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PECULIARITIES OF INFLUENCE OF DEFECTS IN CAST BILLETS OF STEEL 110G13L ON MECHANICAL PROPERTIES OF JOINTS DURING FLASH-BUTT WELDING

S.I. KUCHUK-YATSENKO[1], **Yu.V. SHVETS**[1], **A.V. KAVUNICHENKO**[1], **V.I. SHVETS**[1], **S.D. TARANENKO**[2] and **V.A. PROSHCHENKO**[2]

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The features of defects formation in butt welds, made by flash-butt welding of cast billets of steel 110G13L (GOST 7432–87) with austenite rolled billets of steel 12Kh18N10T (GOST 5949–75), which are used in manufacture of welded railway frogs, were investigated. It was established that casting defects, being located in the butt weld zone, lead to formation of defects and, depending on conditions of their formation, affect the strength properties of welded joints in different ways.

Keywords: *pulsed flash-butt welding, high-manganese steel 110G13L, rail steel M76, austenite insert*

At the E.O. Paton Electric Welding Institute the technology and equipment for flash-butt welding of railway frogs [1] were developed, the main feature of which is the application of a pulsed flashing [2], which allows producing joints of high-manganese cast steel 110G13L with rail steel M76 through an insert of rolled chromium-nickel austenite steel 12Kh18N10T. The frog with welded-on rail ends is shown in Figure 1.

The actual task at the modern stage is the increase of reliability and life of operation of railway frogs. Its solution is closely connected with the development of rational methods of non-destructive testing both of a ready product (welds) and also incoming materials, which are used in producing of a welded frog.

The purpose of this work is the investigation of influence of weld defects, connected with available defects in initial materials before welding, on mechanical properties of the joints. This is especially important in welding of cast billets, as far as this problem practically was not investigated.

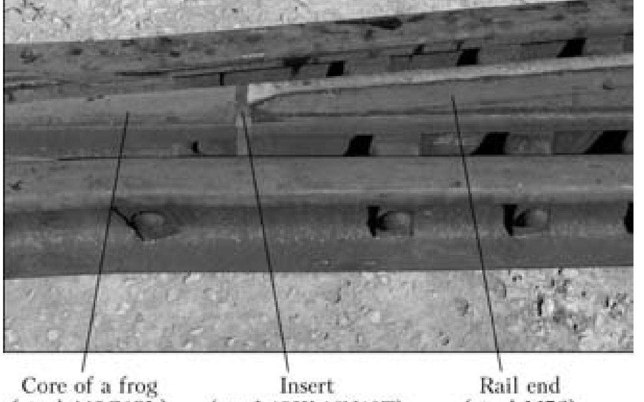

Figure 1. Frog with welded-on rail ends

The evaluation of influence of defects of butt welds, occurring as a result of getting the defects of casting (cavities, pores) into the zone of welded joint, on strength properties of the latter and their detection using radiographic method of inspection were conducted on specimens of a rail profile R65. For this purpose the batch of castings of steel 110G13L was cast with violation of casting technology which resulted in formation of cast defects. The ends of castings were subjected to radiographic inspection to the depth of up to 100 mm, from the results of which the sites of location of defects and their sizes were determined. After that the facing of specimens was carried out in such a way that during welding a defect could get into the zone of joining. In the specimens of castings, where natural defects were absent, the holes were drilled which simulated the hollows in the casting. The mechanical tests of specimens were carried out according to the TS U 27.3-26524137-1342:2006 [3]. Before the tests the radiographic inspection of welds on specimens was carried out to check up the presence of defects.

Having performed the mechanical tests of welded specimens on static bending in the areas, where defects of casting caused the fracture along the line of joint of 12Kh18N10T to 110G13L, the sections were cut out and metallographic examinations were carried out. The sections were also cut out from the defective sites, which were found in welds using radiographic inspection, though they did not lead to fracture of specimens along the joining line. The investigations of microstrucutre were performed using optical microscope «Neophot-32», and the analysis of chemical heteroge-

Chemical composition of melt in artificial defect, wt.%

Measuring zone	Mn	Cr	Ti	Ni
A	11.006	6.637	0.075	3.624
B	14.390	0.139	0	0.037
C	13.247	3.562	0	2.221
Matrix 110G13L	14.367	0.078	0	0.042
Matrix 12Kh18N10T	1.783	18.712	0.326	9.657

neity was made using the CAMEBAX microscope-microanalyzer SX-50.

In Figure 2 a macrosection is represented, cut out from specimen with an artificial flaw, which was fractured during the tests along the rail end (steel M76) at the force of 1100 kN and bending deflection of 21 mm. As is seen from the Figure, the hollow of an artificial flaw (horizontal hole of 8 mm diameter at the bottom of the casting 110G13L) was filled during flashing with a melt of steels 110G13L and 12Kh18N10T being welded. During upsetting the increase in defect area filled with a melt does not occur, and fusion line in defect zone preserves its straightness, characteristic for the zones without defect. Along the line of fusion even some decrease in defect area is occurred due to pressing in layers adjacent to the defect of layers 110G13L into the melt, lateral deforming of melt occurs which results in press welding of melt with base metal 110G13L along the lateral surface of an artificial defect. It is confirmed by tears formed in the steel 110G13L as a result of mechanical tests (Figure 3). Thus, the flaw in a form of a pore without slag inclusions is subjected during flash-butt welding to some «curing» and is not critical at static tests.

Filling of an artificial pore with melt occurs in the process of flashing. Therefore chemical composition of melt is interesting from the point of view of amount of metal which gets to the surface being flashed from the other surface being flashed during explosion of

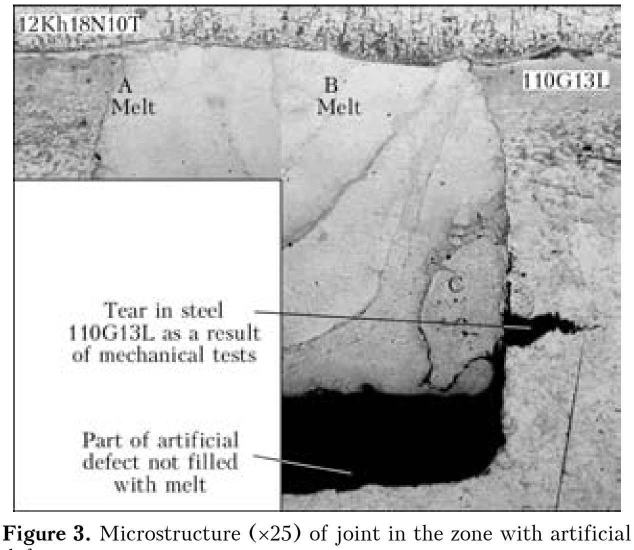

Figure 3. Microstructure (×25) of joint in the zone with artificial defect

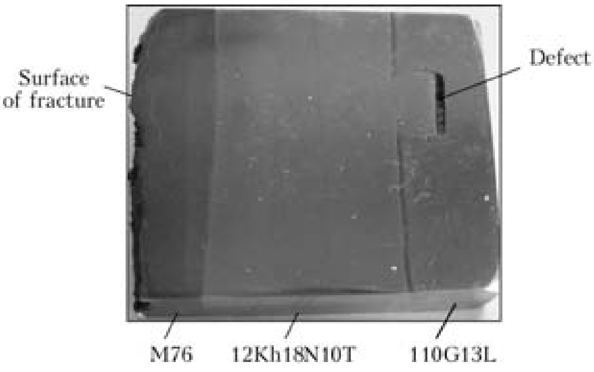

Figure 2. Macrosection of joint with artificial defect

bridges. According to the obtained results about 20 % of metal on the surface being flashed (in liquid layer) is the metal from the opposite flashed surface which gets there during explosion of bridges.

The results of analysis of chemical composition of melt in the zones A, B, C (Figure 3) are given in the Table. In microstructure of metal filling the hole the layers are observed delaminated by the chains of non-metallic inclusions. The formation of laminated structure is caused by a portion filling of a hole during explosion of bridges.

In Figure 4 a macrosection is represented, cut out from specimen with a real flaw, which was fractured during tests along the joining line of M76 to 12Kh18N10T at the force of 106 tf and bending deflection of 22 mm. This flaw was detected by radiographic inspection of the weld (Figure 5). Figure 6 shows microstructure of a joint in the zone of a real

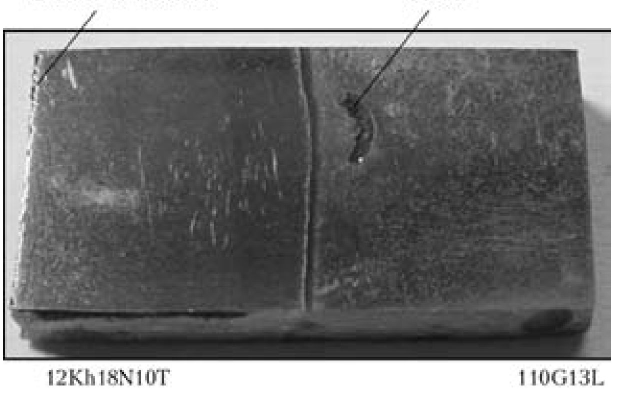

Figure 4. Macrosection of joint with natural defect

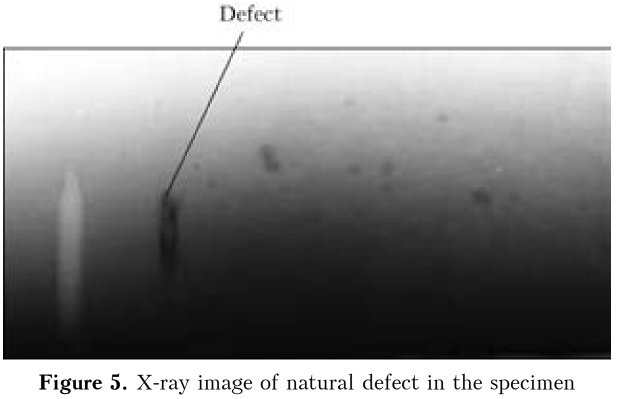

Figure 5. X-ray image of natural defect in the specimen

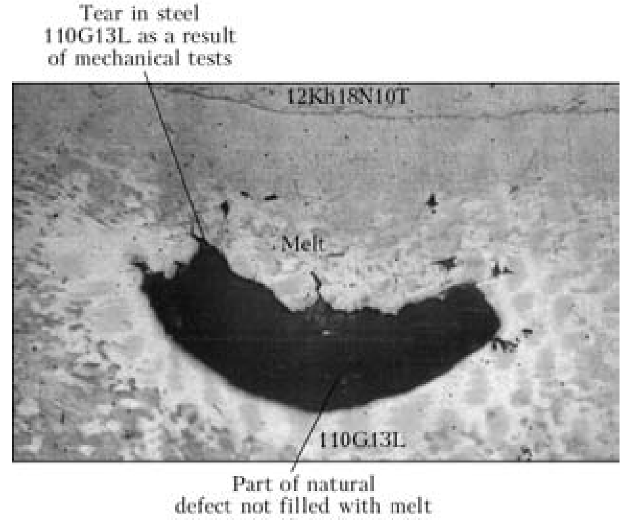

Figure 6. Microstructure (×25) of joint in the zone of natural defect

flaw (cast pore with slag inclusions). As is seen, the hollow of a flaw during flashing is filled with melt of steels 110G13L and 12Kh18N10T being welded. A slag of melt, being more fluid, is forced out to the periphery part of a pore and remains in a form of slag inclusions, a part of which gets to the metal melt. Though a defect was at the bottom of casting, the fracture of specimen along the defect did not occur. It is explained by the fact that during such formation of a joint the slag inclusions are forced out to the pore periphery and the zone of the joining line is formed from a melt where slag inclusions are absent. Thus, a defect of a pore type with slag inclusions behaves itself similarly to an artificial defect at the possibility of forcing out the slag melt from the zone of joining and does not considerably decrease the mechanical properties of specimens during static tests.

Figure 7 shows an appearance of natural defect in the specimen fracture surface. The fracture of specimen occurred along the joining line of 110G13L to 12Kh18N10T at the force of 800 kN and bending deflection of 12 mm. The main reason for fracture of specimen at low values of mechanical properties is the presence of defect of lack of penetration type [4]. The radiographic inspection performed before welding de-

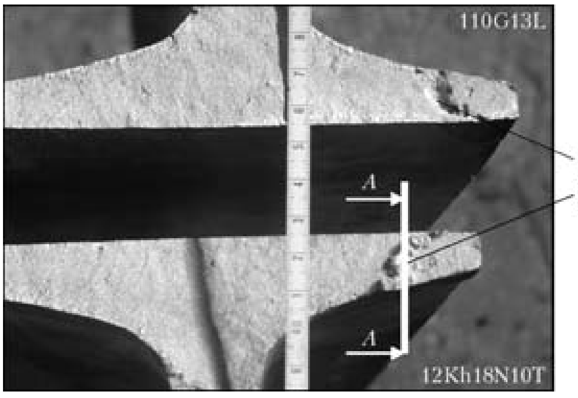

Figure 7. Appearance of defects in the fracture surface of specimen: *A–A* — scheme of cutting out of section from the specimen

tected a defect in the casting (cast pore). During flashing its filling with melt of steels 110G13L and 12Kh18N10T being welded occurred, as well as forcing out a slag melt to the periphery part of a pore. The deformation during upsetting due to lack of volume of a pore resulted in pressing in a slag melt and its dissolving in melt of metals being welded, and during solidification of a volume the shrinkage porosity was formed which is hard-to-detect during radiographic testing of joints, especially when thicknesses of metals being exposed to radiation are large.

Figure 8 represents microstructure of a joint in the zone of defect and in defectless area of a weld on the side of steel 12Kh18N10T. As is seen, the fracture occurs along the joining line of 110G13L to 12Kh18N10T and in the zone of defect the explosion along the bottom of initial pore occurs where maximal concentration of slag inclusions is observed.

In conclusion it should be noted that mentioned metallographic examinations of welded joints showed that casting defects (cavities, pores) do not almost increase their sizes during plastic deformation, that is a positive factor to conduct incoming radiographic testing of castings before welding. During testing of welded joint, the defects in castings, the sizes of which are less than limit of sensibility of radiographic inspection will not be detected, and after welding their sizes will not be increased.

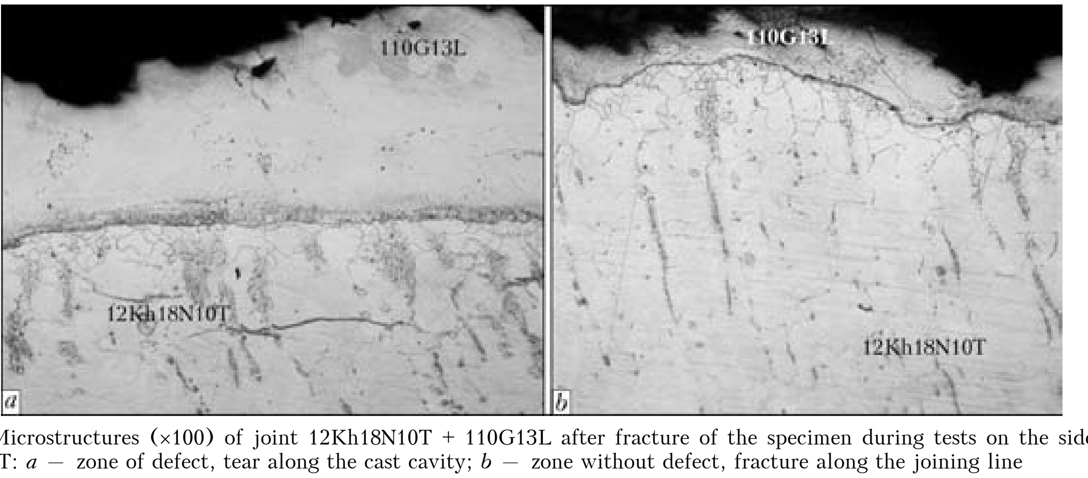

Figure 8. Microstructures (×100) of joint 12Kh18N10T + 110G13L after fracture of the specimen during tests on the side of steel 12Kh18N10T: *a* — zone of defect, tear along the cast cavity; *b* — zone without defect, fracture along the joining line

If cast defect (cavity or pore with slag inclusions) gets to the zone of welded joint, two variants of weld defect formation are possible:

• during the first one, when sizes of a defect allow forcing out slag inclusions in the form of a melt to the periphery of a pore, the zone of joining is formed from the melt where slag inclusions are absent. Such defects in a weld are good detected using radiographic inspection due to presence of slag hollows, but they do not decrease significantly the mechanical properties of specimens at static tests;

• during the second one, when sizes of defect do not allow forcing out slag inclusions in the form of a melt to the periphery of a pore, during deformation the pressing-in of a slag melt and its solution in melt of metals being welded occur due to lack of volume, which results in formation of shrinkage porosity during solidification of a volume, which are not detected during radiographic inspection of the joints. These defects lead to inadmissible reduction in mechanical properties of welded joints.

The radiographic inspection of ends of castings of frog cores, which are subjected to flash-butt welding, allows detecting casting defects, as well as their repairing before welding, which in combination with incoming ultrasonic testing of rail ends and an intermediate insert will provide guaranteed quality of incoming materials for welding. The system for control of welding condition parameters can guarantee the required quality of welded joints using inspection of incoming materials for welding. Therefore, the radiographic inspection of welds of the frogs after flash-butt welding is not reasonable.

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3. *TU U 27.3-26524137-1342:2006*: Frogs and cores with welded-on rail ends of R65, R50 and UIC60 types. Valid from 2006.
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FORECASTING THE CONTENT OF σ-PHASE IN THE HAZ OF WELDED JOINTS OF DUPLEX STEELS IN ARC WELDING

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Numerical algorithm is suggested for calculation of the content of σ-phase in HAZ metal of multipass butt-welded joints on duplex steel DSS 2205. Experimental temperature-time diagrams of formation of σ-phase under isothermal conditions at different temperatures are used in combination with thermal cycles of points of welded joint HAZ.

Keywords: *arc welding, duplex steels, butt joints, heat-affected zone, σ-phase, temperature-time diagram*

Over the last decades chromium-nickel duplex steels have become ever wider accepted in engineering owing to their properties, which are due to the initial structure (50 wt.% of ferrite and 50 wt.% of austenite). In connection with the high resistance to intercrystalline pitting corrosion in an aggressive medium in combination with good weldability and comparatively high fracture resistance, as well as moderate cost, this class of stainless steels is widely used to develop various-purpose critical structures.

However, alongside acquiring the above advantages, these steels partially inherited also the disadvantages of stainless steels of both austenitic and ferritic classes. The most significant disadvantage at 50 wt.% of initial ferrite content in the structure is their sensitivity to temperature impact, when ferrite decomposes with formation of σ-phase, which abruptly lowers the steel mechanical properties. This problem is quite well-studied in terms of service loading of structures from such steels. Respective temperature-time diagrams (TTD) allowing evaluation of the probability of appearance of intermetallic formations of σ-phase type under isothermal service conditions were plotted. As regards welding heating, there is a number of publications ([1], etc.), where this issue is studied experimentally on samples cut out of HAZ metal that allowed defining certain limitations on heat input in welding [2]. Nonetheless, at present there is no calculation procedure for forecasting (with a certain degree of validity) the extent of the influence of specific modes and conditions of welding on σ-phase content in the HAZ, thus limiting the effectiveness of predictive estimates at selection of technological modes and conditions of welding specific components.

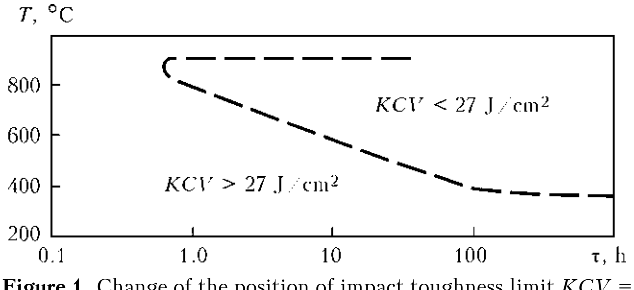

Figure 1. Change of the position of impact toughness limit KCV = = 27 J/cm^2 of DSS 2205 steel depending on soaking time τ at different temperatures

This work is an attempt to develop a procedure based on calculated thermal cycles in specific points of the HAZ and experimental data of TTD, plotted for specific steel. The idea of such an approach was tried out to a certain extent at prediction of the degree of sensibilization of HAZ metal of chromium-nickel steels with an increased content of carbon at formation of intercrystalline corrosion cracks.

Samples of butt-welded joint of pipes of 271 × × 20 mm cross-section from duplex steel DSS 2205 of the following composition [3], wt.%: 22.43 Cr; 1.88 Ni; 3.13 Mo; 0.14 Mn; 0.07 Si; 0.18 N; 0.023 C, were selected as the object for procedure development. The above steel composition ensures a high resistance to pitting corrosion in chloride solutions. Respective equivalent PRE = Cr + 3.3 wt.% Mo + 16 wt.% N = = 35.64, that is quite close to limit value PRE = 40 [2]. DSS 2205 steel similar to other duplex steels is sensitive to heating above 475 °C in connection with a high ferrite content (50 wt.%) that is manifested in considerable embrittlement. In duplex steels at more than 538 °C temperature part of ferrite is transformed into σ-phase, which combines different intermetallics, promoting a lowering of steel ductility, particularly at temperatures below −40 °C.

Figure 1, based on the data of [2], presents the change of the position of impact toughness limit KCV = 27 J/cm^2 of DSS 2205 steel, depending on soaking time at different temperature. At superposition of these data on experimental data [3] on the change of the content of σ-phase in DSS 2205 steel (Figures 2, 3) it is seen that lowering of KCV value occurs at the content of σ-phase of 15–18 wt.%.

Proceeding from the data of Figures 2 and 3, obtained for HAZ specific thermal cycles $T(\tau')$, V of σ-phase, wt.%, can be calculated as follows:

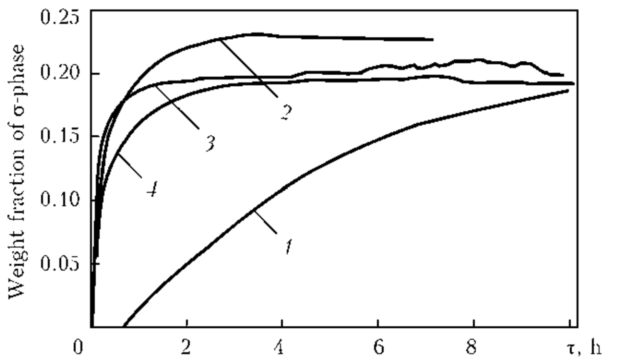

Figure 2. Kinetics of the change of σ-phase content at isothermal soaking of samples of DSS 2205 steel at temperature T = 700 (*1*), 750 (*2*), 800 (*3*) and 859 (*4*) °C by the results of experimental measurements

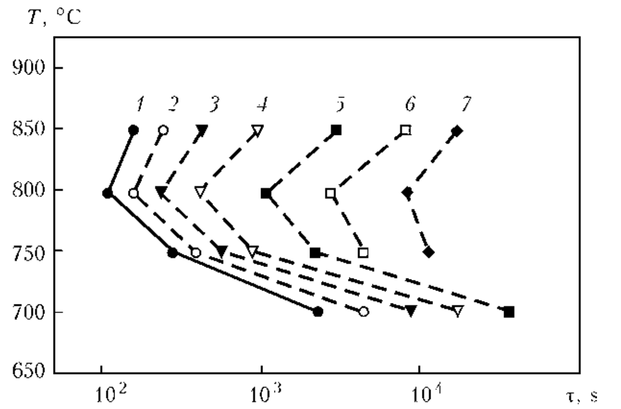

Figure 3. C-shaped curves of the change of σ-phase content depending on temperature T and soaking time τ: *1* — 1; *2* — 10; *3* — 25; *4* — 50; *5* — 75; *6* — 90; *7* — 99 wt.%

$$V = \sum_j \int_{T_{st}}^{T_{end}} \frac{(V_j - V_{j-1}) \dfrac{V^{max}(T)}{100}}{\tau_j(T) - \tau_{j-1}(T)} d\tau'(T),$$

where j = 1, ..., 7 is the number of C-shaped curves (Figure 3); V_j = 1, 10, 25, 50, 75, 90, 99 wt.% is the

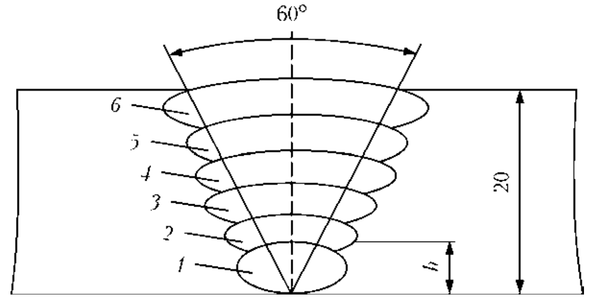

Figure 4. Schematic of layer-by-layer welding-up of butt joint by multipass arc welding: *1–6* — number of passes

Results of calculation of σ-phase content

No. of welding mode variant	Welding procedure	H, J/mm	η_s	$q_{h.i}$, J/mm	T_0, °C	V^{max}, wt.%
1	MIG	2270	0.75	1700	20	1.0–1.2
2		2270	0.75	1700	150	2.0–2.4
3	TIG	5000	0.60	3000	20	3.5–4.0
4		5000	0.60	3000	150	5.6–6.4

«price» of this curve from maximum value $V^{max}(T)$ at $T_{st} > T > T_{end}$ (here T_{st}, T_{end} is the temperature of the start and end of tracing the thermal cycle $T(t')$); and τ' is the current time.

The modes of multipass arc welding were selected using the recommendation of [2] as regards the applied electric heat input:

$$H = 60 \frac{IU}{v},$$

where I is the welding current; U is the arc voltage; v is the welding speed. According to [2], H values are in the ranges of $512 < H < 2520$ J/mm under the

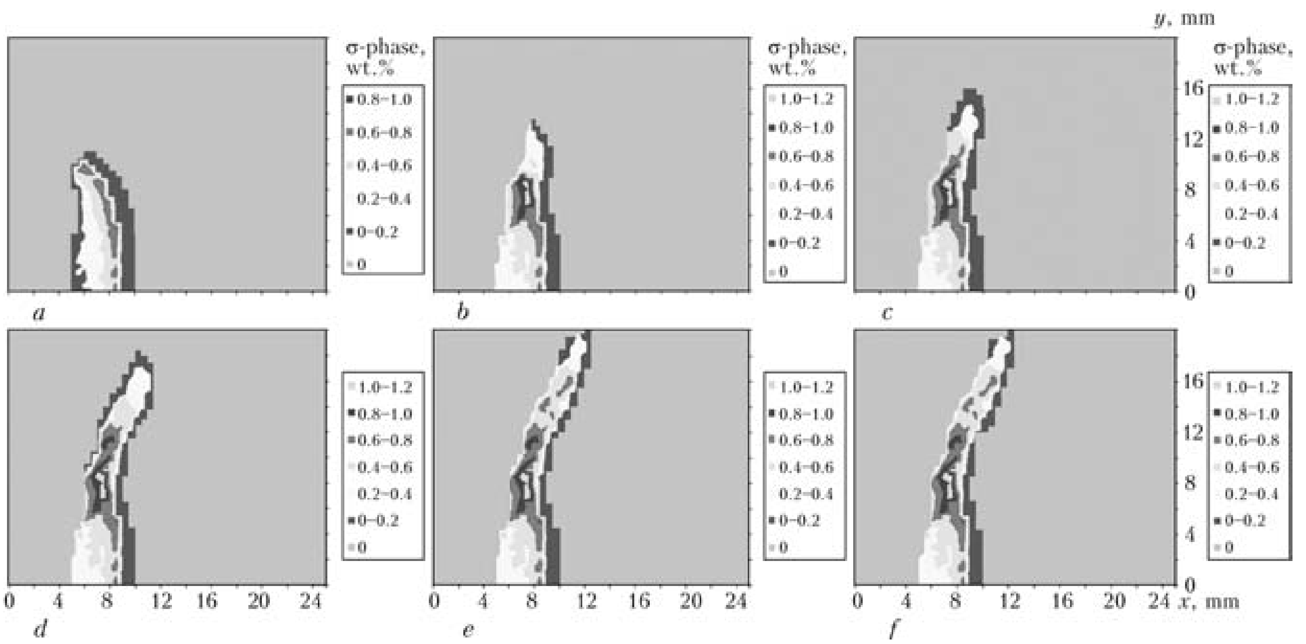

Figure 5. Accumulation of σ-phase in the HAZ metal of butt weld of pipe with Dn 270 × 20 mm made by arc welding at $q_{h.i}$ = 1700 J/mm and T_0 = 20 °C: *a–f* — after 1st–6th passes, respectively

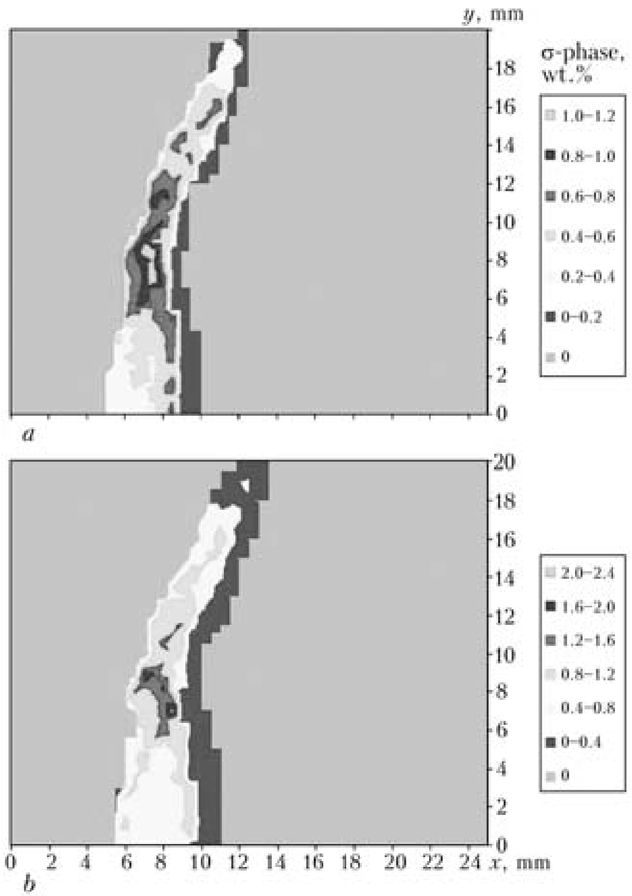

Figure 6. Distribution of σ-phase in the metal of the HAZ and butt weld of a pipe with Dn 270 × 20 mm from DSS 2205 steel made by six-pass MIG welding (after 6th pass) at $q_{h.i}$ = 1700 J/mm: *a* — T_0 = 20; *b* — 150 °C

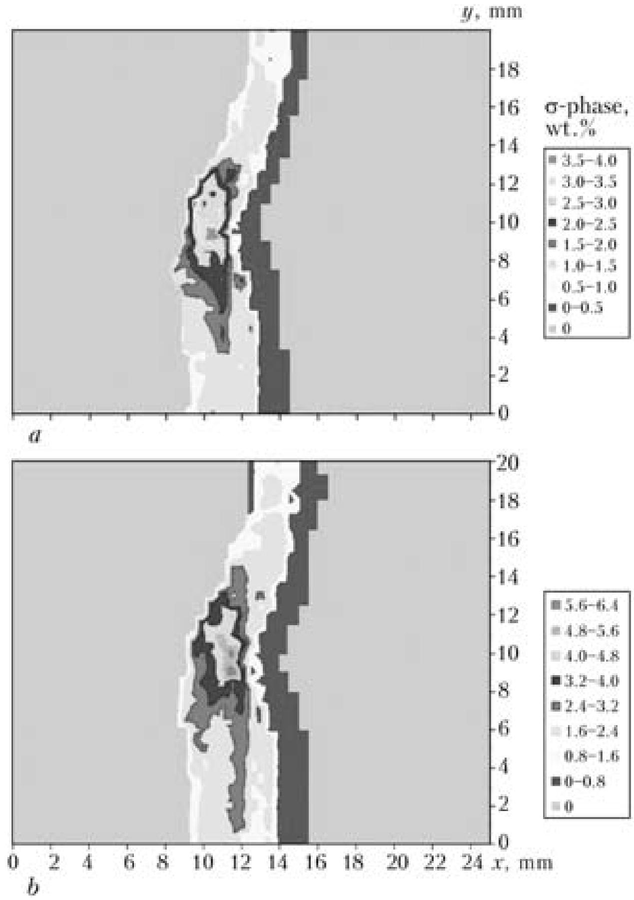

Figure 7. Distribution of σ-phase in the metal of HAZ and butt weld of a pipe with Dn 270 × 20 mm from DSS 2205 steel made by six-pass TIG welding (after 6th pass) at $q_{h.i}$ = 3000 J/mm (for *a* and *b* see Figure 6)

condition of preheating application before each pass (T_0 = 150 °C).

Let us consider the following variants of welding butt joints in six passes (Figure 4). Section of each bead is equal to F = 25–35 mm^2. Its thickness (height) h_i at groove angle α = 60° varies in the range of 7–1.8 mm, and width a_i — in the range of 7–20 mm.

Calculation results for the above heat input variants are given in Figures 5–7. It follows from the obtained data that increase of the heat input up to $q_{h.i} \leq 1700$ J/mm at T_0 = 20 °C has only a minor influence on the content of σ-phase in welding of the considered joint. However, at higher heat input ($q_{h.i}$ > > 3000 J/mm) content of σ-phase of HAZ metal is close to the level, at which, according to Figures 1–3, the value of impact toughness decreases to 27 J/cm^2 that is by almost an order of magnitude lower than that in the absence of σ-phase in the HAZ metal of butt joint of the above-mentioned steel. The given data are indicative of the influence of preheating (interpass temperature) on the intensity of σ-phase formation in the HAZ metal, which determines preservation of joint ductility at subsequent technological treatments or in service. It follows that repair of welded joints of duplex steels, at which σ-phase accumulates in the HAZ metal, requires discretion and appropriate predictive estimates. Estimates obtained on the basis of the proposed procedure (Table) agree quite well with the recommendations of work [2] as regards limitations of heat input in welding steels of the considered class.

CONCLUSIONS

1. Formation of σ-phase promotes an abrupt lowering of duplex steel ductility at thermal impact, in particular in welding, and thus limits application of these materials in modern structures.

2. Using standard TTD it is possible to quite effectively forecast the content of σ-phase in the HAZ metal at welding thermal cycle of multipass welding of duplex steels.

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INDUCTION SYSTEM FOR LOCAL TREATMENT OF SURFACES BY LIQUID METAL FLOWS

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Electrodynamic processes occurring in molten metal on the horizontal surface of metal product in the inductor magnetic field were studied. Conditions of intensification of liquid metal flows at local treatment of metal surfaces are determined. Formulas for calculation of induction system are given.

Keywords: *induction heating, metal treatment, intensified liquid metal flows, electrodynamic processes, calculations*

At local remelting of surface layer of metal products, elimination of defects on their surfaces, local alloying, surfacing of protruding elements and their repair, application of induction heating alongside the known electrometallurgical technologies of metal treatment and surfacing is promising and urgent [1–7].

Induction heating is a non-polluting process, allowing control of molten metal flows and of applied power at heating. So far, induction heating found only limited application for the above purposes, in view of the high power consumption. One of the effective methods to reduce power consumption and improve the efficiency of treatment of the surfaces of metal products at induction heating is intensification of molten metal flows in the crucible placed above the treated product. In this case heat exchange between the already molten metal in the crucible and metal of the product to be melted is increased, thus promoting a shortening of the melting time and input power.

PWI developed a method [8] of intensification of molten metal flows in the crucible, directed at the treated surface of metal product at induction heating.

The purpose of this work is investigation of electrodynamic processes in liquid metal, which is contained by the crucible on the horizontal surface of the metal product in the inductor magnetic field, and determination of the conditions for intensification of molten metal flows at local treatment of metal surfaces.

According to Helmholtz theorem, any continuous vector field can be presented in the form of a sum of potential and eddy components [9]. Thus, density of electromagnetic forces of vector **F** causing the motion of electrically-conducting liquid (molten metal) in an open crucible, has potential and eddy components, the ratio of which is different in different points of the liquid. In a closed volume (closed crucible) the motion of electrically-conducting liquid is affected only by the eddy component of the electromagnetic forces.

A characteristic of the magnetic field capability to induce melt motion around a certain contour of length l_i is circulation C_i of force vector **F** around this contour (without allowing for hydrodynamic features) [6]:

$$C_i = \oint_{l_i} \mathbf{F} dl = \int_{S_i} \mathrm{rot}_n\, \mathbf{F} dS,$$

where S_i is the area of a surface supported by a contour of length l_i; n is the index, which denotes quantity components normal to surface of area S_i.

In crucibles of classic induction furnaces (Figure 1, *a*) there exist two eddy flows of molten metal — upper and lower [5–7]. Directions of circulation of electrically conducting liquid in them are opposite, as directions of forces causing them are opposite. Intensity of motion of molten metal eddy flows depends on forces applied to it, hydrodynamic resistance to their motion and crucible shape. In the absence of mechanical obstacles, the region, covered by molten metal motion, can go beyond the zone of action of forces **F** inducing this motion.

At non-uniform distribution of volume density of the electromagnetic force, for instance, in the presence of magnetic field asymmetry, the intensity of molten metal flow will be greater in the region of action of large forces **F** and large C_i values. The cause for magnetic field asymmetry can be a non-uniformity of the gap between the inductor and liquid metal pool, asymmetry of current density distribution in the inductor, crucible shifting relative to the inductor and crucible shape. So, with the cylindrical inductor and crucible rounded from below the largest magnitude of magnetic induction is achieved in the crucible wide part, where the distance between the inductor and crucible is smaller. This increases relative value C_i and extent of eddy zone of the force field, acting in the crucible narrow lower part. Conditions for movement of molten metal flows are more favourable in the crucible broad upper part that is confirmed by experimental data [3]. However, at item treatment, just a change of crucible shape is insufficient for a significant intensification of molten metal flows.

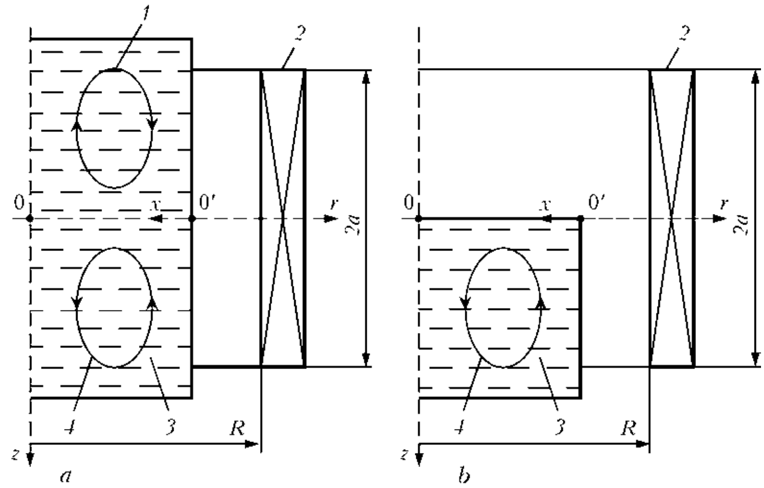

Figure 1. Schematic of motion of molten metal flows at classical (*a*) and proposed inductor position (*b*): *1*, *4* — the upper and lower vortex of the flow, respectively; *2* — inductor; *3* — molten metal

For a more effective utilization of molten metal eddy flows at treatment of metal products it is necessary to ensure the presence of one powerful flow (single-contour motion of the melt) in the crucible, directed to the crucible axial part (axis z in Figure 1, *a*) towards the item being treated. Single-contour motion of the flow arises in the case, when there exists only one eddy zone of the force field in the molten metal volume that is the case in the liquid pool at ingot solidification in induction furnaces with a cold crucible or in electromagnetic mould.

It is experimentally established that the single-contour motion of molten metal can be realized in the simplest and most effective way at the expense of relative displacement of the inductor and crucible along their vertical axis of symmetry. Here, the first eddy contour is enhanced and increased, and the second is weakened and decreased down to complete disappearance. The lower contour can be enhanced even further by rounding the crucible bottom (Figure 2). This Figure shows the schematic of the crucible shaped as the paraboloid of revolution, the open narrow lower part of which is resting on the treated item. Circular cylindrical inductor, acting by its variable electromagnetic field on the molten metal in the crucible, is placed in its upper wide part.

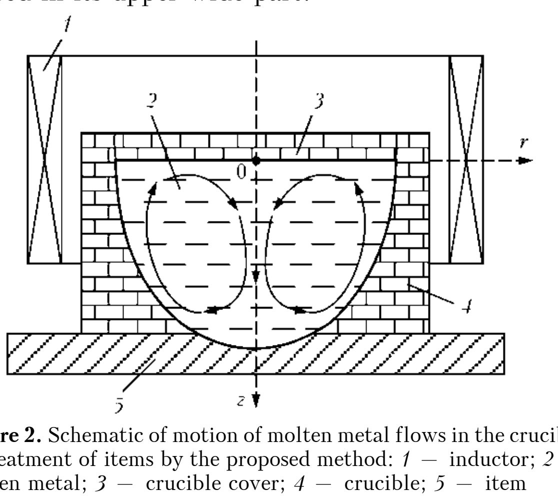

Figure 2. Schematic of motion of molten metal flows in the crucible at treatment of items by the proposed method: *1* — inductor; *2* — molten metal; *3* — crucible cover; *4* — crucible; *5* — item

From [6] it follows that the tangential electrodynamic forces are of secondary importance at metal circulation (less than 3 % contribution to C_i), while the main contribution is made by forces directed normal to the surface, the presence of which is due to electromagnetic pressure of inductor filed on the metal. Proceeding from this fact, let us apply Maxwell–Lorentz law, which is used to find the dependence of density of forces **F** in the form of vector product of current density **J** and magnetic induction **B** [10]:

$$\mathbf{F} = [\mathbf{J}\mathbf{B}],$$

where $\mathbf{J} = \mathbf{E}/\rho$; $\mathbf{B} = \mu\mathbf{H}$; **E**, **H** is the intensity of electric and magnetic fields, respectively; ρ is the specific electric resistance; μ is the magnetic permeability of metal (above Curie point it is equal to magnetic constant μ_0).

Let us consider the processes occurring at quasistationary in time variable electromagnetic field, at which the method of complex amplitudes can be used.

Complex components of intensity of magnetic $\underline{H}_e$ and electric $\underline{E}_e$ fields of a wave, propagating in-depth of the metal, can be expressed with sufficient accuracy through complex values of magnetic field intensity $\underline{H}$ that are generated by the inductor in the ambient space and on liquid metal surface [10]:

$$\begin{cases} \underline{H}_e \approx 2\underline{H} \exp(-jkx); \\ \underline{E}_e = 2\underline{H}\ \underline{Z}_e \exp(-jkx), \end{cases}$$

where $j = \sqrt{-1}$; $jk = (1 + j)\sqrt{\omega\mu_0/(2\rho)} = (1 + j)b$; $b = \sqrt{\omega\mu_0/(2\rho)}$; $\underline{Z}_e = \sqrt{j\omega\mu_0\rho}$ is the normal surface impedance or wave resistance of metal; x are the current coordinates of points, lying on the normal aimed from the surface in-depth of the metal (see Figure 1); ω is the angular frequency of magnetic field variation.

If for instant values of intensity of magnetic and electric fields of a wave passing in-depth of the metal initial phase H_e is selected so that amplitude value of complex quantity $\underline{H}_m$ was equal to scalar value H_m, then they can be presented in the following form [10]:

$$\begin{cases} H_e = 2H_m \exp(-bx) \sin(\omega t - bx); \\ E_e = 2H_m\sqrt{\omega\mu_0\rho}\exp(-bx)\sin(\omega t + \pi/4 - bx). \end{cases}$$

Force $F_{e,\,x}$ acting on a unit of metal surface is equal [10] to

$$F_{e,\,x} = E_e\mu_0H_e/\rho = = 4H_m^2\mu_0\sqrt{\omega\mu_0/\rho}\exp(-2bx)\sin \times \times (\omega t - bx)\sin(\omega t + \pi/4 - bx).$$

Average value of force F_e over $2\pi/\omega$ period is equal to

$$F_e = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} F_{e,\,x}dt = H_m^2\mu_0\sqrt{2\omega\mu_0/\rho}\exp(-2bx).$$

Considering that presence of exponential factor in this expression leads to a fast decrease of force density with increase of x, these forces can be regarded as concentrated on the metal surface (presence of skin-effect), and they can be replaced by pressure p_e, applied to the surface:

$$p_e = \int_0^\infty F_e dx = H_m^2\mu_0\sqrt{2\omega\mu_0/\rho}/2b = \mu_0H_m^2.$$

In the derived expressions it is rational to move from magnetic field intensity H having two components — axial and radial — to electric field intensity E and vector potential of magnetic field A, having in this case one azimuth field component $\underline{E} = -j\omega\underline{A}$ for circular closed current [4].

Considering that

$$\underline{H}_e \approx 2\underline{H} \approx 2\underline{E}/\underline{Z}_e = -2j\omega\underline{A}/\underline{Z}_e,$$

hence $\underline{H} \approx -j\omega\underline{A}/\underline{Z}_e$, at the assumed above initial phase of variation of instant values of magnetic field intensity for their scalar values (amplitudes) we write can as $H_m \approx \omega A_m/Z_e = A_m\sqrt{\omega}/(\mu_0\rho)\}$. Here, force F_e and pressure p_e are calculated by formulas [5]

$$F_e = (\omega A_m^2\sqrt{2\omega\mu_0/\rho}/\rho)\exp(-2bx), \quad p_e = \omega A_m^2/\rho.$$

Inductor electromagnetic field can be described using scalar value of magnetic field vector potential A, the source of which is current I, distributed with linear density $\delta = wI/2a$ along the surface of thin-walled solenoid with turn number w of radius R and length $2a$ (at $r \le R$) [11, 12]. In this case, magnetic field vector potential A has the following form:

$$A = \frac{\mu_0RwI}{\pi a}\int_0^\infty I_1(\lambda r)K_1(\lambda R)\sin(\lambda a)\cos(\lambda z)\frac{d\lambda}{\lambda},$$

where λ is the integration variable, equivalent to spatial frequency of harmonics of solenoid electromagnetic field; I_1, K_1 are the modified Bessel's functions of the 1st and 2nd kind of the first order; r, z are the coordinates of observation point from the origin of axes r, z. At $r \ge R$ the arguments of Bessel's functions should be interchanged.

Axial and radial components of the vector of magnetic field intensity are found from equation $\mathbf{H} = \mu_0^{-1}$ rot $\mathbf{A}$, written in the cylindrical system of coordinates (at $r \le R$) [11, 12]:

$$H_a = \frac{RwI}{\pi a}\int_0^\infty I_0(\lambda r)K_1(\lambda R)\sin(\lambda a)\cos(\lambda z)\,d\lambda,$$

$$H_r = \frac{RwI}{\pi a}\int_0^\infty I_1(\lambda r)K_1(\lambda R)\sin(\lambda a)\cos(\lambda z)\,d\lambda.$$

To avoid calculation of improper integrals, the kernel of integral in these expressions can be approximated with not less than 1 % error by the following formula (at $r \le R$) in the entire range of variable change [11, 12]:

$$I_1(\lambda r)K_1(\lambda R) = = \frac{1}{2}\left\{\frac{r}{R}\exp\left(-0.4\lambda R\right) + \frac{1}{\lambda R}\left(1 - \exp\left[-\lambda R\left(1 - \frac{r}{R}\right)\right]\right)\frac{\sqrt{r}}{R}\right\}.$$

Having used this approximation, we obtain the following expression for calculation of scalar value of magnetic field vector potential A (at $r \le R$) [11]:

$$A = \frac{\mu_0RI}{4\pi a}\left\{\frac{r}{R}\left(\text{arctg}\frac{a+z}{0.4R} + \text{arctg}\frac{a-z}{0.4R}\right) + \frac{1 - r/R}{\sqrt{r/R}} \times \times\left[\text{arctg}\frac{a+z}{R-r} + \text{arctg}\frac{a-z}{R-r} + \frac{a+z}{2R} \times \times\ln\left[1 + \left(\frac{R-r}{a-z}\right)^2\right] + \frac{a-z}{2R}\ln\left[1 + \left(\frac{R-r}{a-z}\right)^2\right]\right]\right\},$$

and for intensity of inductor magnetic flow (at $r \le R$)

$$H_r = \frac{wI}{2\pi a}\left\{\frac{0.8Razr}{[(0.4R)^2 + (a-z)^2][(0.4R)^2 + (a+z)^2]} + + \frac{1}{2}\sqrt{\frac{r}{R}}\left[\ln\left(1 + \left(\frac{R-r}{a-z}\right)^2\right) - \ln\left(1 + \left(\frac{R-r}{a+z}\right)^2\right)\right]\right\}.$$

At $r \ge R$, R/r and $r - R$ should be written in the derived formulas instead of r/R ratio and $R - r$ difference.

Derived expressions lead to the conclusion that magnetic flow intensity H_r is equal to zero along its horizontal plane of symmetry, irrespective of the distance, at which the observation point is located from the inductor (see Figure 1, *a*). In any other place the magnetic flow intensity rises from zero to maximum (closer to inductor), and then decreases at increase of value r. Therefore, electromagnetic pressure due to forces related to magnetic field intensity H_r, above the inductor horizontal plane of symmetry (see Fi-

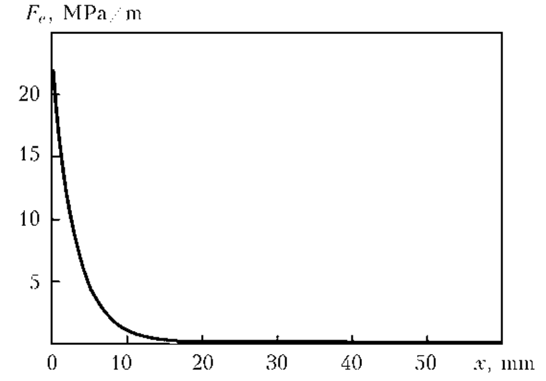

Figure 3. Change of force F_e by the billet depth along axis x

gure 1, *a*) rises from zero on the vertical plane of symmetry of the crucible with the melt up to maximum value on its edge. Here, molten metal motion takes place along the crucible walls downwards and along the crucible vertical axis of symmetry upwards. In the studied process of metal treatment such a direction of molten metal motion is unfavorable. In order to suppress it, the inductor should be placed so that its horizontal plane of symmetry coincided with molten metal surface (see Figure 1, *b*). Here, only one useful eddy flow of molten metal remains, which is aimed along the vertical plane of symmetry of the crucible downwards onto the treated item and upwards along the crucible walls.

Such a location of the inductor leads to intensification of molten metal eddy flows in connection with absence of upper vortex metal pressure onto that of the lower one. Here, the electric power consumed by the induction system is spent only on creation of one useful eddy flow of molten metal. Heat exchange between molten metal in the crucible and metal of item to be melted is enhanced due to intensification of these flows, thus promoting a reduction of melting time and input power.

Electromagnetic pressure to the melt is also applied by forces directed from the crucible side surface to its vertical axis of symmetry z, related to inductor magnetic flow intensity H_a. As the intensities of the magnetic and electric fields have maximum values in this case, the electromagnetic forces will also be the highest. They are exactly the factors that promote formation of eddy flows in the crucible in the axial direction, forming a menisk on the molten metal surface. To enhance the pressure of eddy flows on the treated item, it is rational to place a limiting wall in the form of crucible cover at the melt surface (see Figure 2) that prevents rising of molten metal. To lower the relative value of magnetic field intensity H_r in the crucible zone it is rational to apply an inductor of the length not less than its diameter. All this enhances the energy effectiveness of the induction system.

This work did not deal with forces applied to molten metal upper surface, which are caused by the magnetic field of inductor upper part protruding above the surface. These forces decrease essentially in the direction of the vertical axis of inductor symmetry z, whereas the length of the inductor proper should be greater than its diameter. The influence of these forces can be neglected in the first approximation in inductor design.

At induction system design we will use the above formulas and procedure of inductor design at heating of pipe end parts from [11]. In our case this is a short pipe section with very small internal diameter simulating a continuous cylindrical metal billet, which is heated by the inductor in the crucible.

Two inductors were designed and manufactured — single-turn consisting of four parallel conductors (windings) (four-winding), and two-turn consisting of two parallel conductors (two-winding [8]), of (80 ± ± 5) mm height, 190 mm diameter, in which the conductors are made from copper tubes of 10 × 15 mm section. The conductors of each of the inductors were connected in parallel and as aiding connection. Voltage of 8 kHz frequency was equal to 80 V for the first inductor, and to 160 V for the second inductor. Inductor power was practically unchanged at 170–180 kW. Such inductor designs allowed variation of product weight in a broad range at melting and of inductor position relative to molten metal.

Change of calculated force F_e at $z = 0$ by molten metal depth along axis x from 0 to R_n (at crucible inner radius $R_n = 60$ mm) is given in Figure 3, from which it is seen that F_e decreases from molten metal edge to its center. Figure 4 shows the change of calculated pressure p_e on molten metal surface at $x = 0$ by crucible height along axis z from 0 to 42.5 mm. Pressure p_e has the highest value in inductor center at billet upper edge and decreases towards its lower end face (see Figure 1, *b*), that promotes formation of molten metal eddy flows in the crucible.

Results of testing the induction systems at treatment of metal plates of different thickness are described in [8].

Thus, conducted research was the basis for determination of the method of intensification of eddy flows in the crucible, enhancement of heat exchange between the latter and treated surface of the item at its local treatment, as well as penetrability and reduction

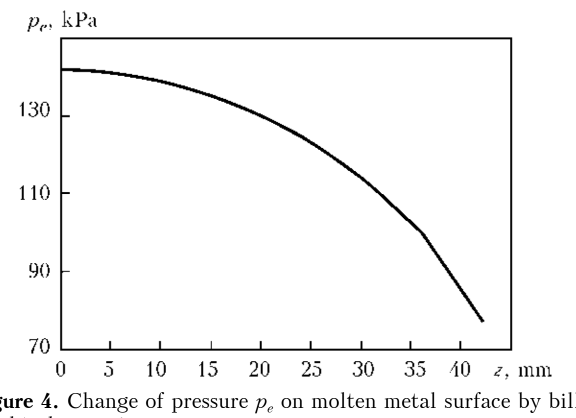

Figure 4. Change of pressure p_e on molten metal surface by billet height along axis z

of power consumption. For this purpose, the inductor should be placed so that the inductor horizontal axis of symmetry coincided with the upper surface of molten metal in the crucible with a rounded bottom, rising of liquid metal should be prevented at the expense of application of limiting cover and inductor of length not less than its diameter should be used.

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STUDYING THE FEATURES OF MASS TRANSFER IN THE PROCESS OF FRICTION STIR WELDING USING PHYSICAL MODELLING

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Model of the process of friction stir welding was used to study the influence of structural dimensions of working surfaces of tool shoulder and tip on the features of material displacement in the thermodynamic impact zone. It is shown that a permanent joint forms due to displacement of a certain amount of ductile material by the tool tip and its mixing across the entire thickness of edges. Shape of working surface of tool shoulder end face predetermines the displacement trajectory, movement speed, uniformity of mixing and degree of compaction of the materials being joined at solidification.

Keywords: *friction stir welding, process modelling, mass transfer, tool tip design, shoulder working surface*

Permanent joints began to be produced in the solid phase by friction stir welding (FSW) for fabrication of welded structures already in 1990s. This welding process became widely accepted in joining aluminium and magnesium based alloys, which feature a high ductility under the conditions of low-temperature heating [1–4].

Weld formation at FSW takes place at metal heating in the welding zone at the expense of friction to plastic condition and displacement at high pressure in a volume limited by working surfaces of the tool and substrate. FSW main parameters are design features and dimensions of tool working surfaces, its location relative to vertical axis and surfaces of billets being welded, tool pressing and depth of penetration of its tip into the butt, as well as speed of rotation ω and linear displacement of the tool at a certain speed, equal to welding speed v_w [5, 6]. These parameters determine the conditions of metal friction heating in the welding zone and essentially influence the magnitude and orientation of forces acting on plasticized metal, as well as the speed and trajectory of its displacement. Understanding of the features of mass transfer in the zone of permanent joint formation is very important for determination of optimum structural dimensions of the tool and welding process parameters, which will ensure production of dense sound welds.

First idea of the nature of plasticized metal displacement at FSW was obtained through experiments, which are based on instant stopping of the moving material flow [7]. The trajectory of its motion in the characteristic zones of the joint was assessed by the change of the position of special markers (very fine steel balls, copper pins, copper or titanium foil, thin tungsten wire, composite material interlayer, etc.), which were placed in the butt between the edges being welded or on the sections adjacent to it [7–10]. Data on the features of metal displacement can be also obtained in welding aluminium alloys of different alloying systems with different etching to each other [11], or of dissimilar materials differing greatly by their colour [12]. However, all the above methods to assess the mass transfer occurring at FSW are quite labour consuming, as their application requires testing of the produced welded joints by X-ray radiation or prepa-

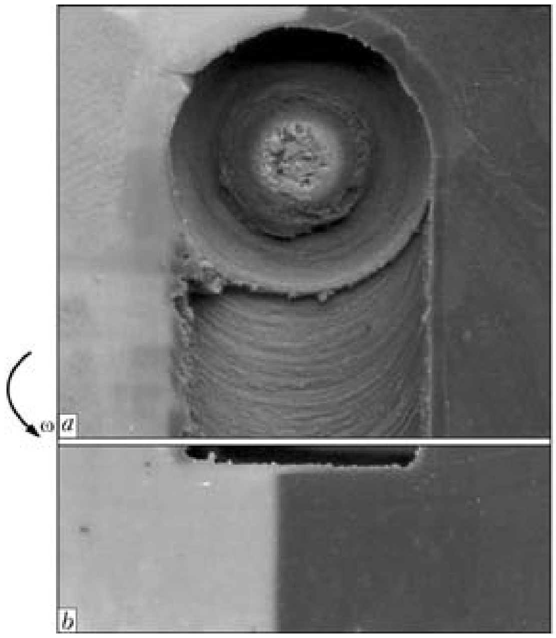

Figure 1. Appearance of face surface (*a*) and transverse section (*b*) of the joint obtained by FSW using a tool without a tip

ration of sections cut out of them by polishing and etching. With this purpose it was proposed to model the FSW process, using plasticin bars of different colours as materials being joined. Sections of such joints in different planes, obtained using tightened steel wire of 0.15 mm diameter, allow without any additional preparation tracing the displacement of materials being joined in the zone of impact of the tool working surface on them.

Such a model allows, in particular, assessment of the influence of structural dimensions of the tool working surfaces on the features of mass transfer during FSW.

Plasticin bars of different colours were butt-joined by linear welds in PWI developed machine for welding sheet aluminium alloys, and then the appearance and sections of the produced joints were studied. Results showed that when the tool is used without the penetrating tip no weld formation occurs across the entire thickness of edges being welded (Figure 1). The weld forms only directly under the shoulder end face at mixing of a very thin metal layer as a result of the tool rotation and displacement along the butt.

The shape of the working surface of tool shoulder end face practically does not influence the weld depth, but has an essential influence on the conditions of mixing of materials, coming from the tool advancing side, where the directions of its rotation and displace-

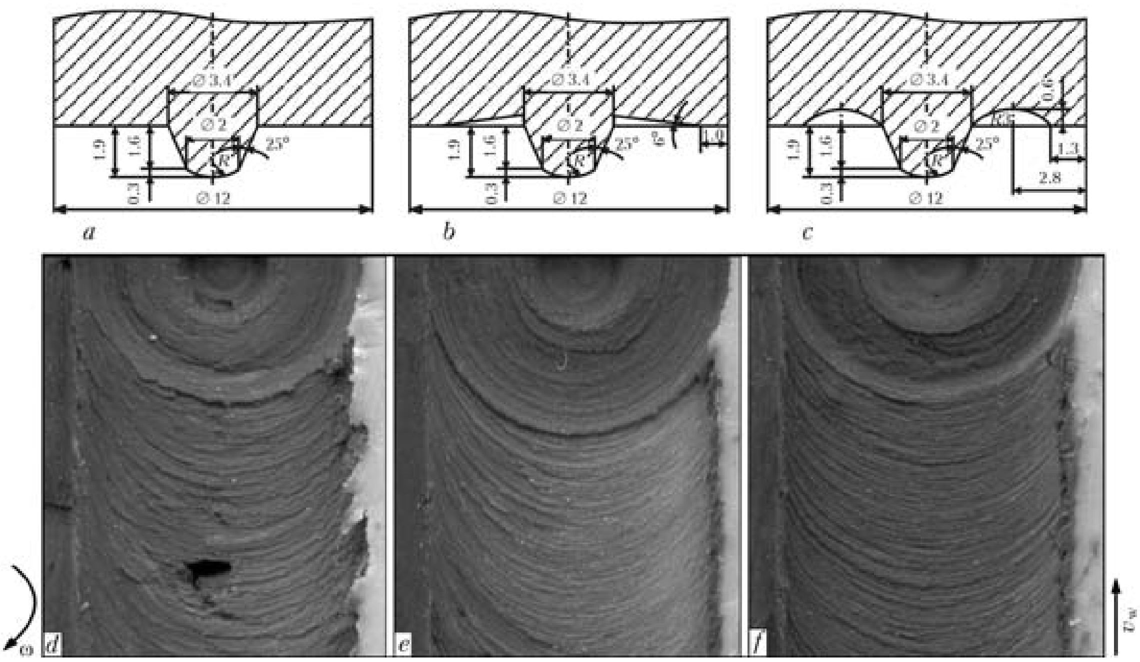

Figure 2. Schematics of working part of tools for FSW with a flat end face surface of the shoulder (*a*), conical (*b*) and semi-spherical (*c*) groove on it and appearance of face surface of welds made using the appropriate tools (*d*–*f*)

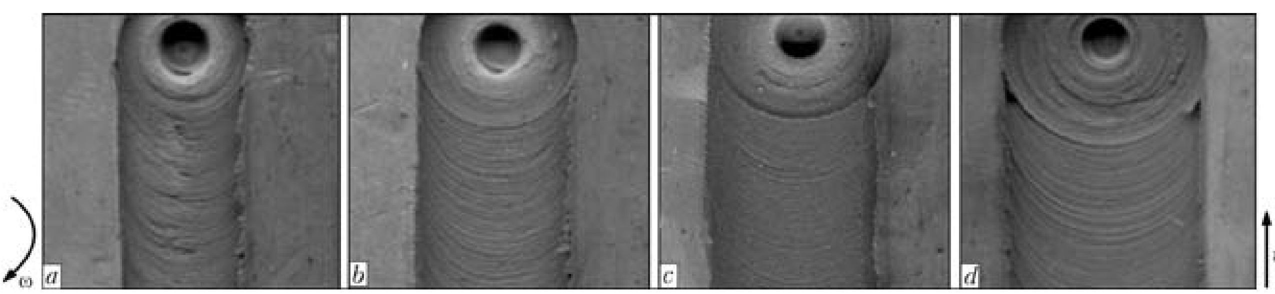

Figure 3. Appearance of welds made by FSW using tools with shoulder diameter of 10 (*a*), 12 (*b*), 14 (*c*) and 16 (*d*) mm and conical groove on their end face

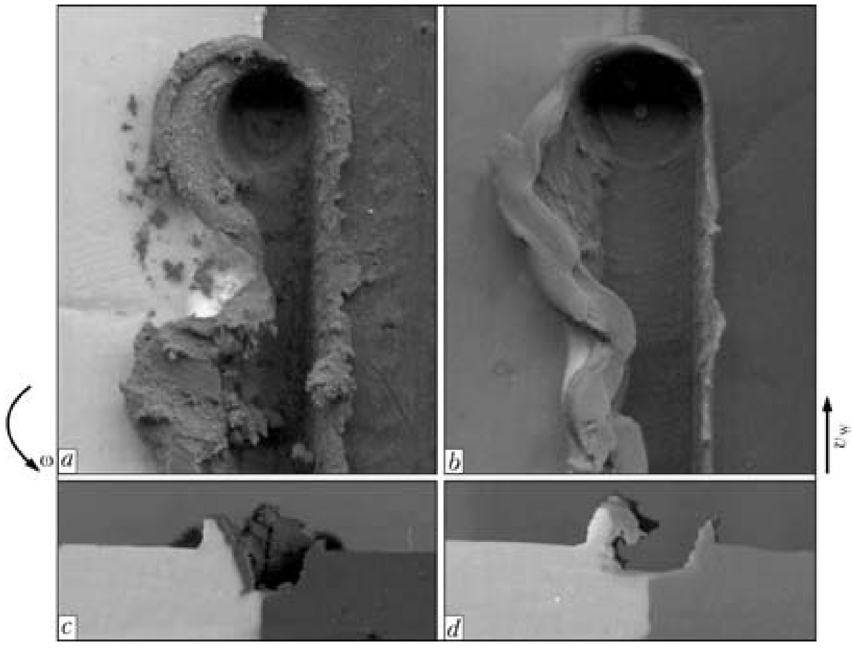

Figure 4. Appearance of face surfaces (*a*, *b*) and transverse sections of welds (*c*, *d*) produced by FSW without pressing the tool shoulder to materials being joined when using tips of conical shape with a smooth side surface (*a*, *c*) and of cylindrical shape with threaded side surface (*b*, *d*)

ment coincide (Figure 2, *d*–*f*, *left*) and retreating side, where the directions of its rotation are opposite (Figure 2, *f*–*e*, *right*). Moreover, it predetermines the displacement speed and movement trajectory of mixed portions of materials being joined in a certain limited space, as well as the degree of their compaction at solidification, thus influencing the quality of formation of weld face surface. So, application of tools of different configuration of the shoulder working surface edge can lead to a change on the weld surface of the shape of flakes, frequency of their appearance and distribution by location depth, smoothness of transition from the depressions to protrusions, etc.

Investigation results showed that in welding by a tool with a flat end face of the shoulder a periodical disturbance of the material flow continuity occurs that results in formation of coarse ripple on weld face surface, and of individual tears in some places that impair the joint quality. Presence of a conical or semi-spherical groove on the weld surface promotes a uniform continuous displacement of material and formation of a weld with a practically smooth surface consisting of fine ripple, differing only slightly in thickness. Here, the degree of mixing of materials being welded on the weld face essentially depends on the tool shoulder diameter. Its increase from 10 to 16 mm leads to a considerable increase of the degree of refinement, the weld face becoming more uniform (Figure 3).

In addition to heating material in the welding zone, the tool tip should chiefly ensure its displacement and mixing across the entire thickness of the butt. In order to follow the trajectory of material movement during welding, the shoulder working surface was not pressed to the material being welded directly during displacement of the tool rotating tip along the butt. In Figure 4 it is readily seen that the material was transported by the tip from the tool advancing side (weld right side) to its retreating side (weld left side). A thin layer formed on it, which was located across the entire thickness of tip penetration. Here, the configuration of the tool tip side surface practically did not influence the nature of material displacement. Also visible under the tip end face is a thin interlayer deposited from material located from the tool advancing side.

However, such a displacement of material is only found in the case, if it occurs in an open space, and not in a limited volume. As during FSW the shoulder end face limits material displacement in the vertical direction, the latter is transferred by the tip from the tool advancing side to its retreating side, and then

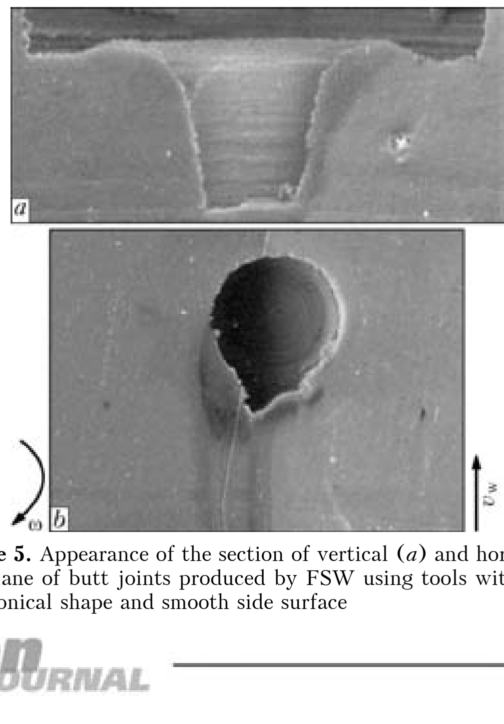

Figure 5. Appearance of the section of vertical (*a*) and horizontal (*b*) plane of butt joints produced by FSW using tools with a tip of a conical shape and smooth side surface

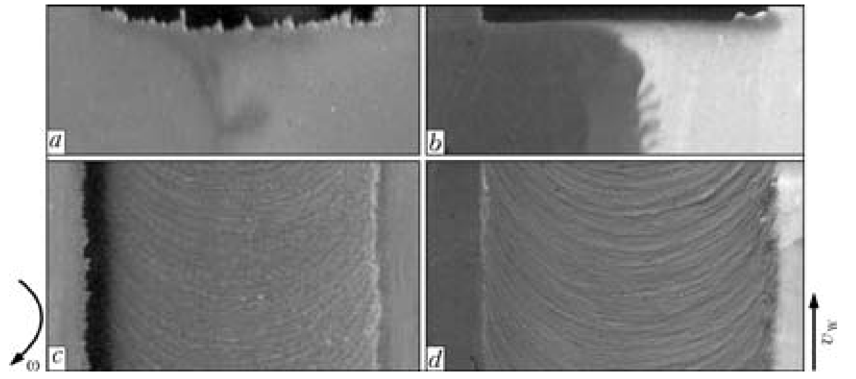

Figure 6. Appearance of cross-sections (*a*, *b*) and face surfaces (*c*, *d*) of welds produced by FSW using a tool with a tip having smooth side surface (*a*, *c*) and thread (*b*, *d*)

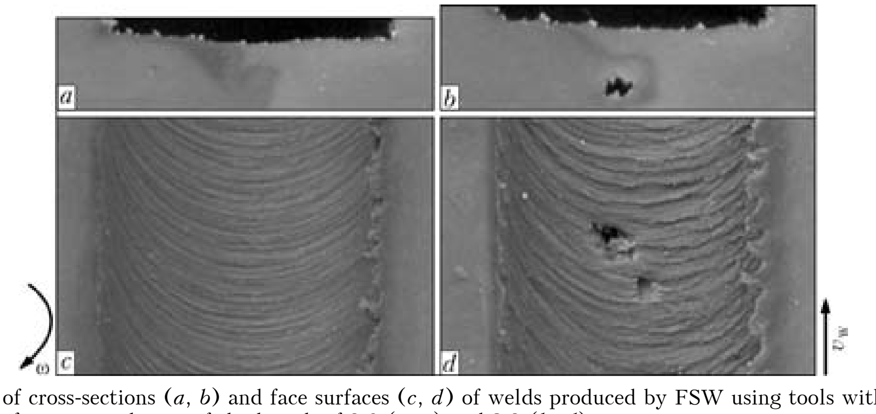

Figure 7. Appearance of cross-sections (*a*, *b*) and face surfaces (*c*, *d*) of welds produced by FSW using tools with smooth side surface of the tip in the form of a truncated cone of the length of 2.9 (*a*, *c*) and 3.2 (*b*, *d*) mm

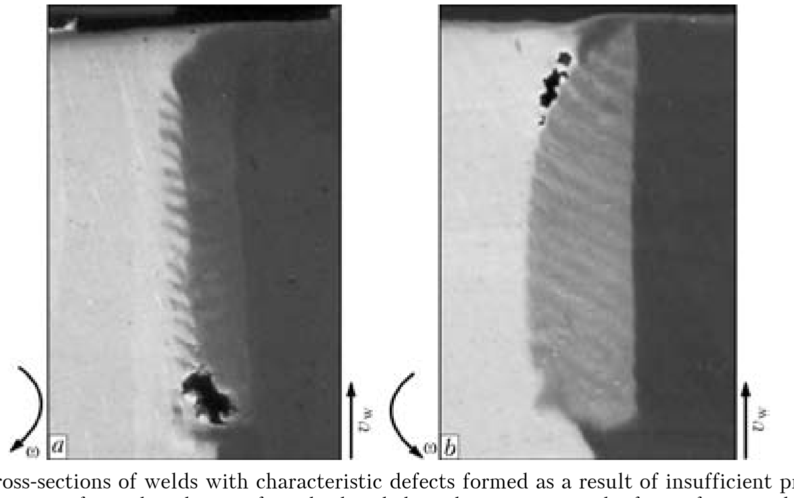

Figure 8. Appearance of cross-sections of welds with characteristic defects formed as a result of insufficient pressing of the shoulder to surfaces being welded at rotation of a tool with tips of a cylindrical shape having cuts in the form of metric thread in the clockwise (*a*) and counterclockwise (*b*) direction

into the space freed behind the tip, and is located along the weld axis (Figure 5).

At displacement by the tip of portions of one material located from the tool advancing side to the second material which is located from the tool retreating side, their partial mixing occurs in a closed space at excess pressure. This process can be intensified when using tips with a ramified and not smooth side surface. Using a tip with a standard thread on its side surface, formation of a laminated structure of the weld from the tool retreating side in the zone of its fusion with base material is ensured (Figure 6). However, the nature of formation and appearance of weld face do not essentially depend on the geometry of the tool tip side surface.

Influence of geometrical dimensions and shape, and particularly threads and branching on the tool tip side surface is enhanced at increase of thickness of material being welded. Conducted investigations showed that application of the tool with a smooth side surface of the tip in the form of a truncated cone allows producing sound welds at FSW of materials of about 3 mm thickness (Figure 7). In FSW of even highly ductile materials a defect in the form of a cavity quite often forms in the central part of the butt closer to weld root. Stability of formation of weld face part here also deteriorates with tears forming on it, and this results in insufficient compaction of material over the shoulder working surface. There is no smooth transition between the layers forming on the butt surface, which differ significantly both by thickness and by height that is indicative of periodical violation of continuity of the flow of materials being joined.

Presence of threads or ramification on the tool tip side surface can have an essential influence on the process of weld formation as a result of the change of direction and trajectory of material displacement in the joint zone. Here, certainly orientation of thread on the tool tip is interrelated with the direction of the tool rotation. Use of one and the same tool with a tip of a cylindrical shape, having cuts in the form of metric thread, can lead to formation of defects in different sections of the weld in case of insufficient pressing of the shoulder to the surfaces being welded (Figure 8). At tool rotation the material, present in the butt zone, is displaced by the thread from its lower part into the upper part, thus leading to formation of discontinuities in the weld root. At the change of direction of tool rotation the material moves along the thread on the tool tip side surface in-depth of the butt, that results in formation of a tight weld in its root part, and appearance of a cavity near the shoulder end face.

CONCLUSIONS

1. Studying the features of mass transfer in the zone of thermodynamic action at modeling the FSW process allowed establishing that formation of a permanent joint occurs as a result of transfer of a certain volume of ductile material by the tool tip from the edge being welded from the tool advancing side to plasticized material located on the opposite edge, their mixing and displacement under pressure in the space that is freed behind the tip at its movement along the butt.

2. Structural features of tool tips determine the trajectory of ductile material movement in the zone of permanent joint formation. To ensure sound formation of welds at increase of joined edge thickness above 3 mm, it is rational to apply tools with tips having a ramified side surface that ensures intensive mixing of materials across the entire thickness of the butt.

3. Configuration of working surface of tool shoulder influences the nature of mixing of materials being joined only on the weld face, and determines the degree of ductile material compaction behind the tool tip. Presence of a conical or semi-spherical groove on the shoulder working surface promotes a uniform continuous displacement of ductile material and formation of a practically smooth weld surface with ripple of almost the same thickness, the presence of which is indicative of alternation of joined material layers.

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MODERN MARKET OF WELDING EQUIPMENT AND MATERIALS*

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Systematised economic-statistical information is presented on the state-of-the-art and development of the world, regional and national welding markets, covering a period of 2006–2009. Quantitative and value indices of volumes of production, consumption and export-import of the equipment and consumables for welding and related technologies are given.

Keywords: *structural materials, welding equipment, statistics, economy, production, world market, regions, countries*

Market of main structural materials. Main structural materials in modern industrial production are steel, aluminium, titanium, magnesium and their alloys, as well as structural plastics. The volume of production of structural materials continuously grows, despite short-time recessions during periodic economic crises. For instance, during the last 40 years the volume of production of plastics has increased 9 times, that of magnesium — 3.4 times, aluminium — 2.7 times, and steel — 2.2 times. Figure 1 shows growth of the volume of production of main structural materials in 1970, 2008 and 2009. It can be seen from these data that steel is an undisputed leader in the market of structural materials. The volume of its production is more than 4 times higher than the total volume of production of other structural materials.

Different indices of production and consumption of steel are indicators of the state of the world and national economies, and development of separate industries and sectors of industrial production, including the welding industry. In particular, the volume and structure of consumption of steel products in types of products, industries and regions give a sufficiently complete picture of the volumes and structure of the welding market.

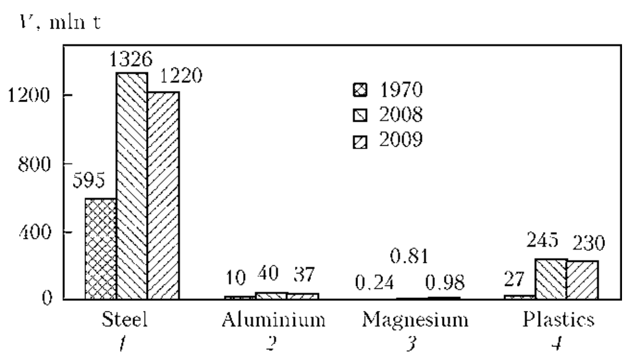

Figure 1. Volume V of world production of main structural materials according to the data of Information Agency «Worldsteel» (*1*), statistical book «U.S. Geological Survey» (*2*, *3*) and Company «Plastics Europe Market Research Group» (*4*)

The effect of changes in the world steel market on the volume of sales in the welding market can be demonstrated by an example of the «Thermadyne» Company — a leader in manufacture of welding equipment (sixth position in rating of leading world manufacturers of welding equipment in 2008) (Figure 2).

In 2007–2009, the market of structural materials experienced substantial fluctuations. For example, the year 2007 was notable for the highest level of production and consumption of steel in the world. The world economic crisis in 2008–2009 led to reduction of the world-wide production of steel in 2008 by 1.5 %, and in 2009 — by another 8 %. An even more substantial reduction of production of steel took place in the majority of the world regions: in North America this reduction amounted to almost 40 %, and in the EU countries, Japan and CIS it was about 30 %. Only three countries in the world (China, India and Iran) increased their production of steel during this period due to increase in volumes of their domestic markets. Thus, production of steel in China in 2008–2009 grew by 13.5 % and reached a record figure of 567.8 million tons.

In 2009 the world volume of consumption of finished steel products was 1,121 million tons, this being 6.7 % lower than the level of 2008. The world con-

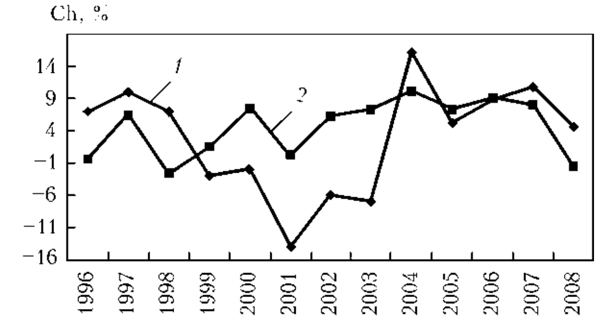

Figure 2. Changes Ch in world production of steel (*1*) and volume of sales of Company «Thermadyne» (*2*) in 1996–2008 [1]

*Based on data of information-statistical book «SVESTA-2010».

sumption of steel, except for the BRIC countries, reduced in 2009 by 26.8 %, compared to 2008. Consumption of steel in the BRIC countries during that period grew by 18 %, mostly due to growth of its consumption in China. Table 1 gives data on the world production of steel in 2007–2009, and Table 2 — data on the world consumption of finished steel products in 2009, as well as the forecast for 2011.

Over 2/3 of steel products (rolled metal) is processed by using joining technologies, and welding in particular. Therefore, the volume and structure of consumption of finished steel products allow estimating the volume of production of welding equipment and, particularly, of welding consumables. In welding production the deposited metal weight factor per ton of the consumed steel is the main indicator of consumption of welding consumables. According to the ESAB data, in 2006 the countries-average deposited metal weight factor (in kilo per ton of a welded structure) was 2.7 kg [2]. The value of this factor varies depending on the type of welded structures and employed welding methods. Demand for welding equipment is estimated also on the basis of the volume of consumption of steel. According to the international practice, it is assumed that for thousand tons of the steel produced in a country it is necessary to manufacture 2.5 units of welding equipment [3]. Figure 3 shows the structure of the main types of steel products manufactured in the world. Plates and bars constitute 46 % (each) of the total output of the steel products.

The volume of consumption of steel in separate industries allows estimating the structure of consumption of welding equipment in the industries (Figure 4). The construction industry and transport (manufacture of trucks and cars, shipbuilding, railway transport and machine building) are the largest customers for steel products. These industries consume about 80 % of all metal products manufactured in the world and, therefore, are the main customers of welding equipment.

Table 1. Production of steel in main world regions, mln t*

Region	2007	2008	2009	2009/2008
Europe, including:	364.5	344.1	265.8	−22.8
EU (27)	209.7	198.0	139.1	−29.7
EU (15)	175.2	167.7	117.7	−29.8
CIS	124.2	114.3	97.5	−14.7
North America, including:	132.6	124.5	82.3	−33.9
USA	98.1	91.4	58.1	−36.4
South America	48.2	47.4	37.8	−20.1
Africa	18.8	17.1	15.2	−11.0
Middle East	16.5	16.6	17.2	3.3
Asia, including:	756.5	768.3	795.4	3.5
China	489.3	500.3	567.8	13.5
Japan	120.2	118.7	87.5	−26.3
Australia/New Zealand	8.8	8.4	6.0	−28.6
Total	1345.8	1326.5	1219.7	−8.0

*Here and in Table 2 — data of the International Iron and Steel Institute.

Half of all steel products manufactured in the world are used in the construction industry. According to the Organization for Economic Cooperation and Development (OECD) data [4], the share of the construction sector in the world gross domestic product was about 13.4 % in 2009, and the market volume was approximately 7.5 trillion USD. The U.S and China markets are biggest in the world. Their shares in the

Table 2. Consumption of finished steel products in main world regions in 2009 and 2010, and forecast for 2011

Region	Consumption, mln t			Growth rate, %		
	2009	2010	2011	2009	2010	2011 (forecast)
EU (27)	118.4	134.6	145.2	−35.2	13.7	7.9
Other European countries	23.9	27.2	30.4	−12.5	13.5	11.9
CIS	35.8	39.8	43.0	−28.2	11.0	8.0
North America	80.9	99.9	107.1	−37.4	23.5	7.2
Central and South America	33.6	40.4	43.1	−24.1	20.0	6.7
Africa	26.4	28.7	31.3	9.6	8.6	9.3
Middle East	40.7	44.7	48.4	−8.0	10.0	8.2
Asia and Oceania	761.5	825.7	857.7	8.7	8.4	3.9
Total	1121.2	1240.9	1306.2	−6.7	10.7	5.3
China	542.4	578.7	594.9	24.8	6.7	2.8
BRIC	640.9	692.0	720.7	17.5	8.0	4.1
World, excluding China	578.8	662.2	711.3	−24.5	14.4	7.4
World, excluding BRIC	480.3	548.9	585.6	−26.8	14.3	6.7

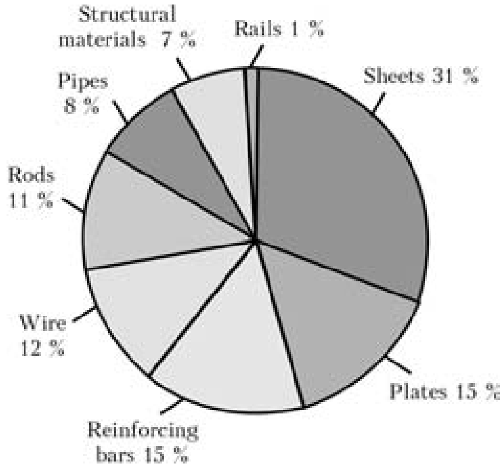

Figure 3. Structure of manufacture of main types of steel products in 2009 (according to the OECD data)

world construction market are 17 and 14 %, respectively. In the USA approximately 33 % of the domestic consumption of steel is in the construction industry. In Europe this figure is 40 %, and in the countries of South-East Asia it is 60 %. Decline in the construction sector market took place during the crisis. For example, in the countries of Europe in 2008 this decline was 7–8 %.

The world transport sector consumes about 16 % of steel produced in the world. It is a capital-intensive industry (the share of steel in weight of a car is approximately 70 %). Starting from 2001, the automobile markets of Japan, North America and Western Europe have continually reduced. In the same years China, India and Brazil featured a 25, 15 and 5 % increase in car sales, respectively. The world manufacture of cars shifted to the growing markets of Asia.

The machine building sector suffered from the economic crisis to a greater degree — the volume of production in regions decreased by 25–55 %, especially in the EU countries, USA and Japan. The fall in production in developing countries (due to the growth of consumption in China) was much lower. At present,

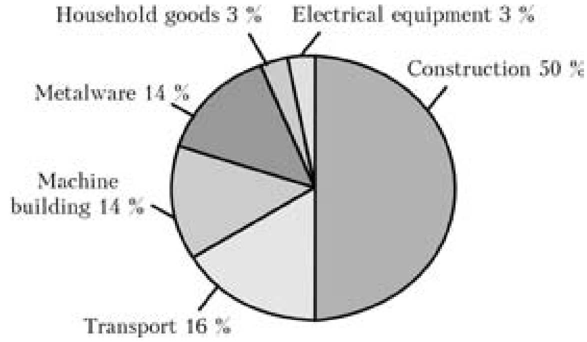

Figure 4. Structure of world consumption of steel in different industries in 2009 (according to the OECD data)

China takes the key position in the world market of this sector. Its share grew from 12 to 17 % during a period from 2005 to 2008.

The volume of consumption of steel products in 2009 reduced to the greatest degree in Europe (see Table 2). Table 3 shows the branch structure and changes in consumption of finished steel products in 2008–2010 in main industrial sectors of the EU countries, as well as the forecast for 2011.

By the end of 2010 almost all metalworking industries had restored their pre-crisis volumes of production and consumption of steel.

In 2008–2009 the volume of production in non-ferrous metallurgy also reduced. Production of primary aluminium, which was the second structural material in application in 2009, fell by 6.2 %. The world production of plastics also reduced by 6 %, compared to 2008, and made up 230 million tons. Table 4 gives data on the world production of primary aluminium in 2007–2009.

World and regional welding markets. The world market of products and services provided by welding and related technologies continues growing steadily, despite short-time recessions in a period of world crises. As estimated by German experts, in 2003 the value of the world market was about 33, in 2006 — 40, and in 2008 — 60 billion USD [5]. According to estimates

Table 3. Structure of consumption of finished steel products in separate industries in the EU countries (27), change rate in 2008–2010, and forecast for 2011 (European Confederation of Iron and Steel Industries)

Industrial sector	Share of consumption of steel products, %	Change, %			
		2008	2009	2010	2011 (forecast)
Construction	27	−0.8	−6.7	−0.5	2.8
Steel structures	11	−1.8	−13.9	0.4	2.9
Machine building	14	−1.0	−21.8	0.8	4.7
Motor car construction	16	−5.9	−28.9	1.2	4.5
Household goods	4	−4.6	−12.8	1.2	0.6
Ship building	1	6.2	−22.7	−10.2	2.0
Manufacture of pipes	12	−1.1	−26.0	3.6	5.8
Metalware	12	−2.3	−22.6	2.6	5.3
Others	3	2.3	−16.6	1.7	4.4
Total	100	−2.0	−18.2	0.9	4.0

Table 4. Production of primary aluminium (thou t) in main world regions (according to the data of the International Aluminium Institute)

Region	2007	2008	2009	2009/2008, %
China	12588	13105	12964	−1.1
North America	5642	5783	4759	−17.7
Central and Eastern Europe	4460	4.658	4117	−11.6
EU	4305	4618	3722	−19.4
Asia	3717	3923	4400	+12.1
South America	2558	2660	2508	−5.7
Australia/New Zealand	2315	2297	2211	−3.7
Africa	1815	1715	1681	−2.0
Total	37400	38759	36362	−6.2

Table 5. Volume of the world market of welding equipment and consumables, mln USD (according to the BCC Research data)

Indicator	2006	2007	2008	2013 (forecast)	Annual increment in 2008–2013, %
Welding equipment and consumables	9842	10219	10677	13615	5.0
Gases for welding	1911	1968	2017	2618	5.4
Protection means	367	383	406	487	3.7
Welding robots and accessories	86	96	108	148	6.5
Total	12206	12666	13208	16868	5.0

of a number of expert companies and commodity producers, the value of the welding market in 2009 was 12–13 billion USD [6]. Table 5 gives data on the volume of the welding market, including indices of the market of welding consumables and equipment, gases for welding, protection means and welding robots.

According to estimation of Company «Thermadyne», the welding market, including the market of filler metals, welding equipment, equipment for gas and plasma cutting and accessories, was 15 billion USD in 2008. In 2009 the volume of sales fell to 12 billion USD. The value of the market does not include gases for welding, gas bottles and protection means [7, 8].

Structure of the world welding market is shown in Figure 5. The market of welding and surfacing consumables in 2009 made up more than half of the world welding market. In 2007–2009 the share of this segment of the market varied from 50 to 57 %. The share of the market of welding equipment in 2009, compared to 2008, reduced by 2 % and constituted 24 %. The sales of gas (−5 %) and plasma (−1 %) cutting equipment decreased. In general, structure of the world welding market was rather stable in a period of 2007–2009, and there were no substantial fluctuations in the sphere of consumption of certain types of products in the welding market.

Main regional segments of the welding market are Asia (40 %), Europe (30 %) and America (30 %). According to estimates of the ESAB specialists, the value of the world welding market, excluding welding robots and automation means, was 13 billion USD in 2009 [9]. Regional distribution of the world welding market, according to the ESAB data, is shown in Figure 6.

The regional structure of the welding market experienced substantial changes in 2007–2009. The welding market, like the steel market, shifted to the Asian regions. In 2009, in value terms the American, European and Japanese welding markets reduced by 30–40 %. The positive trend was noted only in China, India and Middle East (Iran). Compared to 2007, in 2009 the share of the Asian countries in the world welding market grew by 11 %, mostly due to China and India. The growth of sales (by 2 %) was noted also in markets of the South America countries. During that period the share of the EU countries in the world

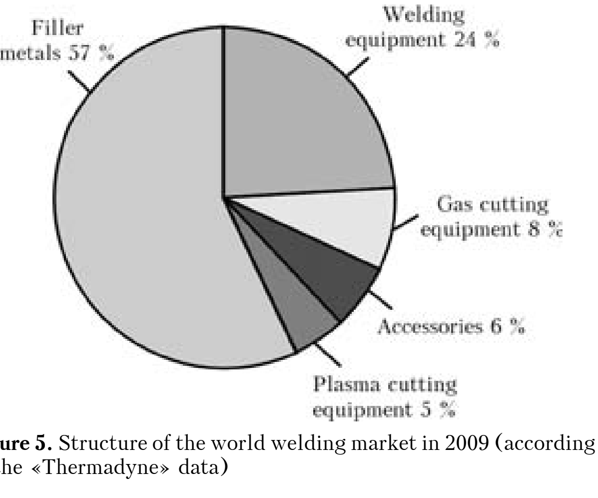

Figure 5. Structure of the world welding market in 2009 (according to the «Thermadyne» data)

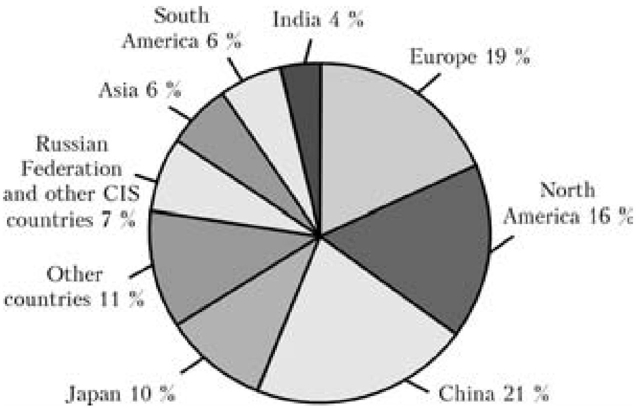

Figure 6. Regional distribution of world welding market in 2009

welding market reduced by 6 %, and the share of the North America countries reduced by 3 % [10]. This trend is supported by the data on changes in sales in the regional markets of ESAB — the major transnational company (second position in rating of the world leading manufacturers of welding equipment and consumables in 2009) (Table 6) [9].

Table 6. Regional structure of ESAB sales

Region	Share, %	
	2009 (volume of sales — 1031.4 million pounds)	2002 (volume of sales — 581.9 million pounds)
Europe:		
developed countries	25	55
developing countries	13	–
America:		
North	23	33
South	16	9
Russian Federation	6	–
India	5	–
China	3	–
Others	9	3
Total	100	100

The industries that are the main customers of welding equipment and consumables are construction, transport, power generation (including oil and gas producing industry, electrical power generation, petrochemistry, manufacture of pipes and construction of pipelines), as well as the sphere of repair and renewal operations. Figure 7 shows mean world indicators of distribution of the world welding market in main consuming industries [8].

In contrast to the majority of metalworking industries (motor car construction, ship building, aerospace engineering, industrial and civil construction engineering, heavy machine building) that reduced their manufacture and, hence, consumption of the welding equipment and consumables during the crisis period of 2008–2009, only the power generation sector (wind, nuclear, hydro and solar power generation) continued increasing its consumption of welding equipment and consumables. In 2008, the share of power generation in structure of consumption of welding equipment and consumables in the world welding market was 11 %. According to estimates of the «Frost & Sullivan» experts, it is expected that the annual growth of this sector of the welding market till 2015 will be 7 %. It is predicted that the volume of the welding market in the power generation sector will grow from 1.9 (2009) to 3.0 billion USD (2015) [11].

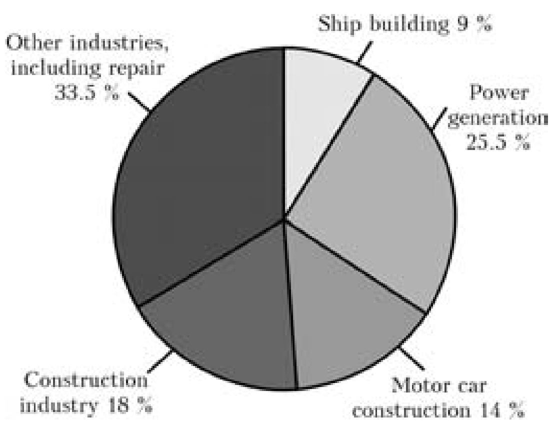

Figure 7. Distribution in main consuming industries in 2009 (according to the «Thermadyne» data)

As estimated by the ESAB and «Frost & Sullivan» experts, the most promising sector of the welding market is wind power generation. At present the share of the world power generation using wind power plants is not in excess of 2 %. However, the rate of increase in commissioning of new facilities continually grows. The world capacity of wind power generation in 2007 was 27,000 MW. It is predicted that in 2012 it will amount to 60,000 MW. In the EU countries (Denmark, Portugal, Spain, Ireland) the share of the power generated by using wind mills is already 10 to 20 %. In general, according to the EU Directive on development of national plans for reduction of power consumption, every EU country should reduce its annual power consumption by 1 % as a minimum in a period from 2008 to 2017. Europe has set a target to raise the share of alternative fuels in a general energy balance by 2020 to 20 %, and by 2040 — to 40 %.

The growth of commissioning of new wind power plants in the USA during a period of 2007–2009 constituted 35, 44 and 39 % of the entire volume of the new power generation facilities.

Table 7 gives data of the U.S. Department of Energy, allowing estimation of the state-of-the-art in wind power generation in leading countries of the world [12].

Investments into the welding equipment of this segment of the market continually grow. According to estimates made by the ESAB specialists, 700 kg of welding consumables and 600 kg of flux are consumed per each newly introduced megawatt of the power. This segment of the market has good prospects for further growth [9].

Table 7. Total and annually introduced capacities of wind power plants in world leading countries in 2009

Country	Annually introduced capacity, MW	Total capacity, MW
USA	9994	35155
China	13750	25853
Germany	1917	25813
Spain	2331	18784
India	1172	10827
Italy	1114	4845
France	1104	4775
Great Britain	1077	4340
Canada	950	–
Portugal	645	3474
Denmark	–	3408
Other countries	4121	22806
Total	38175	160080

In addition to the power generation sector, the experts also class the sector of repair and renewal operations with the industries that can become catalysts of growth of the welding market in the next few years of recovery from recession. A response to the predicted growth of prices of oil will be increase in consumption of steel for construction of pipelines and tankers. In turn, this will lead to growth of the market of welding equipment and consumables.

European market of welding engineering products and services. In 2007 the German Welding Society (DVS) completed a wide-scale project on estimation of contribution of joining technologies (welding and related technologies) to economy of the European countries [5]. Based on the data obtained, it is possible to sufficiently fully estimate the volume and structure of the European market of welding engineering products and services. Table 8 gives data on the volume of production of equipment for welding and related technologies, as well as value-added goods and services in the welding market of the leading European countries — manufacturers of welding equipment.

As seen from Table 8, the volume of production of equipment for welding and related technologies in the EU countries in 2007 was 7.5 billion Euro. The main manufacturers of the said equipment are Germany and Italy, which collectively manufacture half of the entire equipment in Europe, and Germany — one third. The market of value-added goods and services is 1.6 times in excess of the market of equipment. Totally, the market of the joining technologies, value-added goods and services related to the joining technologies in 2007 was almost 20 billion Euro.

Table 9 shows structure of production of equipment for welding and related technologies in Germany and other EU countries. As seen from the Table, the volume of production of welding equipment makes up half of the total volume of equipment for welding and related technologies produced in the EU countries. In Germany this indicator is 66 %. Production of equipment for laser technologies takes the second place. Its share in the EU countries is 18 % on the average, and in Germany — 9 %.

Table 8. Production of equipment and value-added services for welding, and rendering services in this sphere in EU countries in 2007, mln Euro*

Country	Production of equipment for welding and related technologies	Production of value-added goods and services	Total
Germany	2500	2110	4660
France	320	1510	1830
Italy	1170	1800	2970
Great Britain	160	1190	1350
Poland	97	169	266
The Netherlands	29	382	411
EU (27)	7500	12480	19980

*DVS data are used here and in Tables 9–11.

Table 10 gives data on the volume of production of welding equipment in the EU countries. Main manufacturers of this equipment are Germany and Italy. Totally, these countries manufacture 70 % of the entire welding equipment in the region, the share of Germany being 43 %.

Data on the volume and structure of production of value-added goods and services in the field of the joining technologies are given in Table 11.

The main share (almost 50 %) in structure of production of value-added goods and services falls on production of glue. The portion of welding gas is 18 %, and that of welding consumables is 14 %. This structure in Germany is a bit different: the first place in

Table 9. Structure of production of equipment for welding and related technologies in Germany and other EU countries in 2007

Joining technology	Volume of production, mln Euro		Share, %	
	Germany	EU	Germany	EU
Welding	1668	3916	66	52
Brazing and soldering	233	629	9	8
Gluing	112	338	4	5
Cutting	96	582	4	8
Thermal spraying	17	54	1	1
Others	80	324	3	4
Laser technologies	233	1334	9	18
Robots/robotic systems	111	323	4	4
Total	2550	7500	100	100

Table 10. Volume of production of welding equipment in EU countries in 2007, mln Euro

Country	Welding equipment	Spares	Total	Share, %
Germany	1433	235	1668	42.6
France	181	34	215	5.5
Italy	608	110	718	18.3
The Netherlands	–	0.80	0.80	0.01
Poland	55	4	59	1.5
Great Britain	68	15	83	2.1
Other countries	1041	131	1172	29.9
EU (27)	3386	530	3916	100

Table 11. Volume of production of value-added goods and services in the field of joining technologies in 2007

Value-added goods and services	Production volume, mln Euro		Share, %	
	Germany	EU	Germany	EU
Glue	271	6040	12.9	48.4
Welding gas	598	2232	28.4	17.9
Welding consumables	415	1717	19.7	13.8
Testing equipment	229	723	10.9	5.7
Training	241	561	11.4	4.5
Rivets	134	500	6.4	4.0
OH&S	49	277	2.3	2.2
Thermal spraying consumables	78	256	3.7	2.1
Brazing and soldering consumables	83	127	3.9	1.0
Ventilation equipment	9	50	0.4	0.4
Total	2106	12483	100	100

production volumes is taken by welding gas (28 %), the second place is taken by welding consumables (20 %), and the third place — by production of glue (13 %). Services in training of welding personnel constitute a substantial part in the market of the EU countries, especially in Germany, i.e. 4.5 and 11.0 %, respectively.

Figure 8 shows the volume of production of welding engineering products and services in the EU countries in 2007. Based on these data, it is possible to get a sufficiently full idea of structure of manufacture of welding engineering products and services for welding and related technologies in Europe. Glue constitutes over 30 % of the output, welding equipment — about 20 %, and welding consumables — 9 %. These data fully confirm the forecast of German manufacturers of welding engineering products on development of individual sectors of the European market of joining technologies, which was published in 2005. According to this forecast, the laser welding and gluing technologies will have the highest growth in 2005–2015 [13] (Figure 9).

World market of welding consumables. The value of the world market of welding consumables during a period of 2007–2009 was about half of the entire volume of the welding engineering market. In 2009, its value was approximately 6.0–6.5 billion USD. According to estimates of the ESAB specialists [9], in 2009 the world volume of consumption of welding consumables calculated per weight of the deposited metal was about 4.1 million tons, this being 13 % lower than the level of 2008. Figure 10 shows the world structure of consumption of welding consumables in main types of products.

Electrodes for arc welding (about 40 %) and solid wire (about 40 %) predominate in the world structure of consumption of welding consumables. The diagram

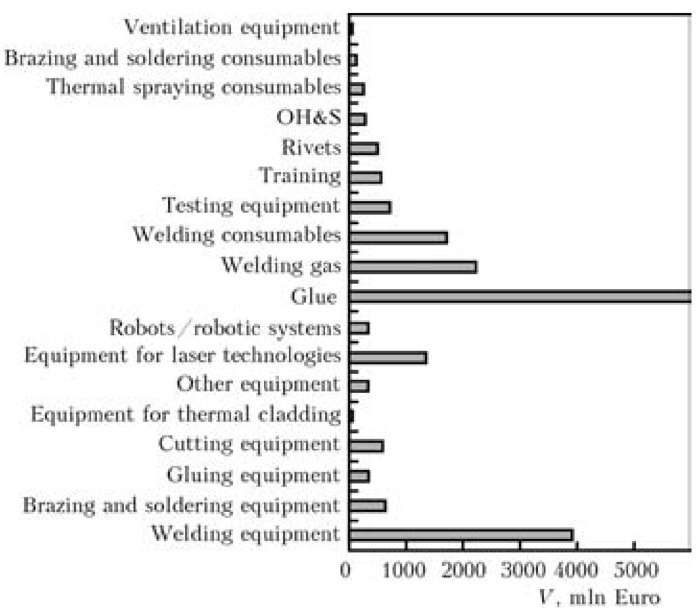

Figure 8. Production volume V of the European market of welding engineering products and services in 2007 (according to the DVS data)

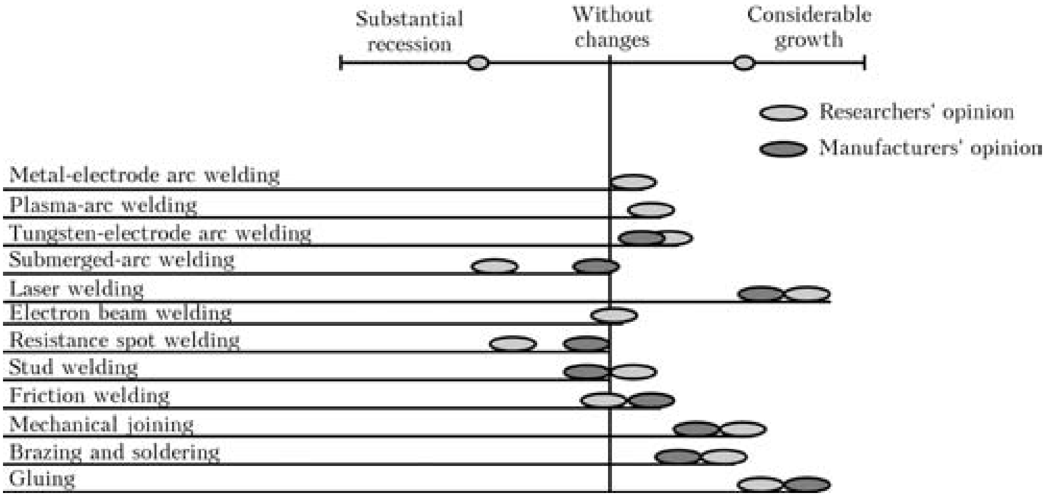

Figure 9. Forecast for development of individual sectors of the European welding market for a period of 2005 to 2015

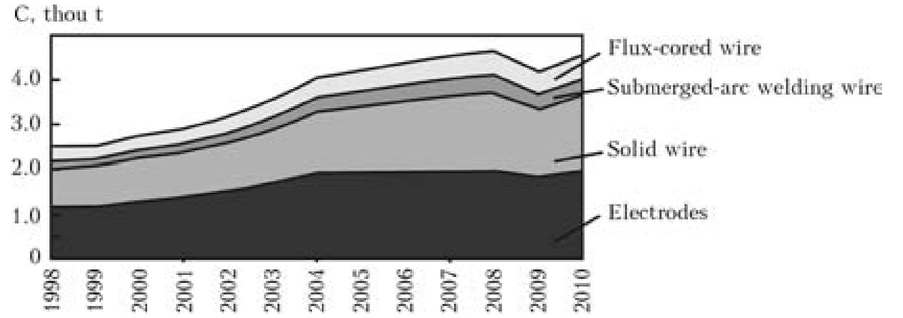

Figure 10. Consumption C of welding consumables in main types of products (according to the ESAB data)

shown indicates that no significant changes took place in a period of 2007–2009 in trends and structure of demand for welding consumables. The trend to decrease in consumption of covered electrodes for arc welding and to growth of demand for flux-cored wire persists. The volume of consumption of solid wire remains invariably high and also shows a trend to growth, which will persist in the next years as well, thus leading to stabilisation of application of covered electrodes at a level of 15–20 %.

Regional markets of welding consumables. Asia dominates here, its share in the world market of welding consumables being 70 %. The share of Europe is 15 %, and that of North America is 10 %. All markets of welding consumables in the main regions, except China and India, experienced a substantial recession in 2009. The volume of sales reduced most significantly in the markets of the USA, Europe and Japan (about 30 %). The market of welding consumables shifted to Asia. Figure 11 shows data on the volume of consumption of welding consumables in main world regions.

China has a world lead in production and consumption of welding consumables. In 2009, according to the data of Chinese experts, the volume of consumption of welding consumables was about 2.5 million tons. As estimated by «Thermadyne», the value of the Chinese market of welding consumables in 2009 was 1.1 billion USD [7, 14].

Electrodes for manual arc welding constitute the major part of all welding consumables manufactured in China. In 2009, their share in structure of production of welding consumables was about 58 %, the share of solid wire was 25 %, and that of flux-cored wire and submerged-arc welding consumables was 17 %. The volume of application of welding consumables for welding of aluminium was roughly 5 thousand tons.

In the last years the structure of production of welding consumables is quickly changing: manufacture of solid and flux-cored wire is growing, and manufacture of welding electrodes is decreasing. According to the forecast of the China Iron and Steel Research Institute, by 2015 the volume of production of welding consumables in China will amount to 3.5–4.0 million tons, the share of production of covered electrodes for manual arc welding will decrease to 22 %, the share of solid wire for CO_2 welding will grow to 50 %, that of flux-cored wire will increase to 15 %, that of wire for submerged-arc arc welding and fluxes will remain at a level of 12 %, and that of consumables for TIG welding will remain at 1 % [15].

In *Japan* the total volume of production of welding consumables reduced almost by 30 % in 2009, compared to 2008, and reached the minimal level fixed over the last 20 years. This resulted in reduction of manufacture of welding consumables in individual types of products (from 9 to 44 %).

The data on the volume of domestic consumption of main types of welding consumables are given in Table 12 [16].

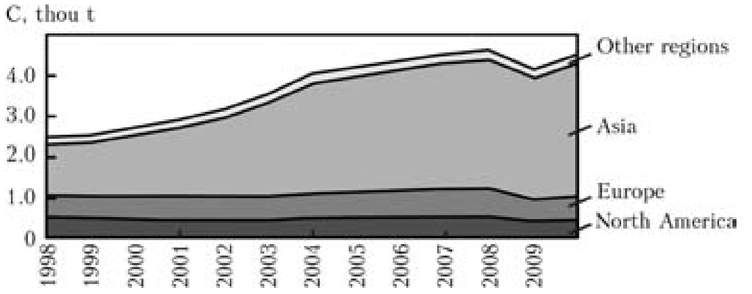

Figure 11. Consumption C of welding consumables in main regions (according to the ESAB data)

Reduction of the total volume of consumption of welding consumables affected the consumption of individual types of welding consumables. Consumption of flux-cored wire decreased to the least degree (–9 %), its share in the consumption structure grew to 38.7 % and became comparable with the share of application of solid wire, the volume of consumption of which reduced most significasntly (44.2 %).

The volumes of foreign trade of welding consumables also reduced: decrease in import of welding consumables being 40 % and making up 33.62 thousand tons. Import of solid wire decreased by 56.6 % (to 11.5 thousand tons), and that of covered electrodes — by 20.4 % (to 1.58 thousand tons). At the same time, import of flux-cored wire increased by 4 %, and in 2009 it amounted to 14.4 thousand tons. Export of welding consumables decreased by 31.5 % and made up 39.98 thousand tons.

According to estimates of the Japanese experts, no substantial growth of production in metalworking industries and in construction was expected in 2010. Hence, the demand for welding consumables remained at a level of 2009. It was predicted that the volume of production of welding consumables in 2010 would grow by 2.1 % and make up 257.6 thousand tons, export of welding consumables would increase by 2 % (to 36.7 thousand tons), and import would increase by 2.3 % (to 34.38 thousand tons).

The *India* market of welding consumables is one of the most dynamically developing markets in Asia. Based on the estimate made by Ador Welding Ltd., which is the India-largest welding manufacturer, the market of welding consumables constitutes about 70 % of the entire welding market of India, and in 2009 it made up about 450 million USD. During a period of 2007 to 2009, the growth rate of the market increased. For example, the growth of revenues of ESAB INDIA Ltd in 2009 was 15 %.

The Indian market of welding consumables is fragmented: about 50 % of it is controlled by «non-organised» participants, and over 50 % of the «organised» market is covered by such companies as AWL (23 %), ESAB (17 %) and D&H Welding. As estimated by the Indian experts, the annual growth of the market of welding consumables in the next years will be approximately 15–16 %.

Table 13 gives data on the volume of consumption of welding consumables according to the structure of application of different arc welding processes in 2007–2010, as well as the forecast for 2011.

The dominant position (about 80 %) in the Indian market of welding consumables is taken by electrodes for manual arc welding. It is predicted that in the next 3–5 years the share of application of covered metal electrode arc welding will reduce to 65 %, the share of gas-shielded covered metal electrode arc welding will grow from 17 to 27 %, and that of other welding processes will remain unchanged. The volume of consumption of welding consumables during this period will increase by 30–35 % [17, 18].

As reported by «Frost & Sullivan», in the *Republic of Korea* the value of the welding market in 2005 was 656.2 million USD. According to the forecast, by 2012 it will amount to 955 million USD. Consumables and equipment for arc welding constitute 85.6 % of the entire welding market, 27.1 % of it is taken by welding

Table 12. Volume and structure of domestic consumption of main types of welding consumables in Japan

Welding consumables	2008		2009		2009/2008, %	2010	
	Thou t	Share, %	Thou t	Share, %		Thou t	Share, %
Covered electrodes	40.6	11.4	30.6	12.1	75.4	29.4	11.5
Wire and flux for submerged-arc welding	40.2	11.3	28.9	11.4	71.9	31.3	12.3
Thin solid wire	167.5	46.7	93.4	37.0	55.8	95.5	38.2
Wire for TIG welding and other processes (gas welding and cutting)	2.1	0.6	1.9	0.8	90.5	1.9	0.8
Flux-cored wire	107.5	30.0	97.4	38.7	90.9	99.5	37.2
Total	358.4	100.0	252.2	100.0	70.4	257.6	100.0

Table 13. Estimated volume of consumption of welding consumables in India according to structure of application of arc welding processes, thou t

Year	Arc welding				
	Covered metal electrode welding	Gas-shielded covered metal electrode welding	Submerged-arc welding	TIG welding	Total
2007	262	58	17.5	2.6	340.1
2008	278	65	19.0	2.8	364.8
2009	296	74	20.5	3.0	393.9
2010	315	82	22.0	3.2	422.2
2011	335	93	24.0	3.4	455.4

consumables. Therefore, in 2005 the value of the market of welding consumables was 177.7 million USD [19].

The market of welding consumables in the Republic of Korea features a very dynamic development. During a period from 1995 to 2005, the volume of production of welding consumables in the country grew 5 times (about 300 thousand tons). Domestic consumption was 62 % of the manufactured welding consumables, the export being 38 % [20]. Out of the welding consumables manufactured in the country, solid and flux-cored wires constitute over 70 %. Figure 12 shows the structure of production of welding consumables in the Republic of Korea.

The growth of consumption of steel was noted in the country during a period of 2006–2008 (11.5 %). Production of welding consumables also grew, this being confirmed by the data on increase in the volume of production of welding consumables by main manufacturers of welding consumables in the Republic of Korea. Table 14 gives data on the volume of production of welding consumables by Hyundai Welding Co. Ltd. in 2006 and 2009. In the domestic market of welding consumables, the share of sales of this Company is 62 %. As seen from the Table, in addition to growth of the production volume, the structure of the manufactured welding consumables also experienced substantial changes. The output of electrodes for manual arc welding was reduced almost twice. Production of flux-cored and solid wires, as well as wire and flux for automatic welding has been growing [21].

In 2009 there was a fall in production of welding consumables because of reduction of orders in the industries that are key customers for welding consumables (first of all, ship building and motor car construction). According to our estimate, in 2009 the volume of production of welding consumables in the Republic of Korea decreased approximately by 20 % (about 260 thousand tons). As shown by the UN data (database COMTRADE), the volume of export of welding consumables decreased in 2009 by 7 % (73 thousand tons), and that of import — by 34 % (26 thousand tons) [22].

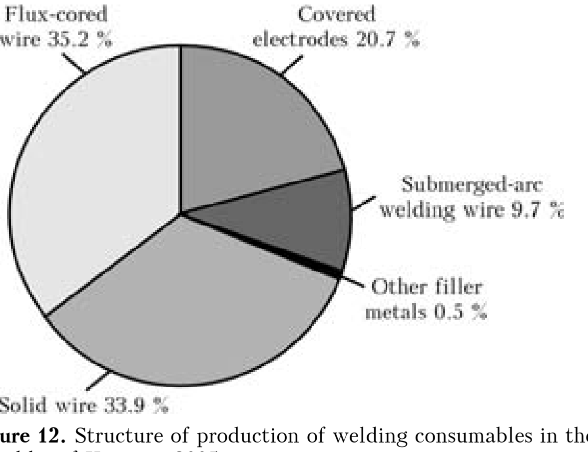

Figure 12. Structure of production of welding consumables in the Republic of Korea in 2005

As estimated by the DVS experts, in 2007 the value of production of consumables in the *EU countries* was 2100 million Euro, the value of welding consumables being 1717 million Euro. The key manufacturers and customers of welding consumables in Europe are Germany, France and Italy. Table 15 gives volumes of production of the main types of welding consumables in the EU countries, which are used for welding and related technologies [5].

Germany produces 30 % of the total volume of welding consumables manufactured in the EU countries, while Germany, France and Italy collectively produce more than half of all consumables.

Solid wire predominates in structure of production and application of welding consumables in the EU countries (its share is about 70 %). The share of flux-cored wire is about 10 %, and that of arc welding electrodes is approximately 10 %. Consumption of welding electrodes, which are intended for application in special areas, continues decreasing in Europe.

According to the DVS data, in 2009 the value of production of welding consumables and filler metals in the EU countries decreased by 30 % on the average, this being confirmed by the data of the leading European manufacturer of welding consumables — ESAB, whose return from sales in the European market in 2009 reduced by 30 %.

The volume and structure of production of consumables in Europe during a period from 2007 to 2009 cab be estimated from the data on the value and quantity of individual types of welding consumables manufactured in Germany, which are given in Tables 16

Table 14. Volume of production of welding consumables by Hyundai Welding Co. Ltd., thou t

Welding consumables	2006	2009
Covered electrodes for manual arc welding	60	36.0
Flux-cored wire for gas-shielded welding	25	45.0
Solid alloyed wire for gas-shielded arc welding	25	36.0
Wire and flux for automatic welding	6	19.2
Total	116	136.2

Table 15. Volume of production of consumables in EU countries in 2007, mln Euro

Country	Consumables			Total
	Welding	Soldering and brazing	Thermal spraying	
Germany	415	83	78	576
France	213	51	47	311
Italy	264	10	28	302
The Netherlands	42	22	9	73
Poland	35	5	10	50
Great Britain	142	19	48	209
EU (27)	1714	127	256	2100

and 17. According to these data, the value of production of welding consumables in Germany in 2009 reduced by 32.6 %, and quantity — by 23.9 %, while by the individual types of products, e.g. covered electrodes, this reduction was 2 times [10].

Based on the data given in Tables 16 and 17, and proceeding from the fact that Germany manufactures 30 % of the entire European volume of welding engineering products, the value of production of welding consumables in the EU countries in 2009 was approximately 1.2 billion Euro, the volume of production of welding consumables being about 420 thousand tons.

In the *CIS countries*, and Russia in particular, welding electrodes constitute 80 % of the entire output of welding consumables. The key advantage of using welding electrodes, compared to other welding consumables, e.g. flux-cored wire, is a low cost of the equipment involved.

The trend in the last 3–5 years in the Russian market, like in the world one, is to decrease of the share of welding electrodes in the total volume of utilisation of means for welding of metals. This trend is associated with increase of the share of wire and resistance welding as the most cost effective and sound welding methods. At the same time, with development of construction, railway, defence and oil and gas industries the demand for welding electrodes among the Russian customers increases by 10–20 % every year, in absolute values. Table 18 gives data on the volume and structure of production of welding consumables in Russia in a period of 2004–2007 [23].

Out of the general-purpose electrodes, Russian enterprises produce more electrodes with rutile (MR-3, ANO-21, OZS-12) and ilmenite (ANO-6) coverings. The share of such electrodes is about 60 % of the total output. They are in great demand, because they can be used in welding at both alternating and direct current almost in all welding positions. Welding can be performed even by low-skill welders. Basic electrodes (UONI-13/45, UONI-13/55) are produced in lower volumes. Their share is about 36 %. These electrodes are used for welding of super critical structures, and welding should be performed by high-skill welders.

In the last years the Russian market of welding electrodes has been characterised by a trend to increase in import and decrease in export, the share of import being low, i.e. no more than 10 % of the output. In 2007 the volume of import of welding electrodes ex-

Table 16. Production of welding consumables in Germany in 2007–2009

Welding consumables and auxiliary materials	Production volume, mln Euro			Change 2009/2008, %
	2007	2008	2009	
Welding wire and strip (excluding wire and strip with covering and filling)	221.2	221.2	145.4	−34.3
Covered electrodes for arc welding	64.5	71.6	31.6	−55.9
Flux-cored wire for arc welding	46.4	53.1	33.0	−37.9
Covered rods for soldering, brazing and autogenous welding	56.1	61.0	44.7	−26.7
Auxiliary materials and consumables for welding, soldering and brazing of metals	109.6	113.4	95.6	−15.7
Total	497.8	520.1	350.3	−32.6

Table 17. Production of welding consumables in Germany in 2007–2009

Welding consumables and auxiliary materials	Production volume, t			Change 2009/2008, %
	2007	2008	2009	
Welding wire and strip (excluding wire and strip with covering and filling)	93437	90873	59159	−34.9
Covered electrodes for arc welding	5379	5351	2967	−44.6
Flux-cored wire for arc welding	18276	22397	14527	−35.1
Covered rods for soldering, brazing and autogenous welding	–	–	9281	–
Auxiliary materials and consumables for welding, soldering and brazing of metals	45584	46010	39313	−14.6
Total	162676	164631	125247	−23.9

Table 18. Volume of production of welding consumables and filler metals in Russia in 2004–2007, t

Type of welding consumables	2004	2005	2006	2007
Covered electrodes	223743	24000	255600	266600
Alloyed welding wire with 2 or more mm diameter, including:	32635	33400	35100	39600
with 0.8–1.4 mm diameter	13980	18200	22400	18800
Flux-cored wire, including:	3458	2965	4785	4800
for welding	2212	1380	1603	2300
for coating	1246	1585	3182	2500
Welding fluxes	10585	12473	10300	8600
Total	270421	289238	305785	319600

ceeded 26 thousand tons, in 2008 — 33 thousand tons, and in 2009 — 21 thousand tons. The volume of export was 14, 13 and 9 thousand tons, respectively.

At present, the major manufacturers of electrodes in Russia are three enterprises — Novosibirsk Electrode Factory, its share in the Russian electrode market being 35.2 %, according to the Factory data, Novocherkassk Electrode Factory, the share of which is 26.8 %, and Chelyabinsk Electrode Factory with a share of 23.2 %. All these three enterprises are governed by Company «Energoprom Management».

In the opinion of experts, the short- and medium-term prospects of development of the Russian market of welding consumables are linked with further growth of the electrode market in the absolute values. The share of electrodes in the total volume of production and consumption of welding consumables will reduce. The growth of consumption of solid and flux-cored wires will continue, but the dominant position in the market will still be occupied by electrodes [24].

Economy of *Ukraine* is among the economies that were most affected by crises in Europe. Because of reduction of demand and revenue, as well as absence of credits, enterprises of Ukraine decreased their production. In 2008 the industrial production reduced by 3.1 %, and in the first quarter of 2009 this reduction exceeded 30 %. The general state of the economy influenced the volume of production and consumption of welding equipment and consumables.

Table 19 gives data of the State Statistic Committee of Ukraine on the volume of production and consumption of the main types of welding consumables, as well as their marketing in 2007–2009 [25].

The structure of production and consumption of welding consumables in Ukraine consists of over 50 % of welding electrodes, among which the share of electrodes of the ANO type is over 70 %. In 2007–2009, production of welding consumables in the country reduced almost two times. This applies to all of the main types of products. Utilisation of welding consumables was reduced by 40 %. Fused fluxes constituted the main part of export of welding consumables, and alloyed welding wire — the main part of import.

Market of welding equipment. The largest regional markets of welding equipment are the USA, as well as the EU and Asia countries (Japan, China and the Republic of Korea). Total sales in these markets constitute 3/4 of the entire world market of welding

Table 19. Apparent consumption of welding consumables and filler metals in Ukraine, thou t

Year	Index	Welding wire		Flux-cored wire	Electrodes	Fluxes	Total
		Conventional	Alloyed				
2007	Production	8.4	13.6	0.9	59.0	29.5	111.4
	Export	–	6.1	0.2	3.9	21.4	31.6
	Import	–	4.7	0.8	2.2	0.3	8.0
	Apparent consumption	8.4	12.2	1.5	57.3	8.4	87.8
2008	Production	9.0	12.8	0.6	43.0	27.8	93.2
	Export	–	5.3	0.3	3.9	19.7	29.2
	Import	–	6.6	1.2	3.7	0.9	41.6
	Apparent consumption	9.0	14.1	1.5	42.8	9.0	76.4
2009	Production	7.1	9.2	0.2	33.7	18.7	68.9
	Export	–	3.0	0.2	5.9	13.1	22.2
	Import	–	2.3	0.7	0.8	1.9	5.7
	Apparent consumption	7.1	8.5	0.7	28.6	7.5	52.4

equipment. In 2009, a fall in sales (by 6.4 % on the average) took place in the world market of welding equipment, this being related to a substantial reduction of demand in the majority of metalworking industries. That affected to the highest degree the markets of Europe and America (up to 30–40 %). However, increase in sales in the markets of Asia and South America, as well as the increased demand for welding equipment in power engineering (manufacture of turbines for wind power stations) and in the sector dealing with repair and renewal operations allowed the fall in sales to be compensated for to a substantial degree.

The world market of welding equipment is highly fragmented. Welding equipment is produced by over 1500 major and medium manufacturers, among which the main ones are ACRO Automation Systems, Inc., Boehler Thyssen Welding USA, Inc., Datalogic Automation S.r., ESAB Holding Ltd., KUKA Aktiengesellschaft AG, L'Air Liquide S.A., Lincoln Electric Holdings, Inc., Miller Electric Mfg. Co., Miyach Corp., Motoman, Inc., OBARA Corp., Panasonic Welding Systems Co., Soudronic AG, Schlatter Holding AG, etc. As to turnover, in 2008 the top five of the world leaders included Lincoln Electric (2.5 billion USD), ESAB (2.5 billion USD), ITW (1.8 billion USD), ALW (900 million USD), and Boehler (800 million USD) [26].

Equipment for arc welding. Like steel preserves its position as a basic material for welded structures, fusion arc welding remains the basic technology among a wide range of technologies for making of permanent joints. A characteristic trend in development of arc welding is reduction of the share of manual covered-electrode welding at the expense of widening of application of more efficient automated gas-shielded welding using solid and flux-cored wire. For instance, during the last 30 years the share of application of manual covered-electrode welding in the leading regions of the world reduced almost twice. In the last years the rate of reduction of utilisation of this welding method slowed down to some extent, and there are good reasons to expect that in the nearest future the share of manual arc welding (by weight of the deposited metal) in industrialised countries will stabilise at a level of about 15 %. In the developing countries the share of application of manual arc welding is still high and constitutes about 60 %.

In 2008, the arc welding equipment segment of the world market was estimated by «Frost & Sullivan» at 3.3 billion USD. The share of the market of welding equipment in the West Europe is approximately 30 % of the entire market of welding equipment in this region. In 2007, sales in this segment of the market were 572.4 million USD or 29.6 % of the entire West Europe market of welding equipment. A fall in sales in the sector of arc welding equipment caused by the crisis of 2009 in Germany, which is the main manufacturer of welding equipment in Europe, was about 10 % (in industry on the average — 33.5 %). Reduction of production of standard arc welding equipment in Japan was 66 %.

Machines for gas-shielded arc welding dominate in the market of arc welding equipment. For example, in Japan this type of equipment constitutes 90 % of the market of arc welding equipment. Demand for gas-shielded arc welding is invariably high. Modern machines for arc welding (MIG/MAG and TIG) are fitted with power supplies with numerical control systems. Application of high-end computers and inverter circuits allows the arc processes to be controlled at a high speed, accuracy and optimality. The equipments is also fitted with numerically controlled wire feed mechanisms. The equipment for combined and hybrid welding processes, such as gas-shielded metal-electrode, hybrid laser-arc and plasma-arc welding, is in high demand.

The market of equipment for aluminium welding, where at present the gas-shielded metal- (MIG/MAG) and tungsten-electrode (TIG) equipment also constitutes the major part, grows with increase in the volume of consumption of aluminium. According to the data of «Frost & Sullivan», in 2009 the world market of equipment for aluminium welding amounted to 912.4 million USD. It is predicted that by 2015 this market will make up 1,222 million USD, the annual growth being 5 %.

The main requirements of customers to the arc welding equipment include reduction of weight, improvement of reliability of devices and their quality, consistency of welding parameters and a wide application field of the equipment. The need for automated welding equipment has grown. For instance, in Japan every fourth of ten power supplies used in industry is equipped with numerical control [27, 28].

Equipment for gas welding and cutting. The volume of application of gas-oxygen welding continues to be reduced and replaced by other, more advanced technologies. Equipment for the gas-oxygen welding processes is characterised by a low cost. The cutting equipment is portable and automated. However, slow manual work and shortage of skilled manpower for operation with this equipment limit its application. Machines for automated cutting are the most promising type of equipment in this segment of the market. Utilisation of this type of the machines continually grows despite a serious competition on the side of equipment for laser, plasma and water jet cutting. With a predicted annual mean growth of the market by 2.3 %, the market of gas-oxygen cutting looks better: according to the forecast, its growth will be 3.2 %. In 2009, the share of equipment for gas welding and cutting was about 8 % of the world welding market, this making up approximately 1 billion USD [29].

Resistance welding equipment. The market of resistance welding equipment is about 20 % of the entire market of welding equipment, and annual sales amount to about 2 billion USD. The key customers of the resistance welding equipment are such industries as motor car construction, ship building and construction industry. However, at present the customers of this type of the equipment, especially automakers, prefer to buy the automated laser equipment, this leading to certain difficulties for resistance welding equipment manufacturers in terms of retaining their share in the market. The highest growth of sales of the resistance welding equipment is predicted for Asia (China, Japan, Malaysia, Thailand, Indonesia, Republic of Korea, Singapore), this being favoured by growth of foreign investments into this region, especially into motor car construction and electronics, where demand for the resistance spot welding equipment has grown [29].

Laser welding equipment. The market of the laser welding and cutting equipment is characterised by stable development in all regions of the world. Despite a high cost, this joining technology provides the high quality of welding, as a result of which it has found a wide application in motor car construction, metalworking industry and aerospace engineering. According to the data of «Optech Consulting» [30], the volume of sales of macroprocessor-based industrial laser systems, which include equipment for cutting, welding, marking and other processes, was 3.8 billion Euro in 2009, this being 40 % lower than in 2008. The share of laser systems used for welding and cutting in 2008 was 51 %.

The world market of industrial laser systems for welding and cutting is more than half of the world market of industrial laser systems. According to the estimation made by «Frost & Sullivan», the European market of laser welding equipment will amount to 802 million USD by 2011. This growth is favoured by improvement of the laser technologies and, in particular, equipping the laser systems with disk and fibre lasers, the volume of sales of which continually increases [29].

Flexibility of production systems, high reliability of equipment and easy integration into production lines are the factors that suggest further growth of scopes of application of this type of the welding equipment. At the same time, high initial costs, lack of knowledge of advantages of this process among the end users and their insufficient skill hamper the growth of sales of this equipment.

Ultrasonic welding equipment. As estimated by the «Frost & Sullivan» experts, the market of ultrasonic welding equipment has a substantial potential. This welding process is applied to join both plastics and metals. Predicted is a 6 % growth of sales of the equipment for welding of plastics, and approximately 9 % growth of sales of the equipment for welding of metals. The volume of the world market of ultrasonic welding equipment was 630 million USD in 2006. A factor that promotes growth of application of this process is reduction of utilisation of adhesion for thermoplastic compounds [29].

Market of welding robots. Along with renovation of technologies, modern welding production is characterised by a high level of mechanisation, automation and robotics by using information technologies, computer control systems, diagnostics and monitoring.

Increase in the world population of industrial robots during the last decade is impressive. In 1990 the number of the robots used in the world was 460,000 pieces, in 2003 this number was 886,000 pieces, and in 2010 this number increased to 1.2 million pieces. Japan and the Republic of Korea use almost 50 % of the total world population of industrial robots. Table 20 gives data on the volume of annual sales and population of industrial robots in the world during a period of 2008–2010, as well as the forecast for 2013.

In 2009 the volume of sales of industrial robots in value terms reduced by 39 %, compared to 2008, and made up 3.8 billion USD. Figure 13 shows data on the quantity of industrial robots annually installed all over the world.

Being the major world manufacturer of industrial robots, Japan has constantly reduced investments into production, starting from 2006. In 2009 the volume of production of robots in this country decreased by 50 %, compared to 2008. In the Republic of Korea the volume of application of industrial robots decreased from 11,600 (2008) to 7,800 pieces (2009). The sales in Europe fell by 41 % (to 20,500 pieces). Motor car construction (–52 %) and machine building (–64 %) decreased their purchases to the greatest degree. The sales of robots in China, India, Thailand and Taiwan decreased, and only in Mexico in 2009 there was some growth of the sales (up to 1,100 pieces), mostly in motor car construction.

According to the estimate made by the International Federation of Robots (IFR) experts, starting from 2010 the world market of industrial robots will annually grow by 5.5 %. In the next few years the largest customer in this sphere will be China, its share in the world consumption will increase to 29 %.

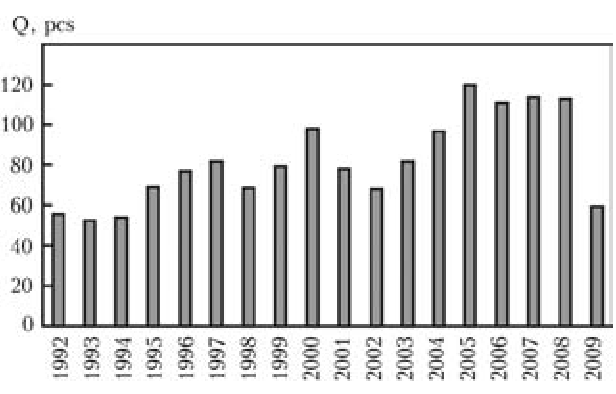

Figure 13. Quantity Q of industrial robots installed in the world in 1992–2009 (according to the IFR data)

Table 20. World market of industrial robots in 2008–2010, pcs

Index	2008	2009	2010	2013 (forecast)
Sales	113345	60018	76000	102300
Sales, excluding Japan and Republic of Korea	68635	39412	49200	69300
Total quantity (population) of industrial robots in operation	1035674	1020731	1173300	1119800
Total quantity (population) of industrial robots in operation, excluding Japan and Republic of Korea	603189	609008	693800	746300

Industrial robots in the current welding production are a basic element in the process of high-efficiency manufacture of the increased-quality welded items and structures. The share of production of welding robots is about 30 % of all industrial robots. Including robots designed for cutting, soldering, brazing, coating and gluing, this share grows to 40 %. In Spain, Great Britain, USA and a number of other countries the share of welding robots constitutes about half of the entire population of industrial robots [31].

Therefore, it can be concluded on the basis of the above-said that the world market of the joining technology and equipment continually grows. At present its growth is attributed mostly to the Asian countries, especially China. Consumption of solid and flux-cored wires dominates in the market of welding consumables, although the share of covered electrodes is also high, particularly in the growing markets of Asia, South America and CIS.

Demand for the arc and resistance welding machines predominates in the world market of welding equipment. The market of equipment for high technologies, i.e. laser welding and cutting, hybrid welding, as well as other joining technologies, such as gluing, soldering, brazing and mechanical joining, grows at a high rate.

The modern welding market is characterised by the following trends: increase in demand for automation of the joining technologies, this corresponding to addressing the problems associated with a rise in productivity, improvement of quality and speed of the welding processes and reduction of production, labour and training costs; growth of the volume of application of special steels and alloys, aluminium alloys and plastics in the key industries, e.g. motor car construction and aerospace engineering, which requires corresponding joining technologies, equipment and materials; and increase in the output of higher valued-added products due to the use of various monitoring sensors, digital control circuits and computerisation of the technological processes.

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WELDING FUME — FACTORS OF INFLUENCE, PHYSICAL PROPERTIES AND METHODS OF ANALYSIS (Review)

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Properties of welding fume, such as dispersion degree, morphology of particle and methods used to analyze physical properties and element composition of colid component of the welding fumes, are considered. Factors affecting emission of the welding fume are presented.

Keywords: *arc welding; welding fume, morphology of particles, electrode coating, methods of analysis*

Interaction of molten metal with slag takes place in a process of arc welding. At that, a welding fume (WF) consisting of solid (PCWF) and gaseous (GCWF) components is formed. Welders and workers of related professions can get the professional diseases as a result of influence of welding fume on organism. The investigations of processes of PCWF and GCWF formation and their affect on health of the welders have been carried out at the E.O. Paton Electric Welding Institute of the NAS of Ukraine and Institute of Occupational Medicine of NAMS of Ukraine during many years. Low-toxic welding consumables, got wide distribution in industry and building, were developed based on these investigations. Works [1–16] show published results of the investigations.

Physical methods became widely applicable for PCWF investigations. Standard ISO-15011 was developed for methods of investigation of welding fumes. Many of these methods are not available for domestic scientists and welder-engineers.

At the same time the welding electrodes being imported from South-Eastern Asia appeared in the market of CIS countries. Their application results in poisoning of welders by manganese. Prevention of professional diseases of welders remains one of the priority directions of investigation in the filed of welding and related technologies. The present paper provides a review of investigations dedicated to WF.

Factors affecting formation of PCWF. High-temperature vapor, which is formed during evaporation of metal drop on a tip of electrode and weld pool, is a source of WF. The drop has large specific surface and is heated up to higher temperatures. Fraction of vapor being formed during evaporation of weld pool metal makes 10–15 % of PCWF [8, 17].

Processes of fume formation, i.e. evaporation with further condensation (with/without oxidation), chemically intensified evaporation and spattering, are also studied in study [17]. The intensity of evaporation depends on metal, slag and weld pool temperature as well as properties of materials being evaporated. Work [1] gives the results of investigations of heat content and metal temperature in the arc welding.

The following factors having influence on PCWF emission, i.e. electrode coating and flux core composition; mode of welding (current and voltage); kind of current and polarity; composition of the base and electrode metal; thickness of electrode coating, and diameter of the electrode were studied in [6, 8, 18].

It was determined that the temperature near the surface of drops formed using industrial grade electrodes lies in the ranges from 2150 to 2500 K and depends on current intensity and composition of the coating. The acid-coated electrodes have the highest temperature, and lower temperature is observed in basic- and rutile-coated electrodes [1].

Figure 1 shows amount of PCWF emitting in welding by electrodes with different coating types. Increase of basicity of the slag phase promotes intensive evaporation of potassium, sodium, magnesium and calcium, and at that the beginning of this process is removed in the area of lower temperatures [6].

Rate of fume formation (RFF) is mainly determined by type of a binder and its content in the electrode coating. RFF maximum is observed at potassium binder application, and lithium shows minimum one. Sodium binder takes an intermediate place. Change of K–Na binder by lithium provides the possibility to

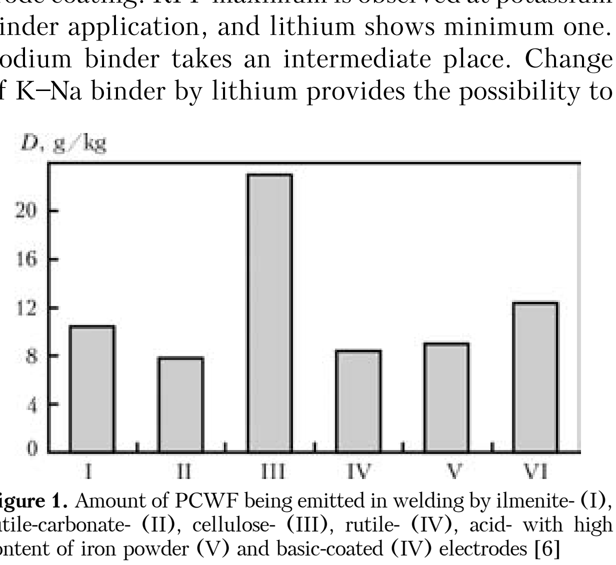

Figure 1. Amount of PCWF being emitted in welding by ilmenite- (I), rutile-carbonate- (II), cellulose- (III), rutile- (IV), acid- with high content of iron powder (V) and basic-coated (IV) electrodes [6]

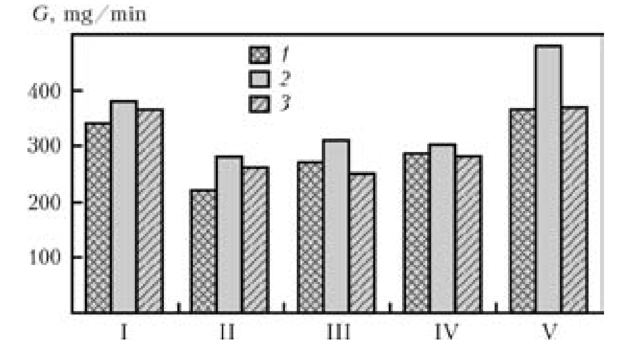

Figure 2. Dependence of intensity of PCWF emission on kind and polarity of current during welding by 4 mm diameter ilmenite- (I), rutile-carbonate- (II), cellulose- (III), rutile- (IV), acid- with high content of iron powder (V) and basic-coated (IV) electrodes [6]: *1* — AC; *2* — DCRP; *3* — DCSP

reduce RFF by 50 % without declining technological characteristics of the electrodes. Application of lithium binder in the electrodes for stainless steel welding results in reduction of gross emissions of WF as well as significant cut of content of hexavalent chromium in PCWF [19].

The increase of welding current intensity results in a rise of drop temperature and intensification of the process of evaporation. Growth of coating thickness promotes some reduction in temperature of the drops of electrode metal and improvement of slag protection of the drop. Increase of electrode diameter leads to rising of PCWF emissions [8].

Figure 2 shows an influence of kind and polarity of current. The highest intensity of fume formation is observed in welding at reversed polarity current, that is conditioned by higher temperature of the drops.

Speed of coated-electrode welding has virtually no influence on the fume formation.

Structure of PCWF particles and dispersion degree. Dimensions of separate particles of PCWF vary from several nanometers to tens of micrometers [11–13, 15, 17, 20], i.e. primary particles (< 100 nm), particles of accumulation range (100 nm–1 μm) and large particles (> 1 μm). Work [14] indicates that the majority of primary particles have dimensions from 5 to 40 nm. The coarser particles accumulate in clusters and small ones tend to form the chains.

PCWF consists of particles and agglomerates of spherical and aspheric shape. Most of the particles have inhomogeneous structure (consist of nucleus and shell) [6, 8, 13, 21]. Partially sintered agglomerates, agglomerates with «open» structure (being formed due to Van der Waals forces, adsorption forces of atmospheric moisture and electromagnetic forces) and linearly agglomerated nanosized particles [10, 14, 21] are observed.

The nucleus of particle with inhomogeneous structure is enriched by iron and manganese, and the shell contains combinations of silicon, potassium and sodium. Such an inhomogeneity of structure of PCWF particles related with sevectivity of the process of evaporation and condensation. High-temperature vapor has complex composition, and separate components condensing at various temperature. The elements with higher vapor pressure (sodium, potassium, etc.) condense after the elements with lower vapor pressure (manganese, iron).

Figure 3 shows WF particles obtained with the help of transmission (TEM) and scanning (SEM) electron microscope.

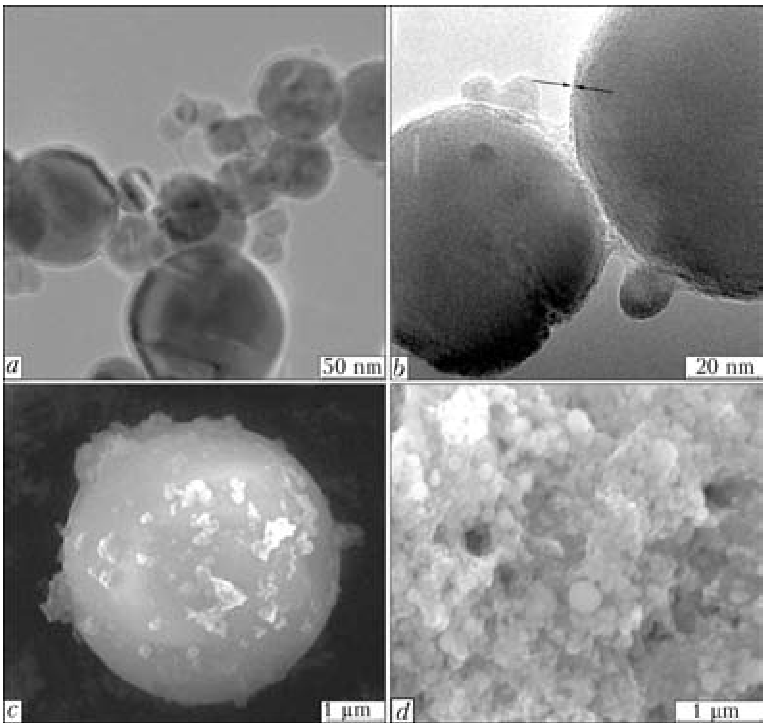

Figure 3. TEM- (*a*, *b*) [17, 22] and SEM-images (*c*, *d*) of PCWF: *a*, *b* — particles of inhomogeneous structure (nucleus is more dark, and shell is light); *c* — safe for the respiratory organs large spherical particle on surface of which the nanosized particles are situated; *d* — conglomerate of nanosized particles

Methods for determination of particle sizes

Method	Size range, μm	Equipment
Electron microscopy	0.002–50	SEM, TEM, electron probe (EPMA)
Optical microscopy	1–400	Optical microscope
Laser granulometry	0.01–3000	Analyzers (different types)
Aerodynamic separation	0.05–20	Impactors (different types)

Various size particles have different affect on organism of welder. Particles of less than 20 μm diameter can remain suspended in the air [11], and particles of more than several micrometers are deposited on the walls of airways of human organism and released outside with the mucus. Around 30 % of particles of 0.1–1.0 μm size are deposited in the lungs. Particles of less than 0.1 μm (100 nm) are also inhaled and deposited in the lungs. 100 % of less that 1 μm particles use airways [17] to enter the organism. The inpour of nanosized particles through the skin [23] is also possible. Thus, they can enter in the brain through nerves in the nasal sinuses [24, 25].

Figure 4 shows frequency characteristics of distribution of particle sizes in welding with cellulose- (E6010) and basic-coated (E7018) electrodes [12]. Study [25] indicates that the size as well as shape of nanoparticles determine their toxicity. The nanoparticles of dendrite and spindle forms have higher cytotoxicity then the particles of spherical form.

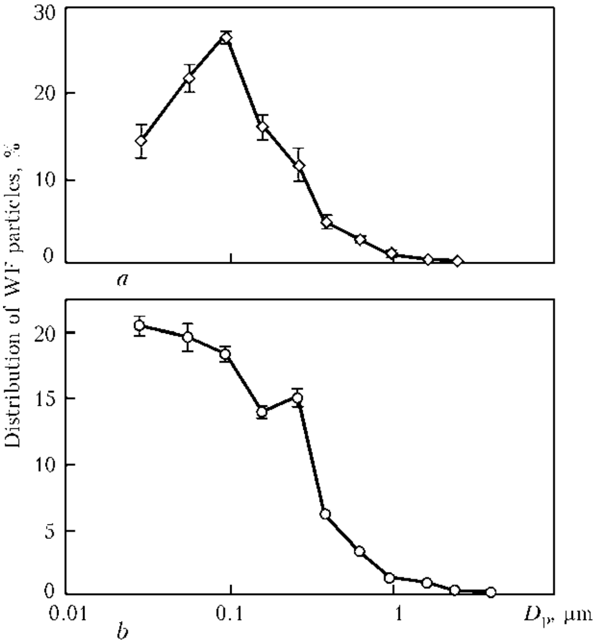

Figure 4. Quantitative distribution of WF particles by dimensions for cellulose- (*a*) and basic-coated (*b*) electrodes

Methods of PCWF analysis. International standard ISO 15011–1 [26] determines specific requirements to structure of fume chamber, types of filters, pump, timer and scale. Data on methods of study of particle dimensions are given in the Table. Given data indicate variety of methods and equipment being used for analysis of particle size, mass and dimension distribution of PCWF.

The size of each particle and their distribution are difficult to measure due to large range of particle sizes. Specific preparation of the samples (deposition on a substrate) and complexity of obtaining of mass and quantity distribution of WF particles are the disadvantages of PCWF analysis by electron microscopy method.

Failure of the clusters at their passing through separate levels of impactor is a significant disadvantage in using the method of aerodynamic separation.

The disadvantage of PCWF analysis by method of laser grain size analysis consists in dispersion by ultrasonic oscillations in dispersing medium (liquid) taking place before or during the analysis.

Besides, measurement equipment for WF with standard settings to spherical particles [11] is difficult to calibrate since WF particles are mainly the agglomerates of complex and inhomogeneous form and surface.

Chemical composition of the particles along with their dispersion degree is a key factor determining a harmful affect of WF components on health of welder. ISO 15011–1 [26] recommends the following analytical methods for determination of element composition of PCWF: inductively coupled plasma — Auger electron spectrometry (ICP — AES); inductively coupled plasma — mass spectrometry (ICP — MS); atomic-absorption spectrometry (AAS); atomic-fluorescent spectrometry (AFS); X-ray fluorescent spectrometry (XRF) for determining aluminum, barium, beryllium, cadmium, cobalt, chromium, copper, iron, manganese, molybdenum, nickel, lead, vanadium, zinc etc.

Ion chromatography and spectrometry are used for determination of hexavalent chromium. It is important that the filter used is to be appropriate for collection of hexavalent chromium. Number of filtering materials (for example, combined cellulose-etheric membrane filters) make a reaction with hexavalent chromium and as a result the valency of the latter is reduced up to three and obtained results have low validity. The filters from quartz fiber, glass fiber and polyvinylchloride obtained successful and wide application.

Ion chromatography and ion-selective electrode (ISE) are used for determination of fluorine.

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ELECTRON BEAM WELDING OF THIN-SHEET THREE-DIMENSIONAL STRUCTURES OF ALUMINIUM ALLOYS

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Variants of improvement of the technology for manufacture of three-dimensional welded structures from thin-sheet elements are considered. Examples of small-size mock-ups of specific products are presented. Recommendations for reducing residual deformations in thin-sheet welded structures are given. Variants of the welded T-joints used in manufacture of stringer panels are shown. Resistance of welded joints to intercrystalline corrosion is estimated.

Keywords: *electron beam welding, aluminium alloys, thin-sheet three-dimensional structures, dissimilar welded joints, mechanical properties, intercrystalline corrosion, crack resistance*

Wide application of aluminium alloys in different fields of industry is determined by a number of their advantages as compared to other structural materials.

Aluminium alloys are characterized by a large range of ultimate tensile strength (100–750 MPa) and high specific strength (due to small density of 2.7 g/cm^3). Besides, they have high heat and electric conductivity and corrosion resistance in different aggressive environments. Aluminium alloys are characterized by good manufacturability, easily subjected to pressure treatment, allow producing intricate shaped sections of them. Parts of aluminium alloys are widely used in different types of structures in ship, automobile and aircraft building and in transport. Here, the riveted and bolted joints are characteristic for the products of aircraft engineering, manufactured of aluminium alloys.

The riveted joint is the main type of joints in the design of a planer, aircraft and helicopter. It operates well at static, fatigue and repeated loadings and allows manufacturing products without distortions and keeping a rigid configuration.

The significant disadvantage of a riveted joint is weighting of a structure, high labor consumption in performing the operations and, as a result, high economic costs.

The application of a bolted joint in aluminium structures is caused by need in periodical dismantle

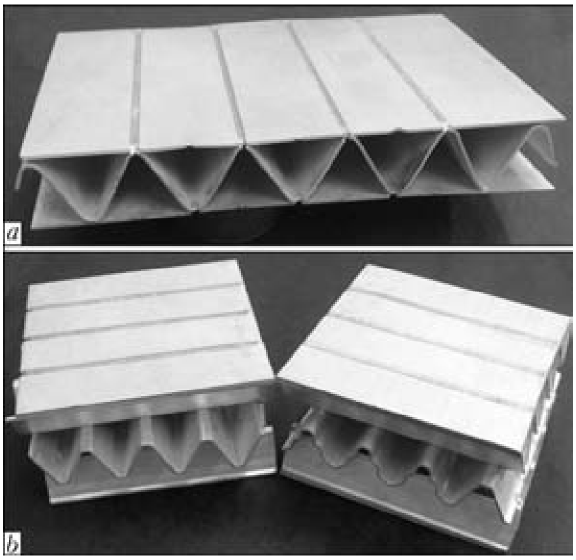

Figure 1. Appearance of mock up of thin sheet (*a*) and 3D panel of increased rigidity (*b*) manufactured of aluminium alloys by EBW

of single elements and assemblies in the process of their service. However, manufacture of bolted joint is rather labor intensive and placing one bolt is about 10 times higher by its labor intensity than installing of one rivet.

The progressive method of joining structures of aluminium alloys is welding which facilitates the process of producing metal structures and allows wide application of automation and mechanization [1].

Welding is one of the leading technological processes of manufacturing structures in different fields of national economy. Welding gains a special great importance in manufacturing different air-tight welded assemblies of long-time service. There have been already many cases of replacement of riveted and bolted joints in aircraft manufacturing by resistance spot and seam welding or such methods of fusion welding as argon arc, microplasma, plasma welding and welding using consumable electrode.

In the last decades the method of electron beam welding is developed and improved in many countries, as well as applied to manufacture of structures of aluminium alloys [2–4].

The EB-welded structures are successfully operated under the conditions of complex loadings, increased temperatures, deep vacuum, aggressive media. Applying the same equipment the electron beam can weld parts of aluminium alloys of different thicknesses: from fractions of millimeters to several tens of centimeters.

The metallurgy production of new ultra-light high-strength aluminium-lithium alloys, the application of which in welded structures reduces weight of products by 10–15 %, is developed intensively. The application of EBW facilitates expanding of application of such alloys in the structures. As it was established previously [1, 2] in EBW of heat-hardened or cold-worked aluminium alloys the ultimate tensile strength of joints is by 15–20 % higher than that using other methods of welding, and the residual welding deformations are by one order lower.

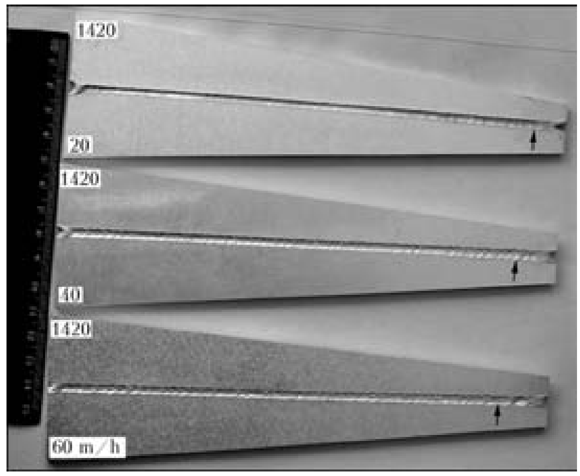

Figure 2. Appearance of welded specimens of alloy 1420 after their test on crack resistance in the range of speeds 20–60 m/h

In our work the first attempts to apply technology of EBW were made during manufacture of three-dimensional structures of thin-sheet elements of aluminium alloys of different alloying systems. The structures of aluminium alloys are designed of rolled sheets, stamped bent and pressed profiles, shaped stampings and forgings. Application of such semi-products in the structures produced using arc welding methods is connected with a number of difficulties both at the stage of preparation for welding, and also in assembly and welding of joints. First of all this is overcoming the welding using the methods on prevention of their appearance or further removal. In this situation more problems occur in application of overlap joints or joints for upper sheet penetration in structure of thin sheet elements.

The examples of EBW application in manufacture of 3D panels of thin-sheet elements, where there are joints being hard-to be performed by arc methods, are given in Figure 1. To achieve high quality of joints and accuracy in keeping the geometric shapes in EBW of similar structures one must strictly fulfill a number of design-technological requirements. The assembly of fragments for welding is performed using assem-

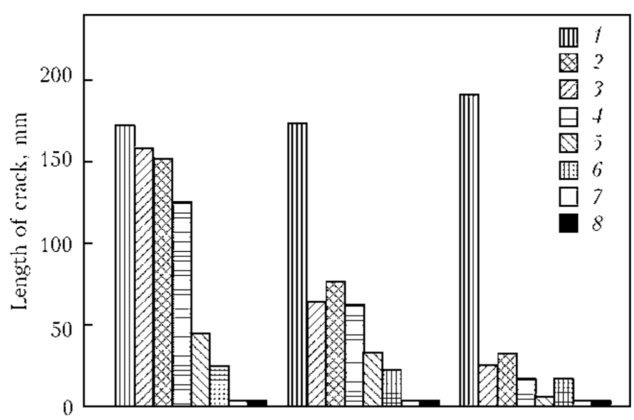

Figure 3. Influence of speed of EBW on tendency of aluminium alloys towards hot cracks: *1* — alloy D16; *2* — AD0; *3* — 1460; *4* — 1201; *5* — AMts; *6* — 1420; *7* — 1570; *8* — AMg6; *I* — v_w = 20; *II* — 40; *III* — 60 m/h

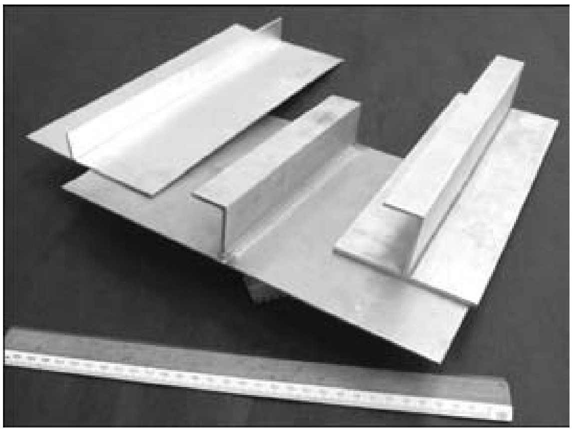

Figure 4. Fragments of thin-sheet stringer panels manufactured using EBW of single- and two-sided fillet welds

bly-welding device which should guarantee the absence of gaps between contacted surfaces of elements to be welded. Besides, in device the heat dissipating elements are provided, positioned on the both sides along the entire weld. Here, the weld formation with a small reinforcement is provided. Any distortions (of buckling or burn-out type) are also absent. Welding condition parameters should be previously preset within such limits that during its performance the lower part would be penetrated for not more than 0.5 of the thickness. In these structures both similar and dissimilar aluminium alloys can be applied.

However, at the stage of designing the products, using different types of aluminium in the structure, it is necessary to dispose information on their tendency towards formation of crystalline cracks. Considering that such welds are produced without application of filler materials and there are no conditions to perform modifying of weld metal due to alloying elements in the filler, the alloys should be previously selected in such a way that their crack resistance was the best. However, if cracking occurs during welding, then measures to prevent cracks should be preset in the technological process.

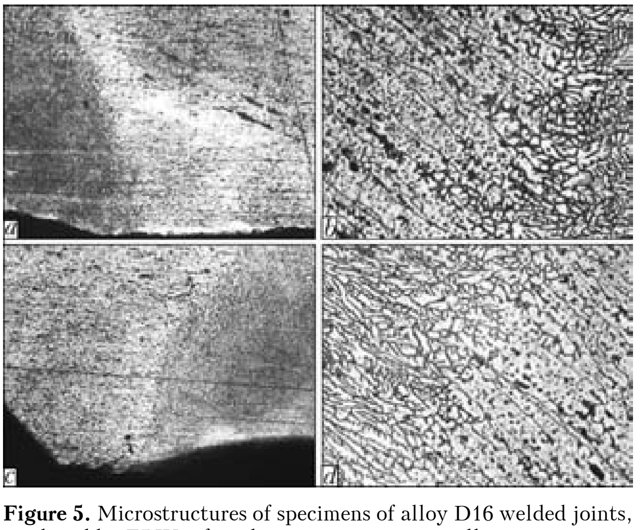

Figure 5. Microstructures of specimens of alloy D16 welded joints, produced by EBW, after the tests on microcrystalline corrosion: *a*, *b* — reference specimen; *c*, *d* — specimen 1 (*a*, *c* — ×100; *c*, *d* — ×500)

Figure 2 shows specimens of the alloy 1420 after their tests on crack resistance in the range of speeds 20–60 m/h. This alloy has short cracks only at the beginning zone of the specimen where it has a thinning shape. The generalized results of investigations of resistance of aluminium alloys to formation of crystalline cracks are given in Figure 3 [5]. It is seen from the Figure that similarly to the alloy AMg6, the cracks are absent in a new high-strength alloy 1570 alloyed by scandium. Besides, the lower the speed of welding and, consequently, the lower the rate of crystallization of weld metal, the higher is the tendency to crack formation.

The category of 3D thin-sheet structures can include welded stringer or stiffened panels (Figure 4). During their manufacture with account for specifics of aluminium alloys, and also the arrangement of welds, the EBW is the most rational method of joining [6, 7]. The process of preparation of elements, their assembly and welding are also characterized by high requirements to performance of all operations. The welding-on of stiffeners can be performed both by one-sided fillet welds, as well as layout of fillets on both sides of the stiffener. As a rule, the application of filler materials is not practiced as both in the first and the second case the fillet of 1.5–3.0 mm is formed on joints. The parameters of welding condition are usually selected so that the penetration of the lower panel did not exceed 50 % of its thickness. For this purpose the inclination angle of electron beam to the panel plane is usually 25–30° in the process of welding. To avoid considerable residual deformations of welded panels, as the authors of the work [6] showed, it is

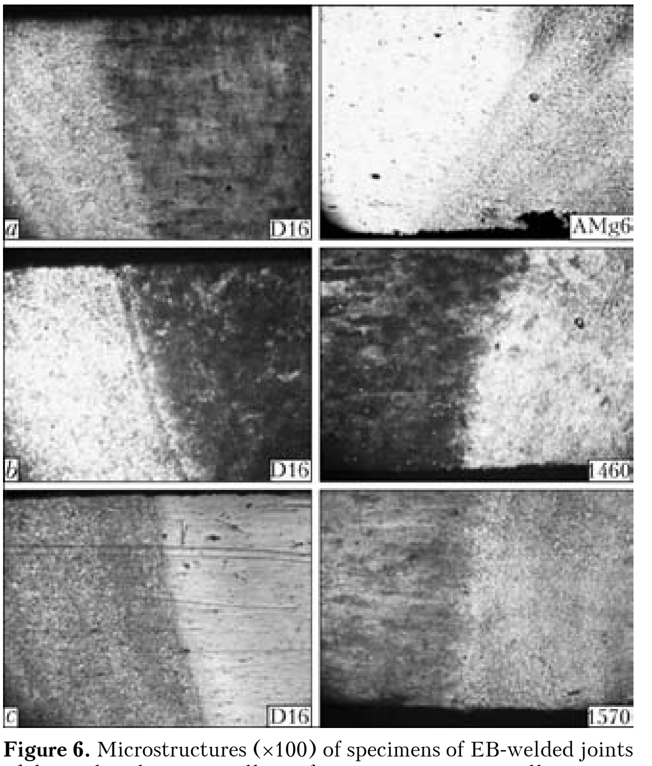

Figure 6. Microstructures (×100) of specimens of EB-welded joints of dissimilar aluminium alloys after tests on intercrystalline corrosion: *a* — alloy D16 + AMg6; *b* — D16 + 1460; *c* — D16 + 1570

rational to use method of preliminary elastic tension of fragments being welded (panels and stiffeners) before welding. The tension forces should not exceed the conditional yield strength of alloy to be welded.

However, from the position of providing reliable performance of welded structures the welding-on of stiffeners, as is shown in Figure 4, is not rational, as the welds are in the zone of concentration of stresses at loading of products. Relocation of welds to the zone, remote from sharp transitions, increases greatly their reliability and performance during loadings.

As the many-year practice showed, one of the factors of latent nature of reduction of terms of reliable and long-time service of welded aluminium structures is their tendency to intercrystalline corrosion, from the sources of which the catastrophic fracture of products begins. In our developments welded joints of alloy D16 and joints of dissimilar aluminium alloys produced using EBW were tested.

To conduct investigations, four specimens of 10 mm width, 20 mm length and 2.5 mm thickness were cut out from welded joints perpendicularly to welds. The investigations were conducted using chemical method according to GOST 9.021–74 «Aluminium and aluminium alloys. Methods of accelerated tests for intercrystalline corrosion».

The temperature of working solution was 30±5 °C, the composition of solution was as follows: solution of sodium chloride plus 0.3 % of peroxide (58 g/l NsCl + + 10 ml/l of 33 % solution H_2O_2), the duration of tests was 6 h with subsequent metallographic analysis of sections at the depth of etching between grains according to GOST 6032–89 «Corrosion-resistant steels and alloys. Methods of tests on resistance against intercrystalline corrosion» using metallographic microscope «Neophot-21» (according to GOST 6032–82 the value of depth of fracture of grain boundaries should be not more than 30 μm).

The preliminary visual inspection of specimens showed that their condition was satisfactory. The results of investigations and photos of microstructure of sections of the D16 alloy welded specimens on the tendency to intercrystalline corrosion are given in Figure 5.

The analysis of obtained results proves that specimens of welded joints of aluminium alloy D16 produced using EBW are not tended to intercrystalline corrosion.

The investigations on tendency to intercrystalline corrosion of joints of dissimilar aluminium alloys D16 + AMg6, D16 + 1460 and D16 + 1570, made using EBW, were performed according to the methods given above and in the solution of the same composition. Having compared the depth of damage of intergranular etching of specimens being tested (three pieces each) with the reference specimen, the estimation of resistance of joints to intercrystalline corrosion was carried out.

The results of investigations and measurements are given in Figure 6 and in the Table.

Mechanical properties of welded joints of dissimilar aluminium alloys (place of fracture of specimens — along the weld)

Number of specimen	Grades of alloys welded	σ_t, MPa
1	D16 + AMg6	$\frac{294-312}{308.5}$
2	D16 + 1570	$\frac{302-316}{314.3}$
3	D16 + 1460	$\frac{296-311}{309.2}$

As is seen from the analysis of obtained results of investigations, all joints of dissimilar aluminium alloys D16 + AMg6, D16 + 1460, D16 + 1570 produced using EBW in vacuum are not tended to intercrystalline corrosion.

The carried out mechanical tests (see the Table) showed that ultimate tensile strength of joints of dissimilar aluminium alloys is at the level of properties of joints of homogeneous aluminium alloys of the lower strength. Thus, in case of using aluminium alloys of different grades in the structure of welded product, the decrease of strength characteristics will not almost occur.

CONCLUSIONS

1. The design-technological solutions have been developed during creation of welded 3D structures and stringer panels of increased rigidity using thin-sheet elements or shaped rolled metal.

2. It was established that welded joints of alloy D16 and dissimilar butt joints of alloys D16 + Mg6, Mg6, D16 + 1460 and D16 + 1570 made using EBW are not subjected to intercrystalline corrosion under the conditions of their tests according to GOST 9.021–74.

3. Results of performed experimental-search works and investigations can be used in selection of materials and variants of joints for further tests on determination of characteristics of fatigue, fracture toughness, stress corrosion, vitality and residual strength of welded structure elements.

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LEVEL OF EFFECT OF PREPARATION AND ASSEMBLY FOR WELDING ON QUALITY OF WELDED JOINTS FOR INDUSTRIAL PIPELINES

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Investigations were carried out, and contribution of the effect of preparation and assembly for welding on the level of quality the welded joints in different dimension-type pipelines was estimated based on the experience of manufacture of welded industrial pipelines by using mathematical modelling and information technologies.

Keywords: *manual arc welding, preparation and assembly for welding, industrial pipelines, welded joints, defectiveness, reasons of reject, dominant factors, quality level*

The good perspectives for application of sufficiently complex models, reflecting multiple-factor and interaction of the effects taking place in the different technologies, is provided by the current level of computer technologies. Computer application for mathematical modelling makes its available for wide range of users connected with investigation as well as development and optimizing of engineer solutions [1–3].

Welding-assembly production (WP), in comparison to heavy machine-building enterprises oriented to gross production of uniform products, delivers with the help of welding the single and small branch products having different orientation to designation as well as internal content, i.e. methods of manufacture, structures being applied, welded materials and welding consumables. Therefore, it is virtually impossible to use classical mathematic statistics, applied for quality control in the gross (serial) production and assembly manufacture. A series of tasks is to be solved in this connection and first of all the task of production systematization for application of mathematical statistics apparatus. It was determined that a grouping on main elements of production is to be taken as a basis in formation of population of the welded joints. A steel grade, pipeline diameter or length of welded joint in a metal structure, thickness of welded material, welding procedure and method of testing were taken as grouping criteria (GC). An algorithm taking into account WP peculiarities was developed on this basis. For example, welded joints of 350–500 mm diameter and 6–8 mm wall thickness made using a method of manual arc welding (MAW) compose an uniform base population (BP) of the joints and objects, in which welding of these joints is carried out, are a space of random events with determined limits [3].

Mathematic description of BP formation is given by following model:

$$\mathrm{CAC} \in \sum \mathrm{OC} \in \sum \mathrm{WP} \in \sum \mathrm{GE} \in \sum \mathrm{GC}, \qquad (1)$$

where $\mathrm{WP} = \sum_{i=1}^{k} \mathrm{PE}_i$; $\mathrm{PE} = \sum_{j=1}^{m} \mathrm{GC}_j$;

or in matrix form

$$N_{\mathrm{BP}_i} = \begin{vmatrix} \mathrm{PE}_1 + \mathrm{PE}_2 + \ldots + \mathrm{PE}_i \\ \mathrm{GC}_{11} + \mathrm{GC}_{21} + \ldots + \mathrm{GC}_{i1} \\ \mathrm{GC}_{12} + \mathrm{GC}_{22} + \ldots + \mathrm{GC}_{12} \\ \ldots + \ldots + \ldots + \ldots \\ \mathrm{GC}_{1j} + \mathrm{GC}_{2j} + \ldots + \mathrm{GC}_{ij} \end{vmatrix},$$

where CAC is the construction-assembly complex; OC is the object of construction; PE is the production element; GE are the groups of elements; N is the number of elements included in BP; k, m is the amount of elements of production and GC, respectively.

The welded joint or area of joint of 300 mm length is taken as a BP unit. Production elements and their groups for each joint population should not vary significantly and form i-th construction-assembly series of the joints manufactured during specific working cycle under determined factor conditions of specific assembly organization. Concept introduced by us differs from known determination for lot of production according to GOST 15895–70 by the fact that the products can be manufactured at different objects and in different time. Mandatory requirement in manufacture of the base lot is a presence of unique technical documents.

The next task consists in a development of unified criteria for defectiveness measurement. Criteria of weld quality on reject fraction, fraction of total defectiveness in percents and relative area of defects g per test area are given in separate studies. Application of such criteria under assembly conditions is complicated on several reasons. Firstly, a relation of the criteria with existing normative documentation for quality evaluation is absent. Secondly, the calculations of relative area of girth welds are complicated. Besides, area of the defects g masks the possibility to detect such a dangerous defect as through worm-hole breaking system in whole. In comparison with the shallow long lack of penetration, g of the through worm-hole is less than in lack of penetration. Calculation formulae set general and unacceptable defectiveness in accordance with the requirements of ISO 3834 and SNiP. A complex criterion was set for evaluation of defectiveness structure and its relations on the whole by base population of the joints allowing evaluating defects on their length L (L_g — general defects being found, L_r — rejected, requiring removal) as well as on amount D (D_g — amount of general defects being found, D_r — rejected). Quality status of welding production, its processes and conditions can be characterized based on information about L and D (or simultaneously) over the specified test cycle (month, quarter, year etc.). Such a criterion is representative for each particular technology, performer and construction organization in whole. Numerical expression of this criterion and its structure are termed by us as a statistical formula of defectiveness (FD) [3–5]. General expression of BP FD is

$$\sum\sum\begin{vmatrix} L_g, & D_g \\ L_r, & D_r \end{vmatrix} = P(x_g, x_r) + S(y_g, y_r) + LP(z_g, z_r) + \ldots , \quad (2)$$

where P, S, LP are the pores, slag inclusions and lack of penetrations, respectively; x_g, y_g, z_g and x_r, y_r, z_r are the general and rejected amount and length of defects, respectively.

Partial expressions for L_g and L_r look like

$$L_g = \sum_{i=1}^{n} L_g^i/n = \sum_{i=1}^{n} P_g^i/n + \sum_{i=1}^{n} S_g^i/n + \sum_{i=1}^{n} LP_g^i/n + \ldots ; \quad (3)$$

$$L_r = \sum_{i=1}^{n} L_r^i/n = \sum_{i=1}^{n} P_r^i/n + \sum_{i=1}^{n} S_r^i/n + \sum_{i=1}^{n} LP_r^i/n + \ldots \quad (4)$$

Formula (3) provides information on general defectiveness and (4) on unacceptable one according to SNiP.

The partial expressions of defectiveness formula are similar to expressions (3) and (4) for criteria D_g and D_r. Thus, a structure of defectiveness due to specific causes according to BP FD is determined in the following way:

$$D_g = \sum_{i=1}^{n} D_g^i/n = \sum_{i=1}^{n} P_g^i/n + \sum_{i=1}^{n} S_g^i/n + \sum_{i=1}^{n} LP_g^i/n + \ldots , \quad (5)$$

where n is the amount of tested areas.

It is well-known that the level of weld quality is affected by variety of different factors. Among them are preparation and assembly, qualification of performers, welding consumables, welding and auxiliary equipment, welding procedure, work organization, qualification of engineers, failure of working rhythm, flaw detection testing, heat treatment, welding conditions, season etc. Additional investigations were carried out for these factors. They allowed determining that preparation and assembly for welding, qualification of performers, welding consumables, welding procedure and welding equipment [4–5] are the factors dominating in formation of defectiveness (90 to 97 %).

However, the level of effect of each factor on quality level is different due to variety of joint dimension-types, different welding consumables, materials to be welded, methods and conditions of welding. Therefore, the main reasons of defects' formation during welding can be determined only under specific industrial conditions for specific BP of the joints.

Welding engineering can be optimized due to strengthening and modernizing of its weak sections through determining the level of effect of that or other industrial factor on quality of the joints of specific dimension-types. The level of quality of each factor, in turn, is determined by its main parameters which can have positive as well as negative effect. The negative parameters of the factor are, as a rule, the reason for defectiveness (reject) formation in welding (Figure 1). The level of defectiveness causes of which are specific factors and their parameters serves an optimality criterion. Thus, the important principle for monitoring of welding quality on a feedback of factor–cause–defect algorithm is realized.

The investigations were carried out in welding of the joints of different dimension-type industrial pipelines by methods of MAW, CO_2 mechanized welding, argon-arc welding (MAAW) and welding in CO_2 + + Ar mixture. Data obtained by non-destructive testing (NDT) methods, i.e. visual (VT), X-ray (XRT) and ultrasonic (UST), were used for defectiveness determination.

Figure 1 shows an algorithm of investigations. Welded joint with specific negative factor parameters were manufactured experimentally and during pre-object trainings of welders from different WP. The aim of investigations is to determine the types of defects and their amount formed during the moment of action of specific causes and the defectiveness structure depending on cause and DC in a series of causes acting on the objects of welding operations.

Classification of WP in BP and development of quantitative units of defectiveness measurement allowed creating a computer system for registration, monitoring and analysis of quality of welding operations and welded joints. A database and information about quality state of works being performed and defectiveness of welded joints was developed based on NDT data. Figure 2 shows an example of system window for processing of operative information about quality state of welding operations.

Qualification of performer	Preparation and assembly	Welding consumables	Welding equipment	Process of welding	Factors
Category	Preparation of edges	Technological properties	Measurement devices	Welding method	Reasons
Training	Gap	Storage conditions	Condition of contacts	Joint type	
Experience	Cleaning	State of coating	Current stability	Modes	
Age	Tack welding	Appearance	Voltage stability	Testing	
1.4 WSh, 0.5 Uc, 0.5 LP, 0.4 P, 0.3 Od	1.4 LP, 1.0 S, 0.8 P, 0.3 WSh, 0.2 Od	0.9 P, 0.7 S, 0.6 APS	Defectiveness allowable on TU and SNiP	0.3 C, 0.6 S, 0.6 P, 0.3 LP	Defects
Defectiveness structure ⇒ DC ΣD_{sr} = 1.4 L + 1.0 S + 0.8 P + 0.3 WSh + 0.2 Od ⇒ Preparation and assembly					

Figure 1. Algorithm for determination of dominant causes (DC) of defectiveness formation in welded joints on their structure: WSh — defects of weld shape; Uc — undercuts; APS — accumulation and chains of pores and slag; C — cracks; Od — other defects

Type of defectiveness representing specified DC and, as a result, specific industrial factor of welding technological process are to be determined for practical conditions. Probability of DC representation was determined based on statistical data of NDT carried out per cycle not less than one year using computer technologies and mathematical modelling:

$$P(\mathrm{DC}) = p_1/p_2 \text{ at } 0 < P(\mathrm{DC}) < 1, \quad (6)$$

where p_1 is the amount of practical confirmations of specific DC; p_2 is the amount of all DC;

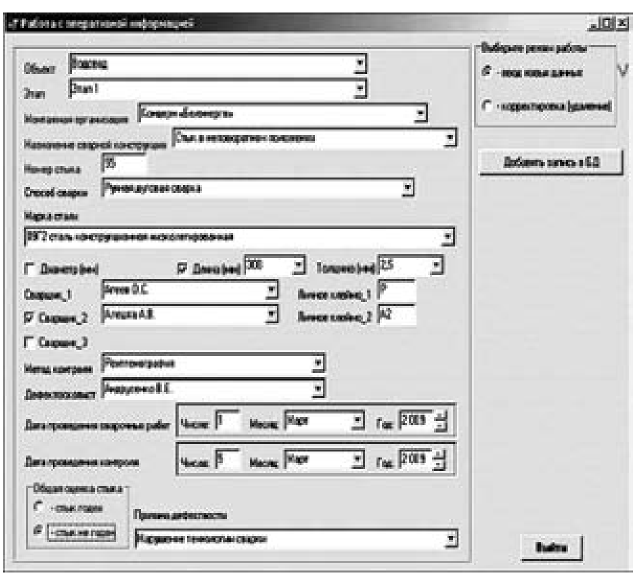

Figure 2. Main system window for processing of operative information on quality state of welding operations

$$P(\mathrm{DC}) = (A/\sum(\mathrm{FC}))\cdot 100\ \%, \quad (7)$$

where Σ (FC) is the amount of all probable repeats of cause; A is the amount of practical confirmations of given cause.

For example, 2053 cases on «Preparation and assembly for welding» factor (PAW) were detected during 2009 when DC of formation of unallowable defectiveness was found by its negative parameters. 1754 cases among them were confirmed by expert judgment. Probability of DC representation by cause

$$P(\mathrm{DC})_{\mathrm{PAW}} = 1754/2053 = 0.85.$$

The causes of defectiveness in factor–cause–defect chain were analyzed using arrays of BP quality history for the period of not less than two years [6–8]. The main causes and defectiveness found in the test area at a moment of indicated cause effect were determined from the reports of the operator-inspectors or by expert judgment. The causes and defectiveness were processed and classified using computer equipment (Figures 3 and 4).

Preparation and assembly for welding is one of the dominant factors determining output level of the quality of welded joints. However, investigations of specific contribution and quantitative evaluation of its effect on quality of specific dimension-types of welded joints are virtually absent.

The reject, made by this factor, results in specific defects which are generated by main causes (negative

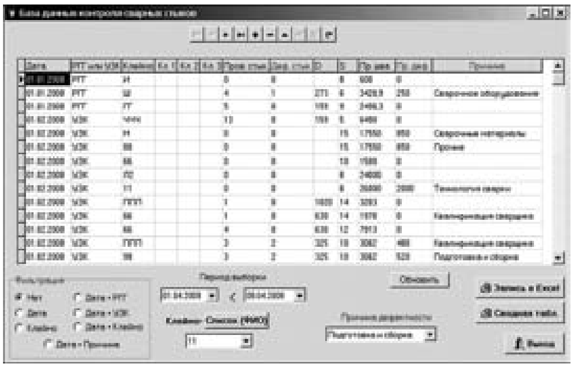

Figure 3. Example of system window for operation with database on quality of welded joints and causes of reject

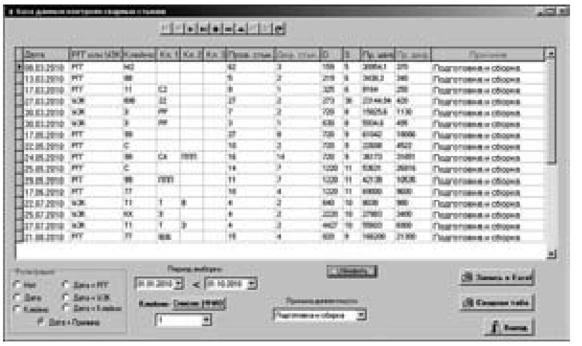

Figure 4. Example of obtaining of output information on PAW factor

parameters) of the reject on this factor, i.e. improper preparation of edges (root face angle, rounding radius), violation of gap dimensions (alignment) between the elements to be welded, low-quality cleaning (presence of rust, dents, chips and oils), tack welding etc. Investigation results are given in Table 1.

Establishment of dependencies of defectiveness formation and relation with causes of its formation is an important task solving which allows taking preventive measures on their warning before beginning of welding-assembly operations, improving technological processes and performing monitoring of welding quality on-line. Experimental investigations showed no functional relation between the causes of defectiveness formation and its amount, however, an important statistical relation was determined between the defectiveness structure and cause of its formation.

The following expressions are obtained using results of study of causes of defectiveness on PAW factor and formulae (3) and (6):

$$PAW_1 = P(0.8) + S(1.3) + LP(1.4) + WSh(0.25) + Od(0.2);$$

$$PAW_2 = P(0.6) + S(0.9) + LP(1.7) + WSh(0.4) + Od(0.3);$$

$$PAW_3 = P(1.1) + S(1.4) + LP(1.3) + WSh(0.3) + Od(0.25);$$

$$PAW_4 = P(0.8) + S(1.0) + LP(1.5) + WSh(0.5) + Od(0.2);$$

$$F_{PAW} = P(0.8) + S(1.0) + LP(1.4) + WsH(0.3) + Od(0.2),$$

where PAW_1 is the preparation of edges; PAW_2 is the gap (alignment); PAW_3 is the cleaning; PAW_4 is the tack welding; F_{PAW} is the structure of defectiveness on PAW factor.

Thus, it was determined by experiment that each negative parameter of studied factor is the cause of formation of unique peculiar only to it defectiveness structure [9–11] (Figure 5).

Defects of LP (1.4 per area of testing), S and P type and their inclusions as well as different WSh defects dominate in defectiveness structure due to causes of PAW factor.

Therefore, the causes of defectiveness formation on PAW factor in the welded joints of industrial pipelines allow making proved solutions on improvement of its parameters, reduction of specific contribution of reject and increase of quality level of the welded joints. Besides, total specific contribution of factor effect on quality level of the welded joints of specific dimension-types under different methods of welding, grades of welded materials and conditions of welding process can be determined.

Table 2 shows investigation results of effect of PAW factor on quality level (defectiveness) of the welded joints of industrial pipelines of different dimension-types. It can be seen that this level varies from 95.1 to 90.7 %. It was determined that the reject is significantly lower in mechanized and automatic methods of welding then in MAW. It follows form the Table that the specific contribution of effect of preparation and assembly on quality level of the welded joints increases with a rise of pipeline diameter independently on methods of welding. Thus, only 61 joint from 1250 joints were rejected in MAW of pipeline of 57 mm diameter, 11 joints (or 18 %) among them were rejected due to causes of factor being studied. At the same time, 167 joints in total from 1790, among which 57 (or 34.1 %) due to causes of studied factor, were rejected in welding of pipelines of 500 mm in diameter, i e. welding of big diameter joints is connected with complication of technology of welded joint manufacture.

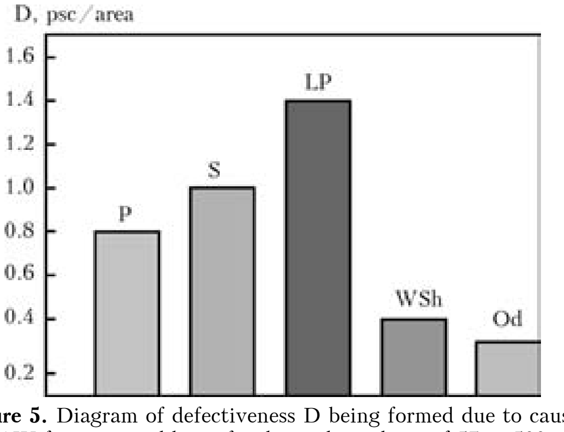

Figure 5. Diagram of defectiveness D being formed due to causes of PAW factor in welding of industrial pipelines of 57 to 500 mm diameter

Table 1. Defectiveness found due to causes of PAW factor, pcs

Method of welding	Amount of joints welded	Tested areas of 300 mm length	Pores and their clusters	Slag inclusions	Lacks of penetration	Defects of weld shape	Other defects
MAW	2450	7320	5850	8050	10980	2930	1830
MAW in CO_2	1600	4200	2940	4100	5900	1350	920
MAW in CO_2 + Ar	2100	5460	4370	4920	7650	1640	1100
MAAW	1820	5100	4590	4450	6650	1530	1020
Total	7970	22080	17750	21520	31180	7450	4870

Table 2. Effect of PAW factor on quality level of the welded joints of industrial pipelines

Method of welding	Steel grade	Thickness of steel, mm	Pipeline diameter, mm	Amount of butt-welded joints, pcs	Amount of rejected joints, pcs	Quality level, %	Total amount of joints rejected on PAW factor, pcs	Specific contribution of PAW factor, %
MAW	09G2	2.5	57	1250	61	95.1	11	18.0
MAW in CO_2 + Ar	20Kh	4.0	89	1270	73	94.3	18	24.6
MAAW	14KhGS	4.0	89	5740	360	93.7	84	23.3
MAW in CO_2 + Ar	20Kh	6.0	112	4300	290	93.3	73	25.3
MAW	14KhGS	6.0	112	2790	215	92.3	64	29.7
MAAW	14KhGS	10.0	289	2900	235	91.9	74	31.5
MAW	20Kh	10.0	289	1500	132	91.2	44	33.2
	14KhGS	14.0	500	1790	167	90.7	57	34.1
Total				21540	1533	92.7	425	27.7

Increase of diameter of pipelines complicates the process of PAW itself that is the main reason of reject growth. Even insignificant deviations of the gap (or alignment) between the elements being welded from that is required by technical regulations result in formation of unallowable defects. Welding in this case is carried out, as a rule, in several passes and after each a cleaning of deposited layer from scale and slag, performance of quality control and other actions are necessary.

CONCLUSIONS

1. The dominant factors, generating from 90 to 97 % of defects being formed, were determined as a result of investigations and based on data of NDT of quality of the welded joints in technological pipelines.

2. Cause-effect relationships of defectiveness formation in the welded joints were determined that allow taking preventive measures for warning reject due to causes of presence of this factor and control of welding quality on the feedbacks of factor–cause–defect algorithms.

3. Specific contribution of effect of preparation and assembly for welding on output quality level of the welded joints depending on dimension-types of pipelines and methods of welding was calculated. This allows quickly making proved control decisions on improvement of specific technological processes and assurance of the necessary quality of the welded joints.

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EXPERIENCE OF APPLICATION OF S355 J2 STEEL IN METAL STRUCTURES OF THE ROOFING OVER NSC «OLIMPIJSKY» (Kiev)

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Information on application of new high-strength S355 J2 steel at Ukrainian enterprises for welded metal structures of the roofing over NSC «Olimpijsky» in Kiev during its reconstruction is presented.

Keywords: *reconstruction, welded metal structures, high-strength steel, technology certification, mechanical properties, welding consumables, welding technology*

As part of preparation for the European Football Cup to be held in Ukraine and Poland in 2012, work is being actively performed on reconstruction of the existing and construction of the new sports facilities, as well as infrastructure in those cities (hotels, airports, bridges, etc.), where football matches will take place. One of the key objects in preparation for EURO-2012 for Ukraine is NSC «Olimpijsky» in Kiev, where it is planned to conduct in 2012 the final match of the championship. After reconstruction the main spots arena of Ukraine should meet the current requirements of UEFA and FIFA, which enable holding the European and world football forums. According to the project and plan of reconstruction (project author is GMP Generalplanungeselschaft mbH) already in 2011 a roofing protecting the spectators from bad weather will appear over the Kiev stadium (Figure 1). Being constructed by the principle of «ring and rope system» and consisting of two external compressed rings and inner stretched ring the roofing will cover the stands of the lower and upper tiers, as well as parts of the running track.

Compressed rings are lightweight hollow boxlike welded structures (Figure 2), which withstand the horizontal forces induced by 80 pairs of radial ropes connected to them. Individual elements of the ring are connected to each other by inclined column supports (Figure 3), which are box-like welded metal structures of variable section along the length and set of inner diaphragms to ensure their stiffness.

All the welded structures were made in Dnepropetrovsk «Zavod Master Profi Ukraina Ltd» from rolled sheets of S355 J2 steel, produced by local metallurgical works to EN 10025-1 2004. Steel with yield point above 350 MPa had the following chemical composition (analysis of certificate data), wt.%: 0.17 C; 0.2 Si; 1.44 Mn; 0.05 V; 0.04 Nb; 0.005V;

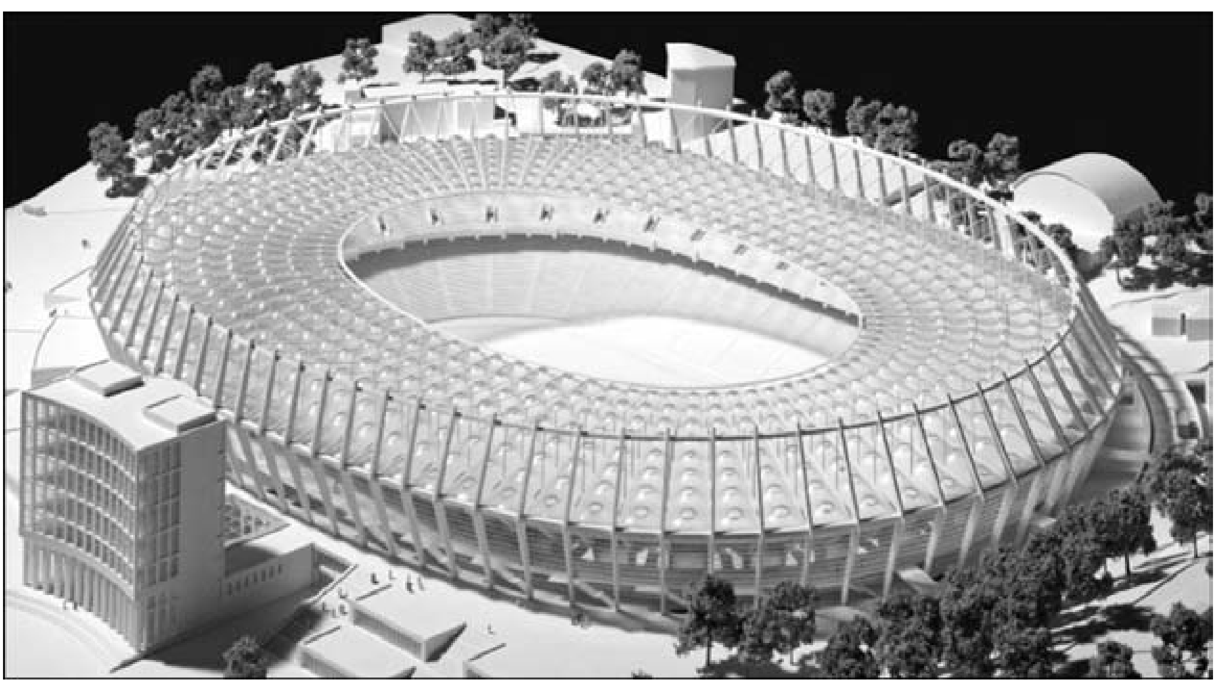

Figure 1. Design structure of the roofing over NSC «Olimpijsky» in Kiev

Figure 2. Compressed girth element in site

Figure 3. Appearance of columns ready for erection

0.005 S; 0.015 P. Rolled stock was made in Mariupol: up to 40 mm — at Illyich Metallurgical Works, and above 40 and up to 100 mm — at «Azovstal» Metallurgical Works.

Highly critical application of the roofing structure necessitated development of rational technologies of welding S355 J2 steel, providing equivalent welded joints with a high resistance to brittle and delayed fracture.

The short period of reconstruction predetermined the need to quickly take technology decisions on welding metal structures from S355 J2 steel. This was promoted by the stage of certification of welding procedures in keeping with DSTU 3951–2000, which preceded structure fabrication.

Proceeding from the developed in «Zavod Master Profi Ukraina» preliminary welding procedure specifications (pWPS), reference butt and tee joints of S355 J2 steel 16, 20 and 50 mm thick were made in the shop. Manual arc welding was performed with OK 53.70 electrodes (ESAB), mechanized welding in M21 mixture (Ar + 18 % CO_2) was conducted with Sv-08G2S solid wire of 1.6 mm diameter, and automatic submerged-arc welding with AN-47 flux was conducted with Sv-08GA wire of 4 mm diameter, using the newest automatic machines of ESAB and «Oerlikon Air Liquid 2143» specially purchased by the plant for fulfillment of this important order.

Proceeding from the obtained positive results of non-destructive and destructive testing of reference joints welding procedures were certified for all the types of welded joints of S355 J2 steel of 16–50 mm thickness, applied in fabrication of metal structures of the supporting frame of the roofing over the stadium.

Obtained from mechanical testing strength characteristics of welded joints (σ_t = 540–570 MPa) and impact toughness values (KCU_{-40} = 75–90 J/cm^2 and with sharp notch KCV_{-20} = 50–80 J/cm^2) meet project requirements made of welded joints in keeping with the local and foreign standards.

Work on metal structure fabrication was conducted from January to September of 2010, by the start of 2011 the last columns were mounted in the site of NSC «Olimpijsky», which was followed by the beginning of construction of the roofing proper.

INDUSTRIAL EXHIBITION «PATON EXPO-2011»

Industrial exhibition PATON EXPO-2011 took place at «KievExpo-Plaza» Exhibition Center in Kiev on April 12–14. It included 46 showcases demonstrating achievements of company-participants from Ukraine (36), Poland (3), Turkey (1), Italy (1), Germany (1) and Finland (1).

Various welding equipment manufactured by Ukrainian enterprises as well as foreign companies were presented on the Exhibition. Power sources, automatic and semiautomatic welding machines for arc welding, equipments for argon-arc welding and air-plasma cutting, machines for resistance spot welding, resistance butt and seam welding as well as welding consumables were exhibited. Kakhovka Plant of Electric Welding Equipment (KZESO), PWI Pilot Plant of Welding Equipment (OZSO) (Kiev), DONMET (Kramatorsk) and ZONT (Odessa) participated in the Exhibition as one of the largest Ukrainian manufacturers. Well-known foreign manufacturers were represented by their branches in Ukraine (Fronius Ukraina, Binzel Ukraine, Weldotherm Ukraina) and Russia — Polysoude S.A.S as well as by Kjellberg Finsterwalde Company. They exhibited the samples of equipment and accessories for consumable and non-consumable electrode welding and equipment for heat treatment. PWI OZSO and Frunze-Elektrod Ltd. (Sumy) were the representatives of manufacturers of welding consumables. «Ekotekhnologiay» (Kiev), «Delta — Modern Technologies» (Dnepropetrovsk), «Triada Svarka» (Zaporozhie) etc. are to be noted among the organizations engaged in selling of welding equipment, materials and accessories in the Ukrainian market.

The great attention is paid to development of compact-size welding equipment taking into account assortment of items represented on the Exhibition, including the power sources which, conditionally, can be divided on groups, i.e. transformers, conventional rectifiers and inverter-based rectifiers.

KZESO and Fronius Ukraina, the largest manufacturers of power sources having international certificate of correspondence ISO-9001, showed the exposition including different alternating and direct current power sources. In particular, KZESO demonstrated the materials illustrating welding transformers with mechanical adjustment for 250, 315 and 500 A current, universal rectifiers of VDU type for 300, 500 and 1250 A and rectifiers from 300 to 600 A for mechanized welding. Advertisement materials about specialized complexes for welding and repair of railway technique were also presented at KZESO showcase.

PWI OZSO exhibited new samples of power sources. These are small-size transformers of TDS series for 150, 180 and 200 A and STSh SGD series transformers for 315 and 400 A equipped with arcing stabilizers, current universal with regard to kind of current power sources of VD-255SGD, VD-400SGD type as well, as VDI-120, VDI-160 and VDI-200 inverter-based rectifiers with additional functions, operated automatically and increasing their technological efficiency. Rectifier VS-650SR for CO_2 welding produced by Plant should also be noted. It is equipped with special choke allowing stabilizing the length of arc space and size of the drops being transferred in the pool. Promotional materials of OZSO presented the information about power sources for electroslag technologies of 3 and 10 kA current.

Fronius Ukraina exposition included current welding equipment, namely: rectifiers for pulse-arc welding and MIG/MAG welding with discreet and smooth adjustment, as well as controllable power sources based on inverter transducers. All the rectifiers for MIG/MAG welding are equipped with feeders.

Kjellberg presented the units for air-plasma cutting for 300 and 500 A currents. Such welding equipment as transformers and semi-automatic machines were shown in the booklets.

The Exhibition showed that the Ukrainian market has sufficiently wide assortment of welding equipment different in structure and design solutions and providing adjustment of welding mode parameters in a wide range as well as high enough service and technological characteristics.

The open house days were organized in the period of Exhibition by training center of Fronius Ukrain. All the interested visitors were delivered in vil. Knayzhichi for participation in this event. Program of the open house day included separate presentations on the following themes made by managers of the company:

- TransSteel equipment for welding steel;
- Hypertherm equipment for air-plasma cutting;
- BTH-equipment for welding of hardware;
- Virtual Welding — practical skills;
- automation: standard components;
- automation: orbital welding;
- automation: review of projects realized in 2010–2011;
- TT 150 Puis: equipment for TIG welding;
- high-efficiency welding TIME, TIME TWIN;
- CMT-process of welding;
- equipment for MMA, TIG, MIG/MAG welding.

Scientific-and-technical conference «Residual life and problems of modernization of a system of main and industrial pipelines» took place on April 12–13 in a scope of the Exhibition. Scientists and leading researchers from institutes of the National Academy of Sciences of Ukraine, companies «Ukrtransgaz», «Neftegaz Ukrainy», «Ukrtransneft», «Gazprom», Bauman Moscow State Technical University, certification centers and other organizations participated in it. The Conference was opened by L.M. Lobanov, Deputy Director of the E.O. Paton Electric Welding Institute, academician of the NAS of Ukraine. He told about unique on length and efficiency system of pipelines for transportation of natural gas, oil and products of their refining that was developed in CIS countries during a short period of time. Extension of the mains exceeds 250,000 km and high-pressure large diameter pipelines prevail in this system at that. Gas-transport system of Ukraine, including main and branch gas lines, has the total length of more than 35,000 km. More than 70 compressor stations support the system operation. Oil delivery is carried out through the main pipelines of total length more than 4,600 km. Around 40 oil-transfer stations secure the system operation.

Intensive construction of the main pipelines began in Ukraine in 1960s and the principal ones, including transit pipelines of large diameter, were laid in 1970–1980s. Thus, the most part of the pipelines have been run already for a long time. For this reason the problems of evaluation of technical state and residual life of the main pipelines are very important. An analysis shows that the main reasons of abnormal operation are pipe defects, divergence from norms in construction, operation and repair, mechanical damages and corrosion. At that, amount of failures due to corrosion significantly rises with increase of operation life. Failure quota due to metal corrosion after 20 years of operation of the pipelines makes 35–45 % from total amount of failures according to data of expert evaluations.

Enterprises of the oil-and-gas complex significantly increased their interest to investigations on evaluation of technical state of the main pipelines in recent years. However, a scope of work being made in this direction is not still enough. Criticality of the problem lies in the fact that the level of such works in many cases does not comply with the modern requirements of object diagnostics. These works are mainly limited by performance of in-tube diagnostics detecting the places of corrosion damage of metal. At the same time, a complex approach to performance of diagnostics work is necessary for determination of a real state of acting main pipelines and life time of their operation.

There is a series of aspects related with design evaluation of allowable defects. Existing norms have differences according to their sizes. Besides, possibility of rising of technological defects and degradation of service properties of the metal as a result of time aging are to be considered. The practice shows that pipeline operation conditions differing from normative ones can significantly change mechanical properties of the metal. At that, stress-strain state and media are very importance. Plastic deformation significantly influences the changes in metal properties. It can appear in the zones of structural stress raisers (places of welding of T-branches and pipe geometry changes) as well as in zones of various type defects (such as cracks, lacks of penetrations, lacks of fusions, dents and scratches).

Participation of highly qualified specialists and application of complex equipment are necessary for fulfillment of the high requirements, which are made of the level of complex diagnostics of pipeline transportation, including their testing using different physical and electromechanical methods, working capacity evaluation based on experimental and calculation methods, development of valid conclusions according to residual life and optimal parameters of operation. Besides, modernization of normative base, methodology and means of diagnostics are required.

Timely performance of repair operations and reconstruction provides safe and secure operation of pipeline transportation system. Welding has an important role in such work performance. Therefore, the joint exhibitions on pipeline transportation, welding and related technologies, nondestructive testing and diagnostics are taking place in the exhibition center simultaneous.

30 plenary papers were made during the Conference. Such papers as «Technical policy of OJSC «Gazprom» in area of welding engineering» by E.M. Vyshemirsky («Gazprom»), «Evaluation of residual life of main pipeline damaged by stress-corrosion» by A.Ya. Krasovsky, I.V. Lokhman, I.V. Orynyak (G.S. Pisarenko Institute for Problems of Strength, NASU), «Current problems of repair of land main pipelines without their withdrawal from operation» by V.I. Makhnenko, A.S. Milenin, O.I. Olejnik (E.O. Paton Electric Welding Institute, NASU), «Prediction of residual life of a pipeline considering service loading conditions» by Yu.V. Banakhevich, I.V. Lokhman, I.Z. Byr («Ukrtransgaz»), «Ultrasonic testing of extended and hard-to-reach areas of the pipelines» by

V.A. Troitsky, A.I. Bondarenko (E.O. Paton Electric Welding Institute, NASU), «Method and structures providing elimination of accidents related with underwater production and transportation of oil and gas» by V.S. Romanyuk (PWI DB), «New technologies for repair and the main pipelines» by V.S. But, I.O. Olejnik (E.O. Paton Electric Welding Institute, NASU) and others gained the highest interest.

In conclusion the participants indicated that the Conference made significant input in solution of the problems of support, operation and safety of pipeline transportation system. The necessity was expressed in thorough development of scientific-and-technical co-operation between the specialists from CIS countries on issues of technical state and residual life of structures and buildings.

Drs V.V. Andreev, A.V. Koritsky,
Prof. V.N. Lipodaev, PWI

PLASMA-ARC WELDING OF LARGE-SIZED PRODUCTS FROM CARBON MATERIALS TO METALS

Welding equipment and technology were developed by PWI Zaporozhie Center of Plasma Technologies with the purpose of replacement of pressure multiampere contacts by welded contacts in such electric metallurgy installations as electrolyzers for aluminium and magnesium production, furnaces for graphitization, silicon carbide synthesis, etc. The cause for replacement of pressure contacts is the transient electric resistance on metal–carbon material interface, increasing tens and hundreds of times during operation, whereas welded contacts change their transient resistance by one to two orders of magnitude less.

Acrotron

ECP macrosection

Such a replacement ensures a considerable saving of power (up to 18 %), and also allows developing new rational designs of energy- and resource-saving electrolyzers and Acheson furnaces based on welded electric contact assemblies.

Welded joints of the type of «metal–carbon material» are made by a nozzle-free plasma generator — arcotron, operating with a new type oxide cathode, so that the process is performed in open air without application of shielding gases or fluxes. Power to arcotron is supplied from DC welding sources with a steeply falling external volt-ampere characteristic.

The main design element of any welded electric contact assembly is electric contact plug (ECP), each of which is capable of carrying the current load from 300 up to 600 A. Individual ECP are used to create contact assemblies for 10–225 kA. Contacts between ECP, current-carrying parts and buses are provided using various types of welded-in and welded-on jacks (metal conductors), thus ensuring failure-safe operation of welded joints at higher temperatures and alternating loads of installation thermal cycles.

TECHNICAL SEMINAR ON WELDING CONSUMABLES

On April 13, 2011, the one-day seminar on welding consumables took place in the Technological Centre «Fronius Ukraina Ltd.» in the village Knyazhichi of Kiev region, organized by the directorship and specialists of «Interkhim-BTV Ltd.» representing Austrian company «Boehler Welding» in Ukraine. In recent years such seminars became already a tradition for «Interkhim-BTV» and are called forth by increased interest of enterprises of different fields of industry in Ukraine towards developments of «Boehler Thyssen Welding».

In the seminar more than 20 representatives of services of the chief welder of such enterprises as OJSCs Turboatom (Kharkov), Krivorozhstal (Krivoj Rog), Kryukovsky Vagonostroitelny Zavod (Kremenchug) and other, and also representatives of the E.O. Paton Electric Welding Institute took part.

The seminar was opened by V.I. Chernetsky, the director of Interkhim BTV. He thanked the directorship of «Fronius Ukraina» for having provided a nice opportunity to hold the seminar at the Technological Centre and delivered audience the program of seminar. It included two presentations: of Timo Swys (Soudokay, Belgium) «Consumables for wear-resistant surfacing» and of Nobert Friedrich (Boehler Thyssen Welding) «Welding of modern duplex steels».

Mr. Timo Swys briefly elucidated the story of development of a Belgium works producing flux-cored wires, strips and fluxes. Since 1991 Soudokay completely passed under jurisdiction of the Boehler Thyssen Welding, since 2010 — in a form of a separate division. Soudokay is also one of the brands of the concern nowadays accounting 39400 employees. The annual turnover of the concern is 8.5 billion Euro. The products of the concern are realized in 40 countries of the world and its production is arranged in 24 countries. For example in Austria the flux-cored wires, electrodes, solid wires are produced; in Germany — all kinds of welding consumables and brazing alloys; in Sweden (AVESTA) — stainless steels and pastes for treatment of steels; in Brazil — electrodes, flux-cored wires for welding and surfacing, in Mexico — electrodes, flux-cored wires for surfacing; brazing alloys, pastes for brazing. To meet the demand on welding consumables at the Asian market the production of flux-cored wires for welding and surfacing was organized in Indonesia and China. The volume of sales of welding consumables of the Boehler Thyssen Welding in Europe is 40 %, in Asia — 36 %.

Describing the production in Belgium, the reporter stated that the factory is specialized on the production of flux-cored wires, strips, fluxes, feed mechanisms, widely used in technological processes for restoration of different types of equipment in metallurgy (charging cones, rolls of machines of continuous casting of billets, hammers, dies), cement industry (bands of furnaces), mining industry (restoration of teeth of machines and buckets, parts of crushers). For each type of products the respective surfacing wire is offered. Often the combination «wire + flux» for restoration works on the objects of chemical and paper industry is offered.

The metallurgy works of Ukraine ever more often purchase Soudokay materials which often allow restoring unique equipment in the shortest terms, idling of which results in considerable losses.

Interkhim-BTV along with realization of welding consumables of the concern in Ukraine renders services on repair-restoration works. In particular they include:

- surfacing of knives of flash removers of rail-welding machines;
- repair surfacing of parts of railway frogs;
- welding of crane rails;
- surfacing of parts of automatic coupling device of railway carriages;
- welding-up of cracks of water-cooled lid of cylinder of locomotive;
- surfacing of teeth of buckets of excavator;
- surfacing of excavator bucket;
- spraying of protective coating on the copper tuyere of a furnace;
- surfacing of hammer of crusher of coke-chemical production;
- repair of vacuum water-circular pumps VVN, DVVN, VK, NESh;
- surfacing of gear teeth;
- surfacing of metal-cutting tool.

Mr. Norbert Friedrich, responsible for technical support of products of the concern in the European countries and America, stated that the Boehler Thyssen Welding is the third one among the largest manufacturers of welding consumables in the world. The main enterprise in Austria produces 20,000 t of welding flux-cored wires per year, 75 % of which are realized at the European market. The range of wires includes materials for welding of low-, middle- and high-alloyed steels, heat-resistant steels, nickel-based alloys. The volume of wires for welding of high-alloyed steels is 17 %, which determines Boehler Welding as a leading producer of this class of materials in Europe. The volume of wires for welding of middle-alloyed steels is 20 % and those of low-alloyed — 63 %.

It is noted in the report that volumes of application of flux-cored wires determine the level of mechaniza-

tion and automation of welding processes in the countries. Today in the European countries the volume of application of flux-cored wires amounts in average 10, in North America — 21, in Japan — 30, and in South Korea — 39 %. That is why Europe is a challenging region where the growth of consumption of flux-cored wires is expected.

The innovation achievement of Boehler Welding is realization of technical solution on welding-up of butt of flux-cored wires using laser, guaranteeing the tightness from getting moisture into the core of a wire and further saturation of weld metal by hydrogen.

In general, the application of flux-cored wires provides the following advantages: reduction of consumption of welding consumables; producing of smooth welds without undercuts; welding practically without spattering; absence of temper colors in the area of a joint; sharp decrease in time for postweld treatment of welded zone; admissibility of lower skills of a welder; considerable growth of welding efficiency (achieving the level, characteristic for automatic submerged arc welding); decrease in buckling of thin-wall welded assemblies; possibility of application of CO_2 (instead of Ar + O_2) as a shielding gas with high-alloyed flux-cored wires; possibility of manufacturing wires from 0.9 mm diameter for welding of thin-sheet products with minimal buckling; the possibility to produce the cermet flux-cored wires on the chromium strip for welding metal of thickness from 0.6 mm. The comparative analysis shows that in spite of higher cost of flux-cored wires as compared, for example, to covered electrodes; the economy from their application considering all costs is 35 % per 1 m of a weld.

Boehler Welding produces a wide range of flux-cored wires for welding of high-alloyed steels. Many of them are produced in both modifications: FD — for high-efficient welding in flat position, and PW–FD — for welding in all spatial positions. These wires are suitable for welding steels of up to 100 mm thickness. The reporter pointed out that solution on welding of duplex steels of up to 55 mm thickness providing complex of physical-mechanical properties and corrosion resistance of joints is a great achievement. The duplex steels are very promising in oil-refinery, in building of tankers for transportation of chemicals, during construction of offshore oil platforms, construction of storages and in other fields.

The consumables offered by Boehler Welding (electrodes, flux-cored wires) of the type 22/9 and also technological procedures in multilayer welding of duplex steels of up to 55 mm thickness, limiting the heat input of welding during producing of a root weld and first pass, prevent running of undesirable phase transformations in the near-weld zone leading to decrease of corrosion resistance and unsatisfactory mechanical properties.

The reports, delivered at the Seminar, arose brisk interest of the audience. The dynamic representation, nice illustrated design, good quality translation, clarifying questions and well-grounded answers in the course of speeches satisfied all wishes of seminar participants.

Prof. V.N. Lipodaev, PWI

INTERNATIONAL CONFERENCE «TITANIUM-2011 IN CIS»

Traditional annual International Conference «Titanium in CIS» organised by the Inter-State Association «Titanium» was held on 25–28 April 2011 in Lvov, Ukraine. The Conference was attended by over 200 people from the CIS countries (Ukraine, Russia, Kazakhstan, Belarus) and from abroad (USA, Japan, Germany, Italy, China, Luxemburg, Poland, Switzerland, Romania). The papers at the Conference were presented by acientists and specialists from leading research organisation and industrial enterprises of Ukraine, Russia and other countries: E.O. Paton Electric Welding Institute of the NAS of Ukraine, G.V. Kurdyumov Institute for Metal Physics of the NAS of Ukraine, H.V. Karpenko Physico-Mechanical Institute of the NAS of Ukraine, Institute of Geological Sciences of the NAS of Ukraine, I.N. Frantsevich Institute for Problems of Materials Science of the NAS of Ukraine, Donetsk O.O. Galkin Institute of Physics and Engineering of the NAS of Ukraine, State Titanium Research and Design Institute, Zaporozhie State Engineering Academy, State Enterprise «Zaporozhie Titanium-Magnesium Works», State Enterprise «Antonov», Federal State Unitary Enterprises «Central Research Institute of Structural Materials «Prometey» and «All-Russian Research Institute of Aviation Materials», Open Joint Stock Company «All-Russian Institute of Light Alloys», MATI — K.E. Tsiolkovsky Russian State Technological University, Ural State Technical University «UPI», Institute of Strength Physics and Materials Science of SB of RAS, Open Joint Stock Companies «VSMPO-AVISMA Corporation», «Chepetsk Mechanical Plant», «Kaluga Turbine Plant», «Uralredmet», etc. Totally over 95 papers were presented in five sessions:

- raw materials and metallurgy;
- technologies for melting and processing of titanium alloys;
- titanium alloys and technologies for medical needs;
- metals science and technologies for titanium alloys;
- economy of titanium.

Special consideration at the Conference was given to the issues of application of titanium in medicine. Results of the efforts of Russian and Ukrainian specialists in development of new high-efficiency titanium alloys for manufacture of implants and endoprostheses with unique physical-mechanical properties, and in particular of titanium-nickelide based alloys with the shape memory effect, as well as the technological processes for their manufacture and processing, were presented at a special session.

Eight papers were presented from the E.O. Paton Electric Welding Institute. They covered the investigation results in the field of development of new titanium alloys, including of the Ti–Si system with dispersion strengthening, examination of their structure, evaluation of mechanical properties and weldability; in the field of production of titanium aluminide and nickelide ingots by using the electron beam and electroslag melting methods; and in development of new processes for TIG and electron beam welding of titanium alloys, as well as argon arc hard-facing using titanium flux-cored wire.

Comprehensive analysis of the state of the titanium market was made in the papers by O.M. Ivasishin (Inter-State Association «Titanium»), A.N. Stroshkov (VSMPO-AVISMA), Nishino Motoki («Advanced Material Japan Co.», Japan), Christian Decolet (Tirus International SA, Switzerland), etc.

The main industries — customers of titanium products — are still military and civil aircraft engineering (42 %), as well as industrial application (51 %), which includes power and chemical engineering, ship building and manufacture of equipment for non-ferrous metallurgy.

The developing titanium markets include manufacture of equipment for sea water desalination, medicine and sport, consumer goods, oil and gas production, and transport engineering, which now constitutes 7 % of the titanium market.

It is necessary to note a high level of holding of the Conference and express gratitude to its organisers represented by the Inter-State Association «Titanium» and its Chairman A.V. Aleksandrov, as well as to the associates of the H.V. Karpenko Physico-Mechanical Institute of the NAS of Ukraine.

Prof. S.V. Akhonin, PWI