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WELDING TECHNOLOGIES UNDER EXTREME CONDITIONS
Part 1. Analysis of multifactortial potential risk

B.E. PATON, A.R. BULATSEV, S.S. GAVRISH, A.A. ZAGREBELNY, S.V. PAVLOVA and **V.F. SHULYM**
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Factors are analysed, which create a hazard during performance of technological work, using an electron beam tool in space.

Key words: *manual electron beam tool, spacesuit, radioactive and light radiation, high voltage, corona discharge, molten metal, electromagnetic noise, space object*

This work consists of two parts. The first part deals with the problems, related to the risk in performance of manual technological processes; the second part is devoted to analysis of the possibilities for lowering the degree of the risk.

Space exploration and practical implementation of many projects in the field of cosmonautics will hardly be possible without a broad application of welding directly in space. Construction of long-term orbital stations is related to their repair and restoration in flight. The increase of structure weight and overall dimensions makes it necessary to deploy, assemble and mount them in open space. In this connection solving the problem of permanent joining and cutting of metals, as well as application of thin-film coatings becomes particularly important [1].

Electron beam welding (EBW) was selected as the most promising process from currently available ones, based on the main criteria of evaluation of both the welding process proper (versatility, adaptability to fabrication and simplicity), and requirements to space equipment (high reliability, safety, minimal weight and volume, small power consumption). Results of numerous experiments, conducted in ground-based space simulation test chambers, flying laboratories and directly in space, confirmed the correctness of selection of the electron beam as the heat source, this, probably, not excluding the application also of other traditional welding technologies [2–7].

The first EBW unit was made in the E.O. Paton Electric Welding Institute in 1969 as part of «Vulkan» hardware [8]. To ensure a higher safety and quality of the weld, the work in it was performed in the automatic mode, which is not always rational, for instance, for repair-restoration work. Further improvement and increasing the flexibility of the welding equipment, aimed at overcoming not only technical, but also psychological difficulties, related to working with molten metal, led to creation of an electron beam hand tool (EBHT) for the cosmonaut, allowing various processing operations to be performed.

Electron beam technology is a comparatively new process, applied both in ground-based welding fabrication and in extreme, in particular, space conditions. It is characterised by the following main advantages:

- high efficiency of conversion of the electric energy into thermal energy;
- considerable concentration of energy in the cross-section of the electron beam;
- absence of reactive forces in operation with the electron beam;
- small volume of the molten metal pool and, therefore, low sensitivity to zero gravity;
- ability to use various processing operations (welding, brazing, cutting, coating application, etc.).

However, the features of space (vacuum, zero gravity, high gradients of ambient temperatures and light pattern, etc.), as an environment for performance of processing operations with heated and molten metal have an influence on the processes, proceeding in welding [9], physico-chemical properties of structural materials, this leading to a change of their operating characteristics [10], as well as on the human operator during work performance.

Even on the ground «hot» manual or mechanised welding is a professionally risky technological process, and in operation in the extreme conditions, in particular, in open space, the traditional risk factors are further aggravated by the specific ones:

- no support for the operator;
- low ambient pressure;
- light and thermal radiation;
- limited mobility of the operator in the protective space gear.

Lack of support makes the actions more difficult and disturbs the coordination of the operator motions, which may lead to unacceptable quality of work performance, accidental switching on of the work tool, its pointing directly at the operator, space object, as well as operator contact with the heated zones of the tool or item being processed.

Low ambient pressure is dangerous for the operator in case of mechanical damage of his gear and possible depressurising of the spacesuit.

Light radiation of the Sun impairs the conditions of observation of the progress of the technological process, influences the change of temperature of the working tool and the item being processed, taking it to a level, hazardous for the gear at accidental contact.

Limited mobility of the operator, because of the rigidity of special gear, leads to fast fatigue, markedly reduces the working and servicing zones, speed and co-ordination of motions, which may cause emergency situations.

Conducting EBW in open space, using EBHT, requires detailed retrofitting of the technologies, as well as designing the processing hardware. Particularly important is provision of maximal safety of welding operator and hardware operation during performance of welding operations in space [11, 12].

Despite the fact that safety was given special attention in development of space welding technologies, designing special hardware and conducting experimental work, these problems were just mentioned in passing in earlier scientific publications. This work is an attempt to analyse the available knowledge, conduct systemic generalisation of the gained experience and suggest methods of risk mitigation (elimination) in performance of such welding operations. It should be particularly emphasised that the authors of this paper during its preparation, benefited from the experience, knowledge and professionalism of their colleagues — specialists of such organisations as S.P. Korolyov Rocket Space Corporation «Energiya», Company «Zvezda», Yu.A. Gagarin Cosmonauts Training Centre, Flight Control Centre (Russia), G. Marshall Space Flight Center (USA), which together with the PWI performed a tremendous scope of theoretical studies, experimental work and unique testing under the actual space and simulated conditions, and are expressing their gratitude to them.

Risk factors. Working with EBHT may involve factors, which create a potential hazard for the operator and the space facility:

- thermal impact of the electron beam;
- X-ray and light radiation, concurrent with the electron beam processes;
- high voltage of electric circuits;
- presence of molten metal on the processed items and in the crucible;
- presence of hot zones on the working tool and the items being processed;
- spatter and contamination of the spacesuit surface and space vehicle elements with products, inevitable in welding technologies;
- electromagnetic interference, influencing the service systems of the space object;
- toxicity of the materials of processing equipment parts.

Thermal impact of the electron beam. EBW process is based on the use of heat, evolved in braking of a focused flow of electrons, accelerated up to high energies [13]. The welding gun cathode emits a beam of electrons, which is accelerated due to the difference of potentials between the cathode and the anode. Electrons, colliding with the item, are slowed down, their kinetic energy is transferred to the atoms of substance, and material heating and melting takes place. Such an impact of the electron beams on the substance promotes their broad and multi-purpose use for heat treatment (welding, cutting, brazing, etc.) of various materials.

Thermal impact of the electron beam depends on energy density, controlled by the focusing system, in the welding zone, and, therefore, is determined by focusing and power of the beam.

Thermal operations with EBHT in space may be the cause for various emergencies. So, in case of the technological process becoming uncontrolled, because of malfunctions of the hardware or the working tool, physical fatigue of the operator and various external impacts on him, it is quite possible for EBHT beam to hit the parts of the space vehicle or operator gear. Beam hitting the soft parts of the spacesuit leads to its de-pressurising, and its hitting the parts of the vehicle leads to their partial or even compete unfitness.

Rigidity of the spacesuit, having excess pressure, impairs the mobility, uniformity of motion of the operator, and increases the fatigue of his hand. All this may lead to disturbance of the welding process and unacceptable quality of the work.

X-ray and light radiation. At collision of the electron flow with an obstacle (material) part of its energy is converted into X-ray radiation. Therefore, each electron beam unit actually is an X-ray tube.

X-ray radiation consists of the characteristic and braking spectra with a considerable quantitative prevalence of the latter. Braking radiation is characterised by a minimal wave length λ_{min} [14]:

$$\lambda_{min} = \frac{12.4}{U} \text{ (nm)}, \qquad (1)$$

where U is the accelerating voltage, kV.

As follows from formula (1), with the increase of accelerating voltage the radiation wave length decreases (radiation becomes more rigid), and its intensity i grows in proportion to the square of accelerating voltage, i.e.

$$i = kU^2,$$

where k is the coefficient of proportionality.

Dependence of radiation intensity on atomic number Z of the material of the item (anode) is close to the quadratic dependence for small values of accelerating voltage, and for high-energy electron beams the radiation intensity is proportional to Z.

X-ray radiation with up to 70 kV energy values propagates from the weld pool towards the electron beam almost uniformly, within the spatial cone with about 120° angle at the apex (Figure 1). Radiation

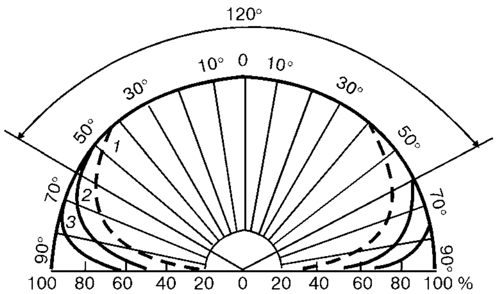

Figure 1. Spatial distribution of the intensity of braking radiation i_x/i_0 at different voltages: *1* — 10; *2, 3* — 70 kV with and without an aluminium filter 10 mm thick, respectively

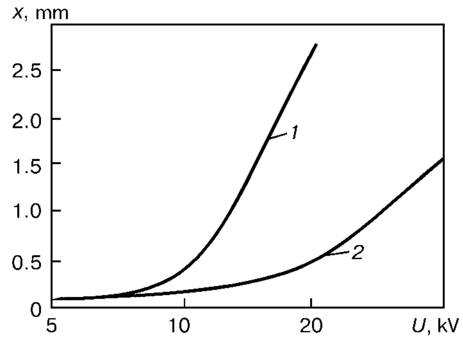

Figure 2. Minimal required thickness of steel (*1*) and lead (*2*) shields, depending on accelerating voltage level

intensity drops in proportion to the square of the distance from the radiation source to the irradiated object.

The given diagram of intensity distribution is characteristic for a point source of radiation and flat surfaces. In the case of performance of work with EBHT this diagram will have a narrower and more elongated shape.

Penetrability of X-ray radiation depends on its wave length λ and protective layer material. Coefficient of radiation attenuation is as follows:

$$\mu = k\lambda^3 Z^4, \quad (2)$$

where Z is the atomic number of the shield material.

After passing a layer of substance of thickness x, the intensity of X-ray beam i_x of initial intensity i_0 is equal to

$$i_x = i_0 e^{-\mu x}.$$

The Table gives the data on attenuation of soft X-ray radiation with wave length $\lambda = 0.071$ nm, when using an aluminium shield at the accelerating voltage of 17.5 kV.

Evaluation of the required thickness x of steel and lead shields may be made, using the data of Figure 2 [15].

As regards light radiation as one of the physical phenomena, accompanying EBW, its understanding is one of the major tasks in visual control of the welding process, performed by EBHT. Radiation of the light range is the thermal radiation from the molten pool surface with the power density $\sigma_{th}T_{cr}^4$ (σ_{th} is Stefan–Boltzmann constant, T_{cr} is the temperature of the weld pool crater) [13].

Dimensions of the welding zone in EBW are small, but its brightness, particularly in welding refractory materials, for instance, titanium with the melting point above 1700 °C reaches the pain limit of sight. Deeper location of the light source (crater) increases the contrast of the image of welding zone and adjacent sections, this causing the sensation of pain and rapid deterioration of sight. In this case the ability to distinguish the degree of brightness is lowered, and information is lost, which is required by the welding operator at direct visual control of the process.

High voltage. EBW hardware, used in space, should be as safe as possible for the welding operator, and should be characterised by minimal weight, volume and power consumption. The totality of electric devices, ensuring the EBW process, can be divided into such groups:

- circuits of high-voltage power source of the gun;
- filament circuits of electron gun;
- circuits of electron beam control.

Some of these circuits are live with high voltage, equal or close to accelerating voltage [16].

Tool actuator in EBW is an electron beam gun with a high accelerating electric potential of cathode circuits (5–10 kV in the manual variant) relative to the anode, which presents a potential hazard of operator electrocuting.

A quite important problem of operational safety of both the operator and the processing equipment is prevention of the appearance of a breaking or damaging corona discharge in any environment of the space vehicle, as well as electrostatic charge on the elements of the hardware structure.

Molten metal. EBW process is accompanied by a set of complex thermal and dynamic phenomena, proceeding in welding and solidification of a substance in the local zone, heated by the electron beam with a high energy density. In this case the substance reaches the melting temperature and part of it goes from the solid into the liquid state. Further heating

Coefficient of attenuation i_x/i_0 of X-ray radiation by an aluminium shield, depending on its thickness

Radiation parameters	*Thickness of aluminium shield, mm*					
	0.1	*0.5*	*1.0*	*2.0*	*3.0*	*4.0*
$\lambda = 0.071$ nm [14] $U = 17.5$ kV	0.87	0.5	0.25	0.06	0.015	0.004
$\lambda = 0.245$ nm* $U = 5$ kV	$22\cdot10^{-3}$	$125\cdot10^{-3}$	$65\cdot10^{-3}$	$1.575\cdot10^{-3}$	$0.4\cdot10^{-3}$	$0.1\cdot10^{-3}$

*Recalculated for 5 kV voltage by formulas (1) and (2).

increases the substance temperature up to the boiling point, at which its partial transition from the liquid to the vaporous state occurs [13].

At microgravity the behaviour of a liquid substance of the weld pool is determined by intermolecular interaction of the surface tension forces. It should be noted that the beam processes are quiet. The molten metal of the weld pool, in view of a small volume of the melt (up to 100 mm^3), characteristic for EBW of thin metal, and rapid solidification (1–3 s) does not present any real hazard for the operator.

To prevent penetration of the molten substance vapours into the cathode assembly zone at coating application by the method of evaporation, the crucible bottom is heated by a defocused electron beam to avoid a burn-through, this allowing a more uniform heating to be provided and the amount of molten metal in the crucible to be significantly increased (up to 1000 mm^3). In this case, it is necessary to take into account the impact of inertia forces on the melt at operator manipulations with the tool, as the possibility of molten metal «floating out» of the pool is not excluded.

Hot parts. Thermal processes in welding are understood to be variation of the temperature of the parts being welded due to heat, supplied from the heat source, heat propagation through the item and its removal into the ambient atmosphere [17].

Hot zones (above 150 °C) on the parts are formed around the weld. Their temperature is gradually lowered due to radiation and heat conductivity of the item materials and their fastener elements.

Certain temperature limitations are imposed to provide the safety of the operator, working in a spacesuit. So, according to the requirements of the American standard NASA-STD 300/Vol. 1/rev., during operator extra-vehicular activity the temperature of the surface, which the spacesuit glove may touch, is limited by the range of temperature values of 113–120 °C and contact time of 0.5 min.

Hot tool. When various technological processes are performed EBHT becomes heated as a result of radiation from the cathode assembly and weld pool, as well as «settling» of peripheral electrons on the gun anode or as a result of heat removal from the crucible with the molten metal in coating deposition.

For instance, when investigations were performed on board the «Salyut-6» space station, no special measures were taken to prevent heating of the working tool of «Isparitel-M» electron beam unit, therefore the temperature of the outer parts of the evaporator block reached 300–350 °C, and the temperature of the other parts did not exceed 70 °C [18].

Spatter and contamination of the operator spacesuit surface. Welding operations and particularly the process of coating deposition by electron beam evaporation are characterised by considerable vaporisation of the molten substances in the working zone, this leading to contamination of the operator gear, working tool and space vehicle elements, and being one of the potential hazards for the operator. In addition, it should be also noted that molten metal drops may hit the gear, tools or elements of the space vehicle interior in case of violation of the technological process.

Electromagnetic noise. High degree of complexity of technological experiments, conducted in extreme conditions of space, and the modern level of development of electronic components for the space hardware make stringent requirements to electromagnetic compatibility of the processing and onboard hardware, this implying complete elimination of the influence of one kind of technical means on the other. Quality parameters of electromagnetic energy are affected by any deviations of the parameters of voltage, current or frequency from the nominal values, this leading to disturbance of equipment functioning.

Electromagnetic incompatibility of technical means may influence their operating safety. It may lead to failure of the systems, ensuring the safety of operations (servomechanisms of the station, self-start of engines, spontaneous firing of pyrotechnical means, antenna pointing, etc.) or malfunctions of scientific and support hardware because of insufficient noise-immunity, or data loss in communications systems, etc.

Toxicity and inflammability of materials of processing equipment. When toxicity factor is considered, special attention should be given to selection of the material of processing equipment components, particularly, for that part, which is placed in the space vehicle compartments (cable lines, test systems, etc.), as otherwise their ignition or penetration of toxic substances into the environment may occur during the operator activity.

All the considered risk factors pertain solely to a specific, i.e. manual electron beam technology. Their negative influence, as well as the problem of reducing the adverse consequences for the operator activity and technological processes was comprehensively studied under various purpose-oriented programs and testing, using special integrated facilities by the scientists and specialists of Ukraine, Russia and the USA in preparation for performance of space projects — VHT (versatile hand tool, its first modification being EBHT), ISWE (International Space Welding Experiment) and «Flagman» (new modification of EBHT, «Universal» hardware). Results of these investigations are presented in the second part of this work.

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IMPROVEMENT OF EFFICIENCY OF LASER TREATMENT USING OFF-AXIS BEAMS FOCUSED BY MIRROR SYSTEMS

V.V. ROMAN
National Technical University of Ukraine «KPI», Kyiv, Ukraine

Method of forming space characteristics of a laser beam, based on a mathematical model of the process of radiation focusing using a spherical mirror and method of evaluation of effect of space characteristics of the laser beam on thermal state of the body being radiated, is suggested. With its use the optimum space distribution of heat source on the material surface is reached, resulting in the improvement of the efficiency of the laser treatment and widening of its technological capabilities.

Key words: *laser treatment, mirror systems, off-axis beams, beam power, efficiency*

It is known that at each kind of the laser treatment the beam has its optimum sizes, section shape and distribution of radiating power [1–3]. Taking into account that the existing tendency of use of the laser centers which can fulfill all the operations of the laser treatment on the base of one radiator [4], there appears a demand for use of a universal system for control of the beam space characteristics. Here, systems with minimum amount of optical elements are preferable [5]. However, at present there are no inexpensive and convenient devices in service which could be capable to control in the wide range the section shape of the beam and distribution of its radiating power [6].

To focus powerful laser beams the spherical mirrors are widely used. Figure 1 shows a focusing of the laser beam *1* of diameter D, power W and divergence Q, to a spherical mirror *2* with a radius of curvature R under angle α. In focusing of an off-axis laser beam by a spherical mirror two focuses are appeared: meridional F_1 and sagittal F_2 in which the radiation is formed in lines MN and NG (Figures 1 and 2), locating in two mutually perpendicular planes: sagittal F_2EG and meridional F_1AB, respectively. This leads to the distortions of the beam section shape and distribution of intensity in it. There is a tendency to decrease these distortions in laser treatment. At the present work, vice versa, the attempts were made to increase them for forming the space characteristics of the laser beam to improve its efficiency and to widen technological capabilities of the treatment.

Determination of space characteristics of the laser radiation, focused by a spherical mirror, and evaluation of their effect on thermal state of the material being radiated. To create a mathematical model of the process of focusing laser radiation by a spherical mirror, the factors characterizing the space structure, have been defined (Figure 1). Moreover, those factors were selected which should be taken into consideration in the creation of a mathematical model. They include space characteristics of initial

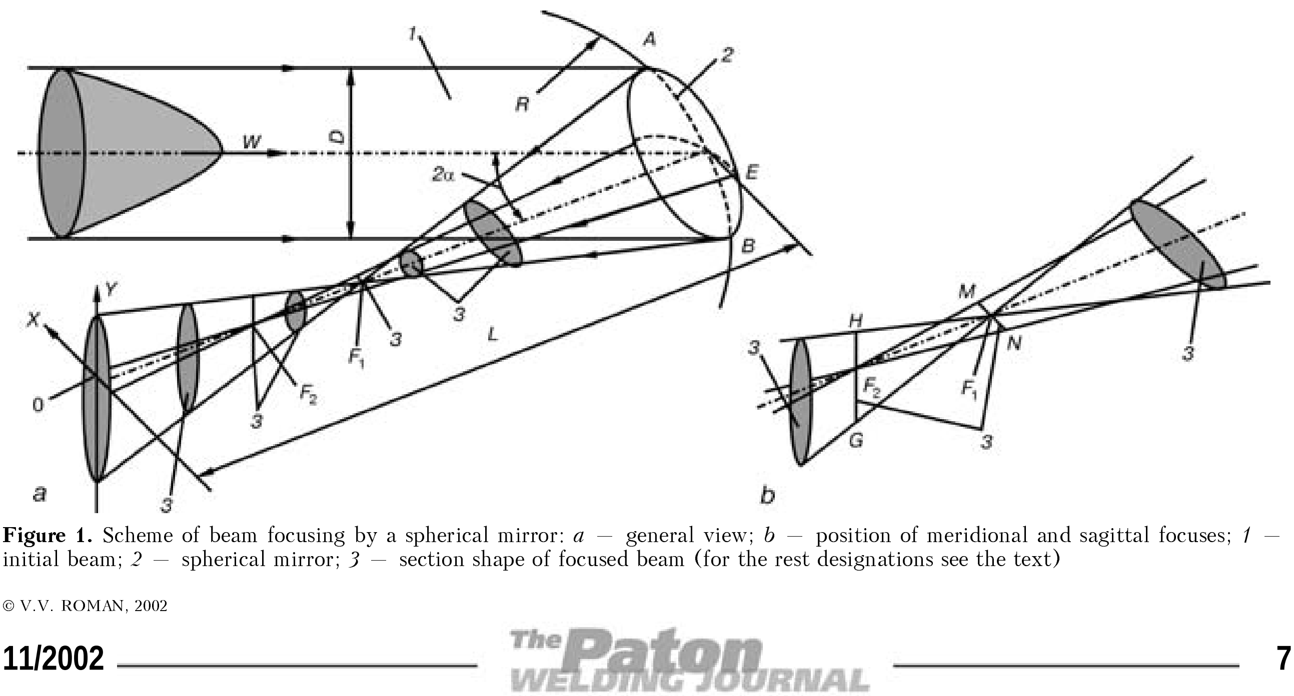

Figure 1. Scheme of beam focusing by a spherical mirror: *a* — general view; *b* — position of meridional and sagittal focuses; *1* — initial beam; *2* — spherical mirror; *3* — section shape of focused beam (for the rest designations see the text)

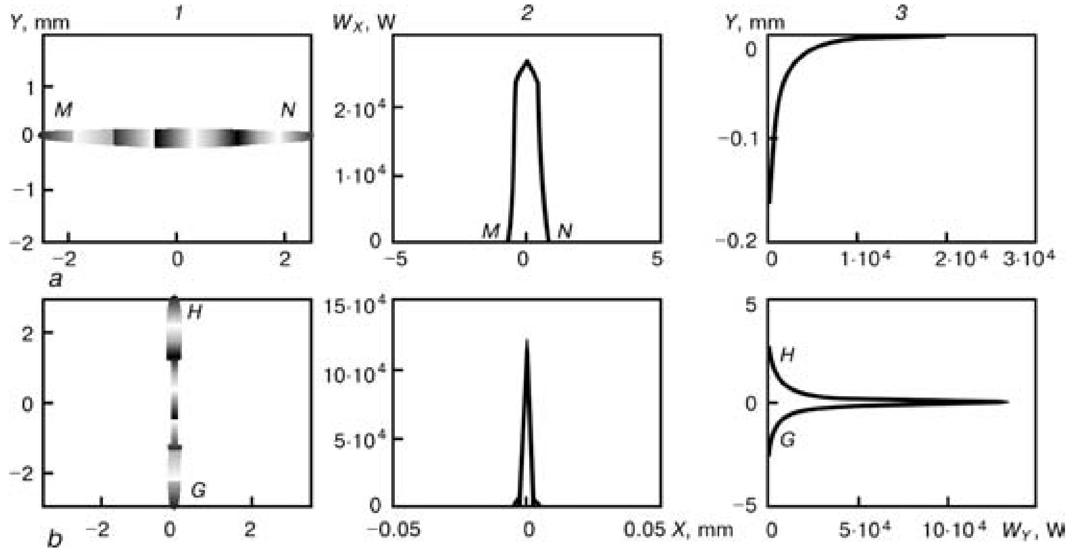

Figure 2. Space structures of laser radiation focused by a spherical mirror in meridional (*a*) and sagittal (*b*) focuses at D = 42 mm, R = 1600 mm, W = 1100 W, α = 20°, θ = 0 mrad at L = 751.5 (*a*) and 851 (*b*) mm: *1* — beam section in focuses; *2, 3* — distribution of power along axes Y and X, respectively

beam (θ, D, W), curvature radius R of mirror, angle of incidence α of radiating beam on it and distance L from the spherical mirror to workpiece.

Based on principles of geometric optics and scheme of «beam packet», a procedure was developed [7] for determination of distortions of section shape and distribution of focused beam power. Using this procedure the calculation of space structure is performed in the following sequence.

The initial laser beam is presented in the form of a packet of beams; direction of spreading of each beam packet is determined after their reflection from the spherical mirror; area of focusing is preset; the points of beams intersection with a plane of focusing are found (their set defines the focused beam section shape); power, concentrated in each packet element, is calculated; it is defined to which elements of focusing plane each of packet beams is entered, and power in any its point is calculated.

Results of experiments, carried out with a Gaussian beam at W = 3 W, θ = 0.75 mrad, α = 20° (Figures 3 and 4), correspond to a calculated model with accuracy of 15–20 %. As is seen from Figures 3 and 4, the sizes of beam section, obtained using a mathematical model, are somewhat lower than experimental sizes. This can be explained by the fact that the laser radiation during calculations was taken limited by an effective diameter of the Gaussian beam.

Using the model the process of laser radiation focusing by a spherical mirror was investigated. This allowed the regularities of distortion of the space structure of radiation to be defined and showed the feasibility of their change within the wide range (see Figures 2 and 3).

To have an optimum use of the laser beam with different space structures it is rational to determine their effect on the thermal state of the material radiated. For this purpose, a procedure was developed on the basis of a method of finite differences [8]. This procedure was used for the body whose shape can be described mathematically. It was possible to calculate the temperature fields occurring due to the effect of a beam with any space-time characteristics at the condition of temperature relationship between the properties of material being radiated and radiation penetration into its depth.

The above-described procedures proved the feasibility to control the thermal state of the workpiece within the wide range due to use of aberrations of the spherical mirrors and showed that change in direction of beam movement along the workpiece surface allows smooth change in rate of cooling the body at its surface from 500 to $3 \cdot 10^4$ K/s.

Focusing system for forming space characteristics of radiation. To realize the above recommendations a focusing system on the base of a spherical mirror [9], and also procedure of selection of its optical parameters and sizes of initial beam depending on the radiation characteristics, which should be obtained at the workpiece surface, were developed. In this system the spherical mirror fulfills two functions: traditional — it focuses radiation to a spot at a preset power density; non-traditional — it forms the space structure of the beam (Figure 5). The system operates as follows. A laser beam *1*, passing through a device for changing sizes of its section *2* (for example, telescopic system, diaphragm), enters a plane mirror *3* which can rotate around its axis, parallel to axis $0X$ and move along the direction of axis $0Z$. Being reflected from the plane mirror, the beam enters a spherical mirror *4* which rotates around tangent to a center of the reflecting surface of axis parallel to $0X$. Displacement of mirrors gives an opportunity to change the angle of incidence α on spherical mirror. Mirror *4* directs the laser beam to the surface *5* being treated. The device is arranged on a mobile platform which can move along the axis $0Z$, that gives an opportunity to change the distance L from the spherical mirror to the focusing plane *5*. The change in curvature radius R of mirror *4* was attained by its replacement.

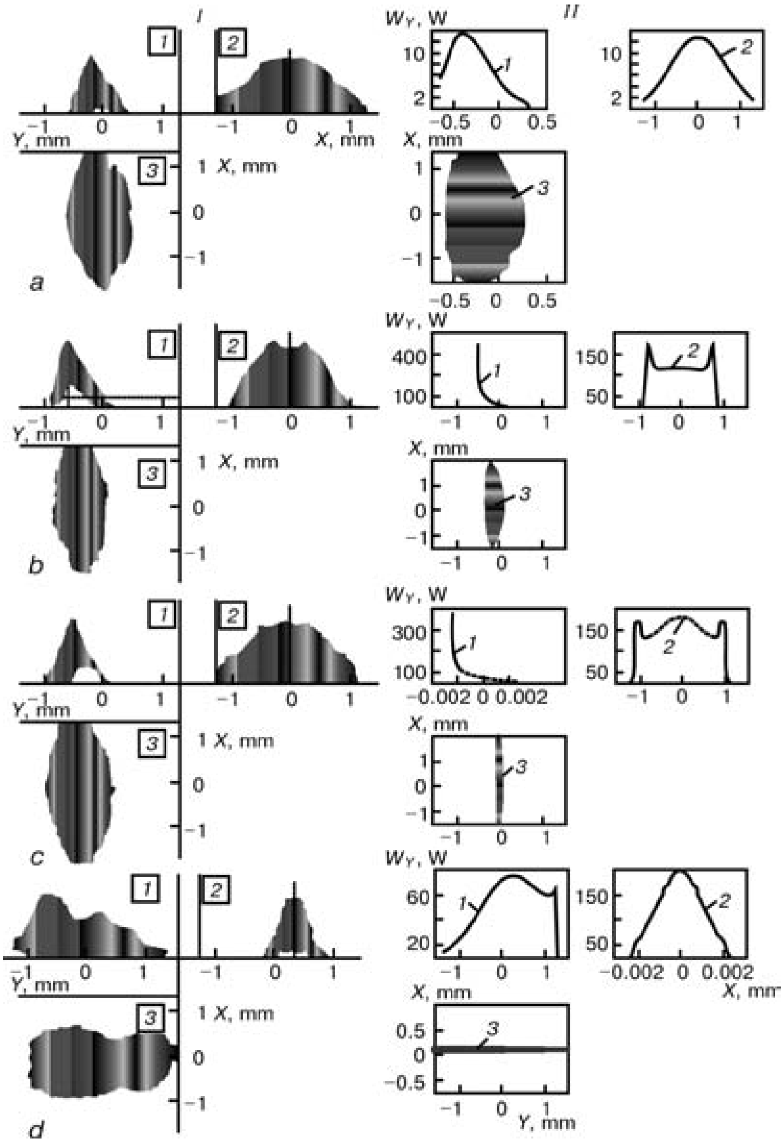

Figure 3. Space structures of laser radiation, focusing by spherical mirror, with a Gaussian distribution of power of experiment (*I*) and calculations (*II*) at D = 42 mm, R = 1600 mm, W = 1100 W, α = 20°, θ = 0.75 mrad at L = 743 (*a*), 750 (*b*), 754 (*c*) and 850 (*d*) mm: *1* — beam section at the surface of treatment; *2, 3* — distribution of power along axes Y and X, respectively

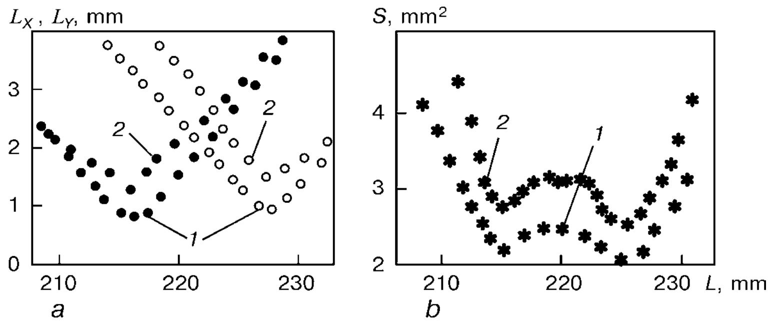

Figure 4. Dependence of sizes of beam section L_X, L_Y (*a*) and area S (*b*) on distance L between spherical mirror and focusing plane obtained with the help of calculations (*1*) and experiment (*2*) at D = 15 mm, R = 450 mm, W = 3 W, α = 20°, θ = 0.75 mrad: ●, ❍ — sizes of beam along the axis Y and X, respectively; ✱ — beam section area

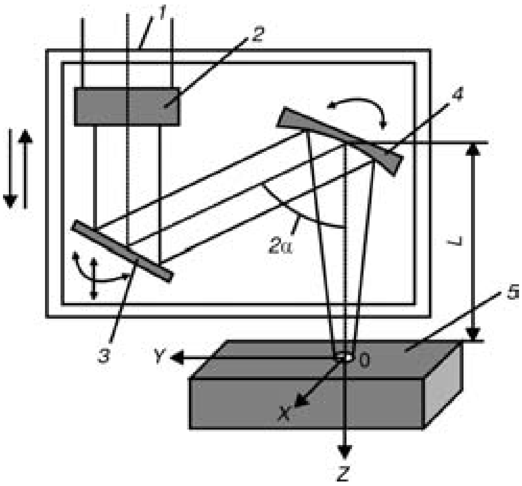

Figure 5. Scheme of device for laser beam focusing into a spot with preset characteristics (see designations in the text)

The efficiency of the developed optical system was tested at a laser strengthening, alloying and cladding. Here, the beams with uniform distribution of power across the section and with a shifted position of its maximum relative to a center (workpiece was arranged near a meridional focus of the spherical mirror (see Figure 3, *b*) were used for comparison).

The use of the beam with a maximum at the leading front and steep trailing front (at density of radiation power $W_r = 1.9 \cdot 10^4$ W/cm^2, rate of beam movement $v = 33$ mm/s, $\alpha = 20°$, $R = 1600$ mm, $D = 41$ mm, $L = 745$ mm, $\theta = 5$ mrad) after treatment made it possible to obtain more homogeneous layer and to avoid the formation of cracks in it at strengthening of matrices and punches of dies, made from steel U10 (wt.%: 1.0C; up to 0.15Cr; 0.25Mn) (Figure 6, *a, b*) and also in case of alloying blades of gas turbines (from steel ZhS6K, wt.%: 10.0Co; 5.0Mo; 5.0W; 2.5Ti; 5.5Al; Ni — base) with powder KhTN (12Kh18N10T (wt.%: up to 0.12C; 17.0–19.0Cr; 9.0–11.0Ni), TiB, CrB), parameters of beam were: $W_p = 2.3 \cdot 19^5$ W/cm^2, $v = 20$ mm/s, $\alpha = 15°$, $R = 1600$ mm, $D = 41$ mm, $L = 770$ mm, $\theta = 5$ mrad.

In case of surface strengthening of gear wheels of an oil pump made from cast iron (at $W_p = 6 \cdot 10^3$ W/cm^2, $v = 8.5$ mm/s, $\alpha = 25°$, $R = 1600$ mm, $D = 41$ mm, $L = 722$ mm, $\theta = 5$ mrad), the use of similar scheme of treatment produced a homogeneous strengthened layer at a large depth (Figure 6, *c, d*). In the transition zone the change in hardness was not so abrupt as compared with treatment using a beam with a uniform power distribution.

The use of beam with a non-uniform power distribution (at $\alpha = 20°$, $R = 1600$ mm, $D = 42$ mm, $L = 745$ mm, $\theta = 5$ mrad) could also prevent the crack formation, 1.4 times decrease the compressive stresses and 2.2 times decrease the tensile stresses in deposited beads of self-fluxing alloys (KhTN and PG-SR4 (wt.%: 0.2–0.5C; 12.0–15.0Cr; Ni — balance)) on steel base (steel 45 (0.45 wt.% C; Fe — balance)) (Figures 6, *e, f*, and 7). Stresses were measured in 80×754 mm samples using a method of layer-by-layer etching [6].

Coming from the above-mentioned the following conclusions can be made. Optimum space characteristics of beam for laser strengthening can be obtained at a large angle of radiation incidence on spherical mirror ($\alpha > 20°$) and arrangement of workpiece surface near the meridional focus (see Figure 3, *b*). This gives an opportunity to perform treatment of a wide band and to obtain a uniform strengthened layer. The direction of beam movement should be selected so that, at first, its part, having a minimum intensity, was acting and then a part of maximum intensity was used to increase the absorptivity of surface due to heating and oxidizing, and, consequently, to use more effectively the radiation energy.

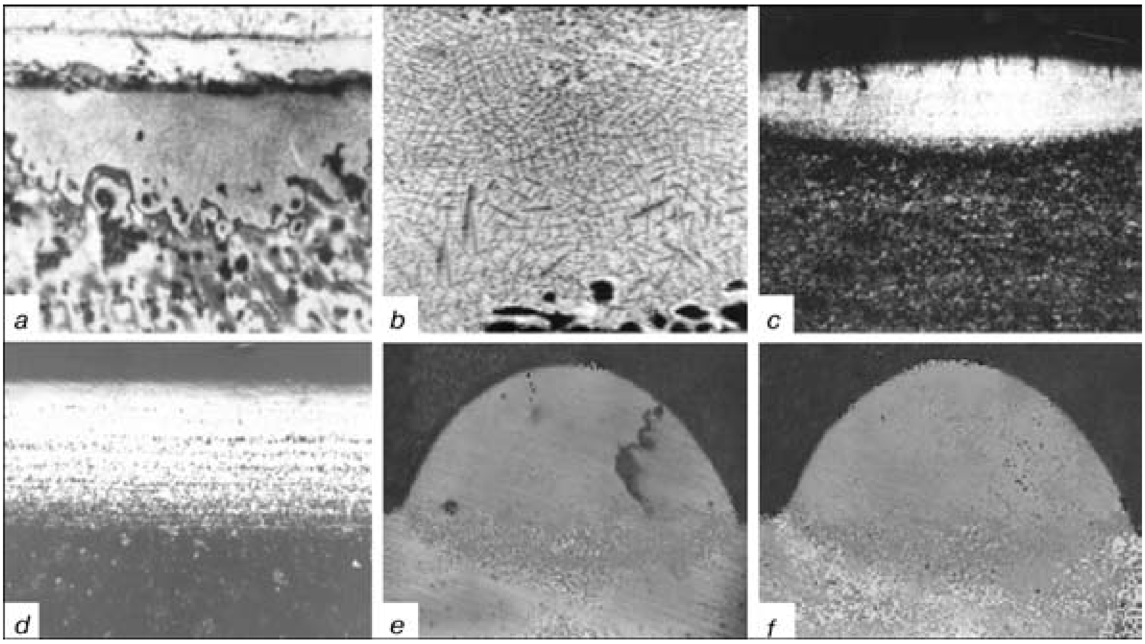

Figure 6. Microstructure of strengthened layers in steel U10 (*a, b*) (×160), cast iron (*c, d*) (×160) and macrostructure of deposited beads on St. 45 (*e, f*) (×32): *a, c, e* — beam with uniform power distribution; *b, d, f* — profiled beam

In treatment of materials, whose primary structure contains carbon in a compact form (for example, in the form of a spheroidal graphite), the use of similar distribution of power is rational. However, at an opposite scheme of treatment it is necessary, to use, firstly, a part of beam section with a maximum power and, then, with minimum power. Due to this, the rate of the workpiece cooling is decreased and the time of material holding at a fixed temperature is increased that leads to a more complete proceeding of diffusion process (more complete distribution of carbon) and, as consequence, promotes the formation of a homogeneous strengthened layer at a large depth and more abrupt change in hardness in the transition zone.

In cladding, the existing of a high gradient temperature in depth of zone of thermal action of beam can cause the crack formation in deposited beads and material of the base. To decrease the probability of their appearance it is rational to use the scheme of treatment and space characteristics of the beam similar to the above-mentioned case, but at a high power density. Due to decrease in cooling rate the crystallization of upper zones occurs when the lower layers are still in a plastic state. Owing to this the feasibility of proceeding of relaxation process is appeared.

The separation of brittle materials by a method of laser thermal splitting is rational when the workpiece is located in a sagittal focus (at $\alpha = 10°$, $R = 1600$ mm, $D = 41$ mm, $L = 812$ mm, $\theta = 5$ mrad), where the radiation section has an elongated shape with a power maximum in the center. In this case during the beam movement along the axis $0Y$ a constituent normal to the direction of splitting is dominated in the configuration of thermal stresses.

To have a maximum of temperatures in the zone of bodies contact in butt welding of plates from dissimilar metals it is necessary to shift the maximum of laser beam power to the more heat-conductive material [3], i.e. to use a beam which is formed by a spherical mirror near the meridional (see Figure 2, *a*) or sagittal (see Figure 3, *d*) focuses (at $\alpha = 25°$, $R = 1600$ mm, $D = 41$ mm, $L = 726$ or 875 mm, $\theta = 5$ mrad). The direction of beam movement should be parallel to axis $0X$.

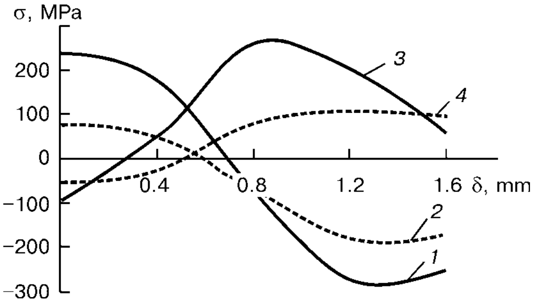

Figure 7. Residual stresses in beads produced in cladding with powders PG-SR4 (*1, 2*) and KhTN (*3, 4*): *1, 3* — non-profiled beams; *2, 4* — profiled beams

Similar space characteristics of radiation at the material surface are rational to use in strengthening of workpieces with limited conditions of heat dissipation (wedge), that allows creation of almost uniform distribution of temperature in the workpiece.

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FORMATION OF CRYSTALLOGRAPHIC TEXTURE IN THE METAL OF WELDED JOINTS ON MOLYBDENUM ALLOYS

B.A. ZADERY, S.S. KOTENKO, A.E. MARINCHENKO, E.P. POLISHCHUK and **K.A. YUSHCHENKO**
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Influence has been studied of high-temperature annealing and heating by the welding arc on the processes of formation of crystallographic texture in the HAZ of sheet molybdenum alloys TsM-10, TsM-12 and MI-5. It is shown that in a low-alloyed molybdenum alloy TsM-10 the initial deformation texture of (001) $[\bar{1}10]$, (112) [110] and (111) $[2\bar{1}1]$ type is practically preserved in the HAZ and weld metal. In alloyed molybdenum alloys TsM-12 and MI-5 the initial deformation texture of (001) [110], (001) [100] and (111) [211] type in the HAZ is gradually transformed into crystallographic texture of (111) [112] and [110] type, and this texture type is preserved in the weld metal.

Key words: *crystallographic texture, pole figures, welded joints, molybdenum alloys, temperature, annealing*

Cold brittleness temperature of welded joints in molybdenum alloys may vary in rather broad ranges, namely from 200 (for molybdenum alloy TsM-6) up to more than 600 K (for alloy TSM-3). Since sheets of molybdenum alloys with a strictly specified content of alloying elements and interstitial impurities were selected to produce the welded joints, and welding proper was conducted under conditions, which eliminated the possibility of weld metal saturation with impurities from the gas atmosphere, the existence of a range of cold brittleness temperatures for material of the same composition becomes impossible to understand.

In this connection it is natural to assume that low-temperature ductility of welded joints, made on sheet molybdenum alloys without using a filler, is to a certain extent determined by the structural state of the initial material. The structural state will be assumed to mean not only the purely structural factors (size of grain or cell), but also the crystallographic and mechanical textures, formed in the sheet during its manufacture, as well as when making the welded joint.

In polycrystalline materials with randomly oriented crystallites the elongation is lower, and the yield strength is higher than the average yield strength of individually considered crystallites [1]. The cause for that is the action of different slip systems in individual crystallites of different orientation. At deformation without fracture, not always the most favourable slip systems may be acting on grain boundaries. As a result, higher stresses are required to initiate the slipping process. On the other hand, at the same or close orientation of adjacent crystallites in relation to the direction of force action, they develop equivalent stresses. Therefore, polycrystalline materials with a favourable crystallographic orientation will, as a rule, have a higher ductility than materials with the static distribution of grain orientations.

In welding of sheet molybdenum alloys or surfacing with deposition of small volumes of molten material on a narrow surface, a two-dimensional schematic of weld pool solidification should be implemented. In this case, solidification nuclei are partially melted grains of the initial material. The crystallites of weld metal may, to a certain extent, inherit the crystallographic orientation of those crystals, from the surface of which their growth started. That is why the presence of different orientations of the initial material grains will promote formation of different types of crystallographic textures in the weld metal and, as a result, will be accompanied by a change of the level of physico-mechanical characteristics.

Crystallographic texture of welded joints of low-alloyed molybdenum alloys MLT, TsM-6, MChVP was considered in [2]. It is established that for the first two alloys the main component of texture of the initial wrought material is (001) [110], and for alloy MChVP — {111} <110> <112>. At transition from the base metal to that of the HAZ, a texture of (001) [110] type is transformed into the one close to (001) [130]. The weld retains the texture of partially melted grains, from which weld metal solidification begins. In MChVP alloy the main components of {111} <110> <112> texture are preserved in transition from the base metal to weld metal through that of the HAZ.

This work deals with the conditions of formation of the crystallographic texture in alloyed molybdenum alloys TsM-12 and MI-5 and the most pure molybdenum alloy TsM-10. Composition of the alloys is given in Table 1.

Immediately before welding the samples of molybdenum alloys were preheated by the arc up to the temperature above the recrystallisation temperature.

Radiographic texture analysis was conducted for those planes of the welded joint, where the grain size corresponded to the size of grains, produced in the studied alloys after their annealing at temperature from 1300 to 2300 K (Figure 1). The HAZ metal in welding of a pre-annealed, deformed by rolling molybdenum alloy TsM-10 or preheated sheets of alloys MI-5 and TsM-12 revealed a gradual change of the structural element size from 2–5 μm in the initial material to 200–1100 μm at the fusion line.

Pole figures of planes {110} of different sections of a welded joint in alloy MI-5 are shown in Figure 2. Table 2 gives the main components of textures for alloys, annealed at different temperatures, and for metal of welded joint HAZ in the sections with an appropriate grain size.

As follows from the presented data, the main component of the textures of molybdenum, alloyed with rhenium (MI-5), does not undergo any significant changes either during hour annealing in the temperature interval of 1300–2300 K, or in different sections of the HAZ.

Figure 3 shows the pole figures of planes {110} of different sections of a welded joint of alloy TsM-12.

Pole figures of molybdenum alloy TsM-10 after annealing at different temperatures are shown in Figure 4. As follows from the figure, the texture of the considered alloy in the initial condition is typical for most of the alloys with bcc lattice and is in good agreement with the data of [3, 4]. Indeed, the initial condition texture is characterised by the following components (Figure 4, *a*): a very strong component (001) [110] and less strong components (112) [110] and (111) [uvw]. After annealing at the temperature of complete recrystallisation, which leads to a replacement of a cellular structure by a granular one with the grain size of 40–100 μm, the shape of pole figures is mainly unchanged, just a considerable lowering of the maximums of pole density occurs, and the scattering is enhanced, i.e. the texture of a sheet, annealed at the temperature of 1400 K, is characterised by a set of the following components: (001) [110] + (112) [110] + (111) [uwv].

Further increase of annealing temperature is accompanied by the change of the shape of pole figures, namely splitting of the maximums, and the ratio of orientations is changed. The final texture is characterised by very strong components: (001) [110]; (112) [110]; (111) [110]; (111) [211] and (112) [233]. An increase of the intensity of texture extremums was found in this case, this being due, most probably, to lowering of the number of imperfections of the crystallographic lattice. It should also be noted that at high-temperature annealing (111) [110] orientation is much more developed than (111) [112].

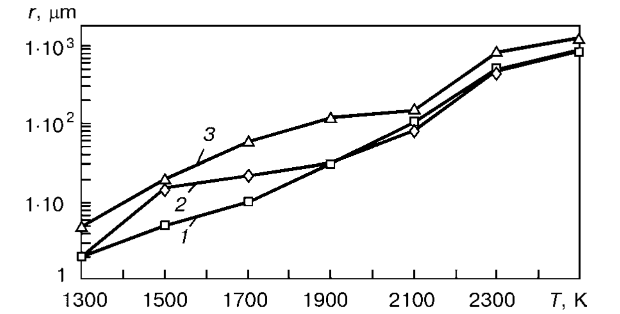

Figure 1. Change of grain size *r* of molybdenum alloys in the HAZ metal in welding: *1* — MI-5; *2* — TsM-12; *3* — TsM-10

From the data given in Figures 2, 3 and in Table 2 it follows that both annealing at different temperatures and the corresponding to these temperatures grain sizes of the plane in the HAZ in welding of a molybdenum alloy are accompanied by a similar nature of change of the crystallographic structure.

If in the initial condition the main components of the texture are (001) [112] and (001) [110], after annealing at 1900 K, leading to complete recrystallisation, this texture turns into a texture of (111) [110] type. At further increase of annealing temperature or transition to HAZ with a higher heating temperature, this type of crystallographic texture is preserved.

Investigation of the texture of columnar crystallites in the cast weld metal, conducted for different materials [5, 6], showed that the columnar crystallites form normal to the front of the isotherms of cooling of the weld pool molten metal, and their growth coincides predominantly with [100] direction. In molybdenum the surface energy of plane (001) is minimal and this, in particular, leads to brittle cleavage of the crystals proceeding along planes (001). Therefore, in case of weld pool solidification under the conditions of a limited volume of the molten metal and realisation of a two-dimensional solidification front, on a substrate of partially melted grains of the initial molybdenum alloy, a predominant growth of columnar crystallites in direction [100] is anticipated. This was exactly what was found for a relatively pure in terms of interstitial impurities and low-alloyed molybdenum alloy (TsM-10).

However, in molybdenum alloys, alloyed with rhenium (MI-5) or zirconium and hafnium (TsM-12), where the HAZ metal forms a structure with plane (111), this texture is preserved in the weld metal due to solidification on a substrate of partially melted grains along the fusion line. Direction of formation of weld metal crystallites, in keeping with the shape of cooling isotherms is turned by 20–30° from the

Table 1. Composition of molybdenum alloys

Alloy	*Weight fraction of elements, %*								
	Re	*Zr*	*Hf*	*Al*	*B*	O_2	N_2	*C*	H_2
TsM-12	–	0.12	0.15	–	0.002	0.002	0.0006	0.003	0.0004
MI-5	4.5	–	–	–	0.002	0.002	0.0004	0.003	0.0004
TsM-10	–	–	–	0.007	0.002	0.002	0.0050	0.003	0.0004

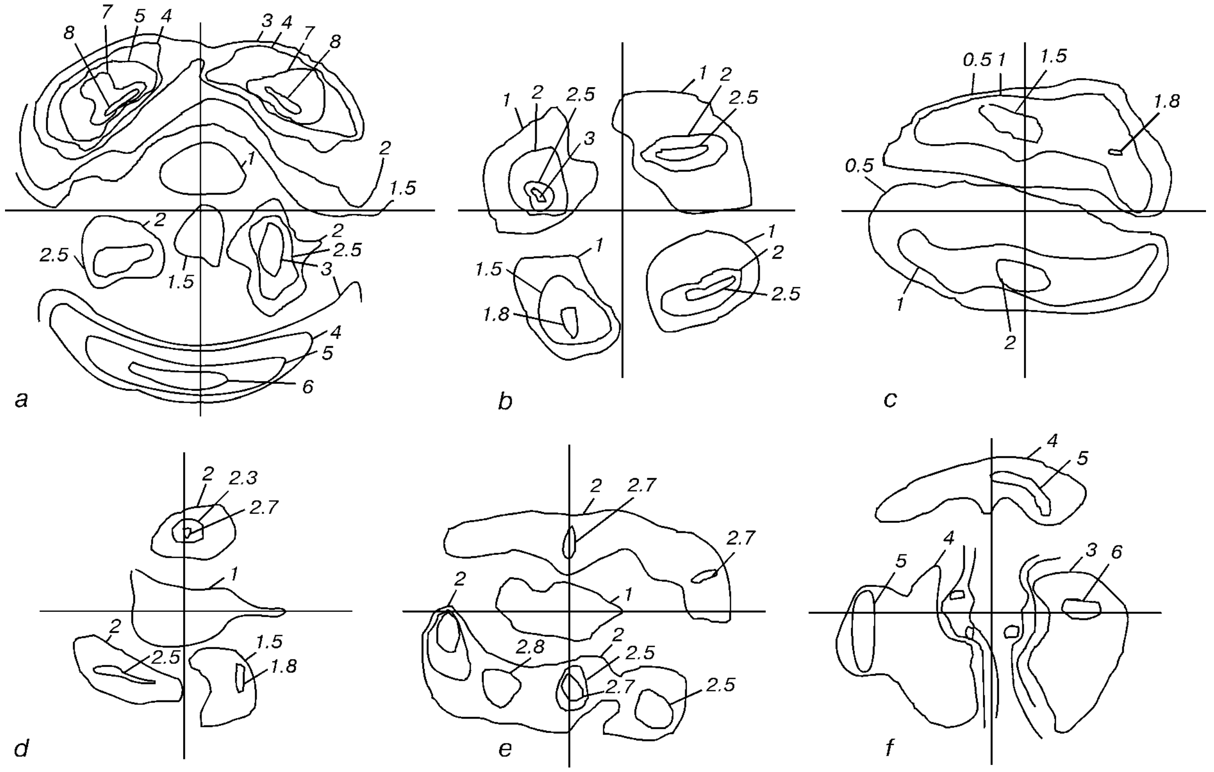

Figure 2. Pole figures of planes {110} of different sections of the HAZ of welded joint in alloy MI-5 with the following maximal temperature: *a* — 1300; *b* — 1500; *c* — 1700; *d* — 1900; *e* — 2100; *f* — 2300 K (here and further on the numbers give the intensity of pole density)

normal to the weld axis. Normal to isotherm front is direction [$\bar{2}$11] or [011], and the closest direction <100> makes a comparatively high angle (35 or 45°, respectively) with the direction of growth of the crystallites and does not belong to the sheet plane. Under these conditions, the columnar crystallites of weld metal inherit the crystallographic texture of partially melted grains of the fusion line, i.e. grow along direction [211] or [110].

Thus, annealing of molybdenum sheets, deformed by rolling, or their pre-heating prior to welding, promote formation of a crystallographic texture with the main component of (111) [110] and [112] in the HAZ metal during welding, which is preserved in the weld metal. Obtained experimental data reveals the influence of preliminary heat treatment and preheating on the mechanical characteristics of welded joints on molybdenum alloys.

Table 2. Main components of textures of alloys MI-5 and TsM-12

T_{aw}, K	Base metal	Corresponding plane of the HAZ
	Alloy MI-5	
1300	(011) [100], (111) [2$\bar{1}$1], (001) [110]	(113) [1$\bar{1}$0], (111) [211]
1500	(111) [110], (001) [110], (112) [233]	(001) [110], (111) [110]
1700	(001) [100], (112) [211], (112) [1$\bar{1}$1]	(111) [1$\bar{1}$2]
1900	(111) [2$\bar{1}$1], (111) [1$\bar{1}$0]	(111) [112], (111) [1$\bar{1}$0]
2100	(001) [110], (111) [110], (112) [1$\bar{1}$1]	(111) [112], (113) [110], (001) [110]
2300	(111) [110], (112) [233], (001) [110]	(111) [112], (111) [112], (112) [233]
	Alloy TsM-12	
1300	(011) [100], (111) [2$\bar{1}$1], (001) [520]	(001) [110], (112) [110]
1500	(001) [110], (111) [1$\bar{1}$0]	(001) [110]
1700	(001) [110], (1$\bar{1}$1) [1$\bar{1}$0]	(001) [110], (112) [110]
1900	(111) [112], (112) [110]	(111) [110]
2100	(111) [112], (112) [233]	(111) [112], (001) [110]
2300	(111) [110], (111) [211], (001) [100]	(111) [112], (111) [110]

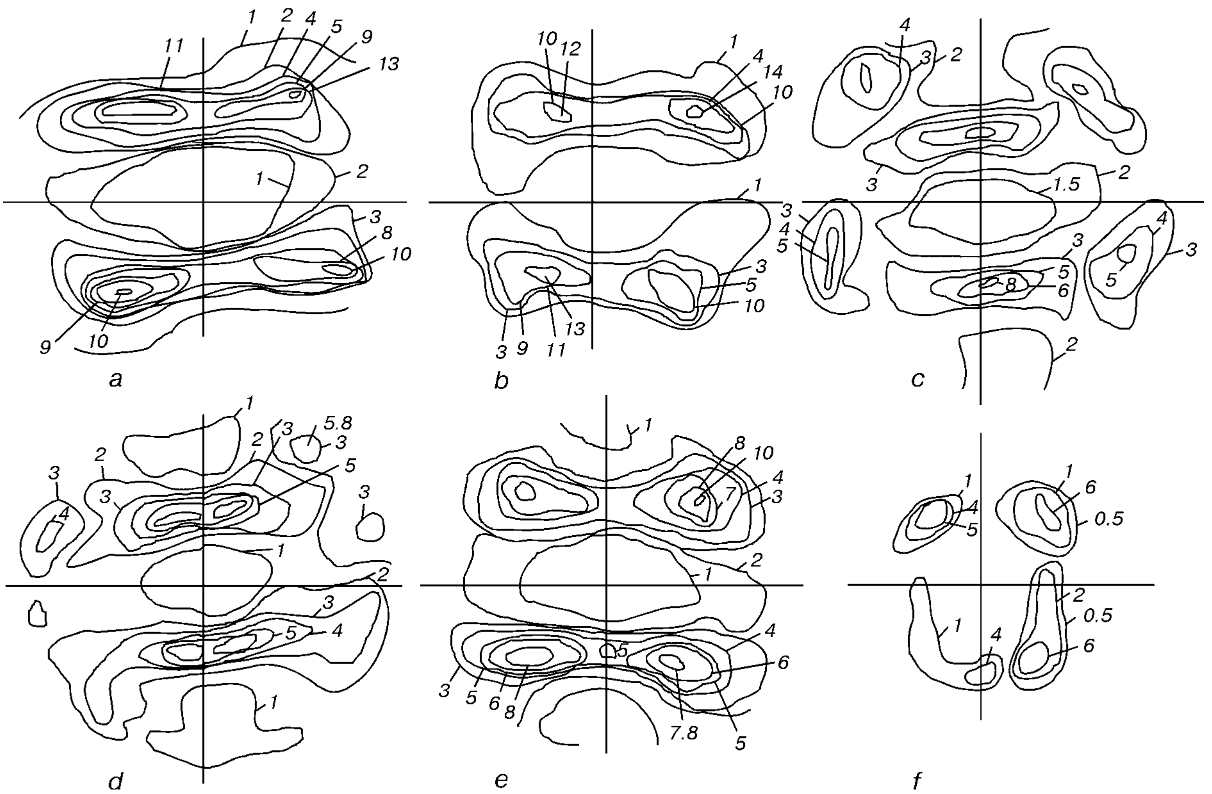

Figure 3. Pole figures of planes {110} of different sections of the HAZ of welded joint in alloy TsM-12 with the following maximal temperature: *a* — 1300; *b* — 1500; *c* — 1700; *d* — 1900; *e* — 2100; *f* — 2300 K

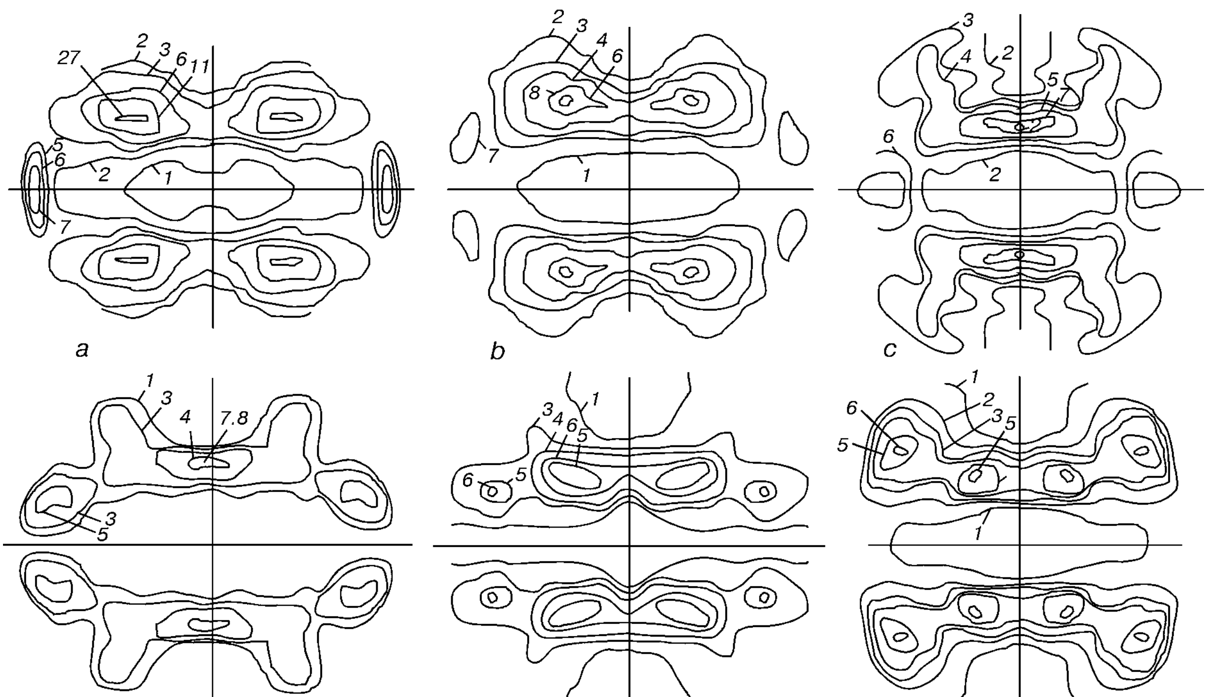

Figure 4. Pole figures of planes {110} of molybdenum alloy TsM-10 after different annealing temperatures: *a* — 1100; *b* — 1200; *c* — 1300; *d* — 1400; *e* — 1500; *f* — 1600 K

At high-temperature annealing the base metal forms a texture of {111} <110> and <112> type, which is fully inherited by the weld metal. Preheating and heat impact of the arc on the HAZ during welding also lead to formation in it of crystallographic texture {111} <110> and <112> near the fusion line, and, as a result, textures of the same type in the weld metal. In other words, irrespective of the initial crystallographic texture ((001) [112] and (111) [211] — alloy TsM-12, or (001) [110], (001) [100] and (111) [112] — alloy MI-5) during annealing at temperatures above 1900 K and during welding with preheating, one type of crystallographic texture forms, namely {111} <110> and <112>.

Inheriting the crystallographic texture of the base metal by that of the welded joint during welding in the case, when no noticeable change of the alloy composition occurs, is accompanied by an inter-relation of the physico-mechanical characteristics of the initial material and the welded joint. Figure 5, *a* shows the dependence of cold brittleness temperature of the base material, determined on samples, cut out at different angles to the direction of rolling of molybdenum alloy sheets, and Figure 5, *b* shows the same dependencies for welded joints.

Since base metal samples and samples for welding were cut out of the same sheet, it may be assumed that their composition, content of interstitial impurities and structural state remained the same, and just the crystallographic orientation at external pressure application changed in bend testing to determine the cold brittleness temperature.

In the case, when low-temperature ductility (of initial base metal) of textured molybdenum alloys is determined by the type of the crystallographic structure, and the welded joint metal inherits the crystallographic orientation of partially melted grains in the fusion zone, it should be assumed that the minimal cold brittleness temperature of the welded joint will correspond to that of the base metal. However, as shown by comparative analysis of the obtained results (Figure 5), minimal cold brittleness temperature of the base metal corresponds to longitudinal samples, and minimal cold brittleness temperature of welded joints was derived on samples, welded at an angle of 90° to the direction of rolling. This discrepancy is due to the fact that in welding of transverse samples crystallographic orientations of longitudinal samples form in the solidifying metal of the weld pool.

CONCLUSIONS

1. It is found that at high-temperature treatment and fusion welding of low-alloyed molybdenum alloy TsM-10 the HAZ metal forms a strong crystallographic (001) [110] and weaker (112) [$\bar{1}$11] and

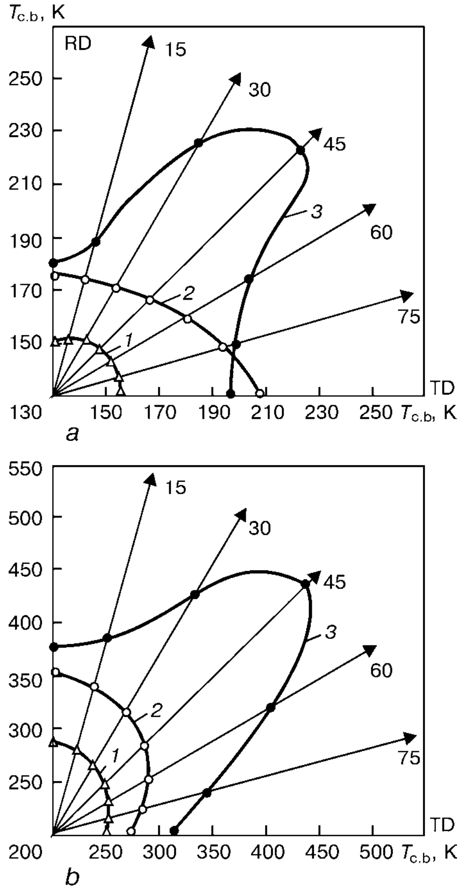

Figure 5. Dependence of cold brittleness temperature $T_{c.b}$ of molybdenum alloys on the angle of cutting out the samples in the direction of welding: *a* — base metal; *b* — welded joint; *1* — MI-5; *2* — TsM-10; *3* — TsM-12 (RD — rolling direction, TD — transverse direction)

(111) [2$\bar{1}$1] textures at the fusion line, which are inherited by the weld metal crystals.

2. It is established that in alloyed molybdenum alloys TsM-12 and MI-5 the initial (001) [112] and (001) [110] texture of the wrought sheet is transformed during high-temperature treatment or welding into a texture of the type of {111} <110> and <112>, which is fully inherited by the weld metal.

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EFFECT OF ALLOYING ELEMENTS ON STRUCTURE OF COMPOSITE ALLOY BASED ON TUNGSTEN CARBIDES

A.I. BELY, A.P. ZHUDRA and **V.I. DZYKOVICH**
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Data on the effect of alloying elements (niobium, vanadium, titanium) on the proportion of phases which form the composite alloy matrix during plasma surfacing are given.

Key words: *plasma surfacing, filler material, composite alloy matrix, reinforcing particles*

In plasma surfacing with a composite alloy based on fused tungsten carbides, using the electrically neutral filler material in the form of a tungsten carbide strip, the main structural components of the matrix are solid solution of tungsten in iron, eutectic and complex iron-tungsten carbides [1]. These phases are formed as a result of dissolution of reinforcing grains. The latter are the eutectic alloy of tungsten mono- and semi-carbides $WC-W_2C$. The above dissolution leads to saturation of the matrix melt with carbon and tungsten [2].

As established in the previous studies dedicated to deoxidation of metal of the molten pool in plasma surfacing with composite alloys, the degree of dissolution of the reinforcing particles decreases with silicon, manganese and aluminium added to the filler material [2, 3]. However, metallographic examinations of the deoxidised and non-deoxidised matrices reveal a substantial amount of secondary iron-tungsten carbides 20–30 μm in size and coarse eutectic the presence of which leads to embrittlement of the matrix. This is indicative that deoxidation alone is not enough for deposition of the composite alloy having the required performance.

Quantitative evaluation of structural components was conducted using analyser EPIQUANT to find a more accurate characteristic of matrix and predict wear resistance of the composition as a whole. The tungsten content of phases was determined by X-ray microanalysis. Results of evaluation of the quantitative amount of phases in the matrix are given in Table 1.

The main source of formation of unfavourable phases in the form of iron-tungsten carbides Fe_2W_2C, Fe_4W_2C and Fe_3W_3C, as well as coarse eutectic, is carbon, i.e. the product of dissolution of the reinforcing grains. Therefore, one of the promising ways of forming the required structural arrangement of the matrix is to alloy the melt with elements having a higher affinity for carbon, compared with iron and tungsten, to take carbon from the formed secondary iron-tungsten carbides and form their own carbide with a smaller specific volume. This principle is widely used to improve mechanical properties of tool steels containing 3–5 % chromium, in addition to tungsten [4, 5].

Considering a number of elements in a decreasing order of their affinity for carbon (titanium, niobium, vanadium, tungsten, molybdenum, chromium, iron) [4] shows that the most active of them are vanadium, niobium and titanium. These elements were added to the charge of a filler material in the form of ferrovanadium, ferroniobium and ferrotitanium. Attempts to use other components characterised by a higher content of the required elements, scarcity and increased cost failed to give positive results.

The content of ferroalloys was selected so that the mass fraction of vanadium, niobium and titanium in the composite material matrix is 0.5 to 5.0 %. The upper limit of alloying is attributable to increase in volume of the matrix in the total volume of the composition caused by a high iron content of ferroalloys.

The samples deposited were examined by the above procedure and using the JEOL scanning electron microscope JSM-T200. It was found that the above alloying elements had a positive effect on formation of matrix and its structural components.

Increase to 2 % in the niobium content of components used to form the matrix leads to increase in the effect of niobium on structural components, and at a content of niobium equal to 2–3 % it has the highest effect which shows up in decrease in the content of

Table 1. Effect of deoxidising elements on the content of phases which form the composite layer matrix

Structural component	*System investigated*	*Amount of phases in matrix, vol.%*	*Tungsten content of phases, wt.%*
Solid solution of tungsten in iron	Fe–W–C	24–26	10–16
	Fe–W–C–Al–Si–Mn	33–35	9–14
Eutectic	Fe–W–C	52–54	36–48
	Fe–W–C–Al–Si–Mn	46–48	35–44
Secondary carbides Fe–W–C	Fe–W–C	21–23	68–74
	Fe–W–C–Al–Si–Mn	18–20	68–74

Table 2. Effect of alloying elements on the tungsten content of structural components of the composite alloy matrix

Structural component	*Alloying element*	*Content, vol.%*		*Tungsten content of phases, wt.%*
		Reinforcing particles in alloy	*Components in matrix*	
Solid solution of tungsten in iron	Nb	46	44–49	11–15
	V	48	46–51	12–16
	Ti	47	59–63	9–11
Eutectic	Nb	46	46–50	33–42
	V	47	47–49	30–43
	Ti	48	31–35	29–40
Secondary carbides Fe–W–C	Nb	46	7–11	67–72
	V	47	4–8	66–71
	Ti	48	2–5	54–69

secondary iron-tungsten carbides 20–25 μm in size, compared with a non-deoxidised matrix, as well as in increase in the share of solid solution of tungsten in iron (Table 2). Structure of the composite alloy in back-scattered electrons and distribution of tungsten in matrix alloyed with niobium in the characteristics radiation of NK_α are shown in Figure 1, *A1*, *B1*.

The presence of 1.0–1.5 % vanadium in the matrix-forming components favours formation of the alloy matrix with a more finely dispersed structure. At 1.5–2.5 % vanadium its effect shows up in reduction of sizes of secondary iron-tungsten carbides to 12–15 μm, the majority of which are formed near the reinforcing grains, i.e. in the zones which are most saturated with their dissolution products. Decrease in the content of the said carbides and increase in the share of solid solution of tungsten in iron to 46–51 % (Table 2, Figure 1, *A2, B2*) were also revealed. It should be noted that the amount of tungsten in all the components hardly changes in alloying with either niobium or vanadium. In the case of increase in the vanadium content to more than 2.5 %, no marked effect of this element was established, except for increase in the volume of the matrix melt.

Addition of 1.0–1.5 % titanium to the filler material components favours formation of structural components, like niobium and vanadium do, i.e. the degree of dispersion of the matrix is increased. Further increase in the titanium content to 1.5–3.0 % leads to a dramatic improvement in the matrix quality. Size and quantity of secondary iron-tungsten carbides in the matrix are decreased. Their insignificant amount (less than 10 μm in size) was detected in close vicinity to the boundary of the reinforcing grains.

In addition, as proved by X-ray microanalysis, increase in the titanium content of the structure characterised by a small volume and composition close to titanium carbide takes place in the above zone. This confirms prediction of combining carbon, i.e. the product of dissolution of the reinforcing particles. Addition of 1.5–3.0 % titanium to the filler material has a positive effect also on other structural components. Eutectic becomes more finely dispersed and is distributed over the entire volume of the matrix (Figure 1, *A3, B3*). Also a more substantial decrease in its content of the matrix was noted, compared with the matrix alloyed with niobium and vanadium. At the same time, no decrease in the tungsten content of eutectic was detected. As to the solid solution of tungsten in iron, a substantial increase in its amount in the total matrix volume was fixed, i.e. to 59–63 % (Table 2).

It should be noted that an average tungsten content of the deoxidised matrix is 33–36 %. With addition of up to 1.5 % of the said elements to the filler material, the most favourable effect on decrease in the tungsten content is exerted by vanadium, then go niobium and titanium. With further increase in the

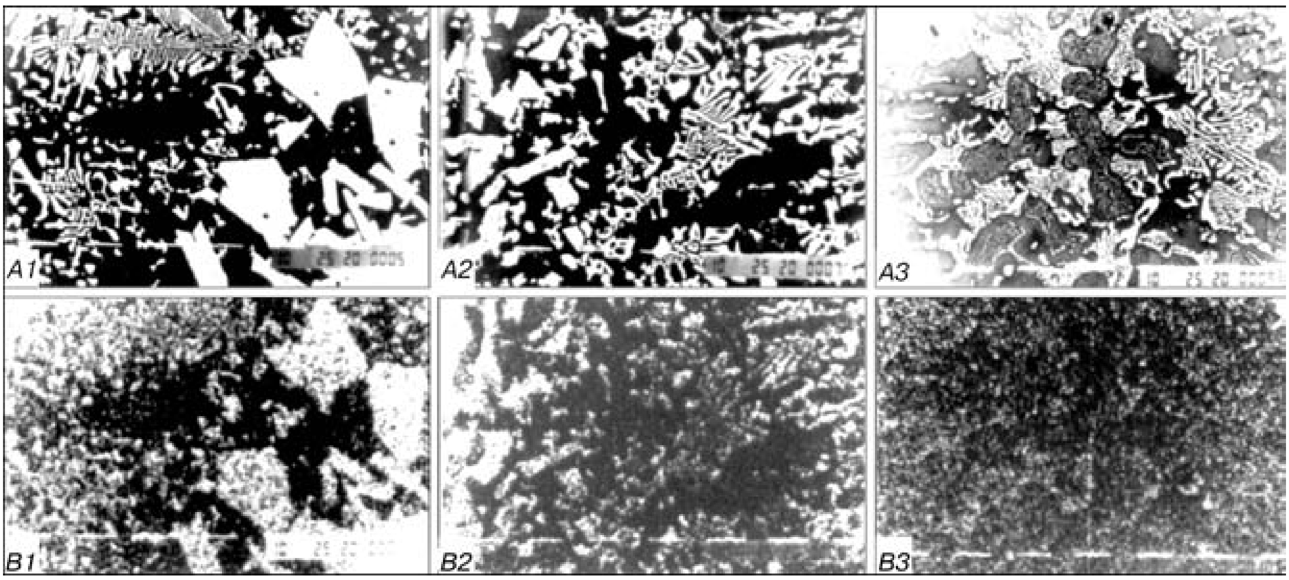

Figure 1. Microstructure of composite alloy in back-scattered electrons (*A1–A3*) and distribution of tungsten in matrix in characteristic radiation (*B1–B3*) at different alloying systems: *1* — niobium; *2* — vanadium; *3* — titanium

degree of alloying the effect of titanium is higher, and after its content of the filler material becomes more than 2 % it plays a dominant role in formation of matrix of the composite alloy with the best performance (Figure 2).

Abrasive wear tests of composite alloys deposited by using a Ti-containing filler material showed increase of 1.2–1.3 times in wear resistance of the composition, compared with alloys produced by reinforcing the molten pool with tungsten carbide grains.

Surfacing of the experimental batch of tool joints of drill pipes ZSh-146A using a Ti-containing tungsten carbide strip provided an increase of 2.1–2.5 times in their life, compared with the life of untreated reference mass-produced tool joints. The new material for plasma surfacing of composite alloys has been applied at the Drogobych drill bit factory, Ukraine, which incorporates a workshop for commercial manufacture of tool joints with reinforced external surfaces.

CONCLUSIONS

1. Efficiency of addition of niobium, vanadium and titanium to the filler material, as well as their effect on conditions of formation of structural components and their proportion in the composite alloy matrix were established.

2. The optimal amount of titanium, i.e. 1.5–3.0 %, to be added to the filler material, relative to components which form the composite alloy matrix after melting and solidification, was determined.

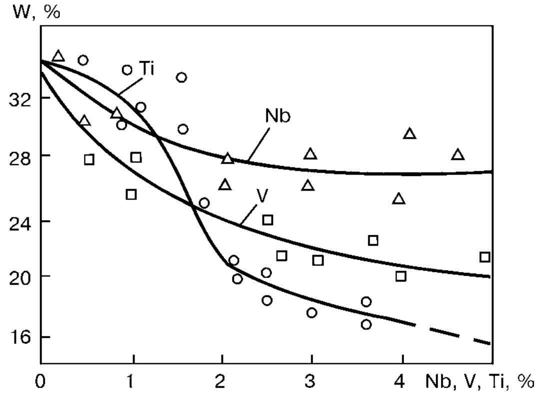

Figure 2. Effect of alloying components on the content of tungsten in the composite alloy matrix

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PECULIARITIES OF MICROSTRUCTURE OF EXPLOSION WELDED JOINTS IN NICKEL

L.I. MARKASHOVA, V.V. ARSENYUK, V.G. PETUSHKOV and **G.M. GRIGORENKO**
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Studies allowing the relationship between collision parameters and quality of explosion welded joints were carried out. Formation of the final structure of the contact zone in the joints, determining their strength and ductility, was found to depend mostly upon the mutual effect of two competing mechanisms, i.e. deformation strengthening and relaxation (recovery). Recommendations on selection of welding parameters to ensure the optimal energy balance during the strengthening and structure relaxation processes are given.

Key words: *explosion welding, nickel, plastic deformation, fine structure, mechanical properties, contact zone, temperature conditions, optimisation*

Service characteristics of the explosion welded joints are determined in many respects by a structural state of metal formed on the surface of the joints. In turn, this state depends upon the collision parameters. There are several criteria on the basis of which it is possible to assign a priori the optimal collision parameters [1–5]. One of them is the energy criterion. It is reduced to analysis of balance of the kinetic energy of the flyer plate. An established premise for this is that the full-strength joint can be formed in the case where for each of the metals joined the plastic deformation energy W_2 consumed for welding proper is not lower than the critical one [3], characteristic of each specific combination of metals. This approach makes it possible to estimate the effect of thickness of the plates welded on the W_2 value and structural state of the joining zone metal. A drawback of this method is that it allows determination of only the integral energy characteristics of the process. Therefore, it is often impossible to reliably estimate the balance of the energy expenditures in explosion welding and, hence, predict the structural state of metal without an additional experimental correction. Al-

Explosion welding process parameters

Welding conditions	α, *deg*	γ*, *deg*	$v_{c.p}$, *m/s*	W_2, *MJ/m*^{2}
I	3	10	4290	2.2
II	5	12	3570	3.2
III	15	22	1980	4.7
IV	20	27	1630	4.9

*γ is the dynamic collision angle.

lowing for such parameters as high pressure, temperature and deformation rate, it is very difficult to determine dynamic strength of a material, its melting temperature and other physical-mechanical characteristics [6, 7].

The purpose of this study is to widen the existing concepts of the possible ways of optimisation of explosion welding parameters through investigation of the effect on the dynamics of structure of the contact zone by the collision parameters. Commercially pure nickel of the NP-2 grade was selected as a model material. Owing to its fcc lattice, it undergoes plastic deformation directly over a wide range of the crystallographic sliding systems. This allows the experimental material to be produced in welding within a wide range of collision parameters by avoiding defects of a deformation origin (cracks, delaminations, etc.).

Four series of experiments under different collision conditions (Table) were conducted. Welding was performed by the angular method. To avoid the effect of an averaged unit mass on the regularity of formation of joints between the flyer and target plates, in all the experiments their thickness (3 and 8 mm, respectively) was kept constant. According to the data of [3], the minimum permissible value of W_2 in this case is approximately 1.2 MJ/m^2. The acceleration velocity being kept constant ($v_0 \cong 730$ m/s), values of the contact point velocity $v_{c.p}$ and W_2 were varied by varying the value of initial (setting) angle α (Table). The RDX material characterised by stable and reproducible detonation parameters was used as the explosive. Height of the explosive charge was kept constant. Values of W_2, depending upon the kinematic collision parameters, were found from the following expression [3]:

$$W_2 = \frac{m_{av} v_0^2}{2} \left[1 - \left(\frac{v_{c.p}}{c_0} \right)^2 \right],$$

where m_{av} is the averaged unit mass of the plates welded and c_0 is the velocity of sound in metal.

Quality of the resulting joints was determined by the degree of homogeneity of metal immediately at the contact boundary. Structural peculiarities of metal in this region were investigated by the methods of optical, transmission and microdiffraction electron microscopy. Thin foils were examined using the electron microscope JEM-200CX at an accelerating voltage of 200 kV.

Microstructures of the joints produced under conditions I and II (see the Table) were found to be almost identical and characterised by an increased quantity of the lack of penetration regions (Figure 1). The presence of such regions leads usually to decrease in electrochemical homogeneity, which in turn causes decrease in corrosion resistance of the contact boundary. Sub-structure of these joints is non-uniform in size and orientation of grains. It is characterised by a very high density ($\approx 1 \cdot 10^{11}$ cm^{-2}) of dislocations present inside the cells and in the region of the subgrain boundaries (Figure 1, *a*). The clearly defined boundaries of the «knife» type with high disorientation angles equal to about 11–12° are also seen (Figure 1, *c*).

Along with the equiaxial cells, individual substructural elements of an elongated shape are also formed. These elements are the deformation bands interpreted as the electron microscopy equivalent of the optically observed shear bands [8]. According to [9], difference in safety factors for ductility of the adjoining metal microvolumes (with perfect equiaxial and band structures), as well as relaxation of the considerable amount of the elastic energy accumulated at the sub-boundaries of the band structures may lead to fracture of a joint under loading. For these reasons conditions I and II cannot be recommended for practical application. Increase in the plastic deformation energy under conditions III caused decrease of ap-

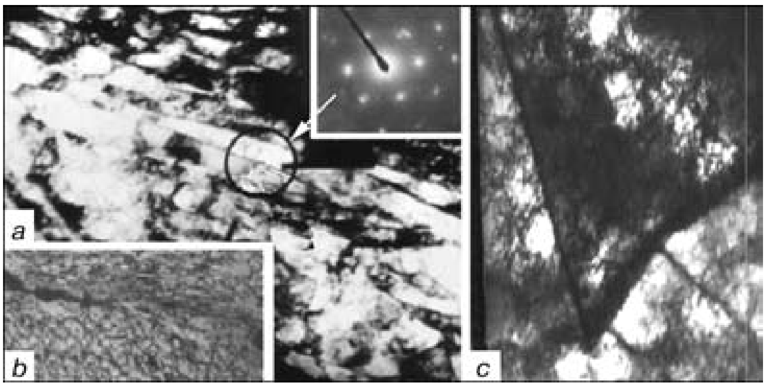

Figure 1. Structure of the Ni–Ni joint made by explosion welding at α = 3°: *a* — fine structure of the welding zone with the diffraction pattern of reflexes in radial direction (×15,000); *b* — general view of the welding zone (×500); *c* — example of the formed fragments with straight-lined «knife-shaped» boundaries (×20,000)

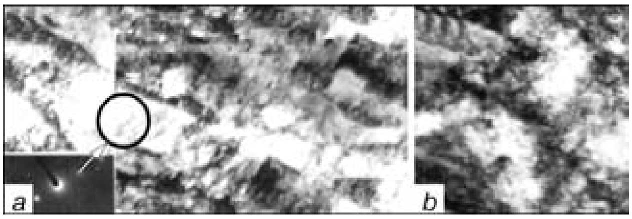

Figure 2. Fine structure of the nickel welding zone (*a*) (×15,000) and its individual regions (*b*) (×20,000) resulting from explosion welding at $\alpha = 15°$ (the region the microdiffraction pattern of reflexes of which was taken is shown by the arrow)

proximately an order of magnitude in the volume density of dislocations (Figure 2). In this case, like in welding under conditions I and II, the oriented band structures are formed in the welding zone. However, redistribution of the crystalline lattice defects leads to formation of more equiaxial cells. Disorientations of the cells inside the bands and of adjoining band species between each other are not high, i.e. within the low-angle disorientation ranges (approximately up to 2°).

Therefore, increase in the W_2 values «softens» the contact zone structure because of disappearance of the clearly defined orientation of the boundaries relative to a deformation stress. This shows up as the «smeared» band structures, fragmentation of the internal volumes of the bands and decrease in the volume and near-boundary density of dislocations. As a result, structural state of the welding zone hardly differs from that of the base metal. The joints produced under conditions IV are characterised, on the one hand, by the presence of equiaxial recrystallisation centres and, on the other hand, by a substantial change in a fine structure of the welding zone toward increase in the volume fraction of the deformation bands, i.e. the cellular non-equiaxial structure dominant under conditions III is degenerated with increase in W_2 into thin elongated packs of the band species with a drastic decrease in the dislocation density inside the bands. Therefore, structure of metal of the welding zone is substantially different from that of the base metal in the dislocation density, shape of structural elements and their disorientation angle (Figure 3).

The revealed elements of a sub-structure of the contact boundary of the joints produced under different welding conditions made it possible to identify the character of the deformation processes occurring in this zone. The high dislocation density, irregularity of structural boundaries, their smeared orientation and fragmentation of the sub-structure with the dispersed and elongated cells formed in the case of using conditions I and II are indicative of an insignificant effect of thermal activation on movement of dislocations.

Fragmentation of structure accompanied by formation of substantially disoriented boundaries is caused mostly by the dominance of the deformation processes in the deformation–relaxation series. In addition, the character of structure of the welding zone metal is indicative of exhaustion of the possibilities of the relaxation processes as a result of movement

Figure 3. Fine structure of the nickel welding zone (*a*) resulting from explosion welding at $\alpha = 20°$ and the corresponding microdiffraction pattern of reflexes (*b*) (×15,000)

of individual dislocations (translational forms of plastic deformation). Therefore, a non-uniform stressed state which causes relaxation of internal stresses through turn of the adjoining volumes is formed in a material. Structural manifestation of such a mechanism of relaxation is the active fragmentation to form the clearly defined oriented high-angle «knife-shaped» boundaries.

Formation of the observed band structures can probably be related to the effect of loss in mechanical stability and collective forms of movement of the crystalline lattice defects. The equiaxial shape of subgrains with a small disorientation angle and the smeared character of the band structures in the case of welding under conditions III (see Figure 2, *b*) are indicative of an increased effect of the thermally activated forms of redistribution of the crystalline lattice defects, occurring mostly by the polygonisation mechanism. Formation of structure with a drastic decrease in the dislocation density inside the bands in the case of welding under conditions IV can be explained by a substantial dominance of the thermal relaxation processes over the processes of deformation (strengthening) of metal in the welding zone.

Therefore, peculiarities of plastic flow of metal in the contact zone, revealed as a result of the conducted analysis, are indicative of occurrence of two competitive processes, i.e. deformation strengthening and loss in strength. Strengthening caused by a high level of plastic deformation is characterised by accumulation

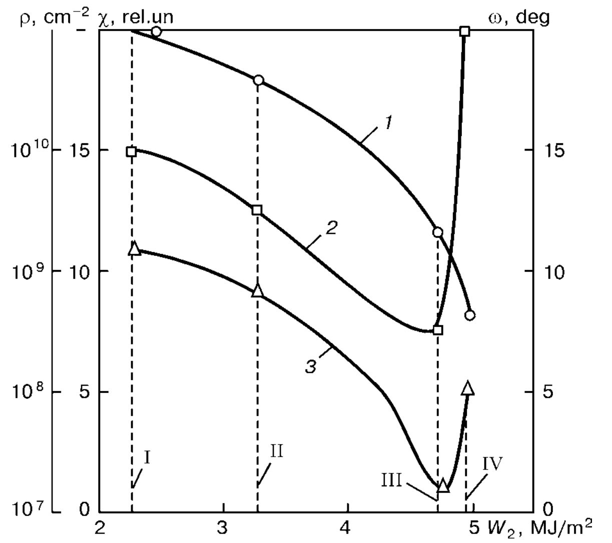

Figure 4. Effect of the plastic deformation energy W_2 on the fine structure of nickel at the contact boundary: *1* — dislocation density ρ; *2* — form factor χ (sub-grain length to width ratio); *3* — sub-structural boundary disorientation angle ω (I–IV — welding conditions, see the Table)

of the crystalline lattice defects, structure fragmentation, etc.

The degree and mechanisms of loss in strength are determined primarily by the following levels of temperatures in the contact zone: comparatively low level, obviously insufficient for any substantial thermal weakening (conditions I and II); level sufficient for development of relaxation by the polygonisation mechanism and ensuring the equilibrium state of structure of the contact zone (conditions III); and a very high level, promoting development of such thermally activated processes as recrystallisation (conditions IV). To optimise collision parameters, for example, for prediction of fatigue strength, it is necessary to allow for the strengthening and weakening processes. It is most likely that the optimal conditions are those which provide the energy balance between the strengthening processes and relaxation of internal stresses.

CONCLUSIONS

1. The methods for proportioning of the energy spent for plastic deformation and limitation of the welding temperature conditions were developed.

2. The explosion welding time measured in microseconds was found to be enough for occurrence of the thermally activated processes of relaxation of stresses in the contact zone, leading to avoidance of band structures and to improvement of ductile properties of welded joints.

3. The optimal range of temperature welding conditions can be established by proportioning the plastic deformation energy through varying the dynamic collision angle during welding at a fixed collision velocity. The latter provides the optimal relationship of the rates of the strengthening and structure relaxation processes.

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OPTIMISATION OF INDUCTOR PARAMETERS FOR UNIFORM HEATING OF DISCS ACROSS THE WIDTH OF THE HARDFACING ZONE, ALLOWING FOR SCREENING

O.M. SHABLY[1], **Ch.V. PULKA**[1] and **A.S. PISMENNY**[2]
[1]Ivan Pulyuj Ternopil State Technical University, Ternopil, Ukraine
[2]The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Method of calculation and optimizing of parameters of inductor for hardfacing edges of discs of an arbitrary diameter and width of the hardfacing zone with allowance for the effect of electromagnetic and heat screening on the distribution of electromagnetic field power in the hardfacing zone width is presented.

Key words: *induction hardfacing, steel discs, optimization of parameters, two-turn ring-type inductors, protective shields, investigations, calculation*

Thin steel discs of different thickness with the edge of an even or toothed shape are used in different sectors of the national economy, including agricultural machinery. To provide self-sharpening of the edges during the disc operation, their working surface is hardfaced with erosion-resistant powder-like hard alloys PG-S1, PG-S27 or of other type at heating by HF currents [1]. In this case the size and shape of the inductor are to be determined for the respective diameters of the discs and different width of the hardfacing zone, this taking time and cost.

Study [2] describes a procedure and gives the results of theoretical and experimental investigations on optimization of the structural dimensions of two-turn ring-type inductors, used for simultaneous hardfacing of thin steel toothed discs over the entire working surface. The required width of the hardfacing zone is provided, which is greater than the tooth height (Figure 1). Developed algorithm allows determination of optimal parameters of the inductor design for arbitrary diameter of the disc and width of the deposit, proceeding from technology requirements. Work [2] presents the calculated geometrical parameters of the inductor, depending on the width of the hardfaced zone and disc radius. It is found that in a number of cases with such an arrangement of the part relative to the inductor (see Figure 1), the power of the electromagnetic field is non-uniformly distributed across the width of the hardfaced zone: the highest power is concentrated at the disc face. This leads to non-uniform melting of the hard alloy on the working edge of the disc to be hardfaced, and to overheating of the base and deposited layer of the metal on its face.

All these processes can be explained as follows. Specific power of the electromagnetic field of heat sources in the absence of the shield is determined from the formula [2]:

$$W = \frac{\sigma\omega^2\mu_0^2}{128\pi^2 h} \times \left[\Delta I_u^2 A^2 a_u^2 + \Delta I_l^2 B^2 a_l^2 + 4 h a_u^2 I_u^2 C^2 e^{-2(r_2 - r)/\Delta}\right], \quad (1)$$

where σ, ω, μ_0 are the electric conductivity, circular frequency of current and magnetic permeability of vacuum, respectively; $\Delta = \sqrt{2/(\sigma\omega\mu_0)}$ is the depth of current penetration into the disc metal; I_u, I_l is the current in the upper and lower branch of the inductor, respectively; A^2, B^2, C^2 are the coefficients (integrals of elliptical type), dependent on the induction system dimensions, the formulas for their calculation being given in [2]; the other geometrical dimensions are shown in Figure 1.

This formula was used to perform calculations, illustrating the distribution of specific power of the electromagnetic field in the zone of disc hardfacing, depending on its geometrical dimensions. Figure 2 (curves *1*) shows calculation results for two cases of hardfacing with zone width of 10 and 50 mm, respectively, at disc radius r_2 = 105 mm. According to the

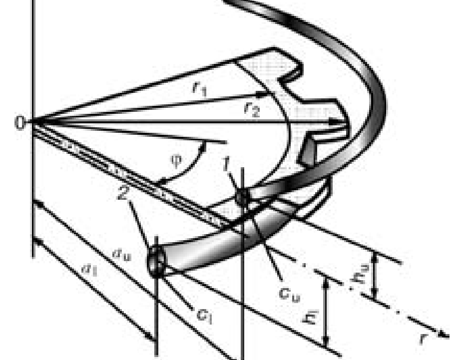

Figure 1. Fragment of the studied system (for designations see the text)

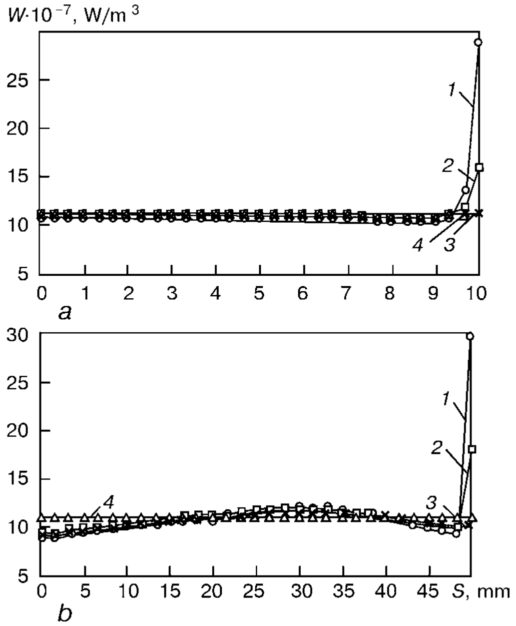

Figure 2. Distribution of power W of electromagnetic field of heat sources across the width of the hardfacing zone S: *a* — S = 10 mm; *b* — S = 50 mm at different screening of disc face; *1* — K = 1 (without screening); *2* — K = 0.25; *3* — K = 0 (full screening); *4* — assigned distribution of electromagnetic field power

presented graphs, in the disc face the values of specific power of the electromagnetic field are 3 times greater than in the main part of the hardfacing zone. In practice this often leads to surface melting of the disc face.

It is known that shields of electromagnetic and thermal fields are used for redistribution and concentration of the power of electromagnetic field of heat sources in the working region of induction heating of the parts [3]. The same technique was used in this work to provide the required power distribution of the electromagnetic field of heat sources across the hardfaced zone width. In this case it was necessary to optimize the dimensions of two-turn ring-type inductor, allowing for the presence of such shields. This is precisely the subject of this study.

Figure 3 gives the schematic of a part arrangement in the inductor with a shield and without it. In the case studied by us the shield enclosed the disc being heated from the side of outer perimeter along its side (end) surface. Such a face shield drives a variable magnetic field, generated by the inductor, out of the zone of side surface of the disc. The intensity of electromagnetic field of the heat source decreases near the disc face, and the surface to be hardfaced is exposed to a more intensive impact of the electromagnetic field. Another purpose of the shield is thermal insulation of the disc face from the environment and thus reduction of heat losses in the hardfacing zone.

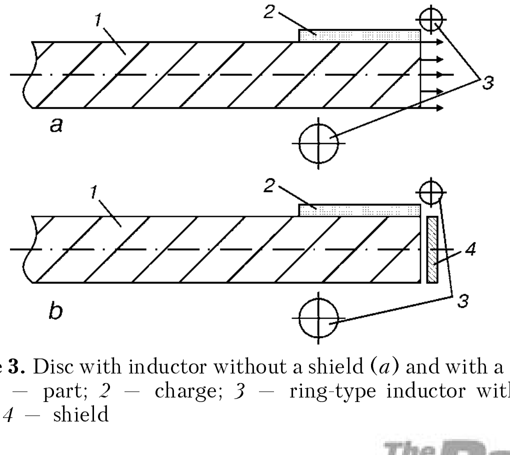

Figure 3. Disc with inductor without a shield (*a*) and with a shield (*b*): *1* — part; *2* — charge; *3* — ring-type inductor with two turns; *4* — shield

Let us take the degree of screening into account, using screening coefficient K, which we will incorporate into formula (1) in determination of specific power of electromagnetic field of heat sources in the disc. In this case, the formula becomes

$$W = \frac{\sigma\omega^2\mu_0^2}{128\pi^2 h} \times \left[\Delta I_u^2 A^2 a_u^2 + \Delta I_l^2 B^2 a_l^2 + K 4 h a_u^2 I_u^2 C^2 e^{-2(r_2 - r)/\Delta}\right]. \qquad (2)$$

In formula (2) screening coefficient K varies in the range of [0; 1]. At K = 0 formula (2) describes an ideal case of complete screening of the face, and at K = 1 the screening effect is absent, and formula (2) will fully correspond to formula (1) from [2]. Now in reality $K \neq 0$, and calculation of this quantity involves certain difficulties of computational nature, as in this case it combines the electromagnetic and thermal effects. Method of calculation of the screening effect will be the subject of a separate publication. In this paper it is assumed to be equal to 0, 0.25 and 1.

Determination of inductor parameters may be performed with the required accuracy at the assigned screening coefficient, using a procedure, described in [2]. The dependence from [4]

$$W_{set} = \frac{T_{set} c a \gamma m}{\mathrm{sh}(am\tau)} e^{amt} \qquad (3)$$

was used in calculations as the assigned mode of supplying the specific power W_{set} to a part, optimal for induction hardfacing. Here, T_{set} is the set temperature of heating of the hardfacing zone, at which sound hardfacing is ensured during time τ; c, a, γ are the specific heat capacity, temperature conductivity and density of disc material, respectively; $m = \mathrm{Bi}/2h^2$; $\mathrm{Bi} = 2h\alpha/\lambda$; $2h$ is the disc thickness; α is the heat removal coefficient; λ is heat conductivity of disc material; t is the current value of process time.

Optimisation of dimensions and determination of inductor current were performed by minimizing the following functional [2]:

$$F = \int_0^{\tau} \int_{r_1}^{r_2} (W - W_{set})^2 r\,dr\,dt, \qquad (4)$$

where r is the current value of the radial co-ordinate.

Calculations demonstrated that the highest uniformity of distribution of electromagnetic field power across the width of the hardfacing zone is achieved in the ideal case at complete screening of the disc face. Deviation from the specified power of the elec-

Dependence of geometrical dimensions of induction system on screening coefficient K and disc radius r_2

K	r_2, mm	S, mm									
		50					10				
		a_u, mm	a_l, mm	h_u, mm	h_l, mm	I, A	a_u, mm	a_l, mm	h_u, mm	h_l, mm	I, A
0	105	115	89	1	18.5	23.50	115	100	0	14.5	20.82
0	125	135	107	1	14.5	21.90	135	120	0	14.5	20.10
0	145	155	123	1	16.5	21.80	155	140	0	14.5	19.53
0	165	175	144	1	19.5	21.71	175	159	2	14.5	19.00
0	185	195	161	1	20.5	21.50	195	179	1	14.5	18.70
0	205	215	182	1	20.5	21.00	205	198	0	14.5	18.50
0	210	220	186	1	20.5	20.10	220	202	2	14.5	18.50
0.25	105	115	88	7	18.5	23.52	116	100	20	14.5	21.01
0.25	125	135	107	11	20.5	23.09	139	119	20	14.5	20.36
0.25	145	155	123	5	16.5	21.77	159	139	20	14.5	19.60
0.25	165	175	145	16	19.5	21.72	182	159	20	14.5	19.30
0.25	185	196	163	14	20.5	21.40	202	178	20	14.5	19.00
0.25	205	215	182	11	20.5	20.90	220	197	20	14.5	18.74
0.25	210	220	187	11	20.5	20.80	230	201	20	14.5	18.80

Note: c_u = 5 mm, c_l = 8 mm.

tromagnetic field is equal to 3–5 %, depending on the width of the hardfacing zone and disc radius (see Figure 2, curves *3, 4*). This procedure was the basis to derive calculated dependencies of geometrical parameters a_u, a_l, h_u, h_l (see Figure 1) and inductor current I, depending on screening coefficient K and disc radius r_2. Similar to Figure 2, the width of hardfacing zone S was taken to be 10 and 50 mm (Table).

Analysis of computation results, given in the Table, shows that introduction of a shield into the technological sequence of induction hardfacing only slightly influences dimensions a_u, a_l, h_l and integral energy parameters of the induction system (which influences the values of inductor current I). However, presence of a shield with a certain screening coefficient leads to a marked change of air gap h_u between the inductor upper branch and disc surface. This is attributable to strong electromagnetic coupling of the shield and the inductor upper branch due to their close location (Figure 3). Observed narrowing of gap h_u at decrease of screening coefficient K is necessary to ensure the required power in the disc being hardfaced.

Thus, use of electromagnetic and thermal shields allows controlling power distribution of the electromagnetic field of heat sources across the hardfacing zone width. The required law of distribution of electromagnetic field power may be derived for arbitrary dimensions of the discs and width of hardfacing zone. Its most uniform distribution across the hardfacing zone width is achieved in the ideal case at complete screening of the disc face. Described calculation procedure enables determination with the assigned accuracy of the design parameters of the inductor for arbitrary diameters of discs and width of hardfacing zone, allowing for screening effect.

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PROBLEMS OF QUALITY IN ELECTRODE PRODUCTION

Association «Electrode» gives a permanent attention to the problems associated with development of production of welding electrodes in the CIS countries, the focus being on improvement of existing and making of new samples of process equipment and high-efficiency electrodes, application of new processes for their manufacture, certification of electrodes and introduction of the system to control quality of their production.

This is favoured by a regular consideration of topical problems relating to production of competitive welding electrodes at meetings of the Board of Directors and the Association assemblies, which, in turn, is determined in many respects by the level of process equipment, technological processes and quality of raw materials. For example, an enlarged meeting on raw materials took place in 2000 under the auspices of the Association Board of Directors. The active part in that meeting was taken by major manufacturers of welding electrodes and suppliers of raw materials and welding wire. The participants discussed issues relating to supply of quality raw materials to electrode manufacturers.

A similar event dedicated to process equipment was held in 2001. It considered the progress in making a new generation of the equipment and its correspondence to the level provided by leading foreign companies.

The last enlarged meeting of the Association included papers and presentations, where again the focus was on the quality problems. So, the Editorial Board decided to acquaint the readers of our Journal with some of them.

Editorial note

STATE OF THE ART IN PRODUCTION OF WELDING CONSUMABLES AND THEIR QUALITY

P.V. IGNATCHENKO
Association «Electrode»

Volumes of production of welding consumables in some of the CIS countries in the last years are given. Issues associated with improvement of the quality of development, manufacture and supply of covered electrodes are considered.

Key words: *welding consumables, covered electrodes, output, quality, competitiveness*

The demand for welding consumables and volumes of their production in the CIS countries depend in full upon the state of the art in production of steel and rolled products in Russia, Ukraine and the Republic of Belarus (Table 1).

In 2001, compared with 2000, the total output of alloyed wire in the CIS countries decreased by 5 %, while in Russia it decreased by 4 and in Ukraine — by 7 % (Table 2), which was caused by a reduction in export of wire to the CIS countries. Out of this amount, the output of copper-plated wire was 6261 t. Compared with 2000, the volume of its production increased by 18 %. Another positive indicator is that at the request of customers this wire is supplied packed in spools and reels with in-line winding. The volume of production of welding flux in the Russian Federation increased by 15 %, whereas in Ukraine it decreased by 12 %. Compared with 2000, in 2001 the CIS countries also changed their volumes of production of welding electrodes with the following types of coverings: rutile-ilmenite — 179231 t (decrease of 10 %), calcium fluoride — 62873 t (decrease of 8 %) and special — 10217 t (increase of 2 %). There was some improvement of the situation with production of electrodes of certain diameters, especially of diameters of 3, 3.25 and 4 mm. The total output of electrodes was 219161 t, that of 5 mm in diameter was 32329 t and 6 mm in diameter was 831 t.

Quality is still the hottest problem of current production of electrodes. Two international conferences on production of welding consumables in the CIS countries, arranged by the Association, were dedicated to this problem. Participating in these conferences were representatives of enterprises, organisations, joint-stock companies, manufacturers of welding consumables, customers and suppliers of raw materials. To solve the quality problem, it would be appropriate that the Association manufacturers of welding electrodes get together with customers. In this case the latter could opportunely address their complaints for quality to manufacturers, and suppliers of raw materials could have permanent clients. This union would enable solution of the problem of quality and competitiveness of welding electrodes, as well as protection of the CIS market from foreign companies. For this, the Association has to establish business contacts with welding societies of the CIS countries and chief welders of leading enterprises for a considerate examination of the existing level of quality of welding electrodes in the CIS countries and their correspondence to foreign analogues. The Association Directors approached more than 100 enterprises in different industries with a request to do the following:

- assess quality of the certified electrodes being supplied and their correspondence to foreign analogues;
- say in which welding-technological properties the domestic electrodes are inferior to the foreign ones;
- estimate to what extent the existing ranges and grades meet the current needs and what properties the welding electrodes must have;
- indicate the main suppliers of welding electrodes.

Answers were received from 14 enterprises, and they are still arriving.

The following complaints were expressed on the basis of results of a long-time experience of application of both domestic and foreign electrodes:

- ignition, especially the repeated one, and stable burning of the arc are difficult;
- increased spattering of electrode metal (it amounts to 10 %, while that of the foreign electrodes is no more than 2 %);
- detachability of the slag crust in groove is difficult;
- high melting point of electrode coverings and susceptibility to formation of collars;

Table 1. Production of steel and rolled products (mln t) in 2001

Country	*Steel*	*Rolled products*	*Growth compared with 2000, %*	
			Steel	*Rolled products*
Russia	59.0	47.1	3.6	1
Ukraine	31.4	22.4	5	23
Belarus	1.6	1.5	−24	1

- high variability of chemical composition and mechanical properties, the latter being especially pronounced in tests at −60 °C;
- electrodes UONI-13/55 provide the required impact toughness only at a temperature of down to −30 °C (on specimens with a round notch), whereas it should be provided at temperature of down to −50–60 °C on specimens with a sharp notch;
- consumption of electrodes per kilo of deposited metal is up to 1.7 kg (1.8 kg with some batches), whereas that of imported electrodes is not in excess of 1.4 kg.

Generalisation and analysis of complaints suggest that the following processes are ignored in making formulations of electrode coverings:

- interaction of individual components of coverings between each other and in the system as a whole;
- effect on structural transformations in deposited metal by components;
- processes occurring in the arc zone.

The quality of coverings is also affected by the following factors:

- absence of standards for welding-technological properties of electrodes and a unified method for their evaluation;
- absence of new technologies and manuals for production of electrodes;
- negligence of iron powder as a filler, rather than an even component of electrode covering;
- insufficient acceptance and commercial application of cellulose electrodes of the E42 and E46 types, instead of rutile electrodes.

In addition, nothing is done to upgrade chambers of electrode-covering presses. Domestic electrodes are inferior to foreign analogues in welding-technological properties (eccentricity, formation of collars, spalling of coverings during welding). It was requested that the domestic electrodes provide a «soft» burning of

Table 2. Output of welding consumables (t) in 2001

Country	*Welding electrodes*	*Alloyed welding wire for mechanised gas-shielded welding*		*Flux-cored wire, total*	*Including*		*Welding flux*
		d < 2.0 *mm*	*d* = 0.8–1.4 *mm*		*welding wire*	*surfacing wire*	
Russia	211949	22290	6076	2336	1398	938	8715
Ukraine	35325	9358	3849	738	212	525	20031
Total for CIS	252321	31648	9925	3073*	1610	1463	28746

*Including wire of a metallurgical application for deoxidation of steel — 4345 t.

Table 3. Comparison of welding-technological properties of electrodes produced in CIS and industrialised countries

No.	*Properties of welding electrodes*	*CIS countries*	*Industrialised countries*
1	Arc burning stability	Satisfactory	Good
2	Hard arc burning	Arc burning is hard, low stability of the arc prevents welding in difficult spatial positions and conditions	Arc burning is soft, elastic, easy to maintain and control in welding in any spatial positions
3	Spattering in welding	Sufficiently high	Low
4	Noise produced by the arc in burning	High	Low
5	Spreading of slag and weld formation	Often unsatisfactory	Always good
6	Melting of electrode covering	Satisfactory	Good
7	Slag crust detachability	Not always satisfactory	Only good
8	Deposition efficiency	It can be maintained depending upon the electrode grade	It can be maintained, depending upon the electrode grade and application
9	Appearance and marking	Satisfactory, not all manufacturers make marking	Good, marking is sufficiently detailed on all electrodes
10	Electrode packing	Not always satisfactory	Only good

the welding arc, good formation of the fine-scale welds, good detachability of the slag crust and low metal spattering. It is necessary to demand that manufacturers arrange separate production of high-quality electrodes with basic coverings for welding in all spatial positions: for root welding — with a diameter of 2.5–3 mm, for making filling welds with high mechanical properties of deposited metal (UONI-13/55 will suit here), and for making final welds to provide low spattering and good decorative appearance of the welds.

Deliveries of domestic electrodes have the following drawbacks:

- absence of sealed packing (polyethylene), absence of identification marking on electrodes;
- non-adherence to requirements for limitation of variations in thickness of an electrode covering;
- inconsistent quality of electrodes of the same grade and from the same manufacturer (batch to batch variations in welding-technological properties).

In pursuit of profit, many electrode manufacturers use lower-quality components instead of the high-quality ones (e.g. they substitute ilmenite for rutile, etc.). This makes it impossible to achieve the required welding-technological properties of electrodes (stable arc burning, low spattering, satisfactory weld bead formation). In a number of cases the welds have unsatisfactory mechanical properties and a high content of slag inclusions (especially in making the root welds on pipelines and metal structures).

Out-of-date requirements of standards (GOST) for electrodes, low level of development of specifications (TU), substitution of lower-quality components for the high-quality ones lead to the fact that certification of electrodes hardly makes anything to improve the quality, as the third (independent) entity participating in certification uses requirements of the same specifications and standards. As a result, electrodes which do not meet international requirements receive fitness certificates as products of a good quality. Therefore, certification of electrodes in a number of cases is a screen for either a low quality or an apparent reject.

Any enterprise manufacturing electrodes, finished charge, components, wire for making rods, etc. should be qualified and have a certificate for the quality system according to ISO-9000 to provide the consistent quality of its products. As proved by experience of operation and introduction of this system, e.g. at Close Joint-Stock Company «ELZ» (St.-Petersburg, Russia), this way, although it is difficult, should be passed by every manufacturer to produce competitive high-quality electrodes.

As a rule, foreign electrodes produced by companies from industrialised countries (Germany, Sweden, USA, Japan, etc.) are better in quality, and mainly in welding-technological properties, than electrodes produced in the CIS countries. Comparison of some welding-technological properties of electrodes produced in the CIS and industrialised countries is given in Table 3.

Complaints made by manufacturers and customers of welding electrodes should be treated in a critical, considerate and serious way. They expressed their concern about the quality of electrodes. And it is our task to provide customers with competitive products.

Proposals on improvement of the situation will be generalised and analysed after we accumulate the sufficient amount of data.

IMPROVEMENT OF QUALITY OF WELDING ELECTRODES ON THE BASIS OF STANDARDS ISO OF SERIES 9000:2000

A.E. MARCHENKO
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Purpose, reasons for development and specifics of structure of the new edition of international and national standards ISO of series 9000, and also the key principles of present management of quality regulated by them, attracting the interest of manufacturers of welding electrodes, are presented. Characteristics of quality of electrodes and their manufacture as an object of quality management according to standards ISO of series 9000:2000 are analyzed. Program of actions was offered, whose fulfillment will contribute to the stabilization and improvement of economical situation of national enterprises-electrode manufacturers.

Quality of welding electrodes means usually a technical-economical level of their development, technological, and also material-technical and organizational-methodological capabilities of its assurance at industrial production of this kind of product.

It is these International Standards ISO of series 9000:2000 that are the effective organizational-methodological tool which, in our opinion, allows the high-skilled present managers to obtain the good results in achievement of the quality production, providing that other above-mentioned resources of the quality assurance are available and used to a full extent. Moreover, the effectiveness and resultativeness of use of the mentioned resources can be significantly increased by putting into action of motive-lawful and organizational-technical key factors of quality management envisaged by the methodology of standards ISO of series 9000.

New versions of international standards and national standards, adopted on their basis, of the mentioned series [1–6] are intended, like their two previous editions, for their use in production of any types of products and by enterprises of all possible scales and form of property.

Standard ISO 9000:2000 describes principles on which this ideology is based, and includes the vocabulary of the quality management terms, used by the new version of standards. Standard ISO 9001:2000 regulates the requirements for systems of quality management (SQM): they are oriented to the satisfying interests of consumers and used in certification. Standard ISO 9004:2000 is the manual on quality improvement. It is oriented to a continuous improvement of production and SQM (final aim — Japanese model TQM) and contributes to the achievement of updating enterprise in the sphere of quality.

Undoubtedly, at the territory of each sovereign state only national standards, including those referring to the sphere of the quality management, can be used. The form of use of the standards can be direct or intermediary, i.e. through intermediate standards, accounting for specifics of definite types of production. Thus, for example, welding manufacturing consists mainly of special processes (term which is used in standards ISO of series 9000). During their realization there is no technical feasibility to evaluate directly the real quality of products. This is provided by trained high-skilled and experienced personnel, use of perfect and well-set equipment, careful performance of manufacture and organizational-technical procedures given in instructions, and also by careful inspection of their realization.

In Ukraine the role of State Standard, with the help of which the internal (special) requirements will be related to the quality management by State Standard of Ukraine (hereinafter DSTU) ISO 9001 (including self-declaration and certification), will be played by DSTU ISO 3834, in Europe — by EN 729, at the international level — by standards ISO 3834 [7–9].

In those cases when the requirements for quality management and systems of quality have a deterministic nature exclusively, the requirements of standards ISO of series 9000 are taken as minimum necessary and supplemented obligatory with requirements of standards or standardized documents, equal to them by status, accounting completely for specifics of definite kinds of products and their production. Thus, in automotive industry of foreign counties standards QS of series 9000 are functioning together with standards ISO of series 9000. These standards were adopted by the proposal of five known automotive companies (International document ISO/TS 16949 is being prepared to replace them). At the market of medical engineering the standard ISO 13485 is valid, at the oil-gas equipment market — standards API, while in the sphere of equipment for nuclear power engineering — the norms of International Atomic Energy Association. There are international standards on quality systems in aerospace, telecommunication sphere, food industry and others. Long ago before the appearance of standards ISO of series 9000 the system of quality, developed in its interbranch standards, was functioning at the enterprises of S.P. Korolyov Rocket Space Corporation «Energiya».

In electrode manufacture the number of special processes is very limited, and requirements for the quality systems are not so deterministic, except some rare cases. Therefore, the quality management can be realized by a direct use of standards ISO 9000:2000 with a specifying of definite procedures, which are fulfilled under special conditions. This is an important moment from the point of view of making creation and assurance of functioning of quality system not so expensive.

There are at least three reasons for achieving favourable economical results (pragmatic, economical, technical), which caused the transition to the new versions of standards ISO of series 9000 [10].

At present the former editions of the mentioned standards are recognized and widely used in many countries of the world. More than 350,000 SQM, corresponding to the statements of previous editions of standards, are certified [10–12]. But, if in the 1980s the certification provided enterprises the certain competitive advantages, then by the end of the 1990s these advantages and investments into the sphere of activity considered became much less effective. Namely, from the pragmatic positions the standards ISO of series 9000 stopped to satisfy the users as they did not reflect the modern tendencies of the management progress. I believe, that the standards in a new version will become again a catalyst of this activity, including the electrode manufacturing.

Structure of the former standards was based on an element-based approach and included 20 obligatory kinds of activity in the sphere of quality, each of them was considered so important as the others. It required officially the distribution of resources, including financial ones, which as a rule, are always insufficient, simultaneously in all the 20 elements of SQM, that decreased the resultativeness and efficiency of the quality management in practice. The new edition of standards gives an opportunity to concentrate resources, when necessary, on key processes which are most important in a given moment from the economical aspect. This statement is very important for the electrode manufacturing, which contains many technological operations of different branch orientation, such as metalware-metallurgical, chemical-technological, mining, etc. Technical and organizational improvement of these numerous operations should also be conducted by the principle of priorities distinguish.

Theoretical reasons concern our manufacturer to a smaller extent, than the above-mentioned, but in future they will become, undoubtedly, important for them as they play a significant role in improvement of the organizational structure of the enterprise. Evolution of the organizing structures in the quality management is presented usually as a result of a constant search for optimum combinations of hierarchic (system-differential or linear) and matrix (system-integrated or multifunctional) structures of management. In the first variant the principle of hierarchy itself requires vertical management links to be much stronger than the horizontal interfunctional interactions. This is a traditional scheme for us. In the second, updated variant, the vertical links are very simplified, though they are preserved to some extent, but the management is performed mainly by cross-functional horizontals, and this provides maneuverability and dynamism to organizing. Instead of management style by the principle « how to do», the new style is coming: action for result («what should be obtained as a result»). During recently they do their best to select optimum combination of these kinds of organization for each definite manufacturing and definite product and, thus, to provide a reasonable conservatism and necessary flexibility of SQM at minimum expenses for restructurization, required for a constant adaptability to rapid changes in environment. At large productions this is reached by inclusion of management elements into continuously functioning scheme by concrete orders. This so-called project style of management is described comprehensively in [13].

Architecture of standards ISO of series 9000:2000, the same as SQM configuration, regulated by them, is multilayer and includes at least three main structures [14].

In the structure of external and internal relations are acting: consumers of products, personnel of enterprise, its suppliers and partners, owners, creditors, regional authority, state and society as a whole. Each of listed sides, should, in principle, be interested in technically successful and economically effective industrial activity of the enterprise, as it is associated with a continuous employment of workers, social welfare of the personnel, tax revenue, dividends of stockholders and creditors, ecological safety of products and production for environment. In model of SQM given in Figure 1, external mutual relations are shown on the left and on the right from a configuration circle.

Products of electrode enterprises consist completely of a purchased raw and other materials. Quality, timeliness and regularity of deliveries influence greatly the efficiency of production, characteristic and degree of competitiveness of electrodes.

Electrodes, used in manufacture of products and critical objects influence, undoubtedly, their reliability and serviceability. Regular conquest of tenders for deliveries and constant remaining among the performers of orders of important consumers is a very challenging prospect for any enterprise.

And, finally, both electrodes and their manufacture refer to the objects of a high risk. The constant demonstration of electrodes to the customers, regional ecological services and health bodies of intentions and actions, having an aim to reduce the mentioned risk, should become important elements of activity of the electrode enterprises.

All the examples show the importance and necessity to establish relations of electrode enterprises with

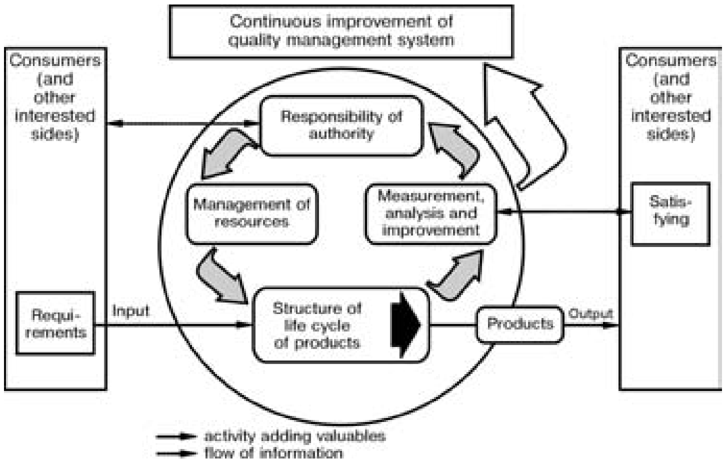

Figure 1. Model of quality management system, made on process-based approach

external customers and suppliers on partnership bases. This realization can define greatly the own economical stability, competitiveness of products and manufacturing. These are standards ISO of series 9000:2000 that assign such relations, developed during many years by the international theory and practice of management of quality of products and services. The detailed description and analysis of experience, whose results will be, undoubtedly, useful for managers of electrode enterprises, are given in [15].

At the same time, the relations of divisions and services of electrode enterprises, organized in internal production and functional processes (in Figure 1 they are arranged within the limits of a configuration circle), in accordance with this approach can also be considered as relations of suppliers and consumers. This subordination without interference of the top bodies should increase the mutual responsibility of managers and performers of cross-functional divisions, and also the efficiency and result of their activity in the sphere of quality.

The technological structure of quality management represents usually a managing cycle of E. Deming, i.e. PDCA (abbreviation of words: Plan, Do, Check and Act). The Figure 1 can convince that in accordance with this cycle (let be not in a so clear form as was envisaged by the developers of the standard, but by realizing of sequence of continuously alternating cycles of improvement) four main chapters are drawn up of each of standards ISO of series 9000, included into a system pair, namely responsibility of authority; management of resources; output of products; measurement, analysis and improvement. All the kinds of activity regulated by each of the above-mentioned chapters of the standards including the above cross-functional relations of divisions, are realized in accordance with cycle PDCA.

At such approach each constituent of the cycle along a hierarchic vertical, from global (strategic) at the upper to detailed at linear horizon of management, is not doubled in any way, but most likely structured. Thus, aim of the strategic planning, realized by the top authority of the enterprise is to develop and bring to the personnel the mission, vision, aims, policy and basic values of enterprise in the field of quality. At a mean (tactic) level the resources, logistics of deliveries, benchmarking, volumes and terms of works on definite types of products, orders, contracts are planned. Operational planning (by months, decades, shift, etc.) are realized for definite production sections.

Structure of life cycle of products (LCP), i.e. its production proper, is regulated by key chapter of the standard «Output of products». It includes marketing, development, purchases, manufacture, transporting and others, up to utilization of remnants after the use of products. Format of previous versions of standards ISO of series 9000 was represented in the form of LCP (20 elements of SQM), therefore, it is well-known to the manufacturers of electrodes. Electrode manufacturing enterprises had an opportunity to be convinced in usefulness and efficiency of this system-forming structure of SQM, in which SQM, created according to previous standards, are still functioning. In interaction with the rest mentioned system-forming structures it acquires a dynamism, i.e. from a plane, continuously reproducible ring of elements it is transformed into rising spiral of improvement consisting of them, each new turn is realized at the higher level.

It should be remembered that each stage of LCP is also fulfilled by PDCA cycle.

All the system-forming structures of quality management have a common information medium, they as if immersed into the system of information assurance of corresponding processes [16]. Here, we mean technical documentation for SQM, resources, products, processes as well as for procedures of measurement, analysis and improvement.

Requirements to documentation in new standards are simplified to limits. Obligatory documentation is required only for those procedures which are subjected to evaluation during certification of SQM. This is management of documentation and reports, internal audit, products management, not corresponding to requirements, correction and prevention of defects. Policy and aims in the sphere of quality and recommendations on quality (description of SQM) are also prepared in documents. Such procedure is considered

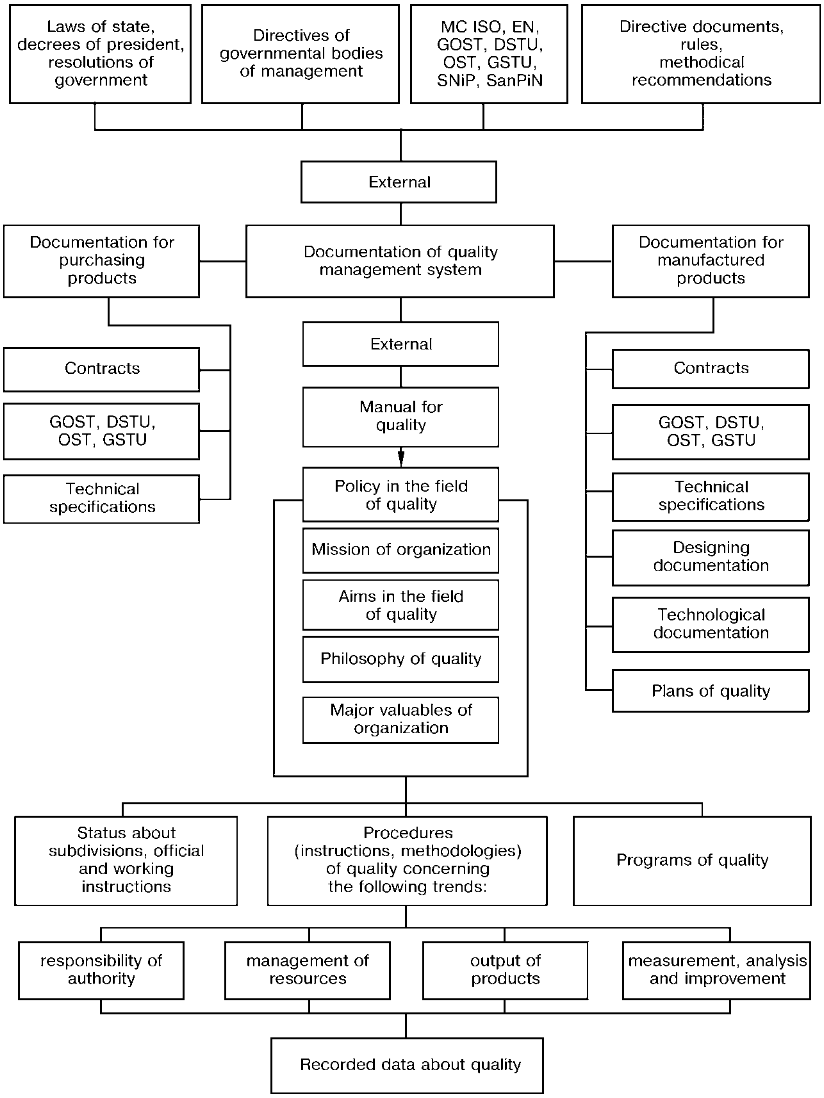

Figure 2. Structure of documentation of quality management system [17]

to be documented which is worked out, prepared in documents, implemented and kept in a working (actual) condition. Inclusion of other documents is under the consideration of top management and aimed at keeping information potential of enterprise at a required level. Here, it should be taken into account that during certification of everything described in [17] is subjected to audit.

In the new version of standards the SQM documents are systematized more strictly and logic (Figure 2). Documents of external (obligatory for fulfillment in any case) and internal origin (fulfilled and considered in certification if they are included additionally to the obligatory documents) are distinguished in it. Nomenclature of purposeful documents is widened. Procedural documents, including those concerning statistic regulation of processes are grouped by chapters of standards and aimed at realizing their major principles.

Causes of appearance and essence of these principles which should be mastered by personnel of electrode enterprises and also requirements which should be followed are described in [18–20].

In accordance with a principle of orientation for the consumer, the customer becomes a major person in business. The enterprises of market orientation should know, have to predict and to fulfil in the best way its requirements. Therefore, the count on conductance and results of marketing examinations is made during the whole LCP.

According to the principle «leadership or leading role of management», the manager-administrator should become a leader in the true sense of the word. This is one of premises of success of the enterprise in business. Without manager-leader it is impossible to create a flexible and dynamic organizational structure of the enterprise, to draw up purposeful documents, to mobilize and to get personnel interested in the achievement of success: the more benefit is made by personnel, the prospects are more widened before it.

From its side the top management considers personnel as the most important its capital, motivates its activity and creative labour in moral and material aspects, and does not try to get its blind obedience and performance. For this purpose the management trains, improves qualification of the personnel, invites it to participation in management (participatory style of management); with entire entrusting the authority delegates some of its obligations to lower stages of management, preserving its responsibility for the result. This is an essence of principle of involving people.

The principle of a process-based approach is used for a long ago in electrode manufacturing in the form of interrelated technological operations, each of them has an input and output [21]. New standards will not change this situation, if a formalistic approach is not prevailed over a common sense. Process for normal functioning should have a complete organizational and economic autonomy. It means that in parallel with a feasibility of control of input and output of operations, and also their complete information assurance the manager should have available all the necessary support means (material-technical, power resources, repair and others), otherwise its leading role will be reduced to the purely administrative work [22]. To reach such degree of autonomy a radical restructuring is required, to which the enterprises are not ready, in particular the large enterprises.

Principle of a system-based approach was first used in Integral Systems of Quality Management of Enterprises (IS QME) [23], and then it was developed in previous standards ISO of series 9000. It unites all the processes into a common system, the scope of which includes planning, fulfillment of the work on quality, evaluation of results, coordination of activity of subdivisions aimed at the envisaged result. This principle is well-known to the electrode manufacturers which had available SQM of previous generations.

The principle of continuous improvement should be used relative to the organizational structure of enterprise, production, products, personnel and SQM itself. Then, the inquiries and expectations of the customers and other interested sides will be really continuously satisfied, and the enterprise will acquire flexibility, and so the vitality, under the conditions of quickly changing and far from comfortable market environment as regards to it.

Making decisions on the basis of facts is one more principle of standards of ISO. It completely avoids the feasibility of use of voluntary procedures of management in the sphere of quality. Facts, necessary for grounding and making decisions are, as a rule, results of statistic processing and evaluation of data accumulated in the coarse of systematic observations, procedures of control and tests made on all the previous stages of industrial and management activity. In these decisions taken by well-prepared and intellectual managers, the chances to make errors are, undoubtedly, much little [24—26]. Renaissance of statistic methods in the new version of standards ISO of series 9000 is more evident, because they in combination with the principle considered become simultaneously a key tool of a continuous improvement of above-speaking products and processes.

And finally, according to the new standard the relations with suppliers are oriented to an obligatory mutual profit. This gives a full freedom to the customer in selection of the suppliers. This principle was studied on the example of electrodes supply in [27], unfortunately, without corrections for specifics of welding manufacturing. Suppliers of welding consumables for critical objects are selected even at the stage of their designing. Welding technology is tested using the selected welding consumables by a special program and in case of positive results they are certified and included into a standardized document. The designer itself is limited in the freedom of selection of suppliers and communicates only with those which are specified in specifications (see, for example [28]). The similar situation in case of deterministic technologies, even those which do not use welding. If the electrode enterprise has intention to supply products to similar customers, then it can combine the certification of SQM by ISO of series 9000 with certification of products by special requirements, thus saving the funds. The latter requirement can be included into documentation of SQM by coordination with inspection body, for example, in the form of an additional self-contained chapter.

The manufacturers of electrodes are also limited in the selection of suppliers of raw materials by instructions of a standardized documentation. Sometimes, even deposits of raw materials are specified in it, and these requirements should be taken into account in their purchase.

Characteristics of quality of electrodes need discussions due to new standards. Let us consider now only technical discussions which can be divided into three categories [29].

Specified rates characterize the most important consuming properties which define the suitability of use of electrodes in either sphere of manufacture. These rates are regulated by state standards and also standardized documents equal by status. This category includes characteristics of designation (including type of electrodes, properties and composition of welds and deposited metal), and also the efficiency of application (productivity, sanitary-hygienic characteristics, safety and others).

The object characteristics make it possible to attain the specified characteristics and to provide manufacture of electrodes with required indices (sizes, chemical composition, physical-chemical characteristics of type of coating strength, tolerances for deviations in sizes, etc.). The object characteristics are specified in documents of the designer and technological documents, which are made by manufacturer on its basis. They may include the characteristics of initial materials, semi-products and intermediate types of products.

Indices of defectness characterize the types and amount of defects (namely deviations from preset object characteristics), allowable or non-allowable for correction. They are specified in the designer's documents. Deviations at the level of non-conformities can be specified in the manufacturer's documents. Difference between terms is interpreted in standard ISO of series 9000:2000.

Object and defect characteristics are the direct objects of management and subjected of control in manufacture of electrodes. Management task is the selection of nomenclature of characteristics for management (support of a required level of quality, the creation of a new object of quality, quality assurance for satisfying demands of consumers at a reasonable price) and reaching these aims each time at a new spiral of a continuous improvement.

Specifics of electrodes as products, whose quality should be controlled in manufacture, consists in the fact that the majority of characteristics of their quality (including the defectness level) are specified by a standardized documentation of the governmental level and designer. In Ukraine they are included into the list of types of products subjected to the obligatory certification by a third (independent) side. The quality index defined by the consumer in contract situations cannot be worse than that in the standardized documents.

Ukraine, the same as Russia, is significantly behind countries with a market economy in the development and application of methods of quality management by standards ISO of series 9000. Number of developed and certified SQM by several orders smaller than in countries of Europe, in Japan and the USA. One of the reasons consists in the fact that economical profits of modern methods of quality management and their great importance in providing survival, stability of position and achievement of a sufficient degree of competitiveness of products and enterprises in crisis situations, which were demonstrated by Japan earlier that others and also by countries of Asia («Asian tigers») and Latin America not ago, have not been yet realized. Problems which are faced by enthusiasts deciding to follow this path are analyzed in [22] on the example of the Russian enterprises. Here, the program of revival is also offered which, undoubtedly, may also attract interest of electrode manufacturers. It can be started after putting the production in proper order. It can be realized by the following ways:

- conductance of measurements and analysis of the level of non-conformities in own production;
- conductance of analysis and classification of revealed non-conformities by causes, importance, place of origin and type (technical, performance and organizational);
- motivation of reducing the level of non-conformities;
- coordination of production capabilities with requirements of technical and technological documentation for products;
- development of program of reducing the number of non-conformities at plant (shop) level, implementation of a statistic regulation of processes (operations) using control charts;
- establishment of production relations using supplier–consumer scheme and acceptance of declaration of rights of internal consumer;
- creation of documented SQM corresponding to statements of standards ISO of series 9000:2000 and aimed at a continuous improvement;
- setting of existing system of mutual relations with external supplier.

Before putting this program into force, the manager of the enterprise should become a real leader of the planned transformations, to be trained and to train personnel on the bases of the quality management. Possibilities at the present time are unlimited.

The Interindustry Training-Certification Center (ITCC) of the E.O. Paton Electric Welding Institute held the first seminar of managers of electrode enterprises on SQM in May, 2001. The texts of lectures are published by a separate Collection [30]. In future such seminars will be planned regularly.

In June, 2002, ITCC in collaboration with Training-Research Institute of Welding in Meklenburg-Felpommerne (Germany) trained in Kyiv the first group of internal auditors of SQM using the 112-hour program. Trainees were awarded certificates «Manager of Quality» of European standard. The ITCC authority has intention to train the groups by this program in future.

Over more than 10 years the technologists of electrode manufacturing are trained and improved their qualification in ITCC. In 112-hour program 40 % of time is used for modern quality management in electrode production. By the desire this number of hours can be increased.

Members of International Association «Electrode» of CIS analyze regularly the problems in the sphere of quality of electrode manufacture at their meetings, scientific-technical seminars and conferences. Here, all aspects are studied: material-technical assurance, status of designs of technological equipment, preparation of personnel, certification of products and production, etc. In other words, the Association realizes the integration approaches to the quality management of products, which were offered by State Standard Organization of the former USSR (Gosstandart) as far back as the 1990s for overcoming barriers occurred due to disintegration of a single economic mechanism.

The experience of enterprises-members of Association, being leaders in the development and application of SQM, is studied and analyzed. Though it does not correspond completely to the above-described program, however, their results are successful. Some of the mentioned enterprises are working by the orders of the major consumers [31, 32]. And this induces optimism in evaluation of prospects of mastering procedures of quality management by standards ISO of series 9000 also by other enterprises included into the membership of the Association «Electrode». Naturally, capacity, organizational capabilities, financing-technical possibilities and current condition of production at these enterprises will be reflected in separate parts of the program and the duration of its fulfillment. But the positive result will be, undoubtedly, achieved.

During the program realization, the question is arisen obligatory about the role of consultants in the working out of SQM documentation, which are invited from other organizations. Experience of other productions showed that without their participation it would be difficult to create effective SQM in required terms. Professional participation of the external leader is necessary and important for a skilled diagnostics of production, proper selection, planning and further realization of actions by stages, including also by a «precise setting» of requirements of standards ISO of series 9000 for the conditions of work of a definite enterprise (up to definite working places). For this, expert should have a perfect knowledge in the methodology of the mentioned standards and know comprehensively the specifics of production of this enterprise. He will be indispensable in training of personnel in common «rules of game», coordination and approval of results of actions of industrial performers, who are working out documentation of SQM and he will be necessary for a constant ensurance from a zero technical result at the final stage of the development. By selecting consultants (they have a honorable name abroad — advisers), the customer may expect a minimum risk of not passing a precertification audit, high price of service and acceptable term. The latter should amount to 1.5–2 years, otherwise the development will become old and not profitable.

At present in Ukraine and Russia only the formal part of the certification on the developed documentation of SQM has been mastered. Here, the desire appears to invite those for consultations who know the requirements for documentation of SQM in formal way, but perfectly, i.e. auditors of bodies of certification or foreign certifying organizations. These examples exist both in CIS and countries with a market economy, including enterprises manufacturing welding consumables.

At the present moment there are no juridical limitations for the development and certification of SQM by the same organization (if even these actions on its behalf are performed by different persons being its staff members, or the one and the same person being in service at its different subdivisions). However, these actions are blamed by professionals–systemizers–designers by some reasons [33–36] indicated below.

Rules of certification by the third (independent) side do not admit, in principle, such combination, as it is impossible to call the side independent if it consults the development which will be subjected to further certification.

There is a high probability that as a result of these actions the enterprise will obtain the «formal» information in the form of certificate of conformity that it is already «o'key» instead of a «real assistance on improvement of health» being very important for overcoming crisis and acquiring a stable position at the market [22].

It should not be expected that developed and thus certified SQM will become really effective and resultative, because, as the experience showed, the number of advantages which enterprise is expecting to obtain are proportional to efforts made by personnel for its development. Documentation of SQM should be created in the organization and by those people who will use it. During the process of documentation development they analyze the state, search and eliminate nonconformities, improve the management structure and technology of production, taking into account here the merits of their enterprise and so on. It is very well if the adviser could have dialog with them in an understanding professional language.

The occurrence of «racing to certification» is hazardous. Not taking into consideration other reasons of this phenomena, discussed in [37], we shall pay attention to the fact that persons dealing simultaneously with the development and certification of SQM are mostly interested in a positive and fast completion of work. They will try to pass ahead each other in making certification even without accounting for the readiness of personnel to accept SQM. The excess of certificates is not so hazardous (we are far from it) as the appearance of faceless, slight SQM, created by pattern and resembling each other like twins. There is a hazard that they can overtook the fortune of IS QME created by common recipes from one even a highly-qualified center. Using approaches based on pluralism it is difficult to fulfil the major requirement: those who are dealing with quality should demonstrate the examples of ethics in all their actions.

Management of quality in electrode manufacture has passed a long way of development [38]. Association «Electrode» has a sufficient authority, organizational efforts and is capable to use a moment of transition to the new versions of standards ISO of series 9000 as a stimulus for beginning of works on quality at the new stage of overcoming the economic difficulties and actual improvement of a potential of competitiveness at the market of welding consumables.

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PROPERTIES OF THE METAL DEPOSITED BY ELECTROSLAG PROCESS USING CHIPS OF TOOL STEEL 5KhNM AS FILLER MATERIAL

O.G. KUZMENKO and **I.A. RYABTSEV**
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

Technology and properties of the metal, deposited by electroslag process with a filler of chips of tool steel 5KhNM, are described. It is established that in electroslage hardfacing (ESH) the content of impurities in the deposited metal is markedly reduced. Production trials showed that the life of dies, restored by ESH, using chips of tool steels, is 1.5–3 times higher than that of forged dies. High and stable performance of ESH dies confirms the rationality of their application instead of the forged ones.

Key words: *electroslag hardfacing, dies, mechanical properties, life, tool steels*

In restoration of worn dies by hardfacing the efficiency and cost-effectiveness of the process have an important role. Various arc hardfacing processes, widely used for this purpose, do not always meet these requirements, particularly with large volumes of the deposited metal, for instance, at restoration of large-sized hammer dies [1].

Process of ESH, using tool steel chips as filler, which was developed at the E.O. Paton Electric Welding Institute, allows a considerable improvement of hardfacing efficiency and quality of deposited metal [2]. The essence of the process is as follows. For hardfacing the die with the gravure facing upwards is placed into a mould of the dimensions corresponding to those of the die. Flux AN-15-M (wt.%: $10SiO_2$; $30CaO$; $20CaF_2$; $40Al_2O_3$) is used for hardfacing the dies, which is first melted in a slag-melting furnace in the amount, required for inducing a slag pool 40 to 75 mm deep. Slag is poured into the mould, non-consumable water-cooled electrodes are lowered into the slag pool and electroslag process is started.

Portion feed of tool steel chips at the speed of 2–3 kg/min is started only after partial melting of the entire surface of the die gravure. When chips feeding is over, specific power of the process is reduced to a certain value, this allowing performance of a controlled solidification of the deposited metal.

Such a technology enables producing a high-quality deposited layer of several millimeter thickness, dense over the entire cross-section, without defects of shrinkage type, slag inclusions, lacks of fusion, etc.

Investigation of the deposited metal composition showed that sulphur content was reduced from 0.024 in the chip metal to 0.012 % in the metal of the deposited layer. Amount of oxygen and nitrogen was reduced from 0.0042 and 0.0073 in the chip metal to 0.0014 and 0.0040 % in the deposited layer, respectively. In addition, the quantity of non-metallic inclusions in the deposited metal was also decreased. So, volume fraction of oxides and sulphides in the deposited metal is 0.002 and 0.018 and in the forged metal 0.016 and 0.120 %, respectively. In the deposited metal non-metallic inclusions are arranged uniformly, and in the forged one mostly in groups. At chip melting in the slag pool the reduced reaction surface is much larger than when using other types of filler or electrode metals (wire, strip, liquid metal, etc.), this promoting better refinement of the deposited metal.

Metallographic investigations showed that microstructure of the deposited layer, when using 5KhNM (wt.%: 0.5C; 1.0Cr; 1.0Ni; 0.3Mo) steel as filler,

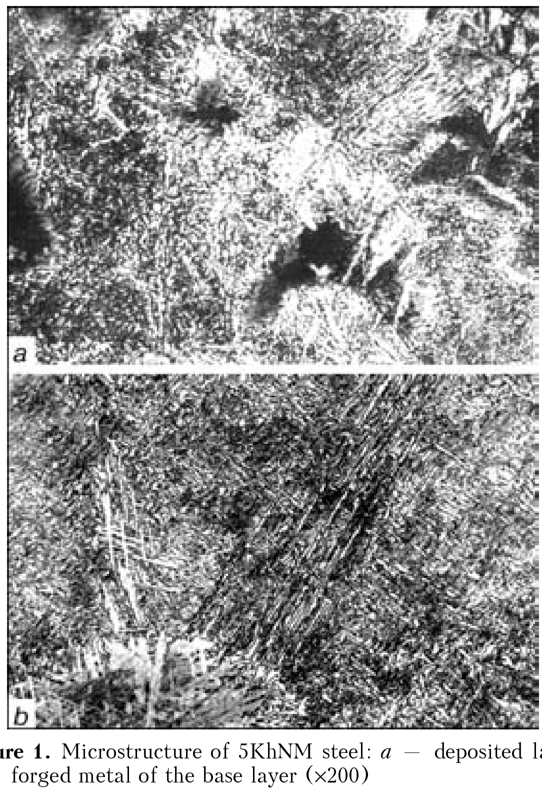

Figure 1. Microstructure of 5KhNM steel: *a* — deposited layer; *b* — forged metal of the base layer (×200)

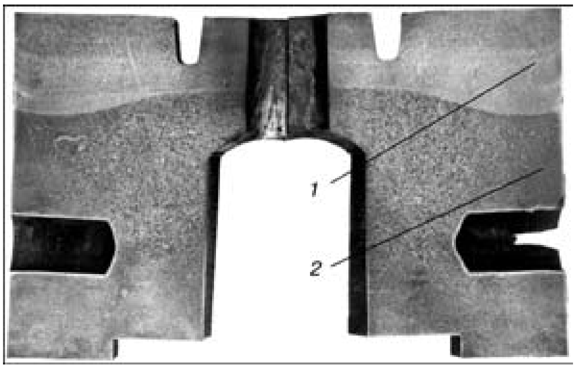

Figure 2. Cross-sectional macrostructure of the die, hardfaced by ESH process with chips of tool steel 5KhNM: *1* — deposited metal; *2* — die

Mechanical properties of forged and deposited steel 5KhNM

Test temperature, °C	*Metal type*	σ_y, *MPa*	σ_t, *MPa*	δ, *%*	ψ, *%*	a_n, *J/cm²*
20	Forged	1160	1302	11.9	38.6	47.7
	ESH	1139	1252	11.0	32.0	45.0
400	Forged	807	934	18.4	67.4	45.5
	ESH	742	932	16.4	57.7	42.5
600	Forged	197	267	47.6	92.6	85.0
	ESH	185	254	46.4	95.1	97.7

consists of troostite, pearlite and small regions of martensite-austenite structure (Figure 1, *a*). Microhardness of regions with troostite-pearlite structure is equal to *HV* 5–(3490–3840) MPa, and that of sections with a martensite-austenite structure is *HV* 5–(4120–4410) MPa. Base metal of the die, compared to deposited metal, has a coarser troostite-pearlite structure (Figure 1, *b*).

Results of mechanical testing (Table) of samples of open-melted forged metal and metal, deposited by ESH process with a filler of chips of 5KhNM steel show that the strength properties of the latter are on the level of those of forged metal at all the test temperatures (20, 400 and 600 °C).

Studying the samples of deposited metal after impact toughness testing demonstrated that their fracture is fibrous, with small regions of crystalline structure, dense, and of mat colour without flakes, pores or delaminations. Investigations of cross-sectional microstructure of the die (Figure 2) confirmed the high quality of the deposited layer. The latter has different height due to different depth of the die gravure.

Comparative testing of forged dies and those restored by ESH, using tool steel chips, was conducted in companies «Tokmak Forging-Stamping Works» and «Postselmash» on hammers with the falling part weight of 1 and 5 t and presses of 2.5 MN force.

Testing in hammers with falling part weight of 1 t showed that the average life of the dies after ESH with non-compact materials (NCM) is 17167 forgings till the first repair. The cause for die failure is gravure wear. Then the dies were repaired with lowering of the die height. Their life was practically not decreased, being 16000 forgings. Wear resistance of similar, but forged dies was 6860 on average at the specified value of 8000 forgings.

Forged and hardfaced dies of 500×500×770 mm size were tested in hammers with falling part weight of 5 t. Testing showed that the average life of dies after ESH NCM is 4415 forgings. The cause of the dies failing is gravure wear. Then the dies were two times subjected to repair with lowering of gravure height, and their life in this case was not decreased (5250 and 4805 forgings, respectively). Life of similar forged dies was 2858 forgings on average, and 1822 after repair at the specified value of 2500. Forged die failure is caused by various defects of metallurgical nature, and that of hardfaced ones are fire cracks.

Dies of 5KhNM steel of 180×300×400 mm size, restored by ESH NCM process, and similar forged ones were tested in presses of 2.5 MN force. Life of hardfaced dies was 8000 forgings, that of forged ones was 3500 forgings. The main cause for their failure were fire cracks.

The above data indicate that the life of dies, hardfaced by ESH process (before repair by machining), is 1.5–3 times longer than that of forged dies. Lowering of impurity content in the deposited metal, absence of defects of shrinkage and liquation nature, high mechanical properties of the metal of the deposited layer provide good performance of the dies, hardfaced, using chips of tool steel 5KhNM as filler. High and stable life characteristics of the hardfaced dies confirm the rationality of using them instead of the forged ones.

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RESISTANCE OF THE HAZ METAL OF STEEL M76 TO COLD CRACKING AFTER SURFACING USING FERRITIC GRADE WIRES

Ya.P. CHERNYAK, G.V. BURSKY and **V.K. KALENSKY**
The E.O. Paton Electric Welding Institute, NASU, Kyiv, Ukraine

The possibility of surfacing tram rails using ferritic wires of the TGM and GSMF types without preheating was studied. Surfacing under optimal conditions was found to cause no cold cracking of the HAZ of rails and deposited metal. The results obtained were proved by testing specimens using the improved implant method.

Key words: *rail steel, surfacing, heat-affected zone, heat input, cold cracks*

Surfacing using austenitic grade wires was employed to repair worn out inside lateral surfaces of tram flange rails in the curvilinear regions of the track [1]. Cold cracks of the cleavage type were detected in the HAZ of rail steel M76 (wt.%: up to 0.82C; up to 0.15Cr; 0.25Mn) under the first deposited bead. It was established that cleavage was caused primarily by martensitic transformation of austenite in the HAZ of the base metal. The unfavourable effect was exerted also by surfacing stresses, which aggravated because of a large difference between the linear expansion coefficients (LEC) of the austenitic deposited metal and high-carbon pearlitic steel M76. Formation of cleavages was eliminated by depositing the first bead at an increased heat input.

Surfacing using the ferritic grade wires, which provide the deposited metal with LEC close to that of the base metal, is the method which is more natural and cost effective for elimination of cleavages. In this connection, the authors developed and applied flux-cored wire of the PP-Np-GSMF (wt.%: 0.6C; 2.0Mn; up to 0.5Mo; up to 0.1V) type for surfacing by the submerged-arc method, as well as self-shielding wire of the PP-Np-TGM (wt.%: 0.6C; 3.0Ti; up to 1.0Mn; up to 0.5Mo) type. Surfacing of samples of worn out rails was performed without preheating. For this 8 horizontal beads were deposited in turn one on the other with 10 min intervals, thus simulating the process of surfacing of an actual rail.

Wire surfacing parameters:

open-arc method using the TGM wire: $I = 450$ A, $U = 26$ V, $v_s = 36.8$ m/h;

submerged-arc method using the GSMF wire and the AN-26P flux: $I = 450$ A, $U = 34$ V, $v_s = 36.8$ m/h.

The values of LEC ($\alpha \cdot 10^{-6}$) of steel M76 and deposited metal of both types, measured in heating from 20 to 700 °C, were as follows:

M76 — 15.2, TGM — 14.4 and GSMF — 14.9.

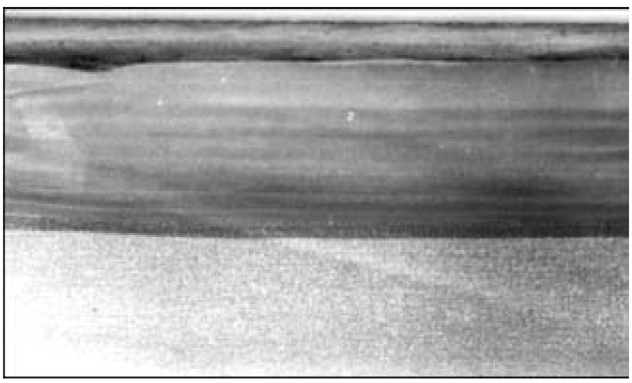

Figure 1. Crack-free longitudinal macrosection of the rail flange deposited with eight beads using an experimental flux-cored wire of the GSMF type

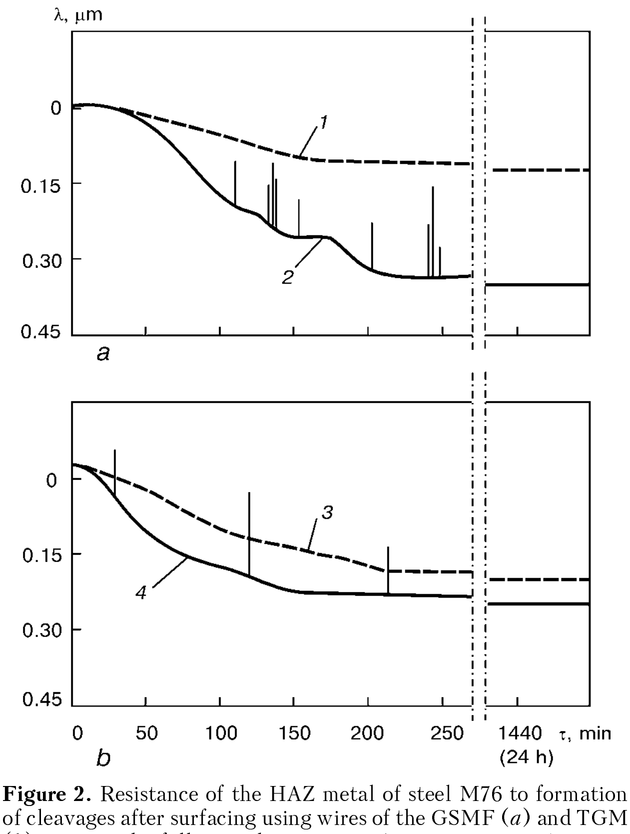

Figure 2. Resistance of the HAZ metal of steel M76 to formation of cleavages after surfacing using wires of the GSMF (*a*) and TGM (*b*) types at the following heat inputs: *1* — 32.3; *2* — 15.1; *3* — 24.7; *4* — 11.6 kJ/cm

Effect of heat input and thermal cycles on resistance of specimens of steel M76 to cold cracking

Specimen No.	Wire	Bead	v_s, m/h	Q, kJ/cm	ω_{3-2}, °C/s	A_i, J/m^2	AE signals
1	TGM	Lower	17.2	24.7	1.4	–	No
		Upper	36.8	11.6	1.2		
2	Same	Lower	36.8	11.6	2.9	72.7	Yes
		Upper	36.8	11.6	1.7		
3	GSMF	Lower	17.2	32.3	1.3	–	No
		Upper	36.8	15.1	1.0		
4	Same	Lower	36.8	15.1	2.3	163.3	Yes
		Upper	36.8	15.1	1.2		

Note. The rest of the surfacing conditions for TGM are as follows: I = 450–460 A, U = 26 V, open arc; and those for GSMF are as follows: I = 450–460 A, U = 34 V, flux AN-26P.

Examination of metallographic sections showed no cleavage of the HAZ of the base metal or any other cracks in the deposited metal in both cases (Figure 1).

Studies of delayed fracture of the treated samples were conducted for quantitative estimation of resistance of the HAZ of steel M76 to cold cracking after surfacing using the above ferritic wires.

Method and equipment used to conduct the studies are described in [2, 3]. According to the method described, it was necessary to estimate specific energy of microcrack initiation A_i in the HAZ of specimens made from steel M76 and, in the case of fracture of the specimens, specific energy A_{sp} required for formation of the centre of fracture. The method used to make the specimens and experimental procedure are described in [4]. Parameters and results of the tests are summarised in the Table. Two beads were deposited on each specimen: first the lower bead and then, after 10 min, the upper bead. On specimens No.1 and 3 the lower beads were deposited at a low speed, which provided the corresponding increase in heat input.

The level of the load applied was selected on a condition of $P_{sp} \approx \sigma_y$ (σ_y = 610 MPa is the yield point of steel M76). The experiments showed that all the specimens subjected to this load for 24 h did not fracture.

It follows from Figure 2 that relaxation of stresses in the HAZ of steel M76 occurs because of microplastic strains. In specimens No.1 and 3, where the lower bead was deposited at a low speed, relaxation takes place under more favourable conditions. Relaxation of stresses in the HAZ of specimens No.2 and 4 treated at a decreased heat input occurs under less favourable but acceptable conditions. Here the displacements under deformation are higher, and they are accompanied by initiation of microcracks. However, this does not lead to their growth and formation of macrodefects. Initiation of microcracks was detected by a piezotransducer. It is marked on curves *2* and *4* by the acoustic emission signals of a differing amplitude.

The fact that all the specimens deposited using ferritic wires did not fracture and withstood the tests is indicative of a high resistance of the HAZ of steel M76 to delayed fracture.

High resistance to delayed fracture and absence of cold cracks in multi-layer surfacing of samples of worn out tram rails using ferritic wires of the GSMF and TGM types show that cold cracks of the type of cleavage which cause fracture of the deposited joint do not present a problem. Therefore, the rails can be surfaced using the above wires under optimal conditions, which allows an increased heat input to be avoided in deposition of the first bead, in contrast to what is recommended in [1, 4].

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2. Bursky, G.V., Savitsky, M.M., Olejnik, O.I. (1999) Improved method for evaluation of HAZ metal resistance to delayed fracture. *Avtomatich. Svarka*, **4**, 31–-34.
3. Bursky, G.V., Sterenbogen, Yu.A. (1990) Evaluation of resistance of HAZ metal of medium-alloy high-strength steels to delayed fracture. *Ibid.*, **8**, 33–35.
4. Chernyak, Ya.P., Bursky, G.V., Kalensky, V.K. (2002) Some peculiarities of delayed fracture of HAZ metal in steel M76 after cladding using austenitic wire. *The Paton Welding J.*, **8**, 40–42.

Development of the PWI

RDK-300 RESONANCE WELDING POWER SOURCE WITH A COMBINED EXTERNAL CHARACTERISTIC

Device RDK-300 represents a welding unit designed for MMA welding in the range of currents 50–300 A. As to the design it is two-moduled. Combination of two modules provides a combined external characteristic with wide ranges of welding current adjustment. Approach, based on multichannel transformation of power flow, makes it possible to improve significantly the efficiency of the welding equipment.

The use of the principle of reserving a capacitance reactor increases greatly the reliability of the device and can provide the duty cycle ≥ 60 %.

The application of the resonance principle of transformation of power flow (resonance of voltages in the secondary circuit) provides high welding-technological properties of this class of equipment at a sufficiently low open-circuit voltage (36–42 V), that guarantees the highest electrical safety and allows this equipment to be recommended for use in the field conditions.

The use of the resonant circuit in the secondary circuit with high selective properties leads to the fact that the level of electromagnetic noises generated into the mains and surrounding medium is lower by order as compared with other types of welding machines. In principle, the capacitance reactors, on which the welding machines are based, are the longitudinal compensators of a reactive power, therefore, the power factor cos φ is 0.95–0.98.

The unit is manufactured in three modifications:

• for welding at alternating current (model M1);
• at direct current (M2);
• variant of a universal modification for DC and AC welding (M3).

Main parameters of the unit corresponding to model M1 are given below:

Mains voltage, V	220–380
Mains frequency, Hz	50
Maximum primary current, A	36
Maximum secondary current, A	300
Rated secondary current, A	280
Primary current in short-circuit condition, A	25
Method of welding current control	manual (12 steps)
Open-circuit voltage, V	40

Ranges of welding current change, A	50–300
Duty cycle, %, at 180 A	100
at 220 A	80
at 250 A	60
at 280 A	40
Maximum mass of device, kg	36

The device RDK-300 can be used for welding with rutile-coated rod electrodes of diameter 2, 2.5, 3, 4, 5 and 6 mm. Models M2 and M3 can realize welding using almost all types of electrodes, because by the mentioned modifications have the units of «hot» start. When the oscillator is used the device RDK-300 can be used for TIG welding.

As to the parameters of electromagnetic compatibility the developed device corresponds completely to all the requirements of the European standards.

For additional information, please, contact:
Dr. Korotynsky A.E.
Tel.: (380 44) 261 51 02

INTERNATIONAL CONFERENCE «MATHEMATICAL MODELLING AND INFORMATION TECHNOLOGIES IN WELDING AND RELATED PROCESSES»

The International Conference «Mathematical Modelling and Information Technologies in Welding and Related Processes» was hosted by the House of Scientists of the National Academy of Sciences of Ukraine in Katsiveli, Crimea, from 16 to 20 September, 2002. The Conference was organised by the National Academy of Sciences of Ukraine, Ministry of Education and Science of Ukraine, E.O. Paton Electric Welding Institute of the NAS of Ukraine, Inter-State Scientific Council on Welding and Related Technologies, International Association «Welding» and Journal «Avtomaticheskaya Svarka» (Automatic Welding). Co-chairmen of the Conference Organising Committee were Prof. I.K. Pokhodnya, Prof. V.I. Makhnenko and Prof. L.M. Lobanov.

The Conference was attended by more than 60 scientists and engineers from 9 countries, including famous experts from the world-leading centres on mathematical modelling of phenomena occurring in welding and related processes, such as V.I. Makhnenko, V.F. Demchenko, I.V. Krivtsun (the PWI, Ukraine), P. Seyffarth (SLV Rostok, Germany), V. Pavlyk (Welding Institute, Aachen University, Germany) and W. Zhang (The Pennsylvania State University, USA).

The Conference revived a tradition of holding conferences on mathematical modelling which had been organised by the Department of Mathematical Methods for Investigation of Physical-Chemical Processes in Welding and Special Electrometallurgy of the PWI, as well as conferences on welding arranged by the International Association «Welding» in the last years.

Papers dedicated to the following areas of research were presented at the Conference:

mathematical modelling: physical phenomena determining efficiency and distribution of heat input during welding heating; process of metal transfer in welding; formation and hydrodynamics of the weld pool in fusion welding of solid and porous materials; solidification of the weld pool, chemical composition of the penetration zone and formation of chemical heterogeneity; kinetics of microstructural transformations in single- and multi-pass welding; chemical composition–microstructure–mechanical properties relationships; kinetics of deformation processes in temperature ranges of hot cracking and conditions for its elimination; thermal-deformation processes in pressure joining allowing for high distortions; transport of hydrogen in welded joints; estimation of risk of cold (hydrogen) cracking; residual stresses and strains in mulit-pass welding allowing for microstructural transformations occurring in metal; degradation of properties of the welded joint material under the effect of high temperatures, reactive environments and nuclear radiation; process of identification of defects of welded joints by non-destructive testing;

information technologies in welding, surfacing and coating: generation of databases on characteristics of structural materials and welding consumables for mathematical modelling of physical processes in welding and related technologies; computation-information systems for deriving rational technological solutions concerning specific problems of welding and related processes, as well as Internet and information services in the field of welding and related technologies.

A distinctive feature of subjects covered by the Conference is prevalence of materials science issues associated with welding heating. This includes melting and solidification, chemical composition and chemical heterogeneity, microstructural transformations, behaviour of gases (especially hydrogen) in a welded joint, mechanical stresses and local strains, risk of formation of cold and hot cracks, and mechanical properties in different zones of a welded joint. Much consideration was given to development of computation systems to solve typical technology problems on the basis of mathematical modelling of the entire package of characteristic phenomena taking place in welding and related technologies, thus forming a tool for finding engineering solutions.

Computer demonstrations of different types of software for modelling welding and related processes were carried out during the Conference. Participants of the Conference and potential customers expressed great interest in these demonstrations.

Organisers of the Conference are planning to publish the book of proceedings by the end of 2002. The book will be available at the library of the PWI or at the editorial office of the «Avtomaticheskaya Svarka» Journal and The Paton Welding Journal. Also, the book can be ordered from the International Association «Welding» via e-mail: journal@patom.kiev.ua.

Dr. A.T. Zelnichenko

VISIT TO THE E.O. PATON ELECTRIC WELDING INSTITUTE BY Dr. WAYNE THOMAS, THE LAUREATE OF THE EVGENY PATON PRIZE OF THE INTERNATIONAL INSTITUTE OF WELDING

On the 21st–23rd of October the E.O. Paton Electric Welding Institute was visited by Dr. Wayne M. Thomas, the laureate of the Evgeny Paton Prize, who was awarded this Prize at the 55th Assembly of the International Institute of Welding in Copenhagen in June 2002.

Dr. Thomas is a member of the Governing Board at TWI, he has many British and international awards for his great contribution to fundamental and applied research in the field of welding.

During his visit to the Institute, Dr. Thomas was introduced to the studies performed at different laboratories and departments. He visited the Pilot Plant for New Technologies and engineering centres.

On the 22nd of October Dr. Thomas delivered lecture «Friction Welding and Allied Processes: a Feasibility Study». The lecture attracted a big audience, including Director of the Institute Prof. B.E. Paton, Deputy Directors Prof. L.M. Lobanov and Prof. K.A. Yushchenko, leading scientists and specialists of the Institute, as well as representatives of the aircraft engineering plants of Kyiv, Kharkiv and Zaporizhya.

In his welcome address to the winner of the Evgeny Paton Prize, Prof. Boris E. Paton acquainted the attendees with biography of the Dr. Thomas and his basic scientific developments. The most significant achievement of Dr. Thomas is his invention of friction stir welding in 1991. It took this method no more than 5 years to pass the way from initial experiments to commercial application, and this is a major achievement of Dr. Thomas. By this year more than 30 enterprises and companies all over the world have bought licenses for this method and are using it to advantage.

After the welcome address the floor was given to Dr. Thomas. The speaker presented historical facts concerning invention of friction welding and, in particular, emphasised the role of the former Soviet Union scientists in its emergence and development of technologies for friction welding of different parts in the 1950–1980s. He examined some of the potential

applications of this process. Dr. Thomas dwelt in detail on the rotary FSW process developed by TWI.

The most elaborated in the area is the technology for FSW of aluminium alloys. Now this method can be employed for one-sided joining of aluminium alloy plates with thickness from 1 to 50 mm and double-sided joining of plates up to 75 mm thick. FSW of aluminium alloys has wide commercial application: it is applied in aerospace engineering to weld fuel tank casings, in ship building — to weld aluminium panels of light boats, and in the fabrication of high-speed railway train wagons — to weld aluminium skin and casing elements from extruded profiles.

The work on FSW includes also other non-ferrous metals, such as lead and zinc. The record high speeds have been achieved in welding these metals.

TWI is involved in friction welding of ferrous metals. The efforts made in this field prove the feasibility of achieving a satisfactory mechanical strength with this class of the materials as well. Technically, this method shows promise for welding relatively thin steel sheets, including with zinc coatings.

An important element of the FSW equipment is the tool the design of which is a result of long efforts of scientists and engineers. The tool available now for welding aluminium alloys is characterised by a complex shape and very high wear resistance, allowing up to several kilometres of the weld to be made without tool change.

As to the tool for welding steels, here the situation is worse — the tool life is enough to weld no more than a few metres of the weld. Further work is needed to solve this problem.

Then Dr. Thomas answered numerous questions of the attendees.

Prof. Paton thanked Dr. Thomas for the interesting and informative lecture and expressed the hope that the close collaboration between the PWI and TWI would help to promote the FSW process to the Ukrainian market. As a souvenir of the visit to the PWI, Prof. Boris E. Paton presented Dr. W. Thomas with an engraving by artist S. Belyaev, showing the all-welded Evgeny Paton bridge in Kyiv. The bridge will be 50 years old in 2003, and it is still one of the world-largest all-welded bridges.

The attendees were demonstrated the video showing the ceremony of awarding the Evgeny Paton Prize to Dr. Thomas at the 55th Assembly of the IIW in Copenhagen, where the Medal and Diploma were given to Dr. Thomas by Prof. K. Yushchenko, Deputy Director of the PWI.

In conclusion, Dr. W. Thomas expressed his deep appreciation to Prof. Boris E. Paton and those present at the lecture for the warm reception and the opportunity given to him to visit the Institute, its laboratories and engineering centres, and get acquainted with the latest achievements of the Institute scientists.

I.A. Ryabtsev
PWI Press Release