under conditions of impact-abrasive wear under the effect of a chemically non-aggressive loose material. It can be concluded on the basis of the data on the character of interaction between the environment and working medium that a specialised consumable should provide the deposited metal with a basic structure (matrix structure) of fine-needled or acicular martensite and metastable austenite (30–50 wt.%) with uniformly distributed carbides (5–15 wt.%). Under intensive impact loading, metastable austenite absorbs part of the impact energy and transforms into martensite that strengthens the deposited metal and increases its wear resistance. Having an idea of the required (secondary) structure of the deposited metal, we can start calculation of the primary structure and chemical composition of the weld metal. The calculation presents solution to the inverse problem, where input parameters are the secondary structure of the weld metal and values of the thermal-deformation welding cycle parameters. Results of the calculation of chemical composition and structure of the deposited metal for the four iron-base welding consumables being designed are given in Tables 1 and 2, respectively.

Based on the data on the required primary structure and chemical composition of the deposited metal, it is possible to determine electrode formulae for the specialised welding consumables designed. The calculation is made in the operator–expert system interactive mode. The calculation is based on a package

Table 1. Chemical composition of the deposited metal samples under consideration

Sample designation	*Content of elements, wt.%*				
	C	*Si*	*Mn*	*Cr*	*Ti*
RI 1 / 01.7	1.58 1.40	0.680 0.550	0.360 0.420	8.54 8.50	3.61 3.35
RI 1 / 11.2	1.62 1.80	0.700 0.290	0.380 0.440	6.89 6.63	3.60 2.64
RI 1 / 08.3	1.31 1.50	0.530 0.600	0.380 0.360	7.87 8.15	2.56 2.10
RI 1 / 10.1	1.32 1.40	0.704 0.537	1.110 0.607	7.93 5.62	2.62 2.28

Note. Calculated content of elements is given in numerator, and experimental content of elements is given in denominator.

Table 2. Structure and properties of deposited metal

Sample designation	*Structural components, wt.%*			*Hardness HRC*	*Hardening under loading ΔHRC*
	Martensite	*Austenite*	*Carbide phase*		
RI 1 / 01.7	55.52 Base	33.97 36.00	10.47 12.00	56.16 56–57	+(3–4) +4
RI 1 / 11.2	44.94 43.00	45.29 47.00	9.74 10.00	46.19 46–50	+(4–5) +6
RI 1 / 08.3	77.12 Base	13.65 11.00	9.20 8.00	56.39 54–56	+(2–3) +3
RI 1 / 10.1	81.16 Base	9.76 8.00	9.05 8.00	57.23 55–58	+(2–3) +2

of applied programs developed on the basis of a mathematical model of the welding process [7, 8] and phenomenological model of primary non-equilibrium solidification of the weld metal developed under this study and studies [10, 16]. The results obtained were checked by the calculation that presented solution to the direct problem. After making an experimental batch of specialised welding consumables in compliance with technological requirements and performing a three-layer deposition on a representative part (16 mm thick vertical plate of steel 1501 Gr. 161-400, 151-400 (BS United Kingdom)) under recommended conditions, the samples were cut from the resulting depositions. The samples were then subjected to a set of full-scale tests and examinations, the results of which are given in Tables 1 and 2.

It was established on the basis of analysis of the examination and full-scale test results that all the developed consumables could be applied to deposit a protective coating, as they are characterised by the values of wear and impact loading resistance that are substantially (5–6 times) higher than those of steel 1501 Gr. 161-400, 151-400 (BS United Kingdom).

Adequacy of the model was estimated by comparing the design and test results. As follows from the data given, the discrepancy between them is mainly not in excess of 20 %, which is indicative of a high adequacy of the developed phenomenological model to the real process of non-equilibrium solidification of molten metal of the weld pool.

The consumables developed are characterised by good welding-technological and service properties.

CONCLUSIONS

1. The new approach to development and design of welding consumables was formed. The efficient method for development of a new welding consumable is a solution to the inverse problem that suggests finding the electrode formula for this consumable as a function of service properties of the weld metal.

2. The CAD system for welding consumables was developed. It is based on the expert system operating with the systematised knowledge that allows for the phenomenological model of non-equilibrium solidification of the weld pool. This CAD system is organised as an open system for individual use with a possibility of continuous updating and replenishment of the knowledge and data bases as they are augmented and further generated.

3. Surfacing flux-cored wires were designed using the developed CAD system. The wires are intended for deposition of a protective coating resistant to impact-abrasive wear on low-carbon and low-alloy steels. An experimental batch of the flux-cored wires was made on the basis of the design results, and deposition of samples under conditions with calculated parameters was performed.

4. The full-scale tests and comprehensive examinations of the deposited layers, as well as analysis and processing of the results to check adequacy of the model showed high agreement of the experimental and design data.

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MECHANISM OF LONG ARC MIG / MAG WELDING METAL TRANSFER MIXED MODES PROVOKED BY INADEQUATE DYNAMIC FEATURES OF THE POWER SOURCE

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A mixed metal transfer mode in MIG / MAG welding, in which two or more transfer modes happen in a periodic sequence, is usually undesirable, because it may deteriorate the welding process stability. Thus, there is a strong appeal for investigating the causes of such a metal transfer mode in order to determine means of deal with this phenomenon. This work was aimed to make an experimental and descriptive analysis of the mechanisms that govern one of the free-flight metal transfer mixed mode in the MIG / MAG welding. For that, current rising and falling rates were systematically adjusted in an electronic power supply. The droplet formation and transfer were observed using an arc visualisation system based on a laser and a high-speed camera. The arc voltage and welding current signals were monitored, in synchronism with the droplet images (frames), using a computer-based measuring system. It was verified that one of the factors that provoke this mixed metal transfer mode is inadequate dynamic characteristics of the power source, namely, excessively fast current rising and falling rates that happen during welding circuit resistance changes caused by the metal droplet formation and detachment. The received results seem useful for electronic power source adjustments, as well as for designers of new welding power sources.

Keywords: MIG/MAG welding, physics of arc, power sources, metal transfer

Introduction. Mixed metal transfer modes observed in short arc MIG / MAG welding are introduced and described in IIW Doc. XII-1773–03 «Mechanism of Short Arc MIG / MAG Welding Metal Transfer Mixed Modes» (Ponomarev V., Scotti A., Miranda H.C. and Costa A.V.). An experimental approach to study these modes of metal transfer was employed. Short-circuiting metal transfer conditions were considered. A detailed analysis of the short-circuiting mixed metal transfer mechanism was done and evidences of grounds for this phenomenon to take place were found. It was shown that the main cause of such a metal transfer mode was inadequate dynamic characteristics of the power source, namely, excessively high short-circuit current rising rate and too low post short-circuit current falling rate. The same approach is used in the present work for studying free-flight mixed metal transfer modes.

Experimental procedure. The experiments were aimed to analyse the determining factors for the transformation of a globular-like metal transfer mode into a mixed one, such as «globular–spray» or into «globular–streaming». These experiments were conducted with welding parameters that favour a globular transfer mode, such as Ar + 5 % O_2 as protective atmosphere; an AWS ER70S6 wire of 1.0 mm diameter; setting wire feed speed WFS ≈ 6 m / min; the resulting average welding current I_w stayed around 165 A; travel speed V_s = 30 cm / min; contact tube to work distance CTWD = 18 mm. The preset (reference) voltage level (U_{ref}) and both current rising rate and current falling rate were subjectively varied to obtain the desired mixed mode transfer.

Figure 1 shows the metal transfer and current and voltage traces behaviours when a constant current power source is used, what corresponds to current rising and falling rates equal to zero. In such conditions, typical globular transfer is guarantied when the welding current is lower than the transition current level. During the transfer phenomenon, the droplet grows while the arc column shortens, in balance for the given CTWD. As seen in Figure 1, the arc voltage varies cyclically, increasing progressively with the droplet growth and reducing abruptly the same amount after the droplet detachment. The current signal is rather constant.

There is still another phenomenon to be pointed out regarding the results shown in Figure 1. The electrode tip (without taking the droplet into consideration) does not displace during the metal transfer, i.e. it keeps itself at a same level (remarked by the dashed line). This result proves that the electrode melting rate is not changing during the droplet growth, or, in other words, the droplet size has no effect on the electrode melting rate. As it will be shown below, the electrode melting rate depends, first of all, on the welding current level.

Almost the same behaviour observed in Figure 1 is observed when a constant voltage static current versus voltage curve is set, as seen in Figure 2, as long as the range of welding current deviations (caused by alterations of the arc resistance R_a) is kept

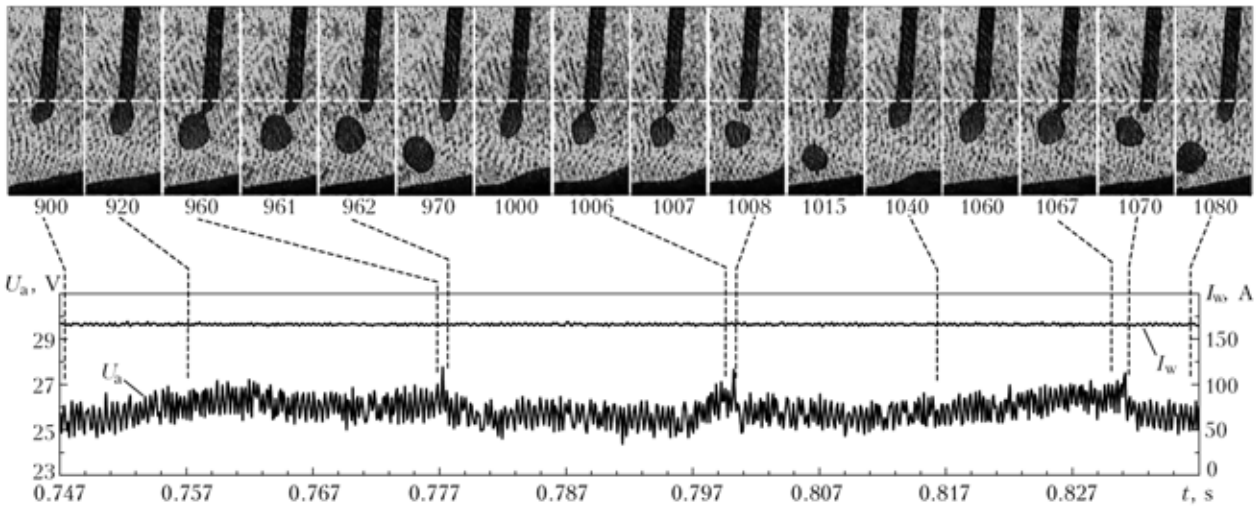

Figure 1. Globular transfer type when using an electronic power source set in a constant current mode (U_a = 26.1 V; I_w = 166 A)

limited. Such limited welding current deviations are conditioned by power source dynamic properties, namely, current rising and falling rates.

As it can be seen in Figure 2, the welding current deviation range does not exceed 30 A for this particular case. If the welding current deviations are not restricted within certain limits, the welding current can periodically exceed the transition current level, causing formation of small-sized droplets (spray-like transfer). In other words, the globular metal transfer can cyclically transforms into one of the mixed metal transfer types, for example, in the «globular–spray», as shown in Figure 3. One can see, that in this particular case, the welding current deviation range reached 70 A.

The mixed mode problem aggravates even further if the globular metal transfer is characterised by larger droplets (caused, for example, by a protective atmosphere used), as it is shown in Figure 4. In this case, a different shielding gas was applied (Ar + + 2 % O_2). The other experimental conditions were: WFS ≈ 6.5 m / min; U_a = 28.4 V; I_w = 177 A; v_s = = 36 cm / min; CTWD = 18 mm. As a result, a globular metal transfer transformed into a «globular–short-circuit–streaming» mixed mode, in which the droplets (globular-like) grow as far as to touch the pool, developing a short-circuiting transfer. After the globular droplet detachment, a series of droplets transfer as in an axial spray mode (usually with a size just about the electrode one) or in a streaming spray mode while the electrode extension shortens progressively until a stable condition for larger drops to grow is reached again. In phase with the current curve, the alterations of the electric resistance resulted from the circuit segment «electrode extension + droplet + anode and cathode regions + arc column» (Figure 5) during the «globular–short-circuiting–streaming» mixed trans-

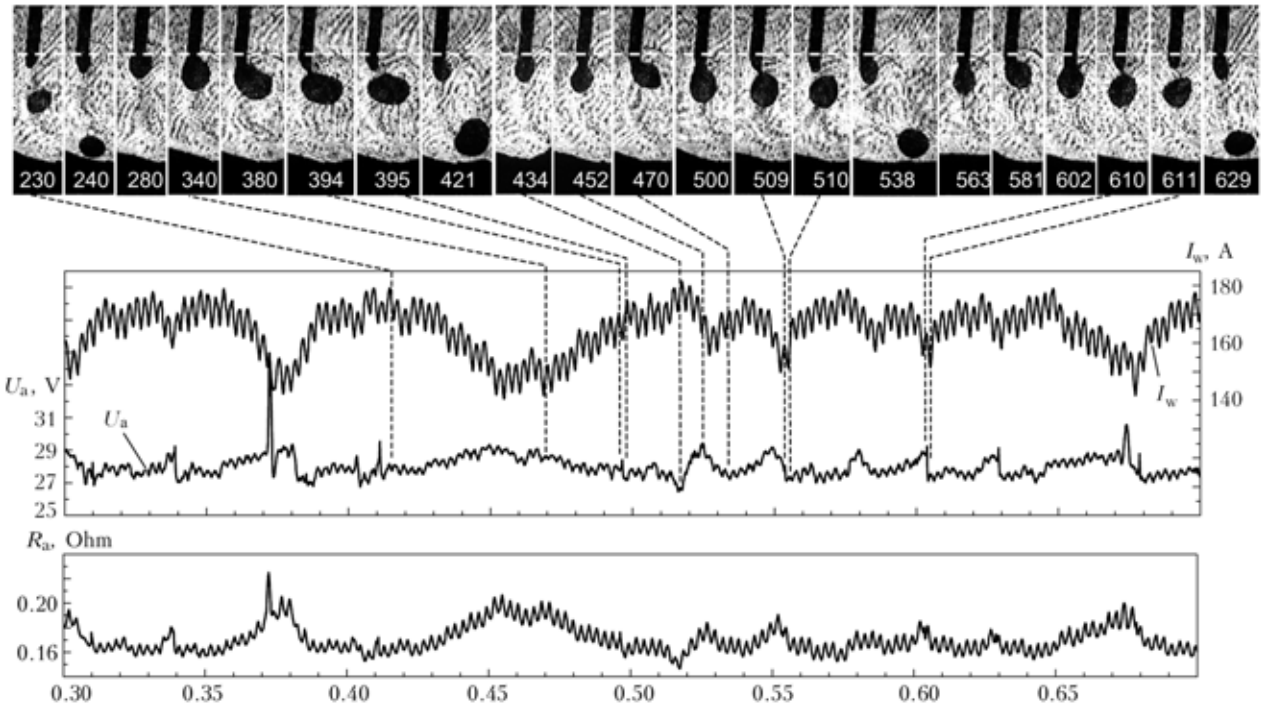

Figure 2. Globular transfer type when using a constant voltage electromagnetic power source with high induction (WFS = 5.7 m / min; U_a = 28.0 V; I_w = 165 A)

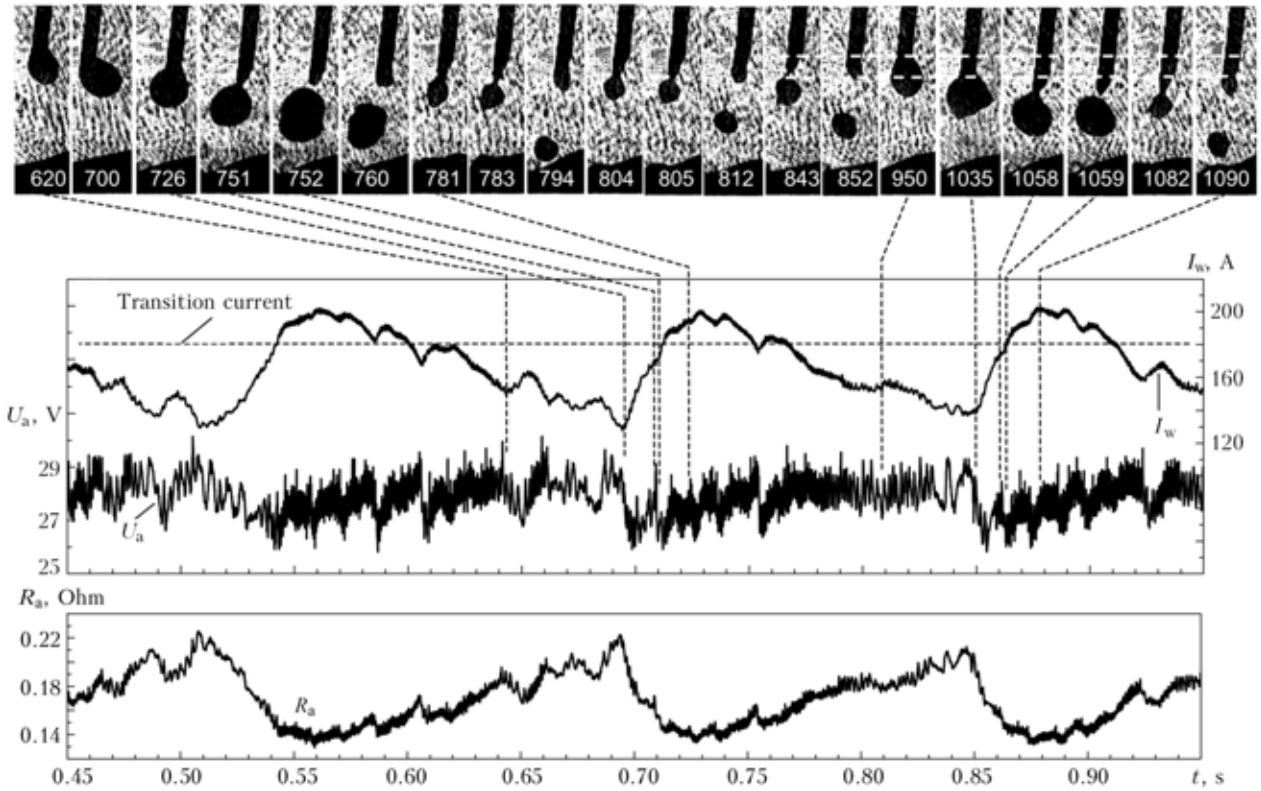

Figure 3. «Globular--spray» transfer mixed mode when using an electronic power source set in a constant voltage mode and with moderated rising and falling rates of current (WFS = 6.3 m / min; U_a = 27.9 V; I_w = 166.3 A)

fer are also displayed in Figure 4. There is shown a schematic equivalent electric resistance circuit at different stages of the droplet detachment in Figure 4 as well. These data and drawings are needed to reveal the factors conditioning a mixed transfer mode.

As seen in Figure 4, the traces of welding current I_w and resistance R_a are mirror symmetrical. The reason for this is that the welding current level is a inverse function of the resistance R_a when a constant voltage power supply is used (assuming that all other components of the total resistance of the welding circuit remain invariable) and it varies according to the resistance alterations; when the resistance is rising, the current drops and on the contrary. Thus, the analysis of the welding current trace does not represent any difficulties. That is not the case with the resistance trace. As seen in Figure 4, the resistance curve is not synchronised either with the droplet growth phase, and consequent arc gap shortening, or with the arc elongation phase, after the droplet separation from the electrode tip. For instance, it can stop increasing at the middle of the droplet growth phase and start falling down (see Figure 4, frame 1350). The resistance R_a can also decrease after the droplet separation, on the contrary to an arc length increment. All that indicates that the R_a value might be influenced by a combined effect of many factors.

It is clear that the observed alterations of the electric resistance at the welding circuit segment «electrode extension + droplet + anode and cathode regions + arc column» are real. They are determined by physical phenomena taking place in this segment of the welding circuit and, accordingly, they should be analysed taking into account the influence of these factors on the resistance R_a. This matter may be treated assuming the physical phenomena as follows.

- The first phenomenon concerns the droplet growth up to its detachment from the electrode tip. As shown in the IIW Doc. XII-1773–03 «Evaluation of the Voltage Drop in Electrode Metal Droplets under MIG / MAG Welding Conditions» (Ponomarev V., Costa A.V. and Scotti A.), the droplet specific electric resistance (the voltage drop per unit of the droplet length) is approximately 2 times higher than that of the arc column, and approximately 10 times as high as that of the electrode extension (for the welding conditions indicated above). Thus, it becomes apparent that as the droplet is progressively replacing the arc column (within the growth phase), the resistance R_a might increase during this period.
- Secondly, there are electrode extension alterations, caused by melting rate changes, which, in turn, are conditioned by the current oscillations. Electrode alterations are accompanied by adequate changes of the arc length; the longer the electrode extension, the shorter the arc. Taking into con-sideration that the electrode wire possesses a considerably lower specific resistance than the arc column, the resistance Ra will fall down during the electrode extension growth (and consequent arc shortening) and vice versa.
- Thirdly, there are alterations of the arc column specific resistance and of the resistances of the anode and cathode regions as a function of the welding current oscillations. The arc is a non-linear resistance, and the resistance value is decreasing as far as the current is rising (within the rising part of the arc volt-ampere characteristic).

Taking these phenomena into account, it is possible to explain the changes of resistance R_a observed

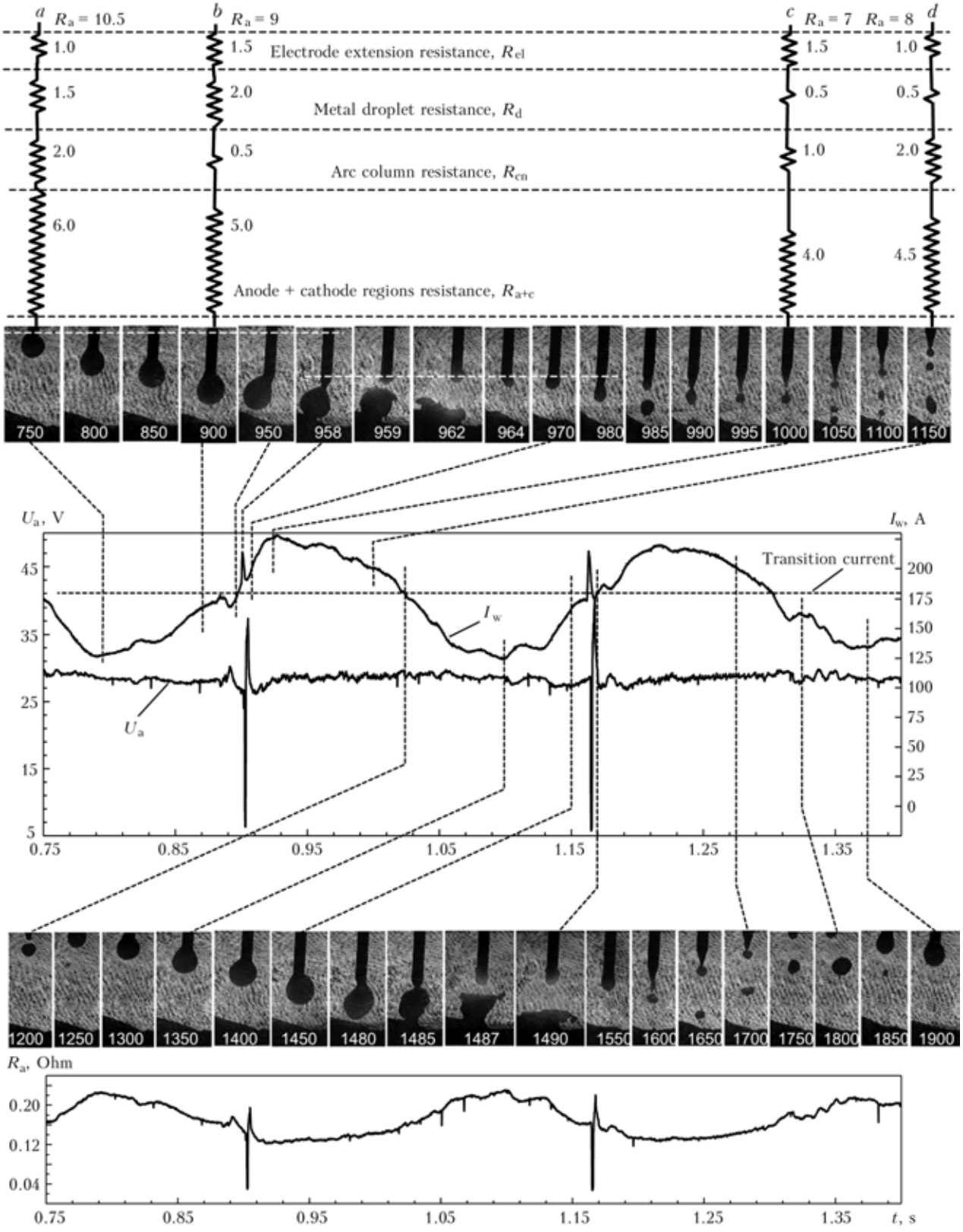

Figure 4. «Globular–short-circuiting–streaming spray» transfer mixed mode when using an electronic constant voltage power source with high rising and falling rates of current and alterations of the electric resistance at the circuit segment «electrode extension + droplet + anode and cathode regions + arc column». There are no units indicated in the equivalent resistive circuits, since the values are relative, i.e. they indicate how greater or smaller one resistance is of the other

in Figure 4. In order to do it, the phenomena occurring in the arc region at the moments corresponding to the frames 750, 900, 1000 and 1150 will be analysed. For the convenience of the analysis, the equivalent circuits corresponding to the indicated instants are presented in Figure 4. The electric resistance in the equivalent circuits is expressed in relative dimensionless figures. These resistance values show only the ratios between the resistance levels of the electrode extension, metal droplet, arc column and cathode + anode regions.

At the moment of the frame 750, the total electric resistance R_a is the greatest, because the arc is long and the droplet reaches a large size. As a result, the welding current decreased up to the lowest value that, in turn, result in some additional increase of the arc column resistance (R_{cn}) and of both cathode and anode region resistances (R_{a+c}). A low current brings down the electrode melting rate. The electrode tip starts to move towards to weld pool, fact that can be observed in the posterior frames. The droplet growth is decelerating.

When the electrode tip with the droplet on it is moving towards the weld pool, the arc column is being replaced by the electrode wire. Due to the fact that the electrode wire possesses a considerably lower specific resistance than the arc column, the resistance R_a starts to drop and the welding current, correspondingly, begins to grow (see Figure 4, *b*). A certain increase of the droplet resistance (R_d) is caused by a further growth of the droplet. Because of the increase of the welding current, the cathode and anode region resistance reduces.

The resistance R_a will fall even more after separation of the droplet from the electrode tip, because the droplet will be substituted by an arc column increment, which possesses smaller resistivity than the droplet. Thus, the welding current will be continuously growing. There is one more factor in favour of the resistance R_a reduction at this moment: an elevated current (which has already exceeded the transition current level before the droplet detachment or which does it afterwards) makes the metal transfer type to change from a globular one into a spray transfer, with droplets almost completely «absorbed» by the arc (shunted by the arc) and, consequently, the droplet resistance is taken away from welding circuit electrical resistance. At this moment, the arc remains still short (see Figure 4, *c*). All these factors, and also a further decrease of the arc column resistance and of both cathode and anode region resistances, occasioned by a current increase, result that the total resistance R_a in this moment turns to by the lowest, and, consequently, the welding current the highest.

A high welding current results in intensive melting of the electrode tip and, as a consequence, to an elongation of the arc. The resistance R_a starts to grow again and the welding current begins to drop down (see Figure 4, *d*). After the welding current falls below the transition value, the metal transfer type changes back into a globular one; a new droplet starts forming at the electrode tip. The droplet resistance R_d will grow proportionally to the droplet size. It will result in a further increase of the resistance R_a and in a further decrease of the welding current. Hereinafter, the mixed metal cycle, which has just been examined and described, repeats again and again.

The conducted analysis shows that mixed metal transfer types, such as «globular–short-circuiting–streaming» or «globular–spray» are observed only if the welding current periodically exceeds the transition current level. Such oscillations of the welding current are occasioned by changes of the electric resistance at the welding circuit segment «electrode extension + droplet + anode and cathode regions + arc column».

It is worth to remind that, as it is shown in Figure 2, the mixed metal transfer had not been observed when a constant voltage power source, with current oscillations limited within a narrow range, was used. It was also not observed when a constant current power source was used, i.e. when the welding current was kept changeless (see Figure 1).

Thus, to avoid a mixed metal transfer occurrence, it is necessary to optimise dynamic properties of the power source, for example, by restricting the current rising and falling rates. Most often problems with dynamic properties occur with respect to electronic power sources. One must remember that some of them allow the current rising and falling rates being adjusted within an excessively large range.

It is clear that in a constant voltage mode, the power source must respond to any change in the welding circuit electrical resistance, increasing or lowering the welding current accordingly. However, such reaction of the power source should not be excessive to prevent from disturbing the metal transfer mode. Moreover, the MIG / MAG welding process possesses also other possibilities of self-regulation, which contribute to the welding process recovering (its return to the pre-set conditions). For example, even in the case of using a constant current power source, the MIG / MAG welding process has a capability of maintaining the arc of a determined length owing to the fact that the arc length alterations are accompanied by adequate changes of the electrode extension length (the shorter arc length, the longer electrode extension

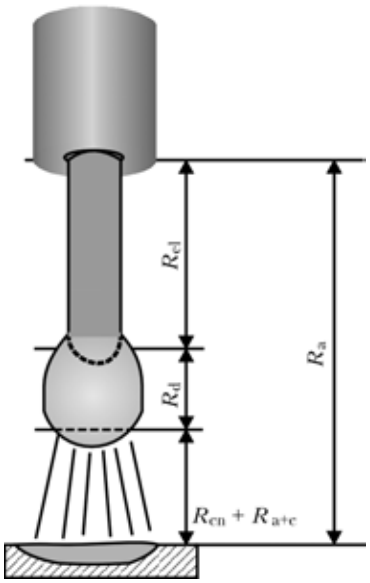

Figure 5. Electric resistances at the circuit segment «electrode extension + droplet + anode and cathode regions + arc column»

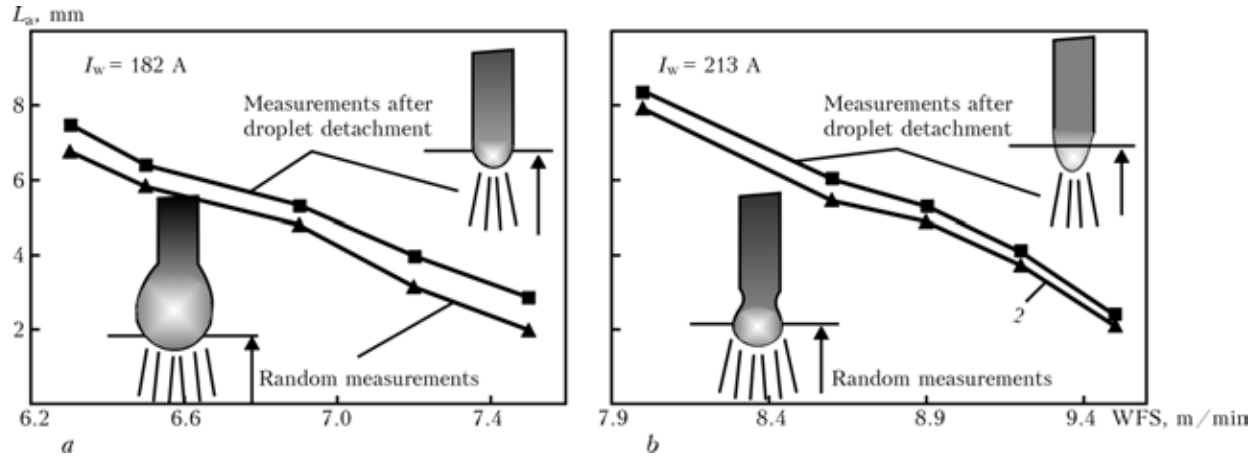

Figure 6. Influence of the arc length on the electrode melting rate (which is equal to the WFS) when using a constant current power source (AWS ER70S6 wire of 1.0 mm diameter; CTWD = 20 mm; shielding atmosphere — Ar + 2 % O_2): *a* — globular transfer; *b* — spray transfer. The curves referred as «measurements after droplet detachment» correspond to arcs determined only just after the droplet detachment, in contrast to the curves referred as «random», for which the measurements were taken at different stages of the droplet growth

and vice versa). The electrode wire melting efficiency depends of the extension length due to the Joule heat evolution in the latter (the longer electrode extension, the higher heat generation and, so, the higher melting rate). As a result, the shorter the arc becomes, higher electrode melting rates are observed (Figure 6). A certain reduction of heat losses from a shorter arc (the heat source becomes more concentrated) intensifies this tendency. The results presented in Figure 3 were obtained when welding with a different WFS for each test, but which was kept constant during the welding. In these conditions, the arc sets itself in such a length, at which there is an equilibrium reached between the WFS and the electrode melting rate. These very pairs of values of the WFS and its respective arc length are adduced in Figure 6.

Influence of the droplet electric resistance on the mechanism of the arc length self-adjustment. It has been suggested here that the principal cause for mixed metal transfer to occur in long arc MIG / MAG welding is an inadequate dynamics of the power source. The algorithm of maintenance of a desired arc length that is built in electronic controlled constant current power sources follows the same principle of the arc length self-adjustment found in constant voltage power sources, i.e. it is based on a presupposition that alterations of the electrical resistance R_a at the welding circuit segment «electrode extension + droplet + anode and cathode regions + arc column» are determined, mainly, by changes of the arc column resistance (i.e. of the arc length). In the case if the arc becomes longer, the resistance R_a rises and there is reduction of the welding current (by itself, in the case of constant voltage power source, and imposed, in the case of an electronic controlled constant current power source). The droplet electrical resistance is ignored in this reasoning.

Because of the fact that the electrical resistance at the welding circuit segment «electrode extension + droplet + anode and cathode regions + arc column» represents the sum of the resistances of these components of the welding circuit, R_a is sometimes not proportional to the arc length. For example, in the case of a large droplet formed at the electrode tip, the resistance R_a turned to be elevated, fact that will be erroneously interpreted as an arc elongation (while, in the reality, the arc becomes shorter). The welding current will be reduced and the wire melting rate will be decreased, contrary to the necessity of their increase. The arc length self-control will be compromised.

This fact may explain the reason why a welder of semi-automatic MIG / MAG welding finds more difficult to maintain the process stable when welding in globular metal transfer mode with a low-carbon electrode wire, than with an aluminium electrode wire. As shown in the IIW Doc. XII-1773–03 «Evaluation of the Voltage Drop in Electrode Metal Droplets under MIG / MAG Welding Conditions» (Ponomarev V., Costa A.V. and Scotti A.), the specific electric resistance of the metal droplet when using an aluminium electrode wire is smaller than that of the arc column, and the droplet transfer does not infringe upon the arc length self-control.

Conventional power sources of the electromagnetic system easily face the influence of the metal droplet electric resistance on the arc length self-control performance. Owing to their low dynamic responses, the welding current deviation range is restricted. As it follows from the conducted analysis, this problem is considerably graver for electronic power sources. Some of them might need an additional adjustment to fit for a particular MIG / MAG welding process in order to ensure a proper functioning of the arc length self-control.

CONCLUSIONS

A high electric resistance of the droplet and an inadequate dynamics of the used power source are the principal causes for originating the free-flight mixed mode of metal transfer in MIG / MAG welding. They also can infringe upon the performance of the arc length self-adjustment.

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EFFECT OF METALLURGICAL HEREDITY OF THE AMts ALLOY SEMI-FINISHED PRODUCTS ON THEIR BRAZING ABILITY

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Chemical composition and structure of materials applied for manufacture of brazed heat exchanges from alloy AMts have been studied. It is shown that defects in parts can be caused by the use of low-quality extruded billets containing oxide films and cavities in cast metal. The latter are located in sub-surface layers of an ingot and transform into extended oxide films and discontinuities during ingot processing.

Keywords: brazing, aluminium alloy AMts, band clad with brazing filler alloy, extruded strip, chemical composition, structure, oxide film, discontinuity, wettability and spreading ability of brazing filler alloy

Welding and brazing remain to be the key processes for making permanent joints in structures of aluminium alloys. The main problem in this case is the presence of Al_2O_3 or a variable-composition metal hydrate ($Al_2O_3 \cdot nH_2O$) on the surface of an extruded strip semi-finished product [1].

Appropriate measures and technological instructions are available now for preparation of materials for welding and brazing, including surface machining, etching and passivation. These treatment stages are aimed at removal of oxide films from the surface of an extruded strip semi-finished product or inhibition of their growth.

The important factors that determine the state of a welded or brazed joint include also the quality of the base material, brazing filler alloy and filler wire, as well as brazing or welding parameters and methods. Available are the state standards for aluminium and aluminium alloys intended for manufacture of different-purpose semi-finished products.

Also available are processes and equipment for brazing of aluminium alloys using fluxes [2, 3].

The use of a more expensive method of flux-free brazing of aluminium alloys in vacuum leads to a substantial improvement in quality of the products and operators' working environment [4].

Special silumin-clad bands are used to produce brazed joints in alloy AMts.

Aluminium heat exchangers are manufactured from billets of an extruded strip 4–6 mm thick and 1 mm thick band of alloy AMts, clad on both sides with silumin brazing filler alloy. Reject of brazed parts can be caused by different factors, including non-conformity of the materials used with the requirements of state standards, violation of a technological process for preparation of materials for brazing or a brazing technology.

The purpose of this study was to investigate quality of the materials used and find the probable cause of reject of brazed heat exchangers made from alloy AMts.

Different batches of extruded strip semi-finished products of alloy AMts, manufactured by the Open Joint Stock Company «M.V. Frunze Sumy Machine-Building Research and Production Enterprise», individual samples of extruded strips made by the Open Joint Stock Company «Belo-Kalitvinsk Metallurgical Association», as well as samples of cast homogenised metal, brazed joints and clad bands were used for the

Table 1. Chemical composition (wt.%) of metal of different batches of semi-finished products made from alloy AMts

Semi-finished product	*Mn***	*Mg*	*Cu*	*Fe*	*Si*	*Zn*	*Ni*	*Ti*	*Ga*	*Na*	*K*	*Li****
1	1.30–1.45	0.100–0.014	0.010–0.017	0.11–0.45	0.14–0.43	0.012–0.030	0.005–0.008	0.01–0.04	<0.010	<0.020	<0.020	<0.030
2	1.35	0.013	0.010	0.42	0.15	0.020	0.008	0.05	–	–	–	–

*Here and in Table 2: 1 — extruded strip semi-finished product manufactured by the Company «M.V. Frunze SMBR&PE»; 2 — same manufactured by the Company «BKMA».
**Ultimate content of main alloying element in eight batches of semi-finished products.
***Content of alkali elements in three batches of semi-finished products from different manufacturers.

Table 2. Chemical composition (wt.%) of metal of cladding coating on two batches of the AMts bands

Semi-finished product	*Si*	*Mg*	*Mn*	*Fe*	*Cu*	*Ni*	*Na*	*Ca*
1	5.07–8.90	0.183–0.208	–	0.342–0.388	0.028–0.037	0.041	0.207–0.264	–
2	13.70–23.70	0.119–0.138	0–0.055	0.160–0.531	–	0.315–0.484	0.228–0.258	0–0.264

investigations. Metallography, chemical, X-ray micro- and spectral analysis methods were employed.

Investigation results. Spectral analysis of chemical composition of samples of different batches of alloy AMts, which was used as a charge material for the manufacture of ingots, showed that their chemical composition was in compliance with requirements of GOST 4784–97 as to the main alloying elements and impurities (Table 1). The presence of impurities of alkali elements was established by the method of chemical atom-adsorption analysis in the emission mode. No differences between different batches of the extruded strips were revealed.

Because of a small thickness of cladding, composition of the brazing filler alloy was determined by the X-ray microanalysis method using probe with an irradiation diameter of 1.5–2.0 μm. For this, several measurements were made, and a maximal, minimal and average mass fractions of alloying elements were fixed. According to the data obtained, chemical com-

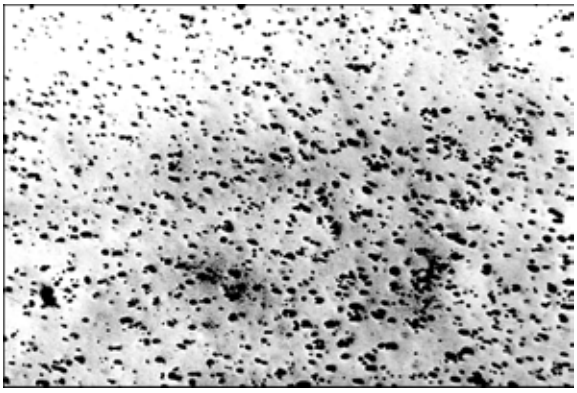

Figure 1. Typical microstructure of metal of AMts extruded strip (×400)

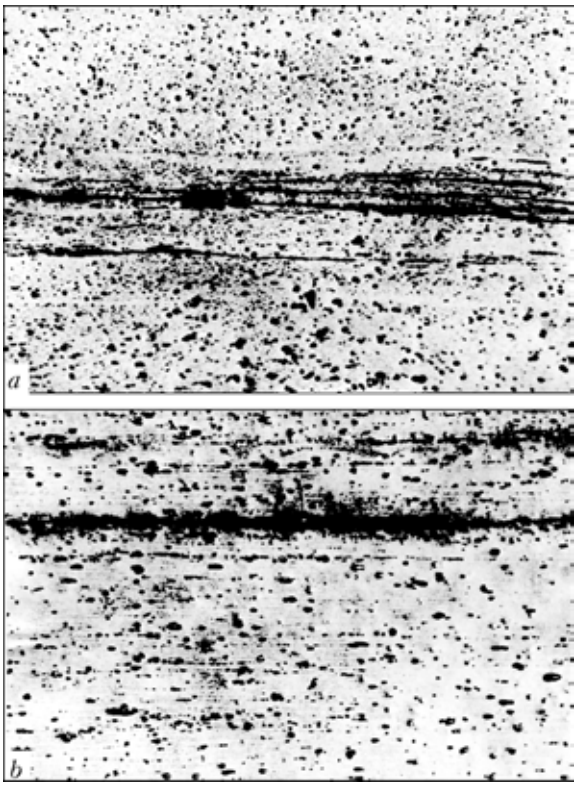

Figure 2. Microstructure of metal of the AMts extruded strip with extended non-metallic inclusions of different types of oxide films (*a*) and micro discontinuities (*b*) (×400)

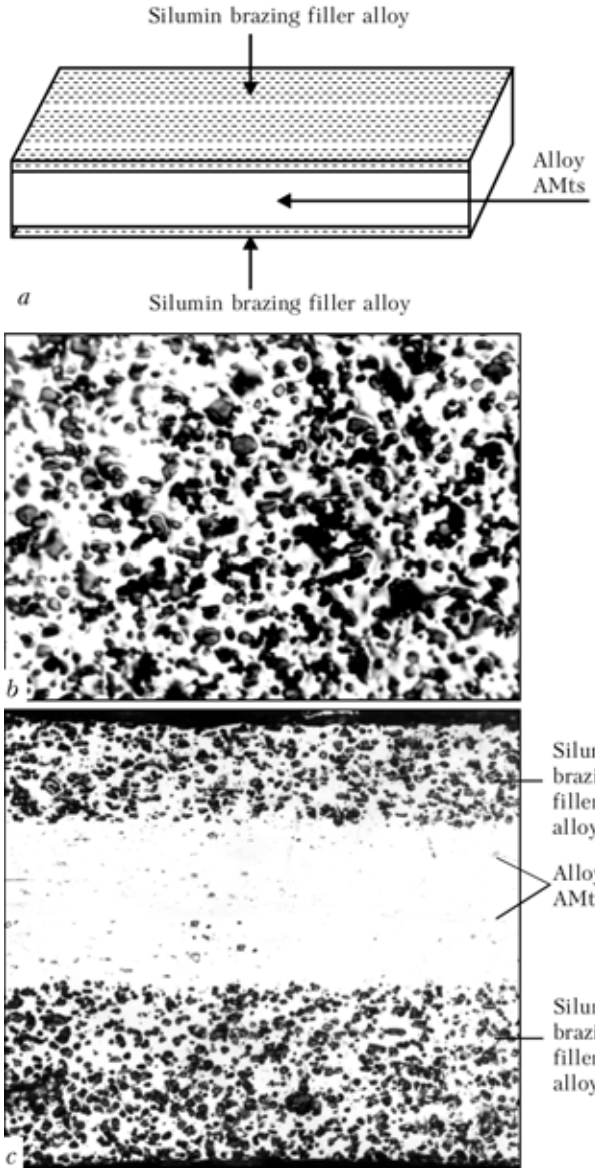

Figure 3. Schematic of appearance of clad band (*a*) and its microstructure (×500) in plane (*b*) and cross section (*c*)

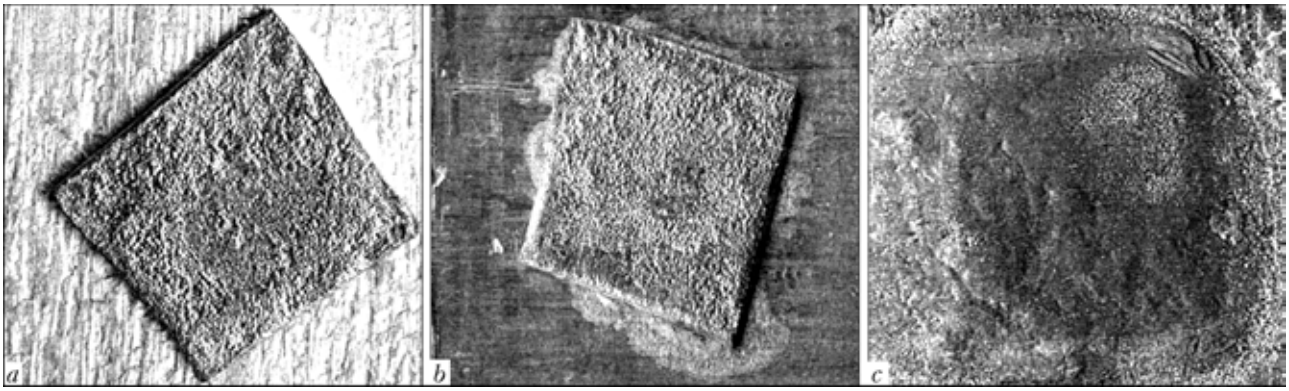

Figure 4. Appearance of joints in alloy AMts with different degree of wetting after electron beam heating of the extruded strip with a clad band: *a* — no wetting; *b* — partial wetting; *c* — complete spreading

position of the cladding coating corresponded to specifications (Table 2).

Investigations of the hydrogen content of the AMts base metal and clad bands of different production batches, conducted using the LECO gas analyser, detected no substantial differences between them.

Structure of brazed semi-finished products. Investigation of metal microstructure on a large number of extruded strip samples taken from different batches showed some deviations from the standard. Typical microstructure of metal of the AMts alloy billet (Figure 1) is a solid solution of alloying elements in aluminium and precipitates of dispersed Al–Mn phases. Some samples contained metal regions with a different degree of dispersion of inclusions, as well as band precipitates of non-metallic inclusions, oxide films and discontinuities (Figure 2).

The surface of metal of a cladding layer has a typical structure of eutectic silumin. Figure 3 shows appearance of the band clad with silumin and microstructure of a silumin brazing filler alloy in plane and in cross section of the AMts alloy band of different production. The microphotographs presented are indicative of a probable variation in thickness of the cladding layer in different regions of the band.

According to the data obtained, thickness of a cladding layer of the band produced earlier varies from 50 to 150 μm, and in some regions it amounts to 170 μm. On the recently produced samples, thickness of the cladding layer varies from 80 to 150 μm. Comparative examinations of microstructure of metal of the cladding layers of bands produced in different periods at larger magnification (up to 500 μm and more) revealed that they hardly differed in the character of distribution of silicon inclusions and degree of dispersion.

Brazing ability and structure of the resulting joints. 5 × 5 mm samples of a clad band were placed on the surfaces of the earlier investigated 20 × 20 mm base metal billets of different production batches. To remove oxide films, the surface of the base metal was preliminarily subjected to machining. Brazing was performed in radial heating. For that, the samples were put into a tubular container, which was heated by the electron beam. The value of vacuum in the chamber was not less than $2 \cdot 10^{-2}$ Pa, and the temperature of heating was not less than 600 °C. The brazing quality was assessed visually from appearance of the joints (Figure 4) and by the known methods, where the ratio of the area of spreading of a filler alloy after brazing to the area it occupied before heating was used as a quality criterion, as well as by the results of metallography of transverse microsections of the samples.

Some of the resulting joints in alloy AMts had a 100 % filler alloy spreading area. On some other samples, although wetting of the base metal did occur, no spreading of the filler alloy was seen (see Figure 4). Also, there were samples where no brazing took place, despite even an excessive increase in temperature up to a partial melting of the base metal. In this case the clad band could be readily separated

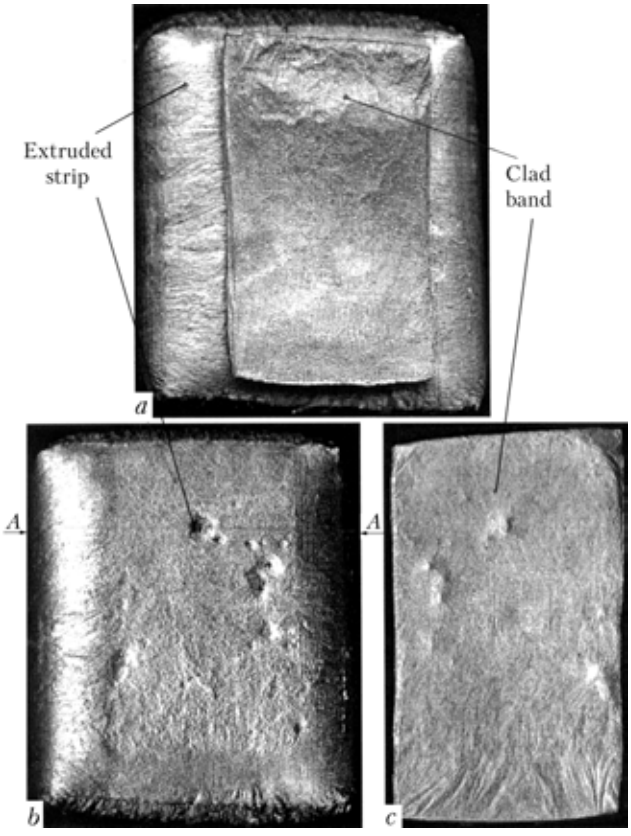

Figure 5. Appearance of a joint in alloy AMts (*a*) and defects on internal surfaces of extruded strip (*b*) and clad band (*c*) in electron beam heating in vacuum

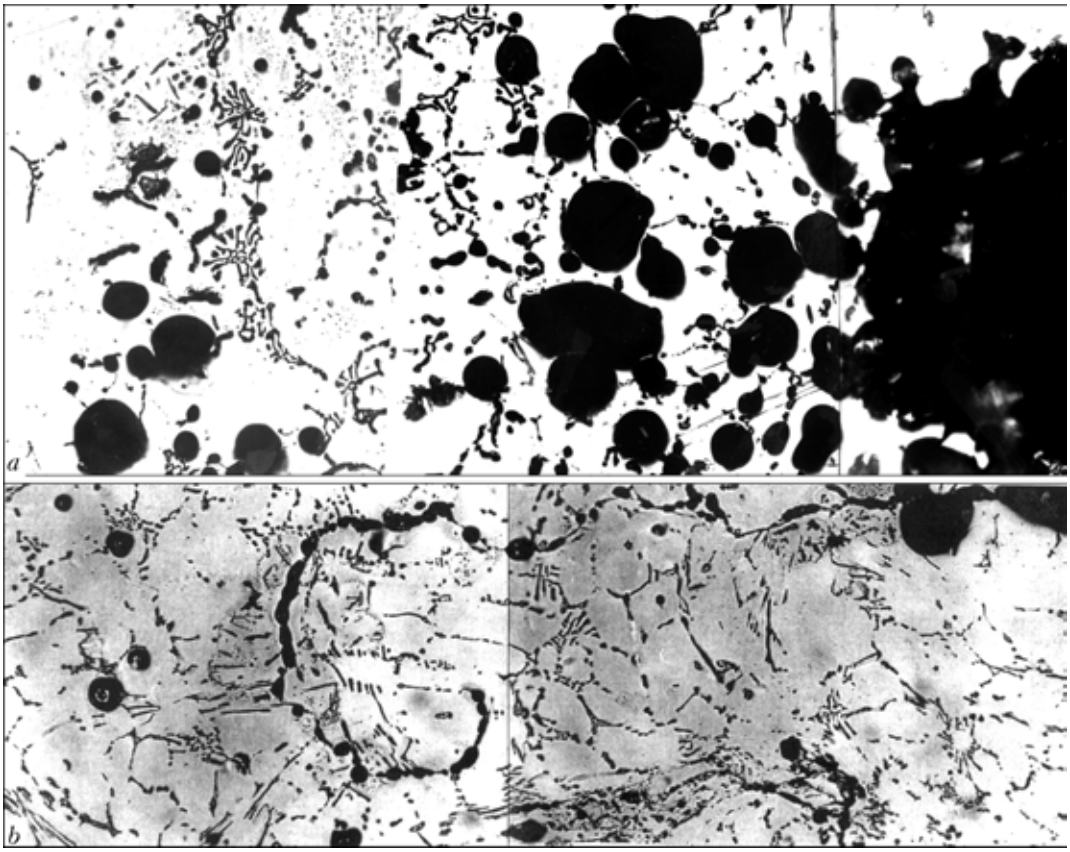

Figure 6. Micropores (*a*) and oxide films (*b*) in extruded strip metal in a case of poor-quality brazing (see Figure 5, section along *A*--*A*) (×125)

from the base metal, and a considerable number of defects in the form of cavities and micropores were revealed on its internal surface (Figure 5).

Analysis of microstructure of metal (cross section *A*--*A*, see Figure 5) of the extruded strip shows that formation of Si--Mn eutectics in the incipiently melted base metal is accompanied by formation of discontinuities, pores and cavities (Figure 6, *a*). The presence of oxide films is also probable (Figure 6, *b*). In contrast to oxide films oriented in a direction of metal flow during extrusion, in the incipiently melted metal they have an arbitrary form (Figure 6, *b*). In both cases a large amount of pores that form continuous chains transforming into discontinuities are accumulated on the film surfaces.

It can be concluded on the basis of the results obtained that the quality brazing of samples was not achieved because of a substantial quantity of defects of the type of oxide films present in the base metal.

Figure 7 shows structure of metal of a sound brazed joint characterised by good wetting of the base metal, formation of a fillet and absence of defects. If the base metal is of a high quality, formation of the joints normally involves no problems.

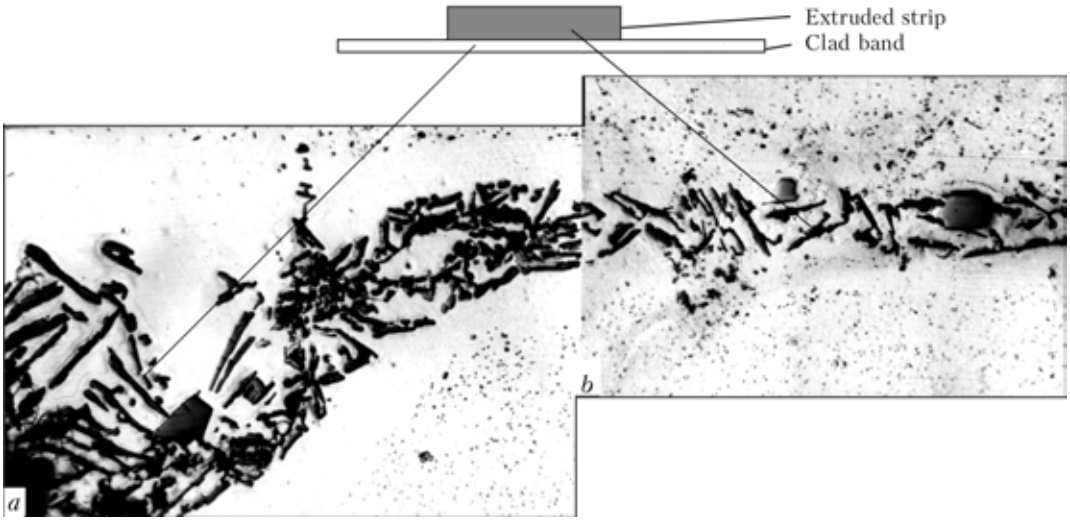

Figure 7. Microstructure of metal of a sound joint between clad band and extruded strip of alloy AMts produced by vacuum brazing: *a* — fillet; *b* — centre of the joint (×250)

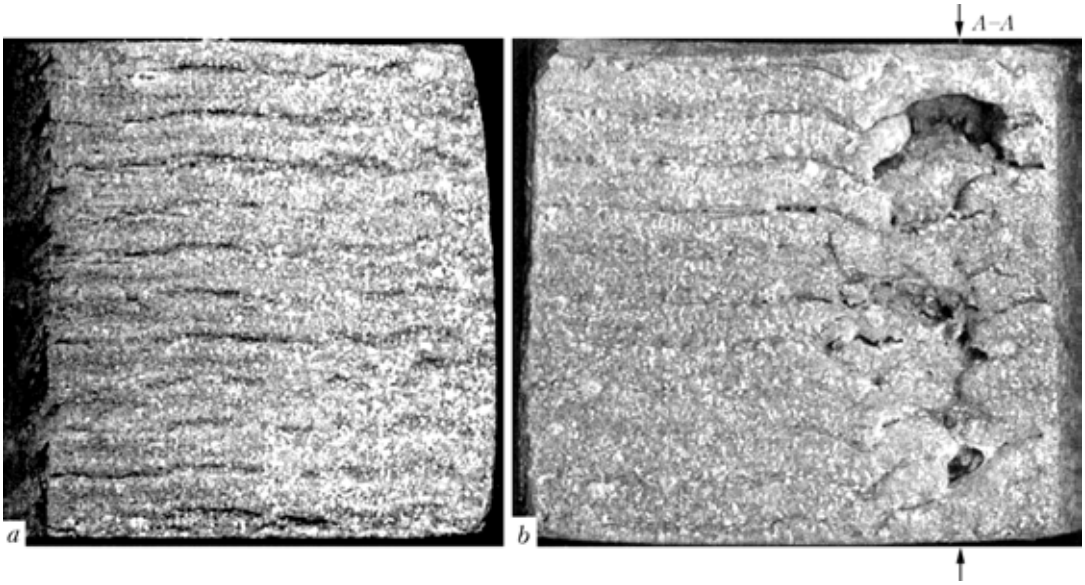

Figure 8. Appearance of good-quality (*a*) and defective (*b*) surface of AMts alloy ingot 200 mm in diameter

Ingress of oxide films into the brazing zone may be caused by different factors. It may be contamination of metal with oxide films at the stage of production of a cast billet, or formation of the films during processing of an ingot into a semi-finished product.

Different degree of dispersion and structural heterogeneity of metal of the billets for brazing may also be caused both by primary structure of the base metal and by thermomechanical treatment of a semi-finished product.

This made it necessary to conduct metallographic analysis, including examination of macro- and microstructure and phase composition of a cast and homogenised ingot of alloy AMts. The examinations were carried out on samples taken from different regions of a 200 mm diameter ingot in the as-cast state and after homogenisation in two spatial positions with respect to the ingot, i.e. transverse and vertical.

As shown by visual examinations, the ingot has a laminated surface, which is caused by peculiarities of its production. Some regions on the surface have defects in the form of deep cavities and individual filamentary delaminations (Figure 8). The depth of location of the defects was determined by making a corresponding cut in section along *A–A* (see Figure 8) in the zones of their presence. The character and depth of their location were determined after machining and etching in a solution of caustic alkali (Figure 9). To eliminate the probability of growth of size of the defects during the process of chemical etching, the surface of a section was subjected to electropolishing. It was found that the defects were discontinuities of a different shape. Hair-like delaminations branched off deep into metal from the cavities to form a network in the sub-surface layer of the ingot. A deeper microstructural analysis revealed formation of grains of a different size and orientation in these regions, as well as accumulation of redundant phases and pores. This suggests that they were formed during solidification of the ingot and concentrated on oxide films. Their shape varies within wide ranges, i.e. from hair-like, commensurable with a grain boundary, to cavities of a substantial size (Figure 10). This is associated with location of a film in plane of the section, as well as with the fact that a large amount of gases, non-metallic inclusions and basic phases were accumulated on its surface as early as in the liquid metal. The depth of location of the oxide films from the ingot surface is no more than 10 mm (see Figure 9). During the extrusion process, the sub-surface layers of the ingot metal may get into the middle part of the strips. In this case the defects are dispersed and oriented along the flow of metal in a direction of its deformation. The defects acquire the shape of extended thin discontinuities, which are found in semi-finished products intended for brazing.

A small zone of fine crystalline grains is formed on the periphery of the ingot, and coarse crystalline grains of different shape and orientation are formed in the bulk of the ingot. It is necessary to note the presence of zones with oriented columnar crystals. Microstructure in the state after homogenisation is more homogeneous and characterised by the presence of equiaxed crystals, as well as individual zones of a columnar structure.

The cast metal is a solid solution of manganese in aluminium and precipitates of eutectic, which has a

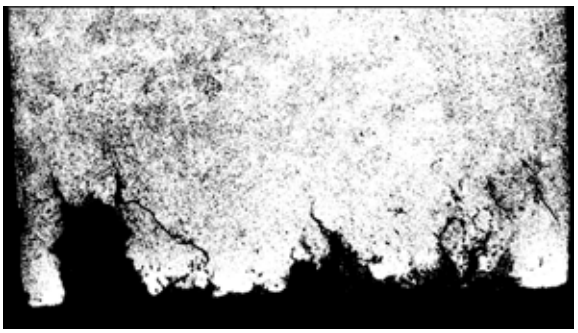

Figure 9. Formation of defects in AMts alloy ingot, section along *A–A* (see Figure 8) (×3)

Figure 10. Microstructure of AMts alloy ingot with oxide films and discontinuities (distance from the ingot surface is about 10 mm) (×200)

degenerated shape and contains the $MnAl_{16}$ phase in the form of plates, needles and cages. The cages fracture during homogenisation of the ingot to form individual precipitates of the Al–Mn phase. They are located mainly at the grain boundaries (Figure 11).

Investigation of chemical heterogeneity of alloy AMts showed that the Al-base solid solution contained up to 0.9 wt.% Mn, small amount of up to 0.33 wt.% Si and about 0.1 wt.% Fe. The eutectic precipitates are enriched with Mn (up to 6.7 wt.%), Si (up to 2.3 wt.%) and Fe (up to 4.1 wt.%). During the homogenisation process the content of Mn in solid solution is 1.1 wt.%, Si — 0.4 wt.% and Fe — 0.06 wt.%. The phase precipitates are enriched with manganese and iron, and to a lesser degree with silicon.

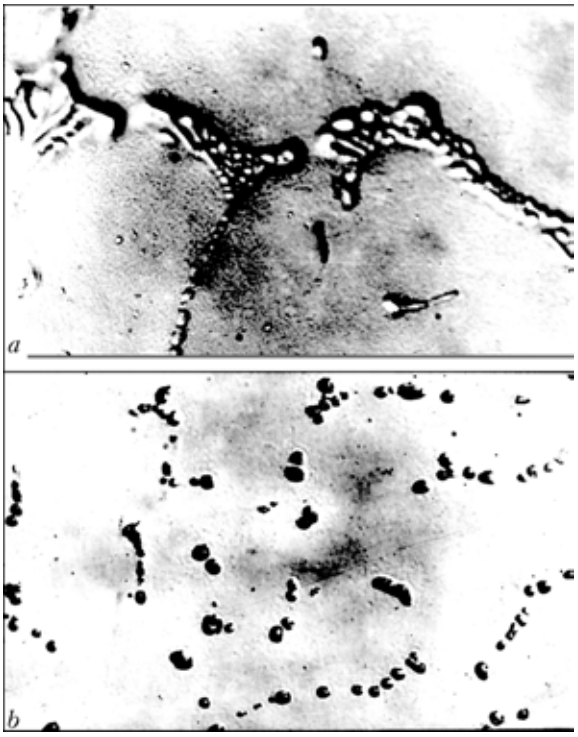

Figure 11. Microstructure of metal of cast (*a*) and homogenised (*b*) ingots of alloy AMts with a diameter of 200 mm (×1000)

Comparative analysis of structure and chemical heterogeneity of metal in the cast and homogenised states excludes the effect of heat treatment on brazing ability of the AMts alloy billets.

Therefore, wettability and spreading of the brazing filler alloy over alloy AMts are influenced by the defects of an internal character, which may take place in semi-finished products. The sources of defects in the AMts alloy semi-finished products are oxide films and cavities in a cast billet, which transform during processing of the ingot into extended thin discontinuities and clusters of non-metallic inclusions.

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PECULIARITIES OF FORMATION OF STRUCTURE OF TITANIUM-STEEL JOINTS UNDER EXPLOSION WELDING CONDITIONS

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Considered are principles of formation of structure and character of its variation in titanium-steel joints made by explosion welding, as well as factors provoking deterioration of properties of the joints.

Keywords: explosion welding, dispersed formations, titanium flow, steel flow, turbulence zone, eutectic formations, intergranular layers, stressed state, slip, twinning, turns of microvolumes

Fabrication of structures and assemblies operating under severe service conditions requires development of new dissimilar multilayer materials, the special place among which is taken by titanium-containing compositions. This is proved by analysis of over 250 studies published during the last decade.

As far as the methods employed for manufacture of the above materials are concerned, the preferable methods, along with the traditional ones (rolling, brazing), include pressure joining (diffusion bonding in vacuum, combined process of diffusion bonding and superplastic forming [1, 2], etc.). However, the high-speed welding deformation methods are receiving recently an increasingly wide acceptance. They include, in particular, percussion welding in vacuum and explosion welding [3–10], which, unfortunately, do not rule out all the difficulties associated with production of sound joints between dissimilar materials, especially those that are related to formation of low-melting point eutectics, intermetallic phases [4], lack of penetration, residual stresses [5, 7], exfoliation [10], and microcracking in layers of adiabatic shear [9].

It is obvious that traditional examination methods cannot reveal causes of deterioration of properties of the joints because of the lack of data on the key processes occurring in the welding zone (structure and phase formation, character of plastic deformation, distribution of internal stresses and cracking in different regions of a welded joint). These data can be generated using the direct examination methods, such as transmission examination of fine structure.

This article presents some results of investigations conducted in this area as applied to joining of stainless steel to titanium by explosion welding.

The welding zone in explosion welded joints between titanium VT1-0 and stainless steel 12Kh18N9T (SS 304) was investigated by complex methods, including optical microscopy, analytical scanning electron microscopy (SEM-151, Philips, The Netherlands) and transmission microdiffraction electron microscopy (JEM-200CX, JEOL, Japan) at an accelerating voltage of 200 kV. Detailed transmission examinations of fine structure of the joining zone between dissimilar metals and peculiarities of phase formation were conducted using the specially developed methods for ion thinning of test pieces with ionised argon flows [11].

General view of the joining zone and some fragments of structure of the metals welded are shown in Figure 1.

Analysis of structure (Figure 1, *b–d*) and chemical composition (Figure 2, Tables 1 and 2) of the wave formation zone, evaluated by scanning electron microscopy in reflected electrons and in characteristic radiation, shows that structure of this zone is characterised by particular complexity. One of its characteristic peculiarities is formation of titanium and steel flows (Figure 1, *c*, *d*) 10–50 μm wide, differing in chemical composition, which can be clearly seen

Table 1. Variations in elemental composition (wt.%) of metal within the zone of the VT1-0 + 12Kh18N9T joints at different distances from the contact surface in regions free from phase precipitates (regions I and II)

Chemical element	*Titanium VT1-0*						*Steel 12Kh18N9T*			
	At distance from contact surface, μm									
	15	*10*	*7*	*5*	*2*	*At interface*	*2*	*5*	*7*	*10*
Ti	97.30	98.00	97.04	93.50	66.0	59.30	18.80	15.34	4.30	1.72	1.61
Fe	1.60	1.20	1.97	4.60	22.3	27.20	55.70	57.26	67.08	67.70	66.90
Cr	0.50	0.40	0.48	1.22	7.6	8.62	11.16	11.40	15.12	18.40	19.05
Ni	0.10	0.18	0.25	0.26	2.8	3.80	12.00	13.52	11.20	10.02	10.18
Si	0.35	0.05	0.04	0.14	0.7	0.43	0.10	0.30	0.24	0.85	0.82
Mn	0.07	–	0.06	0.23	0.4	0.34	1.00	1.02	1.59	1.18	1.25
V	–	0.20	0.15	–	0.2	0.30	1.20	0.12	0.38	0.12	0.14

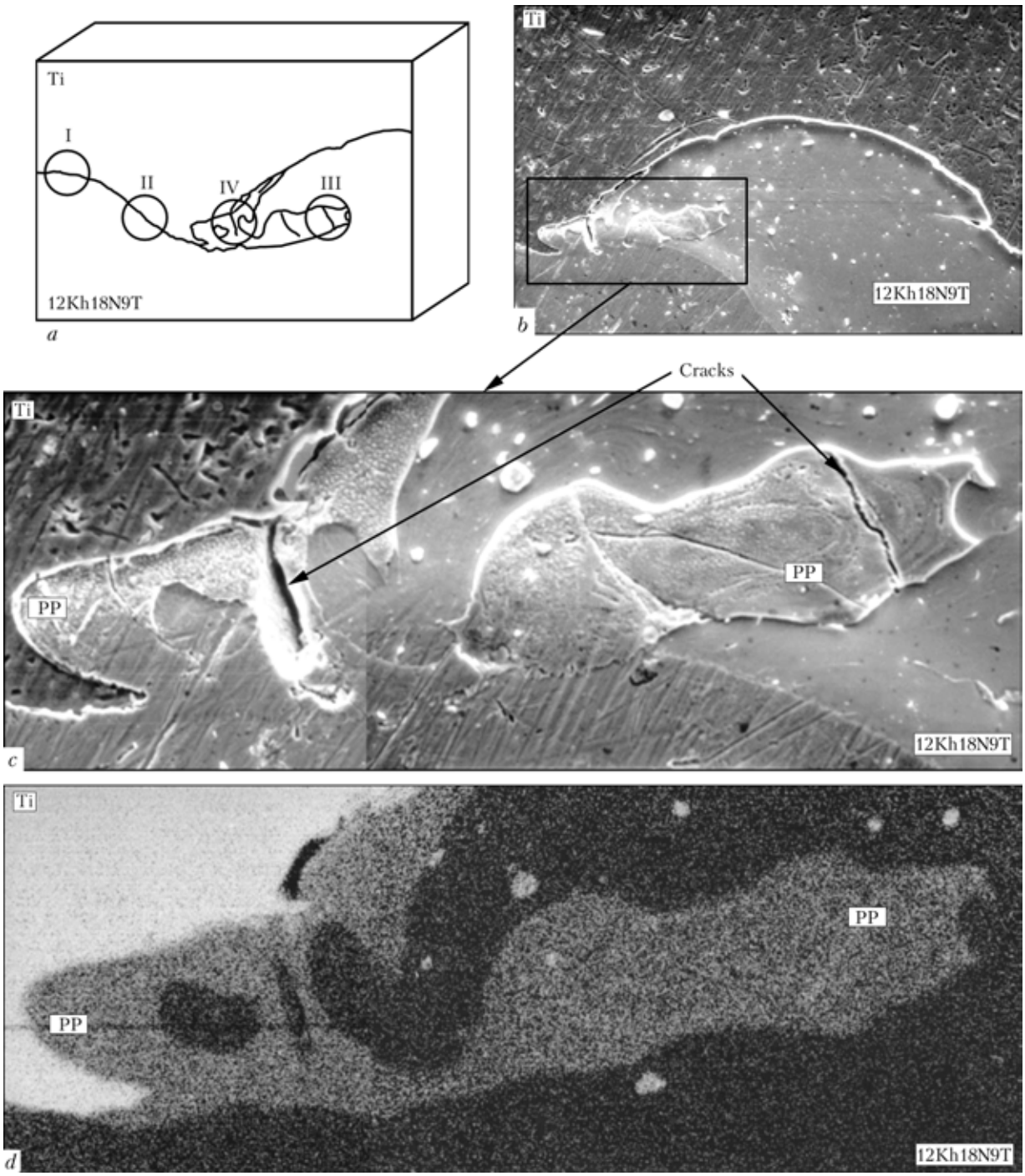

Figure 1. Microstructure of metal in the joining zone between titanium VT1-0 and stainless steel 12Kh18N9T: *a* — schematic; *b* — general view; *c* — transition zone between titanium and steel (×163); *d* — image of distribution of titanium in characteristic radiation (×655); PP — phase precipitates

in photos made in characteristic radiation, where the distribution of titanium is shown by light regions against dark regions corresponding to the distribution of steel (Figure 1, *d*). Besides, the steel and titanium flows differ in compositions from those of the metals welded, i.e. steel 12Kh18N9T and titanium VT1-0. Thus, the content of the latter in the titanium flow is 16–18 % and the content of iron is 56–57 %. Tables 1 and 2 give more specific data on concentration variations in the flows.

Judging from the identical intensity of reflections (Figure 1, *d*) and results of analysis of chemical composition, the titanium and steel flows have an almost constant concentration over the entire path of their movement within the welding zone. It should be noted that the titanium particles of a globular shape, approximately 2.5–9.5 μm in size, which show up as white spots on a dark background of steel reflections (Figure 1, *d*), are revealed in the bulk of the steel flows. The titanium content of these particles corresponds to that of the base metal ---- 95–97 %.

Formation of the flows seems to be related to a direction of cumulative flows, whereas the globular particles in the bulk of steel are fragments of detachment of titanium from these flows. Here we can see a specific «spiral» shape of both titanium and steel

Table 2. Variations in elemental composition (wt.%) of metal within the zone of the VT1-0 + 12Kh18N9T joints at different distance from the contact surface in regions containing phase precipitates (regions III and IV)

Chemical element	Titanium VT1-0				Phase precipitates						Steel 12Kh18N9T	
	At distance from contact surface, μm											
	10	5	2	At interface	2	5	10	5	2	At interface	2	
Ti	96.50	96.30	96.20	79.30	20.0	16.60	16.50	15.40	13.80	13.40	12.60	2.05	1.59
Fe	2.53	2.67	2.50	13.80	53.8	56.60	56.60	57.00	58.50	58.60	58.60	66.50	65.90
Cr	0.40	0.50	0.70	4.60	15.5	16.20	16.20	16.40	16.50	16.40	17.10	19.00	18.60
Ni	0.20	0.14	0.18	1.44	8.8	8.59	8.70	8.81	8.78	9.50	9.37	10.40	11.50
Si	0.20	0.30	0.22	0.53	0.7	0.40	0.86	1.15	1.00	0.60	1.30	0.80	0.83
Mn	0.07	0.08	–	0.31	1.1	1.29	1.03	1.04	1.20	1.35	0.90	1.06	1.36
V	–	0.10	0.10	–	–	0.20	–	0.06	0.17	0.13	–	0.07	0.03

flows (Figure 1, *c*, *d*), which is indicative of the fact that a shear opposing movement of flows of the metals is accompanied by their turns and rotations.

Another structural peculiarity of the welding zone is the presence of regions with specific eutectic dispersed formations (0.6–0.3 μm), which can be well seen using the scanning electron microscope at a comparatively low magnification (Figure 1, *c*). Emergence of this type of the formations is localised in certain welding regions, such as collision zone (region IV) and turbulence zone (region III). No structures of this type are fixed in other wave formation regions (Figure 1, *a*, regions I and II).

Figure 2 and Table 1 show that the distribution of chemical elements in the joining zone is non-uniform. However, a rather uniform distribution of the concentration of chemical elements in transition from titanium to steel is fixed in the zones free from dispersed phase formations (regions I and II) (Figure 2, *a*, Table 1). The region of the most intensive variations in the concentrations is localised at a depth of about 5–7 μm from the interface (towards titanium and steel).

With the forming dispersed phases, i.e. eutectics (regions III and IV), present in the welding zone, the depth of variations in the concentrations increases to about 20–25 μm, and chemical composition of metal in this zone is characterised by a constant content of chemical elements, which is proved by the presence of «shoulders» in the concentration curves (Figure 2, *b*), and is indicative of the formation of phases with a comparatively homogeneous composition.

Phase precipitates in region IV are located directly along the interface, while phase precipitates in region III are located at a distance of about 150–250 μm. The forming structural species of the above type contain approximately 8–9 % Fe, 15–16 % Ti and Cr, and 8–9 % Ni. The content of silicon and manganese is about 1 % each (Table 2). Despite a different distance from the contact surface, they have similar concentrations in the above phases of a welded joint.

So, it seemed reasonable to conduct more detailed investigations of structures formed in the welding zone, as it is here that we reveal initiation and propagation of cracks (Figure 1, *b*, *c*; Figure 3, *a*, *b*).

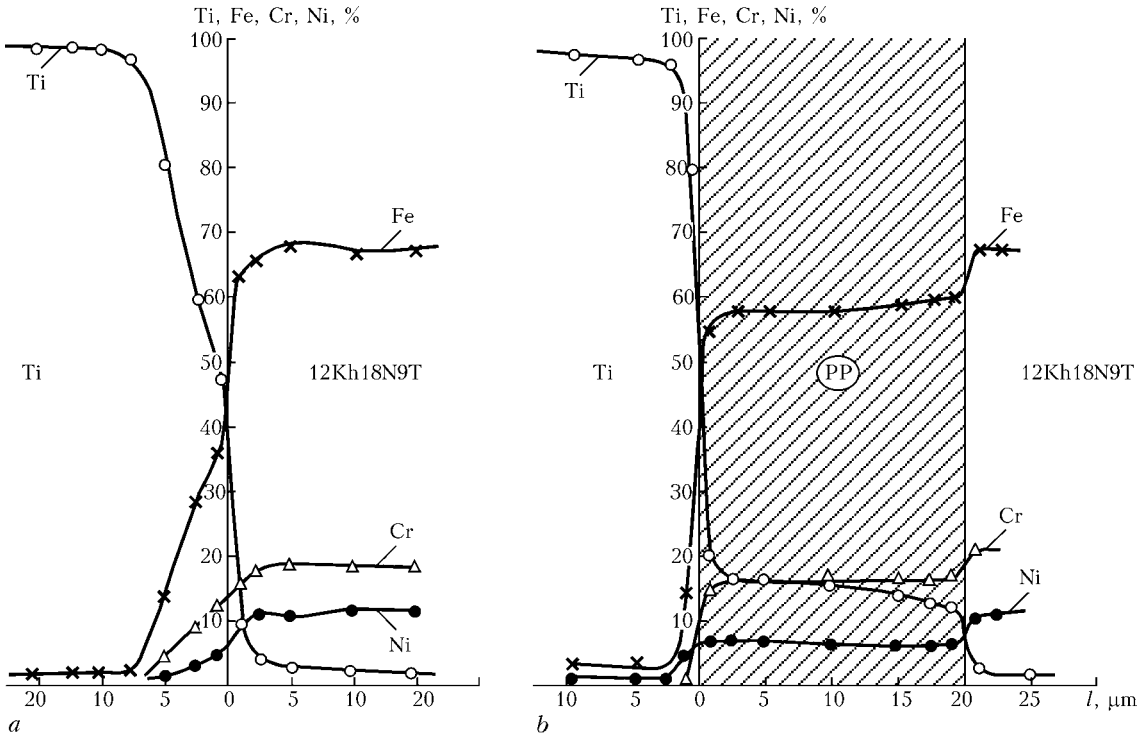

Figure 2. Character of variations in chemical composition of metal in regions without (*a*) and with phase precipitates (*b*); *l* — distance from the interface

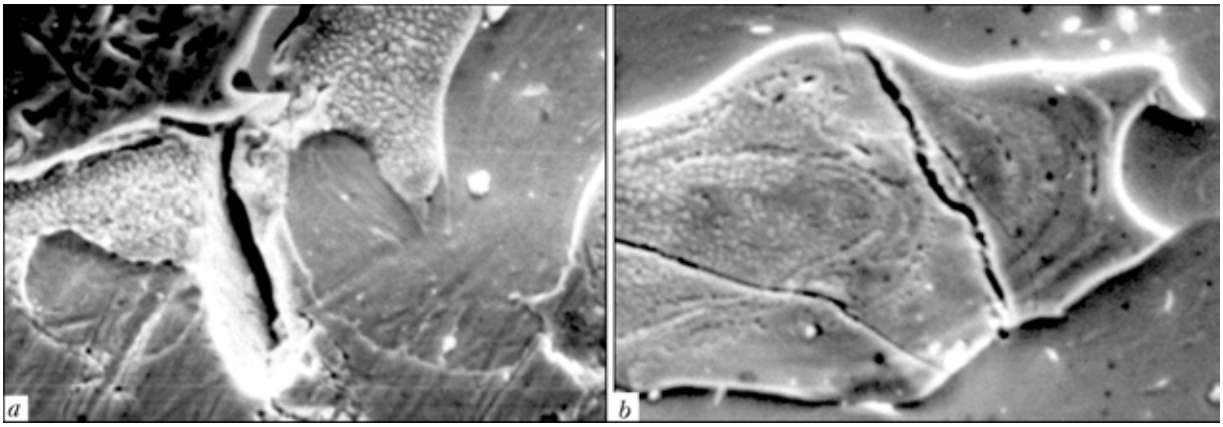

Figure 3. Microstructure of metal of characteristic regions (*a*, *b*) on the steel side, related to formation of cracks (×800)

Comprehensive examinations by the transmission electron microscopy methods show that structure of metal in the region of collision of mating surfaces and wave turbulence is inhomogeneous. The region of collision is a narrow zone from 10 to 30 μm in size, consisting mostly of eutectic formations of a globular shape. The turbulence zone (region III in Figure 1, *a*) is wider (approximately 40–50 μm) and has a more complex structure. It is located in the titanium flow. As seen in a general image of the collision and turbulence zones, obtained at different magnifications (Figure 1, *c*, *d*; Figure 3), structural heterogeneity of these zones is a gradual transition from fused structures and structures of the type of eutectics to structures with characteristic indicators of the effect of high and lower temperatures. The transition structures can be clearly seen in enlarged pictures obtained by transmission examination of thin foils (Figures 4 and 5).

The fused structures (Figure 4 *a*, *b*) are coarse grains with no clearly defined boundaries, the internal volumes of which are characterised by low dislocation density ($1 \cdot 10^8$–$2 \cdot 10^9$ cm^{-2}).

The fusion region is immediately followed by the region of eutectic formations, the images of which were obtained in different modes of photography using transmission electron microscopy, i.e. light and dark fields (Figure 4, *c*, *d*).

The first provides a clear picture of structure and individual dispersed phases in the internal volumes of eutectic grains. It can be seen that these grains have mostly a globular shape, and that they are 0.75–0.25 μm in size. The dark field image of the same eutectic regions with a more contrast picture of peculiarities of structure of the intergranular layers formed around the grains allows details of structure of these layers 0.07–0.17 μm thick to be analysed.

Analysis of structure images combined with reflections of microdiffraction reflexes shows that the globular dispersed grains of eutectic consist of γ-Fe, and the layers fringing them are solid solution of titanium and iron. In addition, both intergranular layers and grains of γ-Fe are saturated with finely dispersed phase precipitates about 0.020–0.003 μm in size, consisting mostly of titanium and chromium carbides (Figure 4, *c*, *d*).

The eutectic formations are followed by the region of non-equilibrium structures, which are the structures of a mixed type, comprising regions of recrystallisation centres (Figure 4, *e*), subgrains, blocks and fragments (marked by arrows in Figure 4, *f*), wherein the processes of redistribution of dislocations and polygonisation have occurred. As a result of ordering of internal volumes of structures of this type, the dislocation density is minimal, i.e. $1 \cdot 10^9$ cm^{-2}.

Note that the above changes in structure are characteristic of welding regions IV and III, i.e. collision and turbulence, the latter being located in steel within the titanium flow.

With transition directly from the titanium flow to the stainless steel region, the structure exhibits substantial and dramatic changes. Thus, the region of partially relaxed structures is changed by structures with multiple slip and intensive twinning (Figure 4, *g*), accompanied by a considerable increase in the dislocation density and formation of local dislocation clusters with a density of $1 \cdot 10^{11}$ cm^{-2} or more, which are the internal stress raisers [12].

In addition, the said zones corresponding to the interface regions between the titanium and steel flows contain specific structures (marked by arrows in Figure 4, *g*, *h*) having clear evidences of turns and rotations of structural elements in steel. The latter is proved by the character of microdiffraction pictures having a clearly defined system of reflections with splitting of reflexes in radial directions (Figure 4, *h*).

Therefore, a sudden change of structures from soft and relaxed, weakened on the titanium flow side, to substantially weakened on the stainless steel side, where the rigid stressed state of metal is fixed, takes place at interfaces between the titanium and steel flows (this region is localised in a very narrow zone, only a few microns wide). This difference in structures of the titanium and stainless steel flows is related to their different relaxation ability in deformation, which is determined in many respects by the value of stacking fault energy (SFE) [13], not excluding the effect of temperature of certain physical processes (melting, recrystallisation, polygonisation). While the value of SFE for α-titanium is substantial (approximately 0.2 J / m^2 [14, 15]), which explains occurrence of very intensive processes of structural relaxation and plastic relief of internal stresses, for the stainless steel, the value of SFE of which is more than by an order of magnitude lower (approximately 0.013 J / m^2 [12], the strengthening processes are dominant.

As shown above, the weakening region (on the titanium side) is suddenly changed by a region of

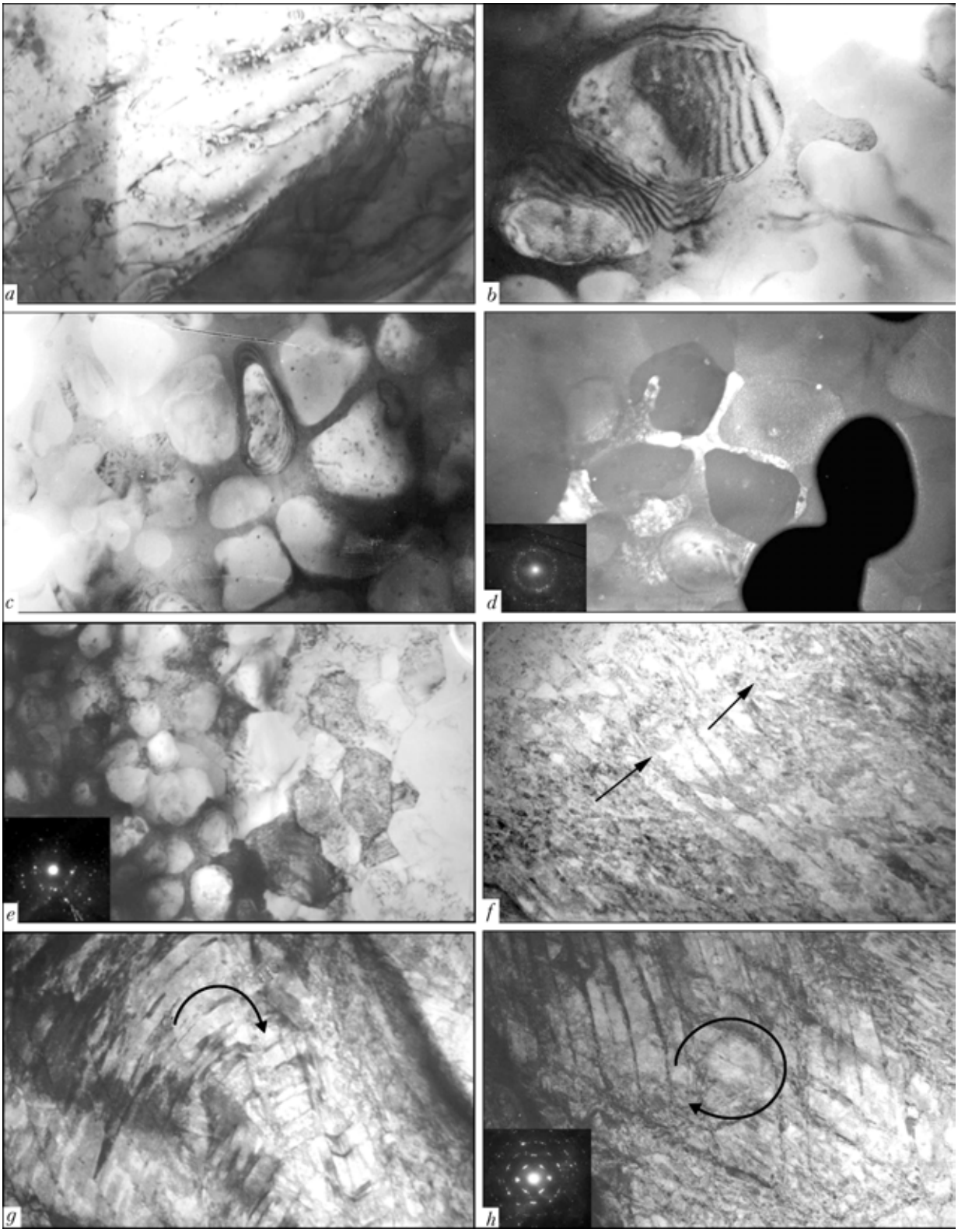

Figure 4. Fine structure of metal of the joining zone between titanium VT1-0 and steel 12Kh18N9T on the side of steel: *a* — fusion zone (×20,000); *b* — structure in a region of transition to eutectic (×59,000); *c, d* — structure of eutectics in light (×30,000) and dark field (×50,000) images; *e* — structure in recrystallisation region (×20,000); *f* — region of polygonisation in transition zone (×15,000); *g, h* — turns of microvolumes in steel are marked by arrows (×15,000 and ×10,000, respectively)

substantial strengthening (on the stainless steel side). The latter is characterised by the presence of local raisers of internal stresses, which are relieved due to multiple slip, twinning and turns (rotations) of metal microvolumes. Formation of cracks is also fixed. However, cracking shows up, as a rule, in certain zones, i.e. the zones of turns of the flows (marked by arrows in Figure 1, *c*; Figure 3). The presence of cracks is indicative of the fact that the processes of plastic relief of local internal stresses, which are the dislocation slip, twinning and turns of metal volumes, are obviously insufficient to neutralise the intensive stress

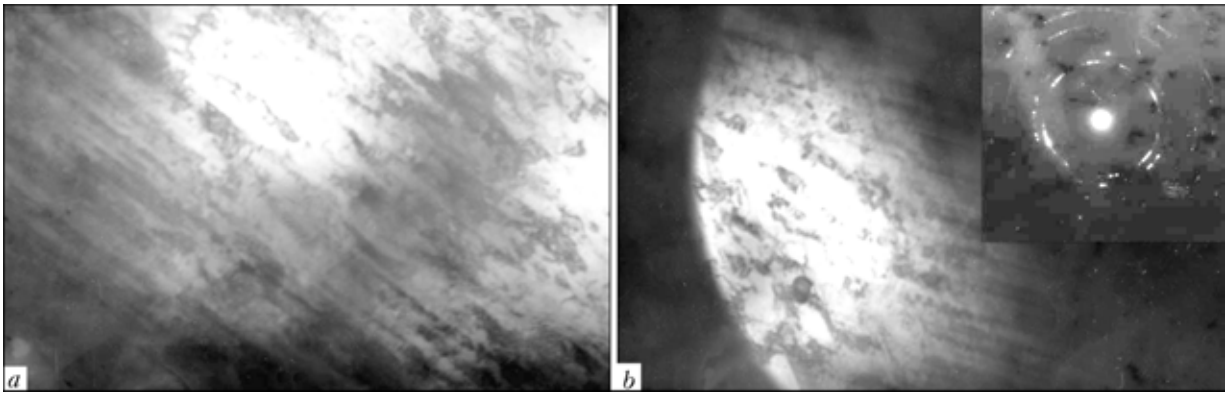

Figure 5. Fine structure of titanium in the titanium + stainless steel joint at a distance of 0–10 μm from the interface: *a* — ×50,000; *b* — ×39,000

raisers formed on the steel side particularly in the turbulence zones. The final relief of stresses in them occurs now through cracking.

Analysis of internal stresses in metal volumes differing in level of the dislocation density, conducted using relationship $\tau_{in} = Gbh\rho / \pi(1-\nu)$ [13] (where G is the shear modulus; b is the Burgers vector equal to $2.5 \cdot 10^{-8}$ cm; h is the foil thickness equal to $2 \cdot 10^{-5}$ cm; ρ is the dislocation density; and ν is the Poisson's ratio (0.28)), showed the following.

At a dislocation density of $(1–2) \cdot 10^{8}$ cm^{-2}, which is characteristic of the welding zone where the structures are relaxed, the formed stress field yields $\tau_{in} = G / 5 \cdot 10^{4} – G / 2.5 \cdot 10^{4}$, which is not in excess of theoretical strength $G / 10$ [16, 17]. In this case there is no risk of cracking. At a dislocation density of $(5–6) \cdot 10^{11}$ cm^{-2} characteristic of the stressed regions in stainless steel, the induced stress field yields $\tau_{in} = G / 9 – G / 10$, which exceeds theoretical strength $G / 10$ and leads to fracture.

As far as the eutectic and intermetallic phases are concerned, they have dispersed sizes, are distributed comparatively uniformly in the collision and wave turbulence zones, and cause no changes in the character of distribution of dislocations. No clearly defined relation of cracks to the points of localisation of eutectic formations is detected.

Structure of the joining zone on the titanium side is comparatively uniform and finely dispersed (Figure 5). Formation of phase precipitates of ultra dispersed sizes is revealed. Despite the fact that titanium experiences substantial deformation directly in the contact zone and at a distance from it, which is evidenced by a circular character of microdiffraction reflections, no stress raisers and cracks on the titanium side is fixed.

CONCLUSIONS

1. It is shown that variations in concentration of chemical elements occur along the collision surface (up to 5–7 μm) and at a depth of about 150–200 μm in the welding zone, which is caused by movement of the titanium and steel flows into the internal volumes of metals welded under the effect of an internal welding stress.

2. It is established that formation of intermetallic and carbide phases and eutectics, which are dispersed grains fringed with intergranular layers, occurs the mostly in collision zone and internal volume of the moving flows of metals welded. Intermetallic and carbide phases with ultra dispersed sizes are distributed in the bulk of grains and interlayers.

3. It is established that the most gradient structures, as well as considerable raisers of internal stresses, which are in excess of theoretical strength, are formed in certain zones at an interface between the titanium and steel flows, which is caused by dramatic growth of dislocation density, multiple slip, twinning and rotation of structural microvolumes in stainless steel characterised by low stacking fault energy.

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STUDY OF EXPLOSION WELDING PROCESS BY COMBINATORIAL ALGORITHM OF MGAA AND DATA SAMPLING EXTENSION

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A dependence was studied between the geometrical features of wavy interface of the plates formed in explosion welding on plate location and size, as well as on the amount of the explosive used. The paper also gives the results of studying the properties of the combinatorial algorithm of the method of group accounting for arguments (MGAA) for the posed problem. The model was identified by MGAA combinatorial algorithm, using a data sampling extension. Regularity criterion is used as the main criterion, and minimum displacement criterion is the auxiliary criterion.

Keywords: explosion welding, MGAA, combinatorial algorithm, sampling extension

Currently the explosion welding is widely used in the number of branches of the modern industry. According to the data from the Information Center of Business Cooperation [1] proposals related to explosion welding account or 45 % of all proposals at the exchange of technologies.

Explosion welding is a promising method widely used at the enterprises in many Ukrainian cities, including Kiev, Dnepropetrovsk, Krivoj Rog [2]. However, the processes taking place under this welding method have not yet been sufficiently investigated. At present a model describing explosion welding is not available. In this work the authors have taken an attempt to bridge this gap.

Initial data sampling

No. of tests	Output parameters		Input parameters			
	Wave amplitude, μm	Wave length, μm	Clearance, mm	Explosive mass per unit of flier mass, g	Flier thickness, mm	Thickness of the main plate, mm
1	10	200	3	0.8	3	6
2	20	230	6	1.5	3	6
3	30	280	6	0.8	6	6
4	35	290	3	1.5	6	6
5	10	200	6	0.8	3	12
6	35	270	3	1.5	3	12
7	16	240	3	0.8	6	12
8	40	310	6	1.5	6	12
9	16	260	6	1.5	3	12
10	25	300	3	1.5	6	12
11	12	220	6	0.8	3	6
12	40	270	3	1.5	3	6
13	20	260	3	0.8	6	6
14	40	300	6	1.5	6	6
15	10	200	3	0.8	3	12
16	20	200	6	0.8	6	12

Figure 1 presents a diagram of the welding unit consisting of the main plate x_4 thick, an anvil and a flier, which collides with the main plate and combines with it. Let us designate the flier thickness (specific mass) by x_3. The welding unit also includes a buffer, an explosive producing a shock wave for acceleration of the flier, and a detonator. Let x_2 denote the quantity of explosive per mass unit of the flier. A mutual penetration of the wave form takes place in the welding zone. This mutual penetration is characterized by two variable y_1 and y_2, i.e. length and amplitude of the wave, respectively. The variable x_1, a clearance between the main plate and the flier, is also used in the study.

Length and amplitude of the formed waves are the output values in our experiment. They have the order of 10 and 100 μm, respectively. Size of the initial data sampling (Table) is 6×16. This is a result of the 16 measurement of 6 values, two of them being abovementioned output values (length and amplitude of the wave). Out task is to find the «best» dependence of output values y_1 and y_2 on input values --- x_1, x_2, x_3 and x_4.

Construction of the experiment. We use the data from work [3] (Table) to find the explosion welding model. The Iranian scientists carried out a structural identification of the model of dependence of the weld geometry on the thickness of plates, a distance between them and a specific quantity of the explosive by three different methods using a two-level algorithm of the method of group accounting for arguments (MGAA) in one of them. The specifics of this work is that to find the regularities the authors used the

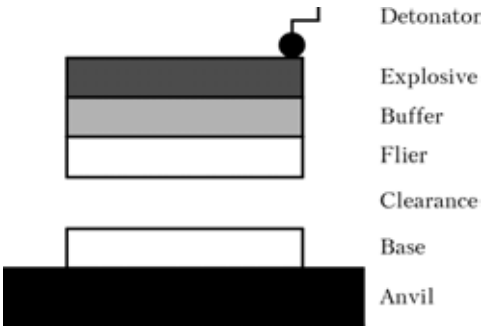

Figure 1. Diagram of the welding unit

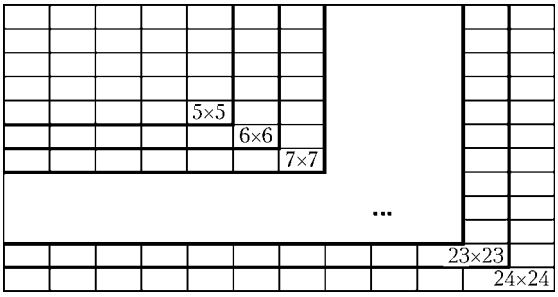

Figure 2. Method for formation of sub-samplings for analyzing the quality criteria variations for approximation

combinatorial algorithm of the MGAA based on the principle of self-organization of the models [4], i.e. the use of two samplings of data processed in turn for determination of the model. One sampling is employed to estimate the coefficients of the polynomial model, the other one ---- to estimate the structure of the model and the quantity of its arguments. Such method of processing of the data from two samplings allows a consecutive consideration of two criteria for search of a set of models-candidates: external criterion of the model error RR and criterion of the model non-bias BS [5]. Bias of the model is equal to zero if the models obtained from two samplings prove similar. Criteria of error and non-bias do not depend on each other. This method goes back to the 1960s. This innovation approach was suggested in [6].

Let us apply the combinatorial algorithm MGAA to the obtained data and perform the sampling extension. The combinatorial algorithm has an advantage over the multi-row one: the method of full search is used for finding the optimal model. First, out of all possible models linear in their parameters the small number of the most accurate models is selected and then the criterion of the bias minimum allows determining one model. Sampling extension is carried out, as a rule, by two ways ---- by modeling of new experimental data (downward extension) or of new data of measurements (rightward extension). A new combined method uniting the above-mentioned two methods is employed in this work [7].

Models were selected consecutively by two criteria, i.e. the models best by the main criterion were tested by the additional criterion. Average percentage error for every obtained model was calculated by the formula:

$$MAPE = \frac{1}{n}\sum_{j=1}^{n}\left|\frac{y_{ij} - \overline{y}_{ij}}{y_{ij}}\right|, \quad i = \overline{1, 2},$$

where n is the number of measurements; i is the number of output value for which the error is calculated; $y_1 = y_{11}, y_{12}, \ldots, y_{1n}$ and $y_2 = y_{21}, y_{22}, \ldots, y_{2n}$ are the output vectors.

Experiments with sampling extension. First, the MGAA algorithm was applied directly to the initial experimental sampling. The following models proved to be the best:

$$y_1 = -28.8893 + 0.1917y_2 + 7.2411x_2 - 0.4495x_4,$$

$$y_2 = 164.2421 + 2.5758y_1 + 5.9153x_3.$$

Values of the regularity criterion and bias minimum for them are equal, respectively, RR = 36.8719, $BS^2 = 1.0186 \cdot 10^{-3}$ and RR = 443.5273, $BS^2 = 5.7911 \cdot 10^{-4}$, relative error is $MAPE$ = 20.67 % for y_1 and $MAPE$ = 5.162 % for y_2.

Then we improved the approximation quality by downward extension of the observation matrix. R. Engle and C. Grange, the Nobel laureates, proved in their work [8] that the results of the initial data sampling approximation improve after introduction of additional additive features, i.e. data sampling extends rightward. Let us extend the sampling downward and see how this will affect the model accuracy. This was done by generation of middle points i.e. lines, being a half-sum of the neighboring ones. The weightiest argument for each output value proved to be another output value used as an argument. Increase of the number of lines failed to improve the model ---- this even deteriorated it. However, multiple selections of the «best» middle points considerably improved the estimate. It is true to say that the use of additional lines may either essentially improve the approximation estimate or produce no effect. All depends on particular experimental sampling.

Then let us extend the sampling rightward and complement it with new columns, which may be obtained by multiplication of their initial or computed mean values (analog of middle points for columns). This sampling showed how the rightward extension affects the approximation quality of output values. The results obtained for y_1 and y_2 showed that rightward sampling extension is very effective especially owing to multiplicative features. If the sampling extends due to additive features, then the positive effect shows up only at the beginning, so there is no sense in adding many additive features. In most problems it is enough to restrict to only middle vector out of all input vectors.

The next step is to extend the initial data sampling both downward and rightward. The obtained sampling was analyzed as follows: first the model was searched by the data of the left upper sub-sampling 5×5 in size, then 6×6 further up to 24×24 (Figure 2). It turned out that addition of «middle points» alone did not produce a tangible effect, but together with addition of new factors it became an effective way of improving the approximation quality of the output values. It is noteworthy that with considerable similarity of vectors y_1 and y_2 ($\text{corr}(y_1, y_2) \approx 0.8392$) the accuracy of the model was improved without using them as input variables.

It is important that length and amplitude of the wave contour in the joint site of the plates produced by welding should be determined simultaneously, i.e. the values of y_1 and y_2 remain unknown until the welding process starts. Actually the task of the welder is to determine the amplitude and length of the wave in advance depending on the thickness of the main plate and flier, the clearance between them and a mass of explosive per mass unit of the flier.

Finding the best model. After such promising results let us refuse from employing y_1 and y_2 as independent variables in searching for the best model. Therefore, the results of this work may spontaneously be applied in the real conditions directly on the production. For improving the model the initial data sampling was complemented with four columns ----

$1 / x_1$, $1 / x_2$, $1 / x_3$, $1 / x_4$. Introduction of the feature of such type improves the sampling informativity and model quality since a new type of dependence was considered in this case.

So, the output value was approximated by means of the sampling of $(n + 1)n$, $6 \le n \le 21$ size, where n is the number of used independent variables as well as the number of lines. With every step the number of lines and columns increased by one like in Figure 2, and a new model was computed for a new sub-sampling. The additive factor $1 / 4(x_1 + x_2 + x_3 + x_4)$ was included into every sub-sampling.

The results have shown that the specific quantity of the explosive is the most important parameter, on which both output values depend. Thickness of the flier has a lesser effect on the outputs while thickness of the main plate practically has no effect on the form of the wave contour between the surfaces welded by explosion.

The best model is:

$$y_1 = 182.356662048 + 10.863406557668x_1 + 124.0341248788x_2 + 10.863406557668x_3 + 5.4317032788332x_4 + 330.715922928\frac{1}{x_4} - 15.98347606x_1x_2 + 0.24185654156x_1x_3 + 0.4613825486x_1x_4 - 11.4229643128x_2x_3 + 0.5116753672x_3x_3 + 1.137106842x_1x_2x_3 - 0.544132x_1x_2x_4 - 0.283593x_1x_3x_4 - 0.792656x_2x_3x_4 + 0.287267x_1x_2x_3x_4.$$

The indices of this model are as follows: $RR = 3.5625 \cdot 10^{-3}$; $MAPE = 0.711$ %; $BS^2 = 7.79 \cdot 10^{-2}$. They are much better than the previous ones proving the necessity to use the additive vector, which is a mean value of all factors.

Curves RR and $MAPE$ in Figure 3, *b* have a vividly expressed minimum at $n = 10$. Therefore, the model obtained on the 11×10 sampling is optimal. It is interesting that a minimum of regularity criterion for output y_2 is also achieved at $n = 10$ (Figure 3, *a*) while a large value of mean relative percent error is, probably, explained by the inaccuracy of amplitude measurements.

Thus, the optimal model for y_2 is as follows:

$$y_2 = 121.27555756 - 10.57224957254x_1 - 42.28899829017x_2 + 129.76965057\frac{1}{x_2} - 10.5722495725x_3 - 237.867936006\frac{1}{x_3} - 5.28612478627x_4 + 8.921349846x_2x_3 + 17.25386x_2x_4 + 7.0527133x_1x_2x_3 - 0.7336352x_2x_3x_4 - 0.4578947x_1x_2x_3x_4.$$

Indices of the model $RR = 2.04 \cdot 10^{-4}$, $MAPE = 0.058$ %, $BS^2 = 2.0084 \cdot 10^{-4}$ are very good. We recommend the obtained model as the best one for describing the explosion welding processes.

Therefore, a dependence of output values (amplitude and length of the wave formed in the butt of the welded surface after joining) on the input values

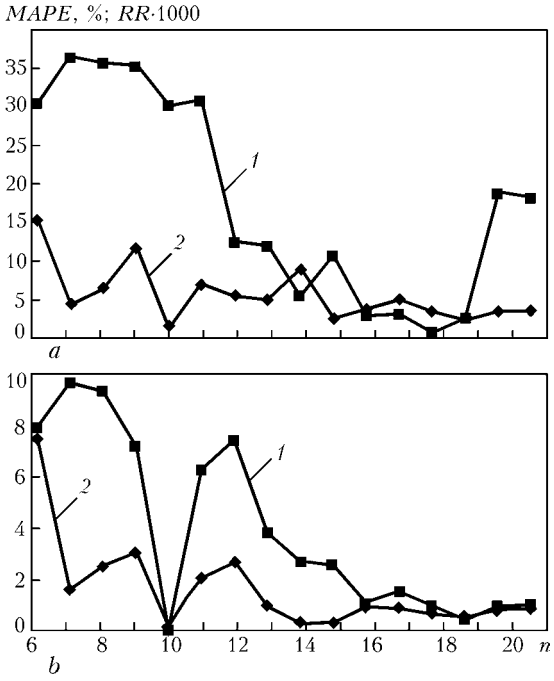

Figure 3. Dependence of the error $MAPE$ (*1*) and regularity criterion RR (*2*) on the number of lines and columns in $(n + 1)n$-th data sub-sampling with additive $(n + 1)n$-th column: *a*, *b* — output values y_1 and y_2, respectively

(thickness of the main plate, flier, clearance between the plates and mass of the explosive per the mass unit of the flier) is found in this paper by the inductive method. In the course of studies presented in this work a rich set of data were obtained including additional factors (multiplicative and additive) and lines, about 15 models for extension of the initial sampling, dependences of the regularity criterion RR and error $MAPE$ on the size of the data sampling.

It turned out that both output values are very much alike in their models and in the obtained graphs. The parameter x_2 (specific mass of the explosive on the mass unit of the flier) dominating over other parameters is the main one for determination of the amplitude and length of the wave. Output values depend on the thickness of the flier x_3 to a lesser degree. Wave contour in the site of joint of two surfaces does not practically depend on the clearance between the plates and on thickness of the main plate.

It also noteworthy that the performed studies are unique for Ukraine. We hope on further close cooperation of two sciences — cybernetics and welding.

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FEATURES OF REPAIR OF WELDED STRUCTURES FROM LOW-ALLOY STEELS (REVIEW)

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Peculiarities of performing the repair welding operations at reconditioning of metal structures, mechanisms, machines and engineering facilities are reviewed. The paper describes the methods which are the most often used during reconditioning operations of defect repair and groove preparation, repair welding technologies, welding consumables used for repair, and techniques of controlling the welded joints quality.

Keywords: repair welding, restoration of welded structures, defect removal, edge preparation, control of welded joint quality, residual stresses, welding consumables, fatigue cracks

A great number of engineering facilities and machines, for which the specified service life is already over, or which are close to this stage, are currently being operated in Ukraine. Most of these constructions have fatigue and brittle damage. Further operation of such constructions is becoming unsafe.

As shown by publications [1–4], this problem is also recognized in other developed countries. According to the data of [2], about 26 % of US bridges need repair. The problem of bridge repair in the US expressways is particularly urgent. In [4] it is stated that many constructions (high-pressure boilers, oil and gas offshore platforms) are already past their design life. Despite that, however, they are not replaced by new ones. The main cause for that is the huge cost of their purchase and mounting. In addition, during replacement of the old structures by new ones, neither will be operating, thus leading to considerable losses. Therefore, methods are being now developed, that would allow a maximum extension of the service life of the currently operating facilities.

In most of the cases, such problems are solved by reconditioning (revitalizing) the metal structures with application of arc welding or strengthening treatment of damaged elements [4].

Considering the great importance of repair-reconditioning work for the industry, the American Welding Institute put together and initiated in 1980s a broad research program on repair welding [2]. Beginning from the start of this millenium, a similar program, conditionally called «Residual service life», has been fulfilled in Ukraine.

The need to perform research aimed at improvement of repair technologies is due to the fact that standard technologies developed for fabrication of new products are, as a rule, used now at metal structure reconditioning. These technologies do not take into account the specific features of repair joints, resulting from the influence of considerable residual stresses in them and a limited choice of the methods of defect removal, edge preparation and welding proper, which may have an essential influence on the properties of welded joints of the reconditioned structure [1, 3, 5, 6].

In [7] it is noted that repair welding promotes a greater amount of damage in the joints than that found at regular initial welding. This is due to the fact that repair welding takes less time than initial welding does. Therefore, its performance creates more sections of welding start and finish. These sections are characterized by increased rates of metal cooling, this leading to an increase of its hardness and susceptibility to formation of cold cracks. Another feature of such joints is formation of metal sections with an unfavourable embrittled structure.

Data of [8] indicate that increase of the residual stress level and formation of inhomogeneous structure in repair welding lead to lowering of impact toughness values by 20–25 %, compared to the initial variant.

In [6] it was established that defects resulting from plastic flow may form near the defective sections repaired by welding. Welded joint susceptibility to formation of such defects is the greater the lower is their deformability.

Repair welding is also characterized by development of microcracks in the ledeburite layer on the surface of the cut made with an oxygen torch [3], presence of undercuts, lacks-of-fusion and non-metallic inclusions. Lamellar cracks may develop in repair welding [5].

In [9] it is noted that repaired tee welded joints of medium-strength steel have a lower resistance to fatigue cracking, than the unrepaired joints of the same steel. This is attributable to the fact that the repaired welded joints demonstrate non-uniform strength properties (metal sections of a higher hardness). Fatigue resistance of the above welded joints rises after arc surface melting of fillet welds.

In the opinion of the authors of [2], the reconditioning technology should be given more attention than the initial welding. A most important task in this case is selection or development of such welding technologies, which would provide a low level of residual stresses and allow eliminating the stress relieving measures in a number of cases.

The main defects repaired by welding, are fatigue cracks. The cause for their appearance can be an inadequate structure design, high stress level, incorrect selection of welding consumables, failing to provide the required toughness and weldability of the joints, poor performance of thermal cutting, incomplete penetration, undercuts, vibration, corroding medium, and operating loads [10].

At operation of large dump trucks, excavators, bulldozers in the North numerous cases of fatigue crack formation were recorded, the cracks initiating brittle fracture at low climatic temperatures [5].

A significant part of truck downtime is related to welded frame repair. Its failure usually starts in the weld in the zone of a structural or technological stress raiser, as well as in the region of transition from a more rigid to a less rigid component. Furtheron the crack propagates both through the weld metal in the HAZ, and through the base metal up to complete fracture of the frame component. Fractures can be caused by lacks-of-penetration, undercuts, and cold cracks. Cracks often develop in the components of fastening of the front suspension, namely in the HAZ through the metal of the vertical post wall (stress raiser, exposed to repeated dynamic loads directly from the suspension).

In terms of cracking, one of the weak points of M-200 dump truck is the rim. Numerous cracks are found in the HAZ of the weld in the wheel, connecting the cone-shaped part of the item to its cylindrical part. The cause for this fracture is the geometrical stress raiser. The crack propagates under the influence of a corroding environment, cyclic and impact loading.

It is established that repeated static loads may give rise to strain damage in the main pipeline metal, where the ageing process develops. Ageing in combination with hydrogenation, leads to metal embrittlement, lowering of the impact toughness and ductility, and, hence, to fracture [11].

The features and causes for structure fracture should be taken into account, when developing their reconditioning technology. In this connection, in [7] it is recommended to analyze the following points before performing repair welding:

- does the condition of a welded structure allow performing repair welding in it;
- how many repair operations can be performed on one and the same section of the welded structure;
- what technology can be used to provide a better performance and lower degree of metal property degradation near the welded joint.

In [1] attention is focused on a mandatory performance of NDT of the damaged components of the item to establish the boundaries of defect location and identify the base metal before repair welding. The latter requires determination of the metal composition, as well as performing metallography and spectrography studies.

Repair welding consists of crack cutting out, edge preparation and repair welding proper [5, 10, 12]. If required, the structure design is improved, welded joints are treated to relieve the stresses and improve the metal properties. Joint quality is always controlled after welding.

Before cutting out the crack, it is necessary to drill out a hole at its tip, and then remove surface cracks by grinding [13]. Metal in the vicinity of the crack should be cut out beyond its visible boundaries, and no defects capable of initiating new cracks should remain [10]. The metal zone near the cut out crack should be controlled by ultrasound or X-ray methods.

Crack cutting-out and edge grooving are performed using different methods of metal treatment, namely gas-oxygen cutting, air-arc gouging with carbon electrode, arc cutting with special electrodes, grinding, milling, etc.

Air-arc gouging of metal with special electrodes is recommended to remove the defects and perform edge preparation [5].

In repair of the post and handle of excavating machines EKG-12.5 made of steels 08GDNFA and IZh-6, edge preparation was performed by air-arc gouging by a carbon electrode [5]. The thus formed carbonized layer was removed by an abrasive wheel. Gas cutting can be used, if air-arc gouging is not available. In this case, however, it is necessary to remove the hard layer of the metal, which is a highly labour-consuming operation. In the same work it is noted that the cracks detected in the dump truck components were removed by air-arc gouging, using carbon electrodes. The beveled edges were ground with an abrasive wheel up to complete removal of rust, scale, oil and other contamination.

On the other hand, machining is the most preferable method for edge preparation [14]. Joints, where the edges were milled off for welding, using a special device, had a higher fatigue fracture resistance than joints, where the edge preparation was performed by gas-oxygen cutting.

In [5] it is noted that the properties of welded joints are influenced by the groove parameters. A too narrow groove promotes initiation of defects (slag inclusions, lacks-of-fusion with the base metal), and a too wide one increases the welding time, makes heat input control more difficult and leads to a great consumption of welding consumables.

In this connection, the most optimum groove parameters for the handle pylon and two-leg support 50 and 30 mm thick are as follows: bevel of each edge of 10°, gap of 12 mm, backing ring more than 3 mm thick and 20–24 mm wide. Preheating temperature for the handle pylon is equal to 230 °C, and that for the post to 120 °C.

After removal of the damage and edge preparation, the welding process proper is started. Development of repair welding technology is usually preceded by investigations, which have the purpose of studying the influence of a particular factor on the performance of a restored structural component. Since a considerable fraction of structure fractures is related to fatigue

crack development in them, it is natural that the studies are focused on development of the methods to improve the repaired joint resistance to this kind of fracture.

Reference [15] describes studies of fatigue fracture resistance in butt-welded joints of offshore structures of steel St-52-3 in which repairs were made. Testing was performed on specimens 200 mm thick and 500 mm long. Specimens had initial butt welds made by submerged-arc welding. These specimens were further used to simulate the repair stages. Edge preparation for welding was performed near the initial weld (in the point of fatigue crack initiation). This was followed by multipass repair welding in a special chamber filled with inert gas at the pressure of 1.6 MPa with application of a pulsed arc. Gas pressure induced in the chamber corresponded to water pressure at 160 m depth.

Fatigue testing was performed in air and sea water based on 2 mln cycles at zero-to-tension loading cycle. Most of the specimens failed along the repair welds, and some of them along the initial welds. Endurance limits σ_0 for specimens made by the optimum and actually applied technologies were equal to 116 and 107 N / mm^2, respectively. For specimens, made by the actual repair technology, and tested in sea water, σ_0 = 40 N / mm^2. Testing showed that the endurance limit of the repair welded joints is markedly reduced under the impact of sea water.

Reference [16] describes improvement of the technology of repair welding of rails by replacement of manual arc welding by mechanized CO_2 welding. Fatigue testing of welded rails showed that the repaired welded joints of rails made by mechanized CO_2 welding with preheating and concurrent heating, have the highest fatigue fracture resistance.

Rail joints welded in CO_2 with Sv-08Kh3G2SM wire with item preheating have several times higher fatigue fracture resistance than joints made with preheating with Sv-08G2S wire. Rails repaired using welding with preheating and concurrent heating with Sv-08Kh3G2SM wire have fatigue fracture resistance equivalent to that of all-rolled rails.

References [17, 18] describe a method of improving the fatigue fracture resistance of welded joints based on application of welding wire with 10 % Ni and 10 % Cr, which provides a low temperature of martensite transformations in the weld metal. Martensite transformations are accompanied by increase of the volume and expansion of weld metal at the final stage of cooling. This leads to development of compressive residual stresses in the welded joint that promote higher fatigue fracture resistance of the welded joints.

This method was used to perform repair welding of tee joints of steel SM 570 with $\sigma_{0.2}$ = 579 MPa in a mixture of 80 % Ar + CO_2 in the following mode: I_w = 290 A, U_a = 30 V, v_w = 30 cm / min. Temperature of the start of martensite transformation was equal to 180 °C, and the transformation ended at room temperature. Endurance limit of welded joints made with the above wire is 2 times greater than in the joints, where the metal does not undergo any transformations, increasing the volume.

In order to improve the fatigue fracture resistance of welded joints, in addition to the above methods, it is recommended to apply special treatment techniques, such as impact peening, grinding, surface melting of the welds by the TIG process, etc. [4, 19–21].

Welded joint treatment by an air-operated hammer induces compressive stresses in them, which increase the fatigue fracture resistance [20]. The best results were achieved at impact load of 280 kPa, and 6 times treatment of the same welded joint. The thickness of plastically deformed zone was 0.5 mm.

Reference [4] gives the results of three-point bend testing of tee joints of higher strength steel with $\sigma_{0.2}$ = = 400 MPa, simulating the most widely applied components of welded structures. Specimens 220 mm long, 68.5 mm wide and 12.5 mm thick, with a transverse rib were welded manually by coated electrodes. Testing showed that removal of weld reinforcement with a grinding wheel increases the fatigue fracture resistance of the specimens more than peening with an air-operated hammer (2.6 and 2.5 times, respectively). This is attributable to the fact that peening results in work hardening of the surface layer of metal 3.5 mm thick and a marked increase of the hardness, while at grinding the metal hardness does not increase significantly.

It is recommended to subject the repair-welded joints to such treatments, which increase the fracture resistance [10]. It is stated that in the repair joints it is necessary to lower the level of residual tensile stresses, reduce the sharpness of the notch, and eliminate cracklike defects. For this purpose the repaired welded joints should be ground, surface melted with a tungsten electrode in an inert gas or with a plasma torch, and treated by peening with an air-operated hammer. The first two methods improve the welded joint shape, and the third method reduces the level of residual tensile stresses in them.

Specimens simulating the components of bridge structures were repaired by welding using different technologies [22]:

- full penetration welding, welding beads treated by an abrasive wheel;
- welding with performance of repair welds by the same technology as in the first case, and then surface melting by a tungsten electrode in inert gas by TIG process;
- welding with making additional welds to increase the penetration depth of the initial weld, then the bead was surface melted by a tungsten electrode in inert gas.

After repair welding the specimens were tested for fatigue. Testing showed that the specimens repaired by the third technology, had the highest resistance to fatigue fracture. Their endurance limit was 3 times higher than that of the initial unrepaired defective welded joints.

A procedure was proposed for evaluation of the fatigue strength of welded structures with defects, based on application of the improvement factor W [23]:

$$W = \Delta\sigma_F / \Delta\sigma_N,$$

where $\Delta\sigma_F$ is the range of the load applied to an actual joint; $\Delta\sigma_N$ is the design fracture resistance of the welded joint at loading similar to that of a real structure.

At $W < 2$ increase of the structure fatigue strength has to be performed with the traditional processes (peening, dressing). In the case of $W \geq 2$, in addition to these processes, it is rational to further increase the endurance limit of the joints.

After selection of welding consumables and welding processes, the actual repair welding is performed. In this case the structure type and properties of the steel, of which the structure is made, are taken into account. Given below are the examples of repair of structures for various applications, operated under different conditions and at different kinds of the load.

Reference [14] describes the process of repair welding of M-200 dump truck, using electrodes of UONI-13 / 55 grade with calcium-fluoride coating. Welding was performed by a short arc with beads of a width not greater than 3 electrode diameters, by a block method. The blocks were welded alternatively. The start and end of a block was shifted relative to the previous ones by 20–30 mm. Preheating up to 110–120 °C was used in welding.

ZhANP-4 electrodes were initially recommended for repair welding of a handle pylon of buckets for EKG-12.5 excavators, made of steels 08GDNF and IZh-6 [5]. However, because of insufficient ductility of the steel and its great thickness (50 mm), preference was given to UONI-13 / 55 electrodes. Equivalent strength of the welded joint in this case was achieved by alloying element transfer from the base metal into the weld. Use of more ductile filler metal eliminates formation of quenching structures in the weld, this preventing propagation of the cracks, developing during operation [5].

In pipeline repair the first and second layer is deposited with electrodes of FOX EV 47 type of 3.25 and 4 mm diameter, and the subsequent layers with electrodes of 6 mm diameter, thus allowing the structure to be refined and cracking to be prevented [24]. A technology is described of repair of bridge cranes, which in service develop fatigue cracks in the upper flange of an I-beam, between the web and flange of the beam and in other components of the cranes [25]. In repair welding of fatigue cracks, the cracks are first removed, then welding is performed by depositing large beads in one pass. After that the weld bead is ground to reduce stress concentration and increase the fatigue fracture resistance.

In repair of welds between the upper flange and the web of an I-beam, cracks are also removed by grinding or air-arc gouging, and then fillet welding is performed. Weld quality is controlled by ultrasound.

Reference [26] describes the so-called wave or two-cycle method of repair welding, which is applied for the electric power plant equipment, made of a steel with 2.25 % Cr and 1 % Mo. Manual arc welding of butt joints was performed with 4 mm diameter electrodes. The time between the two cycles can be up to 40 s in the wave welding process. In the first cycle, the metal heating temperature is equal to 1350 °C, and in the second to 800 °C. Application of the wave method allowed to significantly reduce the hardness of weld metal and the HAZ, as in the second cycle the metal of the weld and the HAZ formed during the first cycle, is annealed. After the second cycle of welding a rather ductile structure of the HAZ metal forms with the hardness of *HV* 276. Application of a three-wave welding method allowed lowering the HAZ metal hardness to *HV* 250.

Quality of the repair joints is tested after restoration of the integrity of individual components or the structure. If after repair welding the quality corresponds to the quality level of the initial welded joint, then fatigue life lowering is usually insignificant [27].

As in repair of welded joints the probability of defects developing in them is quite high, this process is given special attention. As a rule, the welded joint quality is controlled, using ultrasound, radiographic, magnetic particle, selective cutting up of welded joints and other methods.

Repair joints were checked by their selective cutting up [2]. The cut was examined for welding defects, and hardness was measured. It is recommended to perform the ultrasonic and radiographic testing of the repair-welded joints.

NDT of repair welded joints was performed by UST or magnetic particle inspection [1]. UST was conducted to reveal cracks, slag inclusions, pores, etc. In addition, it is recommended to measure the Vickers hardness of the weld and HAZ metal and control the change of the item dimensions.

It should be noted that in practice repair welding can be performed several times in one joint. There is, however, no agreement of experts over the effect it may have on the further performance of the item.

In [8, 28] it is noted that repair results in a larger zone of refined grains by 0.3; 7.6; 48.2 %, compared to the initial welding after the first-third repair, respectively, but such a change of the width of the fine-grain zone does not affect the strength properties of the joint. As follows from [29], the strength properties of the metal of welded joint HAZ decrease only slightly after multiple repair. On the other hand, impact toughness of the metal of welded joint HAZ decreases by 15 to 20 % after three repairs. To improve the fatigue fracture resistance, the repair welds should be made without underbead cracks, and should have a lower hardness.

In [20] it was established that the fatigue fracture resistance of the welded joint metal decreased after the third repair; after the fourth repair, however, it increases, which is attributable to incomplete removal of the fatigue crack before repair welding. Other researchers established that the number of repairs in the same weldment should be limited to three, and a greater number of them lowers the weldability of the metal.

Considering the great importance of repair welding, a special database was established in Japan on

repair of bridges, where fatigue cracks developed in service [30]. It was put on the Internet and contains information on the experience of bridge repair in Japan and other countries. The database includes descriptions of reconditioning 96 bridges, where the repair was performed starting from 1960s, as well as photos of the bridges, their defects, repaired structural components, and description of repair techniques.

The database establishes two approaches to repair of damage caused by fatigue fracture of structures, namely damage removal, and increase of the structure resistance to fatigue fractures.

Database contains the following sections:

- field of repair technology application;
- repair conditions;
- structure type;
- loading features;
- damage description;
- applied repair techniques.

In keeping with the classification given in the database, the welded structures are damaged through the following causes:

- defects formed in welding;
- application of structural components with a low fatigue fracture resistance;
- presence of residual stresses and strains in welded joints of the structures;
- use of structures unsuitable to operation under the fatigue loading conditions.

The database gives the following list of methods to restore the bridge welded structures:

- crack removal;
- welding up the locations, where the cracks were removed;
- surface treatment of welded joints using TIG surface melting or peening by an air-operated hammer;
- fastening with bolts;
- improvement of the structure geometry;
- drilling out holes which slow the crack down;
- modification of fasteners.

The database contains recommendations on application of the repair techniques for different cases of welded structure damage. In the case of the structure having welding defects and fatigue cracks initiation from them, these cracks have to be cut out, locations of crack removal have to be welded up with subsequent surface treatment of welded joints, using an air-operated hammer to induce compressive residual stresses.

If a structure has components with a low fatigue fracture resistance, it is recommended to lower the levels of the tensile residual stresses and operating stresses, acting on the structure, by increasing the structure cross-section.

The database provides information on monitoring the repaired welded structures of bridges for many years, which is indicative of a significant extension of the operating life of the structure before development of new damage after the structure geometry has been improved.

The proposed review demonstrates a great importance of repair welding. The information given in it helps successfully solving certain problems in reconditioning of the damaged structures. On the other hand, there are still a lot of points, which require further clarification.

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SOME DEVELOPMENT TRENDS IN PRODUCTION OF WELDING CONSUMABLES AND RAW MATERIAL COMPONENTS*

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Data are given on overall volumes of welding consumable manufacture in CIS countries in 2003, as well as share of their production in Russia and Ukraine. Tendencies of increasing of volumes of small diameter electrode manufacture are noted. Analysis of the available capacities of welding consumable manufacture has been made.

Keywords: welding production, welding consumables, production development trends, raw material components, quality

Analysis of the development of welding consumables production in 2003 in the CIS countries has shown its direct dependence on the production volumes of steel and rolled stock in the RF and Ukraine.

The RF metallurgists produced 61.4 mln t of steel and 51.4 mln t of rolled stock in 2003. As against 2002 the production of steel increased by 3 % and rolled stock by 5 %. Ukraine produced 36.9 mln t of steel and 29.1 mln of rolled stock (growth rate was 10 and 14 %, respectively). The world steel production achieved 945,140 mln t (growth rate –– 6.7 %).

Total production volume of coated welding electrodes in 2003 was 273,542 t in the CIS countries; of them the RF accounts for 77.5 %, Ukraine — 17.5 %, the rest SIC countries — 5.0 %. Last year the total production volume of coated electrodes increased by 11 % as against 2002 including by 12 % in the RF and by 7.6 % in Ukraine. Production volume of electrodes with rutile-ilmenite coating was 178,480 t, with basic coating –– 82,439 t. Production of electrodes for special purpose for welding of high-alloy steels and non-ferrous metals achieved 12,622 t, i.e. increased by 25 %.

The RF produced 212,194 t of electrodes including 128,535 t with rutile-ilmenite coating, 71,599 t with basic coating and 12,059 t of special electrodes. Ukraine produced 47624.4 t of electrodes including 37636.3 t with rutile-ilmenite coating, 9428.5 t with basic coating and 560.6 t of special electrodes. Growth trend in production of electrodes of small and medium diameter (2–4 mm) was observed with the total output making up 238,543 t, which is by 10.6 % higher than in 2002. Production of electrodes 5 and 6 mm in diameter achieved 33,503 and 1501 t, respectively. Therefore, 87 % of electrodes up to 5 mm in diameter were produced.

Total production volume of alloyed welding wire up to 2 mm for mechanized gas-shielded welding was 38,723 t, including 17,108 t of wire 0.8–1.4 mm in diameter. The RF produced 25,123 t of this wire including 9708 t of wire 0.8–1.4 mm in diameter. Ukraine produced 13,600 t including 7860 t of wire 0.8–1.4 mm in diameter.

As compared to 2002 the total production volume of wire increased by 5.9 %, in the RF — by 6.4 %, in Ukraine –– by 4.9 %. Industrial production of coppered welding wire was launched. This wire is supplied to the customers by their requests in spools and coils with row winding from 5 to 15 kg of weight. Enterprises members of the Association, such as Open Joint-Stock Company «Mezhgosmetiz-Mtsensk», OJSCs MMMZ, ChSPZ and OSPAZ are the main suppliers of this wire. 3890 t of coppered wire were produced in 2002.

The volume of the produced flux-cored wire in 2002 was only 3585.1 t including welding wire –– 1948 t and surfacing wire –– 637 t. Production of strips was 177 t as compared to 2002 (increased by 25 %). The RF produced 25,351 t of flux-cored wire, 1579 t of welding wire and 956.1 t of surfacing wire. Ukraine produced 1050 t of wire including welding wire –– 271 t and surfacing wire –– 779 t.

The volume of produced welding fluxes in 2004 was 31,106 t including 6051 t in the RF and 25,055 t in Ukraine. As compared to 2002 the production volumes of welding flux decreased in RF by 42 % and increased in Ukraine by 29 %.

In 2003 the total production volume of welding consumables was 367,695 t including 94,153 t for mechanized welding. Welding consumables for mechanized welding account for 26 % of the total output.

As it is seen from the presented data the bulk of the welding work in the CIS countries is carried out by using electrodes. However, despite of a low level of mechanized welding this situation is temporary because the signs of improvement have been observed since 2003. It is necessary to concentrate most attention to the development of the mechanized welding in the CIS countries as it is done in the developed countries of the world.

Currently the CIS countries have sufficient production capacity for manufacturing the welding consumables both for manual and mechanized welding, however the available facilities are not operating to their full capacity because of low growth rate of the industrial production.

This is the reason by which a large electrode shop (with its 40 ths t production capacity) of the OJSC «Sulinsky Metalurgichesky Zavod» has ceased its existence and its equipment is being sold out. The same situation is with the electrode shop of the Volgodonsk «Atommash». The electrode shop of the former OJSC

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«Odessky Staleprokatny Zavod» (currently OJSC «Stalekanatny»), which used to manufacture 35 ths t of products is almost not operational. Electrode shops of the Gomel Plant for production of starting engines, OJSC «DEIZSM» (Dnepropetrovsk) and of other enterprises did not work for a long time and have started their operation only now.

Despite of financial difficulties and instable sales of the products the enterprises members of the Association pay much attention to reconstruction and technical re-equipment of electrode shops, replacement of the worn-out and morally obsolete equipment for the new one. In this respect the activities of such enterprises as Closed Joint-Stock Company ELZ, «Sychevsky Elektrodny Zavod, Ltd.», Pilot Plant of Welding Consumables of the E.O. Paton Electric Welding Institute, CJSCs «Artemmach-Vistek», «Spetselektrod», «Mezhgosmetiz-Mtsensk», CJSC ShEZ, OJSCs MMMZ, OSPAZ, «Novooskolsky Elektrodny Zavod, Ltd.» (former OJSC «Don»), CJSC «Svarochnye Elektrody SIBEZ» and others deserve high appreciation.

In analyzing the state of electrode production in the CIS countries one is concerned with the growth of the number of small electrode work bays created without consideration of the demand for electrodes. This process is already expanding to the countries of the Middle Asia. According to the rough estimates the total number of work bays for production of welding electrodes in the CIS countries has exceeded 350 and continue to grow. All this is happening without expectations of a considerable growth of the industrial production in the future. It is also necessary to take into account that a share of the mechanized welding (welding with flux-cored wire, gas-shielded and submerged-arc welding with alloyed wire) is projected to increase in the coming years.

It is remarkable that in the former Soviet Union 251 enterprises produced in 1958 the 208 ths t of electrodes in total but basically for their own needs. Mechanized welding only started developing. Production of alloyed welding wire was 230 t, flux-cored wire was not produced at all while production of flux was 40.6 ths t.

At the same time electrode-producing plants had their own laboratories where they made all necessary analysis. What is happening in the beginning of the 21st century? Majority of small production facilities do not have the necessary analytical laboratories, so the quality of the produced electrodes is very much doubted. The owners of these facilities are interested rather in immediate income than in quality of their production. Many of them are laymen in technological issues, so they seek for advise from various intermediates-consultants interested in profits and indifferent to the fate of the created small production facility.

Does Ukraine really need 100 small producers of welding electrodes (only in Dnepropetrovsk oblast there are 19 of them)? Before perestroika 28 shops in Ukraine produced 192 ths t of welding electrodes and today the production volume is about 50 ths t of which the largest share is manufactured at the large enterprises. The question arises ---- what is the reason for increasing the number of small facilities when the large ones are not fully utilized? To our opinion, it is unlikely to expect a considerable growth in consumption of welding electrodes in the nearest future. In this situation small enterprises should offer only high-quality electrodes to the market. Some of the enterprises are well equipped for this: they have highly qualified staff, relevant equipment in the shops and laboratories capable to produce a wide range of electrodes including high-quality welding electrodes. In this respect it is worth mentioning such small enterprises members of the Association as CJSC «Elektrod» (Zheleznogorsk), OJSC «Electrod» (Toliatti), CJSC «Svama» (St.-Petersburg). There are also similar enterprises non-members such as OJSCs «Roteks» (Krasnodar), «Arksel» (Donetsk) and others.

As to the production volumes of welding consumables for mechanized welding, then the available facilities for production of welding wires of Sv-08G2S for gas-shielded welding are utilized only for 18 %, flux-cored wire — for 10 %, welding flux — for 16 %. Technical equipment of these productions remains at the level of perestroika, so the machinery continues to get worn and morally obsolete. The re-equipment of the production will evidently be needed in the nearest decade.

Shops for production of alloyed welding wire in Russia at OJSCs «Zapsibmetkombinat», ChSPZ, OSPAZ, «Belmetkombinat» and in Ukraine at ZSPZ, «Stalmetiz» (now OJSC «Stalkanat») are still in the satisfactory condition. This is also true for the shops producing powder wire at the ChSPZ (the RF), Pilot Plant of Welding Consumables of the E.O. Paton Electric Welding Institute and «Weldtek, Ltd.» in composition of the OJSC «Dneprometiz» (Ukraine). The shop at OJSC DEIZSM severely suffered after perestroika ---- out of 11 drawing mills only 7 are left.

Shops at the MMMZ where it is planned to produce flux-cored welding and surfacing wires including wire of small (1.2–1.6 mm) diameter were essentially re-equipped.

In addition to the mentioned enterprises the powder wire in Ukraine is also produced at OJSC «Toreztverdosplav», «Arksel», Research and Technical Center of the E.O. Paton Electric Welding Institute and Dubrovitsk subsidiary enterprise «Iskra».

OJSCs «Zaporozhsky Zavod Flusostekloizdely», «Nikopolsky Zavod Ferrosplavov» (Ukraine) and «Chelyabinsky Trubny Zavod» (the RF) are at present the main producers and suppliers of the welding flux. OJSCs ESP ELKOM and «Izhorskie Zavody» produce annually up to 1 ths t of fluxes for special purposes mainly for their own consumption.

Summing up the analysis of the condition of production of welding consumables in the CIS countries it is worth noting that the available production facilities will allow in the nearest years to fully meet the demand of the national economy of the CIS countries in quality welding consumables in the required quantities, ranges and grades.

Organization of production of new competitive welding consumables is one of the most important directions in the development of the sector in question. However, due to the lack of budget financing in the last years the welding consumables of the outdated grades were mainly used, especially it concerns the electrodes. The following enterprises members of the Association are involved into the development activities: CJSC ELZ (St.-Petersburg), OJSCs «Sychevsky Elektrodny Zavod», «Spetselektrod», CJSCs

ShEZ, «Svarochnye Elektrody SIBES», OJSC ChSPZ, CJSC «Artemmash Vistek» and others. Despite of financial constrains the following leaders of the welding science are also engaged into creation of welding consumables ---- E.O. Paton Electric Welding Institute, Federal State Unitary Enterprises of the Research Institute of Structural Materials «Prometej» and others. For example, the E.O. Paton Electric Welding Institute created cellulose electrodes for welding steels including high-strength, new flux-cored wires and fluxes; «Prometej» together with other enterprises developed several grades of electrodes for ship-building, power and petrochemical machine building, which were tested on the pilot and full-scale basis and are widely used in the industry.

Small enterprises cannot afford implementation of such tasks. Besides, potential consumers of welding consumables do not display any interest in creation of competitive products. There is an impression that they are not concerned with the development of domestic production of welding consumable since they continue purchasing them abroad at high prices.

With the above in mind we think that the producers and consumers together must win the financial support from the state structures for creation of new competitive welding consumables providing high welding-technological properties on par with the leading foreign firms.

To achieve this goal the interested stakeholders from Russia and Ukraine (NPO TsNIITmash, «Prometej», E.O. Paton Electric Welding Institute, the Welding Institute of Russia, VNIImontazhspetsstroj and other institutes and stock companies, Russian Research and Technical Welding Society and Society of Welders of Ukraine) should create a working group for elaboration of the comprehensive priority program that would provide development of research in the following directions:

- creation of new generation of welding consumables including electrodes with high welding technological properties for welding of metal structures intended for operation in the extreme conditions of the Far North, in sea and oil-gas complexes, nuclear power engineering competitive with similar foreign products;
- upgrading of technical and cultural level of welding consumables by applying new and improving the available advanced technologies, which allow improving their technical and economical indices;
- searching and use of price-accessible raw material components allowing creation of new competitive welding consumables in comparison with foreign analogs.

It is also advisable for members of the Association (development experts, enterprises producers of welding consumables and technological equipment) to carry out the whole set of works related to improvement of welding consumables.

In this connection the Directorate of the Association should discuss these issues with the above-mentioned institutes, stock companies, Russian Research and Technical Welding Society and Society of Welders of Ukraine and state authorities and then to work out relevant proposals to be considered at the full-scale meeting of the Council.

It is possible to achieve a positive result if the enterprises especially the Association that should be responsible for development of this program get interested in this matter. This effort will require serious justification, strengths and energy because if we fail to achieve the desired solution the domestic welding consumables, especially electrodes, will eventually go down to the second grade quality.

Quality of the produced welding consumables in the CIS countries has considerably grown for the period between the conferences ---- new technological processes have been introduced and novel technological equipment has been developed. Supply of raw material components has somewhat improved. However, since the end of 2003 managers of hardware production and especially intermediates have essentially increased the prices for welding wire for production of electrodes (by 72 % in the RF and by 37 % in Ukraine) and for ferromanganese (by 98 % in the RF and by 268 % at Nikopol Plant for Ferroalloys in Ukraine). However, even with such high prices there is a shortage of wire at the hardware production facilities, which is probably related to export sales of wire rod for damping prices. Who is the profit maker in this situation?

The Association has prepared a letter on this issue and sent it to the Federal Antimonopoly Service in Russia and to the Antimonopoly Committee of Ukraine, however no answer has been received so far.

It has become known from mass media that the Antimonopoly Committee of Ukraine assigned the suppliers of the metallurgical and hardware production to continue selling the products for the earlier prices. However we observed the reverse reaction ---- the supplies stopped even at the new prices, so the situation has worsened. We persist in getting down the prices but with no response.

The first Deputy Director General of the OJSC KFZ N.V. Kuzmin was invited to take part at the large-scale meeting of the Association in Cherepovets in June 2003 held at the OJSC ChSPZ office. Issue of organization of the production of ferrotitanium was on the agenda resulted in the following decision: ELZ together with «Prometej» and «Svama» are assigned to elaborate technical requirements to electrode ferrotitanium; the Directorate of the Association shall send them to particular enterprises involved into production of electrodes for expertise. With the aim of organizing a test lot of ferrotitanium the «Elkom» was assigned to supply to KFZ 2 t of ilmenite concentrate from Areadnensk deposit in the Primorsky Kraj and to ShEZ the same quantity of ilmenite from Volnogorsk deposit. The supplies were carried out but it turned out that Areadnensk ilmenite, according to N.V. Kuzmin, did not meet the previously sent certificate on the sulfur and phosphorus content. Ilmenite from Volnogorsk deposit did not suit for the same reason. The Directorate of the Association evaluated the ilmenite concentrate from Irshinsk deposit and from Kazakhstan. The Irshinsk ilmenite was rejected due to its chemical composition, the Kazakh one also did not meet the certificate requirements. It turned out that extraction of ilmenite concentrate in the Primorsky Kraj and in Kazakhstan is seasonal. The extraction of this concentrate will start there in the nearest future providing its separation to produce titanium of the required quality.

Hopefully, our joint efforts will solve the problem of providing electrode producers with quality ferrotitanium.

NEW ELECTRODES FOR WELDING OF CARBON AND LOW-ALLOYED STEELS

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Data are given on new PWI developments in the field of general-purpose coated electrodes with rutile, ilmenite and basic types of coatings.

Keywords: arc welding, coated electrodes, low-carbon steels, high-strength steels, welding-technological characteristics, mechanical properties

A range of general-purpose electrodes produced by the enterprises of Ukraine and CIS countries is mainly presented by the electrodes with rutile (ANO-4, ANO-21, MR-3, OZS-4, OSZ-12), ilmenite (ANO-6, MR-3M, MR-3V) and basic (UONI-13/45, UONI-13/55, ANO-27) coatings. Most of these electrodes were developed more than 30 years ago and electrodes UONI-13 more than 60 years ago. The above-listed grades rank below the best foreign analogs first of all by their welding-technological characteristics and cannot compete with them. The only factor that restrains supply of foreign electrode to the domestic market is their very high price being 1.5–2 times higher then the prices for domestic electrodes. However in the recent years a difference in prices for domestic and foreign electrodes is reducing (owing to price increase to raw material and energy) and soon foreign electrodes will start expelling the outdate domestic models from the CIS market. In view of the current situation the E.O. Paton Electric Welding Institute together with Scientific-Production Company «Paton-Elektrod» are elaborating electrodes of new generation that may oppose expansion of foreign electrodes to the domestic market. The developments are carried out in the following directions:

- first, creation of universal electrodes with rutile and rutile-cellulose coatings for welding of structures of low-carbon steels;
- second, creation of universal electrodes with ilmenite coating as a variant of electrodes with coating based on cheap titanium-containing raw material;
- third, creation of low-hydrogen electrodes for welding of structures of carbon low-alloyed steels;
- fourth, creation of ultralow-hydrogen electrodes for welding of HSLA steels.

The first direction is presented by two new developments ---- electrodes ANO-37 with rutile type coating and ANO-36 with rutile-cellulose type coating (Table 1). Both grades correspond to the type E46 according to GOST 9467-75. They are intended for AC and DC welding of structures of low-carbon steels in all spatial positions in civil and industrial construction, for repair and other purposes. These electrodes considerably outperform the electrodes ANO-4, ANO-21, MR-3, OZS-4 in a set of welding-technological characteristics. They provide simple initial and repeated arc ignition, excellent formation of weld metal, easy separation of the slag crust, small spattering of metal.

Owing to an increased content of cellulose in their coating the electrodes ANO-36 allow performing vertical welds by high-production downward method. Many customers note that electrodes ANO-36 and ANO-37 are on par with the best foreign analogs, however demand for them is much lower because they are a little bit more expensive (5–7 %) than the electrodes of outdated models. Nonetheless, regarding the above-mentioned technological advantages the demand for electrodes ANO-36 and ANO-37 is gradually increasing especially from organizations that attach significance to the quality of welds.

Table 1. Electrodes with rutile and ilmenite coating for welding of low-carbon steels

Electrode grade	*Type according to*	
	EN 499	*GOST 9467–75*
ANO-36	E 42 0 RC 11	E46–ANO–36–d–UD / E 432(3)–RTs11
ANO-37	Å 38 2 RR 12	E46–ANO–37–d–UD / E 431(3)–R21
ANO-4I	E 38 2 RA 12	E46–ANO–4I–d–UD / E 430(4)–Ð21

Table 2. Low-hydrogen electrodes for welding of structures of carbon and low-alloyed steels operating in conditions of low climatic temperatures

Electrode grade	*Type according to*	
	EN 499	*GOST 9467–75*
ANO-12 ANO-12MR	Å 46 4 Â 32 Í 10	E50À–ANO–12–d–UD / E 515–BZh 26
ÀÍ Î-101	Å 46 6 Â 32 Í 10	E50A–ANO–101–d–UD / Å 517–BZh 26
ANO-102	Å 46 5 1Ni Â 32 Í 10	E50A–ANO–102–d–UD / E 515–BZh 26

Table 3. Typical values of mechanical properties of the weld metal in welding of carbon and low-alloyed steels

Electrode grade	σ_t, *MPa*	δ, %	*KCV, J/cm², at T,* °C			
			+20	*–40 (–20)*	*–60 (–50)*	*–70*
ANO-36 ANO-37	480–520	22–24	130–150	(40–60)	–	–
ANO-4I	480–500	22–24	130–160	(50–60)	–	–
ANO-12 ANO-12MR	600–610	24–26	190–200	90–100	40–60	–
ANO-101	650–660	25–27	190–200	90–100	75–90	65–80
ANO-102	620–630	23–25	170–180	70–90	35–45	–
ANO-100	640–660	24–26	210–220	60–80	(40–50)	

The second direction is presented by new electrodes with ilmenite coating ANO-4I (see Table 1). They are analogs of electrodes B-17 of the Kobe Steel Company, Japan, and are intended for welding of structures of low-carbon steels in all spatial positions in ship-building and ship repair, drilling rigs for extraction of oil and gas. As to a level of mechanical properties of the weld metal they correspond to the type E46 (GOST 9467–75) and as to welding-technological characteristics they outperform electrodes with ilmenite coating ANO-6, ANO-6U, MR-3M and MR-3V. They are less susceptive to undercuts, provide good formation of weld metal, easy separation of the slag crust, small spattering. In terms of price the electrodes ANO-4I are practically on par with ilmenite electrodes of previous models, however as every new grade the electrodes ANO-4I are gaining recognition but slowly.

The third direction is presented by new developments ---- low-hydrogen electrodes ANO-12, ANO-12MR, ANO-101 and ANO-102 (Table 2) recommended as a replacement of electrodes UONI-13 / 55.

Electrodes UONI-13 / 55 are traditionally used for welding of critical structures. However, they have such typical drawbacks as formation of reinforcing beads, poor separation of slag crust especially in deep groove. A threshold of cold brittleness of the weld metal is –30 °C for these electrodes. New electrodes (ANO-12, ANO-12MR, ANO-101) are noticeably superior to electrodes UONI-13 / 55 both in welding-technological and in mechanical properties of the weld metal. They are intended for manual arc welding of structures of carbon and low-alloyed steels. They are also fit for welding in all spatial positions on DCRP or on AC from sources with the open-circuit voltage of at least 70 V. As against UONI-13 / 55 these electrodes are characterized with quiet arcing and little spattering. They provide fine-ripple formation of weld, easy separation of slag crust, high resistance of weld metal to crack formation. They are highly competitive with ESAB electrodes OK 48.80, OK 53.04. Electrodes of this group are multipurpose. They are widely tested in ship-building and ship repair in welding of steels of A, D, E classes. Electrodes ANO-12 and ANO-12MR provide high impact toughness at low temperatures down to –50 °C. Electrodes ANO-12MR are characterized with low hygroscopicity of coating under conditions of high atmospheric humidity (belong to the moisture-resistant class). Electrodes ANO-12 are certified by DetNorske Veritas under category 4Y H10. Electrodes ANO-101 provide a cold-shortness threshold of the weld metal below –70 °C, which is achieved by microalloying without adding nickel into the weld. Electrodes ANO-102 are intended for welding of structures of carbon and low-alloyed steels when weld metal is required to be highly corrosion-resistant in the sea water. This is provided by alloying of weld with nickel and copper.

Despite of indicated advantages the demand for these electrodes is poor. Partly it is connected with their expensive (by 15–20 % higher than for UONI-13 / 55), though it is 1.5–2 times lower than for foreign analogs.

The fourth direction is presented by ultralow-hydrogen electrodes ANO-100 intended for welding of structures of HSLA steels under construction of drilling rigs, traveling cranes, lift trucks. The content of diffusion-movable hydrogen in the weld metal is the most important factor determining the welding technology of structures. The lower is its content, the lower is the temperature of preheating of the structure and probability of cold cracking. Unltralow-hydrogen electrodes with content of diffusion-movable hydrogen in the deposited metal not more than 3 cm^3 / 100 g (on molten metal ---- less than 1.8 cm^3 / 100 g) were created in Ukraine for the first time. The use of these electrodes will allow considerably decreasing labor costs in welding of structures of high-strength steels. Their designation in GOST 9467–75 is $\frac{\text{E60 ANO–100–d–LD}}{\text{E 04H2G–7–B 20}}$ and in EN 499 ---- E 50 5 2Ni B 42 H 5. Demand for ultralow-hydrogen electrodes for welding of HSLA steels will, to our opinion, gradually increase with production and application of high-strength steels in Ukraine and CIS countries. So, it is helpful for potential consumers to know about the available development.

Typical values of mechanical properties of the weld metal in welding with new domestic electrodes (for all four directions) are presented in Table 3.

Additional information about new electrodes is available by the address: E.O. Paton Electric Welding Institute, 10th Dep., 11, Bozhenko st., Kiev, 03150, Ukraine.

CURRENT-CARRYING NOZZLES OF POWDER MATERIALS FOR WELDING TORCHES

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Design and powder materials composition of current-carrying nozzles used in CO_2 welding torches of semi-automatic and automatic devices and robots are described. It is shown that application of the developed current-carrying nozzles allows their wear to be substantially decreased, stability of the welding process to be raised, and probability of formation of defects in the welds to be reduced.

Keywords: arc welding, current-carrying nozzle, resource, wear, powder materials

Current-carrying nozzles (CCN) of torches in semi-automatic and automatic machines and robots used for welding in CO_2 and gas mixtures are the most wearing parts (Figure 1). Depending on the parameters of welding condition, current, welding speed, geometry of edge preparation and thickness of welded parts the operational resource of conventional copper CCN is 4–9 h and that of brass is by 50–70 % less.

CCN are exposed to intensive mechanical and electro-erosion wear in the process of operation (Figure 2) [1, 2]. Mainly the wear of the nozzles proceeds in the site of a contact of the inner surface of the channel with the surface of the work-hardened electrode wire fed to the arc burning zone. Rolls of the feeder usually leave dents, marks and deformation traces on the surface of the electrode wire, which also foster the CCN wear. There are oxide compounds and oil films on the surface of electrode wire. These films destroy in the process of welding, which leads to an increase of the contact resistance and wear of the CCN.

Considering the couple CCN–electrode wire as the links of the circuit by which the welding current flows to the arc burning zone, let us assume the contact resistance of the circuit R_c as

$$R_c = R_s + R_r$$

where R_s is the resistance specified by the surface films, which are formed on the contact surfaces and impede the current flow; R_r is the resistance specified by irregularities (roughness) on the contact surfaces.

Contact of surfaces of the electrode wire and the CCN channel takes place mainly in the sites of the ridges (Figure 2). Contacting metallic surfaces of the contact sites to a different degree provide the current flow. Assuming that there is a film with uniform thickness d and specific resistance ρ_f between the two contacting surfaces, let us express the additional resistance in the welding flow circuit by the formula

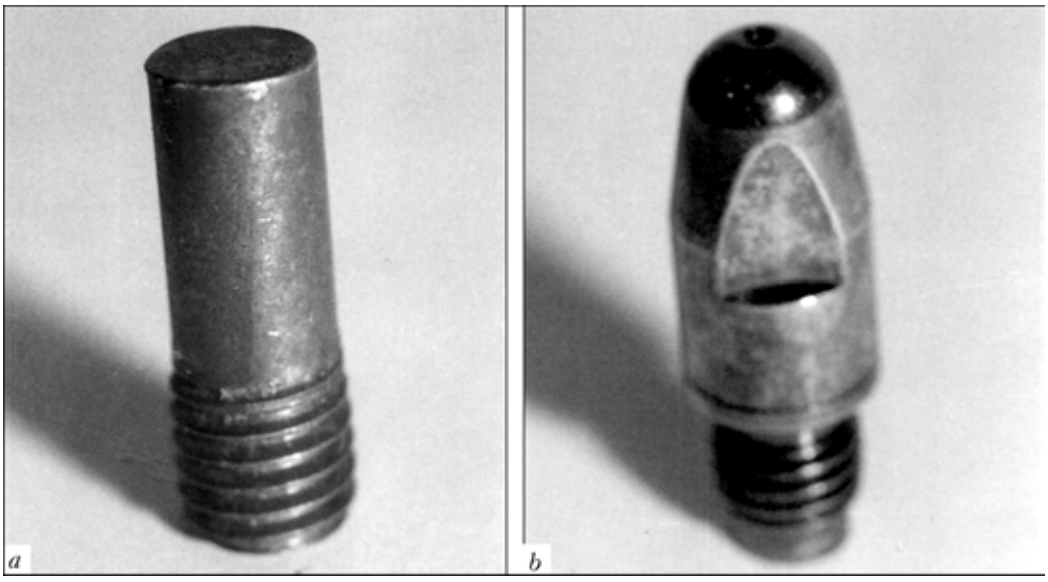

Figure 1. Current-carrying nozzles of powder materials: *a* — experimental (Cu + C + Si_3N_4 + Al_2O_3 + Ti); *b* — produced by Binzel Company

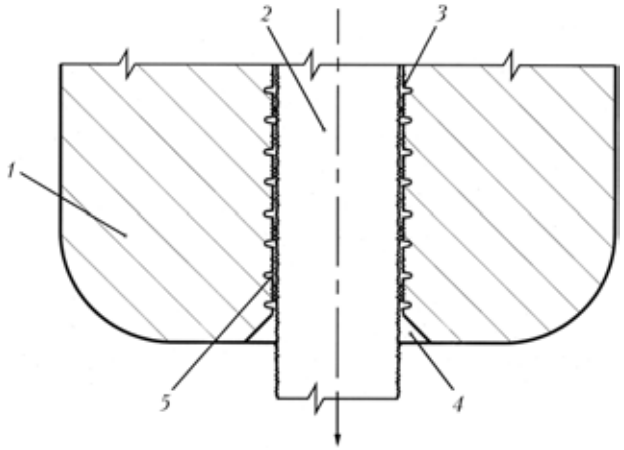

Figure 2. Diagram of the CCN with electrode wire fed to the arc burning zone (arrow): *1* — CCN body; *2* — electrode wire; *3* — site of the contact of CCN cylindrical channel with electrode wire; *4* — cone-shaped hole formed on the end site of the CCN channel; *5* — surface of CCN cylindrical channel

$$R_s = \frac{\rho_f d}{F},$$

where F is the surface of the physical contact of contacting surfaces of CCN and electrode wire.

Instead of ρ_f and d substitute empirically determined value σ (Ohm·mm) defining specific surface resistance since the resistance of such surface films mainly depends on the thickness d. Let us assume the resistance R_s for contacting cylindrical surfaces of CCN and electrode wire as

$$R_s = \frac{\sigma}{2\pi R h},$$

where R is the radius of the contact circle (averaged); h is the height of the cylindrical contact.

Flashing of the sites in CCN ridges (Figure 2) as well as their partial separation as a result of electroerosion corrosion facilitate the intensive wear.

Because of the wear the cylindrical channel of CCN assumes oval shape in the cross section. At the lower part it is cone-shaped (Figure 3). Oval shape of the channel provides an increase of the contact resistance, a decrease of the area of contacting surfaces (CCN and electrode wire), causes a deviation of the electrode wire from axis of the weld and «wandering» of the arc. These factors decrease stability of the welding process and cause defects in the welds.

Many researchers studied a decrease of the CCN wear. Different technological solutions [3–11] and new structural materials were proposed for their production [12–17]. Use of CCN made of powder materials is promising for decreasing their wear. Copper (base), carbon, silicon nitride, aluminium oxide and titanium were introduced into the CCN material composition in different percentage correlations. These components were mixed to receive the uniform content of the ingredients in volume. Then the mixture was sintered at the temperature 800–900 °C. The sintered material was calibrated under pressure P_c = 400–500 MPa. The obtained material has the porosity 3–7 %. Its shape corresponds the geometry of serial CCN (see Figure 1) and does not require subsequent machining except drilling a hole for electrode wire and polishing CCM to reduce its roughness. Aluminium oxide and silicon nitride in composition of the proposed material destroy oxide films on the surface of the moving electrode wire. Graphite forms a solid lubrication between friction surfaces of the CCN channel and electrode wire. Ingredients in composition of the powder material provides for CCN a decrease of R_s by 18–22 % and well a low level of wear and increase its operational resource (Figure 4).

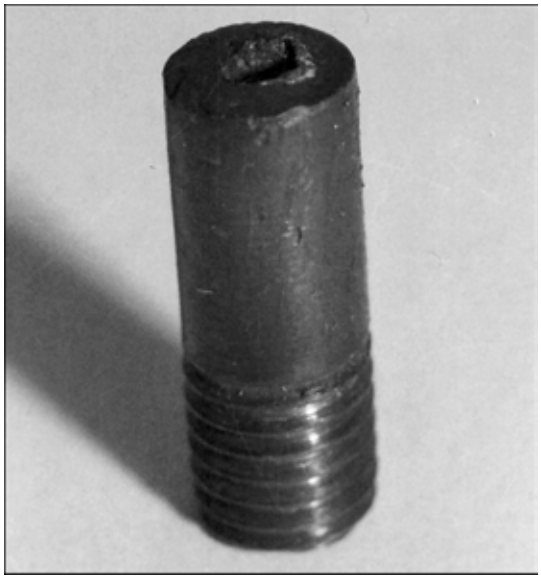

Figure 3. Worn-out current-carrying nozzle of experimental powder material

It is experimentally established that it is appropriate to apply on the surface of copper and ceramic CCN multiplayer heat resistant coatings by the method of ionic deposition on the units of Bulat type. Such coatings are very thin (15–25 μm). Their heat resistance is 1000–1800 °C. They prevent welding of the wire metal to the metal of the CCN channel and decrease about 50–70 % sticking of the spatters to the lower end of the CCN [2, 15]. Operational resource of the CCN with heat resistant coating is by 15–20 % higher than that of analogous ones without the coating.

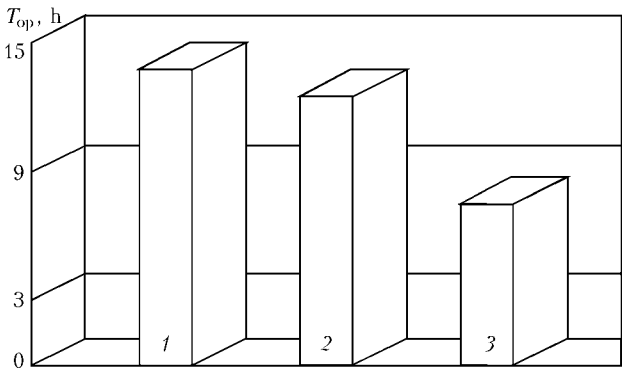

Figure 4. Operational resource (T_{op}) for torches of automatic machines for CO_2 welding at standard conditions: *1* — experimental; *2* — Binzel; *3* — commercial (copper)

Current-carrying nozzles of the torches of semiautomatic machines supplied by the Binzel Company, Germany (see Figure 1), were also produced of powder materials. They have a heat-resistant nickel coating on their surface applied by the galvanic method.

The Binzel is leading in production of welding torches with nozzles characterizing with high wear resistance. Testing of the proposed CCN has also shown their high operational characteristics [15, 12]. Advantage of the Binzel CCN was in small roughness of their surface and relatively high degree of adhesion of the nickel coating to the CCN working surface. However, their adhesion is essentially lower (Figure 4) than in the proposed multiplayer heat resistant coatings produced by ion deposition on the unit of Bulat type [15]. Geometry of the Binzel CCN is their doubtless advantage since its more optimal than in other CCN (see Figure 2). The developed composition of the powder materials [1, 12, 15] is characterized by an increased operational life (see Figure 4).

It is advisable to apply multiplayer heat-resistant coatings with a final layer of ZN, TiN and SiC type on the surface of CCN of powder materials. This will allow preventing the molten metal spatter to stick to the working surface of the layer.

Development of nozzles and tips with heat-resistant coating on the basis of the alloyed silicon carbide [16] made usually two-layer is promising. The first transition layer consists of the mixture of silicon, carbon and copper; the second working layer is a nanocrystal form of the cubic silicon carbide. Microhardness with loading on the 20 g pyramid was 30 GPa; thermal resistance of the coating is 2300 °C. Use of the CCN with SiC coating allowed a 30–50 % decrease of the number of spatters sticking on its working surface. When applying heat resistant coating on the CCN surface it is necessary to prevent ingression of the coating components to the surface of the channel since the presence of such components increased contact resistance. Heat-resistant coating prevent spattering of the CCN end, thus decreasing intense formation of the cone-shaped channel on the surface of the electrode rode outlet.

Thus, development and application of CCN of copper-based powder materials for welding torches and heat-resistant coatings of their working surfaces are technically advisable since they allow increasing their operational resource, improving stability of welding process, decreasing a probability of defects in the welds and lowering a need in the torches.

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PROBLEMS OF QUALITY OF BRAZE WELDED JOINTS AND BRAZING FILLER METAL DEVELOPMENT (REVIEW)

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Trends in development of brazing filler metals, criteria of their selection to produce sound similar and dissimilar joints of products for different engineering fields have been analyzed. Effect of physical properties of the brazing filler metal, specifics of solidification and other factors, which should be taken in to account in development of brazing technologies, on the joint quality, is shown. Promising directions of research in the field of brazing of critical products are outlined.

Keywords: brazing, brazing filler metals, joint quality, dissimilar materials, structure defects, solidification, nanomaterials

Copper, iron and their alloys remained to be the main structural materials for many centuries, biofuel being the main heat source for brazing. More concentrated heat sources such as acetone-oxygen flame and electric arc discharge were introduced starting from the XIX century. Brazing filler metals began to be separated into solders and brazing filler metals based on the brazing temperature, and in a number of publications on terminology the process proper is called soldering (low-temperature) and brazing (high-temperature) in English proceeding from the temperature criteria. Solders are alloys with melting temperature below 450 °C, and alloys with melting temperature equal to and above 450 °C are brazing filler metals [1–3]. Solders, for instance, tin-lead ones, have a low ultimate strength, and, as a rule, are low-melting materials. A brazing filler metal has a high ultimate strength. However, this classification has become unacceptable with introduction of new heat sources, advanced structural alloys, products made of them and the brazing filler metals proper. During the XX century brazing developed from an auxiliary technology into a high technology of fabrication of critical engineering structures from advanced materials-alloys, ceramics, composites and other materials meeting special requirements of high-temperature resistance, corrosion resistance, cryogenic temperature resistance, etc. In a number of cases brazing is the only technology, ensuring the operating reliability of a product [4–9]. Insufficiently high quality of the joints of parts and components in power generation, aircraft construction, rocket engineering and many other fields of engineering can lead to fracture with catastrophic consequences.

It is known that the following factors have an essential influence on the brazed joint quality:

- brazing filler metals, fluxes, active and inert gases, vacuum, braze modes and cycles;
- technological level of the process;
- structure, weight and material of the item;
- preparation for brazing and post-brazing treatment [10–15].

Quality of advanced products, brazed under vacuum, is influenced by the kind of brazing filler metals, features of melting of the applied coating and other conditions. In addition to the melting temperature, other important characteristics of the brazing filler metals are:

- vapour pressure of the components in the brazing filler metal composition;
- variation of brazing filler metal temperature at partial dissolution of the materials being joined in it;
- brazing temperature and time of soaking at a certain temperature;
- mechanical characteristics of the brazing filler metals, etc. [10–13, 16–19].

However, the reference materials lack generalized information on the methods to improve the quality of brazed joints, allowing for the above conditions and factors.

The aim of this study is analysis of publications on improvement of the technique of brazing, selection of brazing filler metals to meet the requirements of preservation of a high quality of the joints in operation, more precise definition of the criteria of physico-chemical properties of materials, used depending on the brazing process.

Brazing technique and flux composition started attracting special attention from 1930s in connection with development of radio engineering, electronics, aircraft and blimp construction. Radio engineering was faced with the problem of provision of reliable joints of copper and other metal parts (wires, plates, etc.) with foil-cladding with Getinaks, glass-cloth-reinforced laminate and glass. It is natural that well-established brazing filler metals or coatings based on tin, lead, copper and silver, and rosin as flux were used at first. In many cases, the blanks were coated with tin, copper, silver or gold by electroplating or other processes. The same technology has been preserved up to now, although proposals on replacement of the silver coating of PC blanks by tin-lead-bismuth ones are known [20, 21].

With the advance of electrical engineering and electronics higher requirements were made of the joint quality and the range of materials and types of joints to be brazed was greatly widened [22]. Starting from 1960s, products of corundum ceramics became widely accepted. Parts of iron-nickel or new for the industry materials such as niobium or other alloys were joined to the corundum ceramics. For brazing ceramics and ceramics to metal adhesion-active elements (titanium, zirconium, hafnium) should be added to the brazing filler metals. A filler in the form of copper or titanium foils 0.10 to 0.05 mm thick was used for brazing ceramics to the nickel bushing. At brazing temperature of 1020 °C in the electric vacuum furnace and rarefaction of $2 \cdot 10^{-4}$ mm Hg a braze weld of the following composition was formed: an alloy of 80 % Cu and 20 % Ti. In this case, the brazing filler metal ensured approximately equal coefficients of thermal expansion of the braze weld and all the parts at the operating temperature of 650 °C, and the required strength of the joints at the same time [23]. In mid 1960s 590 compositions of brazing filler metals with the melting temperature from 3 to 2996 °C were proposed just for brazing parts of vacuum tubes [24]. Several hundred more brazing filler metal compositions were used for joining the same materials, which were not located in the evacuated cavities of the tubes.

Starting from the 1950s more attention was given to the reliability of brazed joints and investigation of the causes for braze weld fracture. In particular, the specialists were attracted to the traditional technology of gas brazing with brass alloys verified by a decade-long operation of structural steel products [25–27]. This resulted in development of a brazing process with washing before assembly, and preliminary application of a paste and its melting [28]. The influence of distribution of the brazing filler metal components in the brazed joint zone on the joint tightness was also established [29].

Performance, corrosion resistance and fatigue life of the metal–brazing filler metal–metal joints is largely dependent on metallurgical interaction of materials, participating in the brazing process [14, 29–31]. In particular, the chemical, structural and physical composition of the coatings affects the joint quality. For instance, when moving over from the gold coating of Kovar bases of microcircuit packages to nickel coatings, it was found that the joint strength is maximum only in a certain narrow range of coating thickness (12 μm for nickel coating). At a smaller thickness a separation of the nickel rim from the board is observed because of a high porosity, and at greater thickness the fracture runs through the glass ceramics [13, 32].

Quality of powder-like brazing filler metals in the form of pastes and suspensions of the same composition depends on the technology of powder preparation. It is established that the fluidity of powder produced by melt dispersion by gas, is noticeably lower than that of powder produced by centrifugal spraying or mechanical crushing. Properties of metal of a weld made by a brazing filler metal with a filler of metal powder, depend on the shape, dimensions and structure, which can be varied to actively control the process of joint formation [33, 34].

It is known that at long-term storage of brazing filler metals (or their components) the quality of brazed joints can be different from the specified properties. This is primarily true for powder-like brazing filler metals and pastes on their base, in particular, the silver-base ones. PSr-45, etc. lose their properties and become unsuitable for brazing at storage in air for more than 10 days [35]. On the other hand, there is data to indicate that the joints made by PMFS6-0.15 brazing filler metal with 5–50 μm particle size, stored for more than 20 days, had almost 25 % higher strength [36].

Achievement of a satisfactory quality of brazed joints requires precisely controlling and maintaining the process parameters during the entire brazing cycle. The method of optimizing the equipment by successively applied criteria, when selecting the units for diffusion brazing processes, can be regarded as the most successful solution of this problem [16]. It, however, should also be precised and improved. In particular, when using highly reactive brazing filler metals, containing aluminium, titanium, zirconium, etc., a criterion should be introduced, accounting for the need to quickly achieve a high vacuum and temperature above 1000 °C. An important process quality factor is observation of the conditions of brazed parts assembly. In products, exposed to variable mechanical and temperature loads (heat exchangers, etc.) at a relatively large brazing gap (at a great mass of braze welds), stress raisers develop because of the difference of the coefficients of thermal expansion [17]. Naturally, this problem can be solved by selection of brazing filler metals by the coefficient of thermal expansion. Important characteristics of the process of brazing filler metal application are feeding schematic, location or application of the brazing filler metal, and kind of brazing filler metal.

Brazing with a pre-placed insert, brazing with prior capillary tinning, and with part cladding by the brazing filler metal can be applied for sealing. At heating the brazing filler metal penetrates into the material being brazed, causing deformation of the solid surface at melt wetting and spreading [37]. This phenomenon is due to the action of unbalanced forces of surface tension around the brazing filler metal perimeter, and, therefore, in addition to other factors, it depends on brazing filler metal composition and nature of interatomic bonds on intercrystalline boundaries. In particular, [18] notes the need for an integrated evaluation of the processes of wetting, spreading and dissolution. The latter is given special attention in [20].

According to the Standard of Ukraine DSTU 3761.4–98 the brazing filler metals are defined by their physical condition before application (multi-

layer, powdered, composite, formed, tubular, paste and self-fluxing). Such a classification is required, first of all, in development of the joint geometry and selection of a heating method. However, metallurgical and physico-chemical properties of the brazing filler metal should be regarded as one of the main criteria for its selection [38].

One of the most important advantages of brazing compared to welding, is a wider range of the possible joining of dissimilar metals and alloys. Intermetallic formation can be avoided with appropriate selection of brazing filler metals, heat sources and brazing technique. From mid XX century advance of chemical and power engineering, industrial and nuclear power generation, and rocket construction necessitated fabrication of structures of titanium, zirconium and other materials.

In 1970s brazing filler metals based on zirconium alloyed with silver, manganese or tin were proposed for brazing joints of titanium and zirconium alloys [36]. Test samples of brazing filler metals of Zr–Ni or Co–Cu, Ti–Cu–Ni systems can ensure higher performance of the products, operating at variable temperatures. This is achieved by a better matching of the coefficients of linear expansion of the brazing filler metal and zirconium and titanium alloys being brazed [40, 41]. The employees of the All-Union Research Institute of Aviation Materials, MIFI-Ameto and other organizations developed several compositions of brazing filler metals, based on Ti–Zr–Cu–Ni system, for brazing titanium and zirconium that now are the dominant materials in industry [42]. It should be noted that the traditional development of brazing filler metal compositions was based on the physico-chemical and metallurgical properties of the materials being joined.

Nonetheless, already in mid XX century a «mechanical» problem arose due to the need to join items of dissimilar materials. Brazed joints are exposed to additional stresses and deformations, caused by different coefficients of thermal expansion and moduli of elasticity of the materials.

At the start of 1970s PWI considered the mechanism and developed a procedure for evaluation of the stress-strain state of multilayer brazed semi-conductor materials at variation of the ambient temperatures and at heating in operation [43]. The most significant problems of ensuring the strength and geometry of the components arose in manufacture of large-sized structures in rocket construction, power engineering, and ship-building.

The issues of the stress-strain state and metallurgical mismatch of the joints of dissimilar materials were studied by specialists of Admiral Marakov Ukrainian State Marine Technical University (Nikolaev, Ukraine). In addition to programs of calculation simulation, they proposed inserts with properties differing from those of the materials being joined [44]. This joint geometry makes special requirements of the brazing filler metals. Considering that the volume of production and the range of products of dissimilar materials are quite high, and will increase in the future, it is logical to suggest that the brazing filler metal specification should include the coefficient of thermal expansion and elasticity modulus. In addition, this problem can be solved by using highly ductile silver, gold, and copper brazing filler metals, as the «deforming» layers, filling the wide gap.

The damping insert, which allows increasing the strength of the joint between a ceramic disc of a gas turbine and the metal shaft, was proposed by I.N. Frantsevich Institute of Materials Science. Such a design not only increases the brazing area, but also provides a uniform distribution of stresses developing during brazing [45]. To ensure the relaxation of stresses resulting from the difference in the coefficients of thermal expansion, hard alloy elements of the metal-cutting tools were manufactured, using brazing filler metals of Cu–Ni–Mn system, having sufficient ductility [46].

In order to lower the stresses, it is recommended to design the products with parts, tolerating deformation in the brazing areas, by thinning of the wall, corrugations, etc. [23]. It is, however, often not cost-effective to use the recommendations developed for small radioelectronic products for the large-sized items, and sometimes this is simply impossible to implement in terms of the design.

Individual components of the power units operate at high (above 1000 °C) temperatures, being exposed to high loads. The brazing filler metals should enable fabrication of brazed structures of compact and porous materials and non-metals with different coefficients of linear expansion. In many cases the base for such brazing filler metals are alloys of Ni–Cr–B–Si system. Sometimes, molybdenum or tungsten are used as the refractory fillers. These metals, which are the most refractory natural materials have the role of modifiers, solidification centers, which improves the seam structure [47]. To reduce formation of brittle phases and the diffusion along the grain boundaries at brazing with nickel brazing filler metals of this system, it is proposed, alongside with adding noble metals to the brazing filler metal composition, to also minimize the brazing gap (not more than 100 μm) [48].

It should be noted that brazing filler metals with large amounts of boron and silicon are erosive and unsuitable for brazing thin-walled structures (honeycomb, latticed panels, plate-fin heat exchangers, etc.) that largely determine the advance of modern engineering. For this reason, the All-Union Research Institute of Aviation Materials, PWI, «Tekhnomash» and other organizations, developed nickel-base low-erosive brazing filler metals for brazing stainless steels. Prof. Khorunov and his colleagues (PWI) proposed brazing filler metal PR-N58F, which is applied in batch production of rudders of air-air missiles [49–51].

Particularly high requirements are made of compositions of refractory brazing filler metals, applied in manufacture of the parts of gas turbine engines.

As the fuel contains sulphur the product is exposed to sulphide corrosion during fuel burning, and the main elements used as depressants, lower the resistance to this corrosion [30]. At the same time, brazing filler metals based on Ni–Cr–Zr system greatly widen the capabilities of brazing refractory nickel alloys, also at arc heating [52–55].

Over the last decade, sheet steel and shaped sections with an anti-corrosion zinc coating, usually less than 1 mm thick, have become widely accepted in the automotive, chemical industry and industrial and civil construction. In welding structures of such materials, the protective coating burns out in the HAZ along the weld over the heated section width, starting from the temperature of evaporation and up to the temperature of zinc melting. Repeated electroplating is an expensive process, and use of solders, which would eliminate evaporation, does not provide a sufficient strength. ESAB, Sweden, proposed using copper wire as a brazing filler metal, as copper readily forms alloys with zinc, i.e. brass, in any proportion. Brazing is performed by the schematic of MIG welding, sometimes adding a small amount of active gas (oxygen) to argon. Copper filler wire ---- electrode with addition of silicon (3 %) and manganese (1 %), has the melting temperature of 910–1025 °C, and zinc melting temperature is 419 °C. Liquid zinc remains on the steel surface and dissolves in copper. Brass is formed, which is what covers the transition area between the brazed seam and zinc coating [56].

Starting from 1960s the task of developing the technology of structure erection in space has become urgent. The electron beam was recognized to be most promising heat source in welding and brazing, and aluminium alloys as material of the structures. When the brazing filler metal was selected, it had to be taken into account that the alloys should not contain any elements with a high vapour pressure, because of a high vacuum of space. The solidus temperature of the brazing filler metals should be above the maximum temperature of solar heating of the structures in space (150 °C) [57]. These requirements are satisfied, in particular, by a brazing filler metal developed at the E.O. Paton Electric Welding Institute by V.F. Khorunov, V.I. Shvets, V.F. Lapchinsky, et al. [55].

However, at erection of aluminium structures under such complicated conditions as those of space, it should be taken into account that chemically active fluxes used for breaking up the aluminium oxide reduce the corrosion resistance of the item and the equipment. Instead of the fluxes, it was proposed to first apply on the surface to be joined a layer of materials, where the oxides have a low dissociation temperature. Positive results were obtained for coatings of Ni, Ni–Cu, Ni–Sn layers, applied electrolytically. A technology was developed for joining the elements of space structures, differing by that the brazing filler metal in the form of a tablet, is first placed into the component to be brazed so that at heating the brazing filler metal would flow into the brazing gap [57].

Compositions of brazing filler metals for low-carbon steels, which were used from the ancient times, did not need any major improvement, just as the brazing filler metals for low-alloyed steels. The correction is due to introduction of new heat sources and brazing techniques, namely induction, arc, electron beam heating, brazing in vacuum, argon, etc. Self-fluxing brazing filler metals have become accepted in batch-production. Brazing of alloyed steels raises problems of carbide precipitation along the grain boundaries, and molten brazing filler metals can penetrate along the grain boundaries, particularly, under the impact of stresses. In selection of a brazing filler metal, conditions of pre- and post heat treatment are taken into account in addition to the regular criteria. In brazing before quenching refractory brazing filler metals are required; in brazing high-carbon steels the heating temperature should be below that of quenching or sufficient for simultaneous quenching [22].

In brazed item operation gases can evolve from the seams. In some cases this may detract from the product performance. One of the methods to eliminate the detrimental effect was proposed by Green-one Tec., which is manufacturing the solar collector absorbers of copper tubes, that are brazed to the coated heat conductor plates. At heating above 234 °C (in the absence of the heat carrier circulation) gases intensively evolve from the brazing filler metal, destroying the antireflective coating. The Company combined brazing and ultrasonic welding, thus ensuring evolution of gases and vapours from the brazing filler metals and pastes in their manufacturing [58].

In many products braze seams should provide the tightness. Material suitability for brazing the flat packages of integral microcircuits of electronic industry products is checked by indirect characteristics, namely mechanical strength and tightness. However, in brazing of the gilded packages, the strength of seams of the Au–Sn–Pb system drops markedly as a result of thermal ageing, which is attributable to formation of brittle intermetallic phases. Therefore, a lot of attention has been recently given to physical metals science of brazed joints in microelectronics devices, in particular, studying the processes running on the brazing filler metal–base metal interface, and formation of intermetallics along this boundary [59]. The problem of saving precious metals posed at the end of 1970s, was addressed simultaneously with the problem of mechanical strength and tightness of the nickel package brazing. This resulted in development of a self-fluxing paste based on a Sn–Pb brazing filler metal, which forms a small amount of intermetallics with nickel [59].

The amount of the brazing filler metal added to the brazing gap, in many cases influences the quality of similar brazed joints, made by the same technology [60].

At the end of the XX century more attention was given to nanomaterials, i.e. polycrystalline materials with crystallite dimensions of 5 to 10 nm. In the

future, they may be used as a high-strength structural material. Moscow Engineering-Physical Institute conducted comparative studies of the properties of joints of copper, steel, titanium, beryllium bronze, brazed with brazing filler metals with different structures, and established the influence on the structure and properties of brazed joints. One of the methods to produce amorphous nanomaterials is super fast solidification. Brazing using thin strips (about 20 μm) of an amorphous brazing filler metal provides a high quality of joints for nuclear reactors [61]. Silver brazing filler metals of nanosized particles (diameter in the range of 10 to 30 nm), proposed by Robert Bosh GmbH, allow lowering the brazing process temperature [62].

The problems of operating reliability of brazed joints have currently been pursued by research and design organizations of such industries as rocket construction and power generation. At SPA «Energomash» V.P. Semyonov developed a model of the fracture mechanism in bimetal structures (EP 202 alloy and VNS16 steel) in brazing, and established that cracks result from tensile stresses in materials at loss of deformability under the impact of the brazing filler metal melt. In local volumes the stresses can be higher than the ultimate strength of the materials being brazed. Solid solution alloying, crystalline lattice distortion, dislocation and accumulation of hydrogen are observed in the surface layer of the joint zone [63]. The problem of crack propagation in a homogeneous brazed material, with varying concentration of alloying elements, penetrating from the brazing filler metal into the layer adjacent to the brazing area, was solved for superhard materials [64].

CONCLUSIONS

1. For a long time the main criteria for brazing filler metal selection were the temperature interval of melting and a number of other physical characteristics, namely, brazed materials wettability, strength, etc.

2. From mid XX century the range of the structural materials used for manufacturing of critical products became broader, which led to development of a considerable number of brazing filler metals for sound joining of dissimilar metals, cermets, ceramics, reactive, refractory metals, etc.

3. Numerous investigations established that the number of defects affecting the characteristics of strength, tightness and corrosion resistance of the brazed joints, depends on several of factors (difference in the physical properties, solidification features, etc.), which should be taken into account in development of material compositions and brazing technology.

4. The most promising areas for improvement of the quality of joint brazing are related to eliminating from the brazing filler metal composition the substances forming intermetallics with the base material, development of brazing filler metals, containing modifiers and nanoparticles, designing parts, components and products to be brazed, allowing for the possible compensation of the deformations and stress lowering, etc.

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WELDED STRUCTURE OF PROTECTIVE FITTINGS OF RAILWAY TANK CARS

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Design of protective fittings and method for strength analysis, allowing for combined stability of tank car vessel and protective fittings of the stop safety valve system, are proposed. Such a solution makes it possible to maintain performance of the fittings under emergency conditions, when transporting hazardous bulked cargo, and provide environment protection.

Keywords: welded structures, protective fittings, safety arcs, emergency situation, design procedure, performance

The intensity of transportation of hazardous bulked cargo (particularly, compressed liquefied gas) by railway transport and increase of its technical parameters in emergency situations requires protection of the stop safety valve and drain-filling fittings located in the upper part of the tank car vessel. In the local and foreign practice this problem was mainly solved by designing various protector caps, fully covering the fittings [1]. As shown by practical experience, such a decision is not effective enough, particularly in emergencies (for instance, at tank car overturning).

Over the last years the fittings started to be protected by mounting the welded safety arcs (the ends of which are hinged on the tank car) above the stop safety valves [2]. Experience and calculations show that in addition to considerable technological complexity in fabrication and assembly of such structures, they have insufficient stability and rigidity in emergencies, particularly at overturning of a loaded tank car.

A solution of the above problem, allowing for the stability and rigidity of the vessel and the welded-on elements of the safety arcs for the most unfavourable operating conditions, is of interest. Rigidity of the safety arc elements should be taken into account mainly in the directions across and along the vessel, provided that a considerable part of the loads is taken up directly by the vessel. Such an approach allows markedly lowering the weight of the protective fitting structure, ensuring the manufacture of its welded variant, and increasing its effectiveness. In the general form this design is protected by the patent of Ukraine [3], and is given in Figures 1 and 2. The procedure of strength analysis of such a structure should allow for the emergency situation, at which the fully loaded tank car is overturned on the safety arcs.

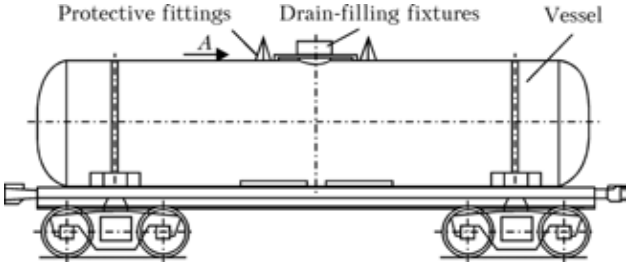

Figure 1. Schematic of a railway tank with protective fixtures

The most effective is application of the finite element method, where the design weight of the structure is distributed in the plates and columns connected to each other in the nodal points. This provides the most realistic mathematical description of the stressed state of a structure in emergencies, and reveals the softest sections of the vessel and its protective fittings. «Iskra» program was used for calculations.

Calculations show that at overturning of a loaded tank car on the safety arcs, stresses in the vessel casing (in the sections of arc welding on) are below the yield point of vessel shell material (σ_y = 305 MPa, 09G2S steel), i.e. integrity and shape of the part of vessel shell mated with the safety arcs, is preserved. In the struts mounted on the upper generatrix of the vessel, stresses are also lower than the material yield point.

Proceeding from calculations and using the engineering solution of [3], «Azovmash» is currently making several models of tank cars for transportation of hazardous cargo, fitting them with welded structures of safety arcs.

In 2003 an accident occurred, which was related to overturning of a link-up of tank cars of 15-1519-01 model loaded with liquefied hydorcarbon gases. Study of tank cars in the accident showed that the welded

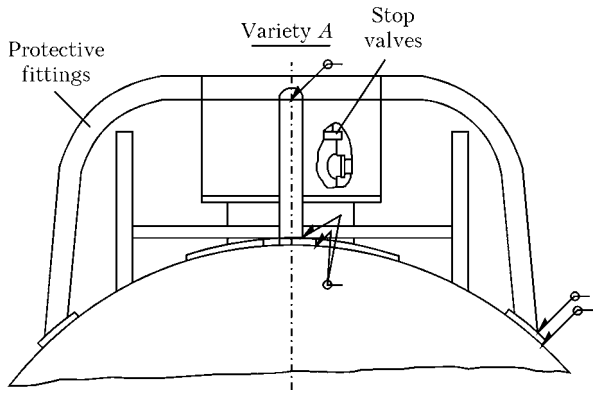

Figure 2. Lay out of welds for welding the safety arcs

Figure 3. Railway tank car after over turning

structure of the fixtures (σ_y = 245 MPa, steel 20) ensured the integrity of the fixtures and the vessel. Safety arcs proper had slight deformations (Figure 3), which did not affect the condition of the fixtures or vessel integrity. This fully confirmed the results of the performed calculations.

Thus, use of the proposed welded structure of protective devices and method of its strength analysis, taking into account the interrelation of the rigidity and stability of the vessel and elements of protective devices of the fittings in tank cars for hazardous cargo transportation, allows avoiding failure of the fittings in emergency situations.

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WELDING ON CERAMIC BACKINGS

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Examples of efficient application of ceramic backings in welding for construction of tankers and other marine engineering facilities are given.

Keywords: arc welding, ceramic backings, quality of formation, arrangement of manufacture

The technology of welding on ceramic backings was intensively applied in welding production as far back as the 1970s–1980s. «Prometej» was involved in development of ceramic backings for ship building, and it arranged their manufacture. However, in the restructuring and post-restructuring time this technology was not employed, despite all its advantages. Its coming back to Russian shipyards took place in 2000, when, after examination of the level of construction of ships at western shipyards, where ceramic backings are widely utilised in welding, by a decision of its managers the «Admiralty Shipyards» Company procured a batch of the ESAB ceramic backings. The efforts of associates of the Chief Welding Department resulted in application of the technology of welding on ceramic backings for construction of tankers.

Today it has also other applications in marine engineering. In particular, it is used for welding of increased- and high-strength steels. The most advanced technology for welding these steels is mechanised welding of the weld root in all spatial positions using the 1.2 mm flux-cored wire 48PP-8N. Ceramic backings provided the high quality of formation of the back side of the weld. This allowed avoidance of an extra operation of gouging of the weld root and argon-arc tungsten-electrode welding, which was often employed in shipyards to guarantee a high level of quality of the weld root.

Imported backings have the following chemical composition of ceramics, wt.%: 47.4SiO_2, 37.5Al_2O_3, 9.1MgO and 3.5CaO.

The most popular types of ceramic backings are round backings with a diameter of 6, 9 and 12 mm, and flat backings with a forming groove 2 × 8 mm in size.

ESAB manufactures backings of a sectional type, primarily 500 mm long with a section of 25 mm. Such backings can be bent to copy a joining line. A backing is attached to a 80 mm wide strip having an adhesive surface, which makes it possible to reliably fix it to the weld, including in the groove, without any additional clamping or other fixtures and hold it during welding, despite burnout of the adhesive in the neighbouring regions. The adhesive has no effect on the quality of the weld metal. To protect it from damage and contamination, the adhesive surface of the strip is covered with a second protective strip, which is removed prior to fixing the backing to a joint.

This brings about a question concerning arrangement of manufacture of such backings by electrode shops, which is what the «Electrode» association member companies can manage. This can be done using available equipment with minor adjustments. This work, as well as building of specialised equipment can be performed by the «Velma» Company.

Experience of the «Admiralty Shipyards» Company in utilisation of ceramic backings for performing contract works shows that upgrading of the arc welding technology for ship building will inevitably involve their utilisation, and the same applies to many other industries.

UNIVERSAL SENSOR OF ELECTRIC PARAMETERS OF WELDING

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Sensor of an electric signal equivalent to measured current or voltage under conditions of increased noise effect is described. Advantages of such devices over traditional sensors of analog signals are shown. Transfer characteristic curves are given, and estimation of the achieved accuracy of the versatile sensor of electrical welding parameters is considered. Ways of enhancement of capabilities of the sensor are indicated.

Keywords: arc welding, welding equipment, sensor, current, voltage, optical isolator, noise immunity

Electromagnetic compatibility of welding equipment constructed, first of all, on the basis of HF converters necessarily requires galvanic uncoupling (GUC) in sensory unit. Such sensors should provide measurements with required accuracy in conditions of arcing, thus possessing stray pick-up and noise immunity and being able to transmit signal within a wide frequency and dynamic range irrespective of its form and polarity.

Sensors produced on the basis of the Hall effect [1], current transformers (CT) [2], devices of modulator-demodulator type (MDM) [3], thermal converters (TC) [4] are usually used in the welding equipment for measurement of current and voltage or for design of control systems with feedback contours by current (voltage).

Owing to their reasonable price, simplicity and reliability CT are widely applied in the welding equipment. Among their drawbacks is inadequate accuracy in measuring currents whose form differs from sinusoidal as well as unfitness for measurement of parameters in DC circuits.

MDM sensors may be applied for measurements of both alternating and direct current and voltage. However due to limited frequency and dynamic ranges of input signals as well as circuit-constructive complexities they did not gain a wide application in the welding equipment.

TC meet the GUC requirements. Besides, they provide a signal equivalent to the acting value of current or voltage irrespective of their form. At the same time considerable lag of TC practically excludes a possibility to use them as elements in the feedback circuits, especially in power sources and systems with HF conversion nodes.

Sensors constructed on the basis of the Hall effect and used for measurements of current and voltage gained the wide recognition. In this case current sensors (CS) meet the most requirements to the sensors in variation of current of any form and polarity. However, commercial specimens of voltage sensors (VS) on the basis of converter do not provide necessary frequency range of variations and accuracy within a wide dynamic range. Besides, such VS require large power and powerful external resistor [1, 5].

Appearance of integral electronic components GUC [6] in the market considerably improved the situation. These devices are characterized with a wide dynamic and frequency ranges, high noise immunity, low power consumption, high values of strength of insulation and other advantages.

The authors attempted to create universal sensor of current and voltage on the basis of GUC with Σ--Δ-converter. They studied its metrological and electrical characteristics. Rating meter (RM) with GUC between input and output is the basic part of such sensors. Simplified circuit of RM is presented in Figure 1.

RM contains input attenuator *R*1, *R*2; linear optical isolator of integral design *DA*1 and scale amplifier *DA*2. Resistors *R*3, *R*6 and *R*4, *R*5 are selected to provide necessary coefficients of amplification. The input attenuator is designed on precision resistors whose resistance is selected regarding a range of possible values of input signal and maximally possible input voltage of optical isolator. The attenuator is not necessary if CS is constructed with shunt.

Microchip *DA*1 is an optical isolator of HCPL series (Aligent Technologies Company), which is widely accepted in the recent time. It includes Σ--Δ-modulator, optron circuit of GUC and Σ--Δ-demodulator. Such construction of optical isolator provides high accuracy in transfer of analog signals [7]. Due to insensitivity of the light flow to the effect of external fields the output signal of the optically coupled isolator does not contain noises and distortions resulted from the action of the external electromagnetic field.

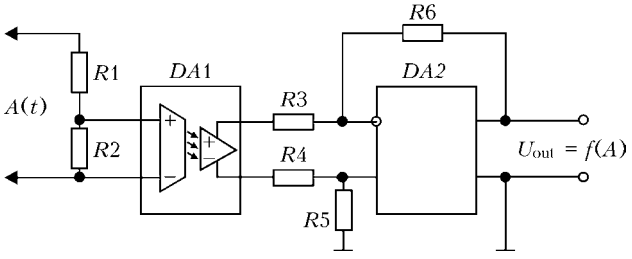

Figure 1. Simplified electrical circuit of the RM basic module

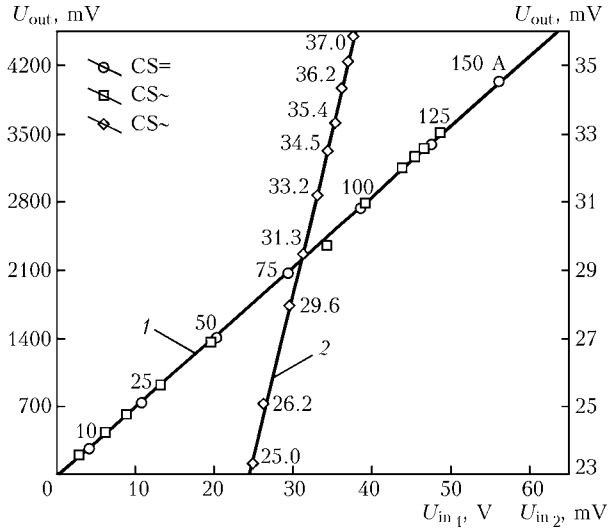

Figure 2. Transient characteristic of the universal sensor in mode of CS (*1*) and VS (*2*)

Scaling operational amplifier *DA*2 made with bipolar power supply is intended for amplification of the sensor input signal to the level necessary for its further processing. It provides matching of the RM output impedance with input impedance of the signal receiver (feedback nodes of control systems, analog-digital converters etc.).

Let us consider characteristics and parameters of the sensors on the example of the sensor UDS-55 / 1, whose test specimen was developed and tested at the E.O. Paton Electric Welding Institute. Transient characteristics of the sensor used in the CS and VS modes are presented in Figure 2. Left coordinate axis with indicated values of CS output signal corresponds to curve *1* and the right coordinate axis with indicated values of VS output signal corresponds to curve *2*. Input values of CS were taken by the measurement shunt of 75 ShSM type consecutively switched to the welding circuit while input values of VS ---- directly from the output of the welding source. Measurements were carried out for constant and permanent signal. Figure 2 shows that transient characteristics of the universal sensor (US) are linear irrespective of the current kind in all measurement modes. Evaluating the results of the test in general one may consider possible to use the developed device as the DC sensor with sufficient level of noise immunity.

To estimate the achieved accuracy let us present the transient characteristic of the device by the formula

$$U_{out} = \prod_{i=1}^{3} k_i U_{in},$$

where U_{out} is the output voltage of US; U_{in} is the input signal of US; k_i is the transfer coefficient of each sensor link.

Graphic dependence $U_{out} = f(U_{in})$ is shown by a line whose slope is determined by the product of the transfer coefficients of every link. Thereby we can find the error of the studied device. With this aim we made an experiment to study the transfer function

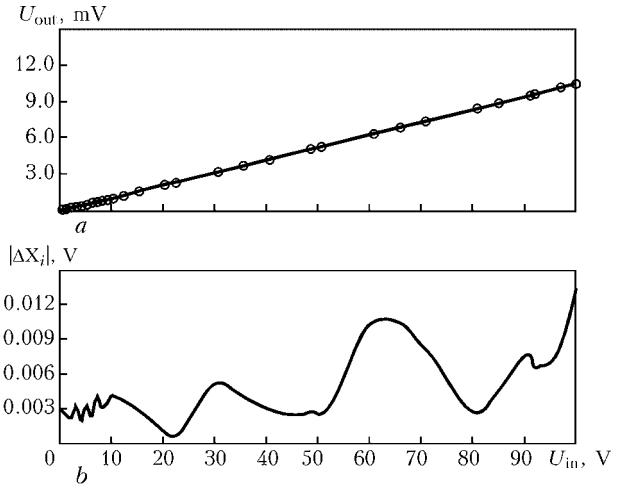

Figure 3. Transient characteristic of the universal sensor in VS (*a*) modes and scatter of its indications (*b*)

of US on direct current. The result of the experiment is presented in Figure 3. Figure 3, *a* shows an approximating straight line plotted by the output data of US; Figure 3, *b* shows deviations of the obtained points from approximating straight line $U_{out} = 9.5545U_{in}$. The error of US may be calculated by the following formula:

$$E = \frac{\frac{1}{n}\sum_{i=1}^{n} |\Delta X_i|}{\overline{X}} 100\ \%,$$

where ΔX_i is the deviation of i-value from approximating straight line; n is the number of measurements; $\overline{X}$ is the average value of all measurement results. The calculation results have error 0.88 %.

Further expansion of the US functions is possible in the following directions:

- switching of multichannel ADC to output channels. Use of the digital signal seems rather promising since is it not exposed to noise effects and may be transmitted for long distances;
- matching of US and microchip AD736 transforming the input signal into signal of DC directly proportional to the mean-square value of the input signal.

In conclusion it is worth noting that the above tests permitted developing test specimens of the universal sensor UDS-55 / 1, which are tested in operation both in welding equipment and in arc analyzers.

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