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INVESTIGATION OF EFFECT OF DEFORMATIONAL TREATMENT ON RESIDUAL STRESSES IN CIRCUMFERENTIAL WELDS

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The paper presents the results of investigations on optimizing technological parameters of the process of pipeline circumferential reduction to induce a pattern of compressive residual stresses in the weld zone root. The problem of lowering the residual stresses under the die is solved by optimizing the die profile along the generatrix, as well as by applying deformable gaskets between the die and pipe.

Key words: *circumferential welded joints, decrease of residual stresses, deformational technology, optimum parameters of process*

The deformational technology is used for decreasing stresses to prevent the formation of stress corrosion cracks. This technology eliminates the residual tensile welding stresses in a root zone of the circumferential weld of a pipeline, thus preventing the crack initiation and delaying their growth.

The investigations were carried out on optimizing the technological parameters of the process of a circular reduction of pipeline to induce a pattern of compressive residual stresses in the weld root zone. The effect of percent reduction of pipeline and width of the reduction zone on the residual stresses is determined and optimum values of a radial reduction δ and a die width b are established. Variants of combination of reduction value $\delta = 1$, 2, 3 and 4 mm and die width $b = 40$, 60, 80 and 100 mm were studied for pipeline of 325 mm diameter and 16 mm wall thickness (steel 08Kh18N9T (C – 0.08; Cr – 18.0; Ni – 9.0; Ti – 0.6 wt.%) of $\sigma_{0.2} = 355$ MPa yield strength).

The investigations showed that the effect of lowering the stresses in the weld zone is accompanied by initiation in the die zone of hazardous circumferential tensile stresses on inner pipe surface, which reach the values of the material yield strength. The task of optimizing parameters of the technology is reduced to the creation of maximum compressive stresses in the weld zone and minimum tensile stresses under the die. The problem of lowering the residual stresses under the die was solved using two methods: optimizing the die profile along a generatrix and use of deformable gaskets of two types between the die and pipe to provide conditions for elastic and elasto-plastic deformations. An optimum curvilinear profile of a die, parameters of gaskets and also the distance from die edge to the zone of maximum unloading were calculated.

Initial information on the principle of the process of deformational technology was given earlier*. The positive aspects of the deformational technology, connected with a creation of zones of compressive stresses near a circumferential weld, were described. However, it is difficult to evaluate from the available data the effectiveness of technological operations, because during investigations the fields of residual stresses caused by a pipe deformation were not distinguished in a pure form and identified. There is no information about the negative consequences of the process, i.e. occurrence of high residual circumferential stresses on the inner surface of the pipe near the die, whose values reach the material yield strength.

As the results of the present work showed, the compressive stresses in the weld zone are determined mainly by radial upset δ, equal to a radial reduction, and a die width b and do not depend on the technology. At the same time the residual tensile stresses under the die depend greatly on such characteristics as profile of a die surface, gasket deformation and so on. We have established that the die profiling makes it possible to regulate to a great extent a system of tensile stresses under the die. The effects being observed are not inferior to the variant of using deformable gaskets, however, the technology and equipment are significantly simplified. Coming from the results obtained, the use of the deformable gaskets cannot be considered as the only and best variant.

In the work mentioned earlier a great attention was paid to the loading of the die zone with a circumferential hydrostatic pressure. It will be shown below that this variant of load applying is the most unfavourable as to the level of hazardous tensile residual stresses.

The deformational technology of decreasing axial σ_z and circumferential σ_θ residual stresses in the weld root is reduced to a radial reduction δ of the circumferential zone of pipeline of width b, located at the

* Porowski, J.S., O'Donnell, W.J., Badlani, M.L. et al. (1990) Use of the mechanical stress improvement process to mitigate stress corrosion cracking in BWR piping systems. *Nucl. Eng. and Des.*, 124, 91–100.

Dependence of circumferential tensile residual stresses in point A under the die on the process parameters δ and b and radius of curvature R at a toroidal shape of the die surface

δ, mm	b, mm	R, mm	σ_θ, MPa	
			Toroidal die	Cylindrical die ($R = \infty$)
2	80	1600	207	280
3	80	1000	235	286
4	80	820	238	306
2	60	1250	209	285
2	100	2000	175	275

distance l' between the weld axis and die edge (Figure 1). After die removal the plastic deformations in the reduction zone cause the occurrence of fields of favourable compressive axial σ_z and circumferential σ_θ residual stresses in the weld zone which prevent the stress corrosion cracking (Figures 1 and 2). The simplicity of method ensures its reliability: the design level of decrease in stresses is guaranteed when the optimum parameters of the technological process are followed. At small plastic deformations in the area of reduction, amounting to 1–2 %, it is possible to form the efficient compressive residual stresses in the weld zone at the level of 50–70 % of the material yield strength. The process takes place in the area of a deforming curve bending.

As the calculations showed, a system of effective compressive residual stresses is created in the zone B after the circumferential reduction of the pipeline, while the high tensile circumferential stresses σ_θ, which approach the value of the material yield strength, are occurred in the zone, locating directly under the die (see Figures 1 and 2). Here, the hazardous effect of stresses σ_θ in the zone OA can deteriorate the effect of decreasing stresses in weld. Thus, the task of investigations is reduced to the determination of the technology parameters providing maximum compressive residual stresses σ_z, σ_θ in section BD and minimum tensile stresses σ_θ in the die zone OA.

The investigations included the following stages: solution of problems of mechanics of interaction of die and pipeline; calculation of active radial displacements of the tool, required for the formation of a preset level of residual displacements under tool and compressive stresses in the weld zone; calculation of a diagram of contact stresses between the die and pipe; determination of residual stresses in pipe in the zone of die action after its removal; calculation of fields of residual stresses in pipeline in the zone of weld location; determination of optimum distance between the die edge and weld axis providing maximum decrease in residual stresses in welding; calculation of a profile of the die active surface, providing minimum hazardous residual tensile stresses in pipe in the reduction area; calculation of pressing forces. A specialized method of examination of stress-strain state has been developed. This method makes it possible to distinguish and analyze effectively the effect of all the parameters of technological process on the

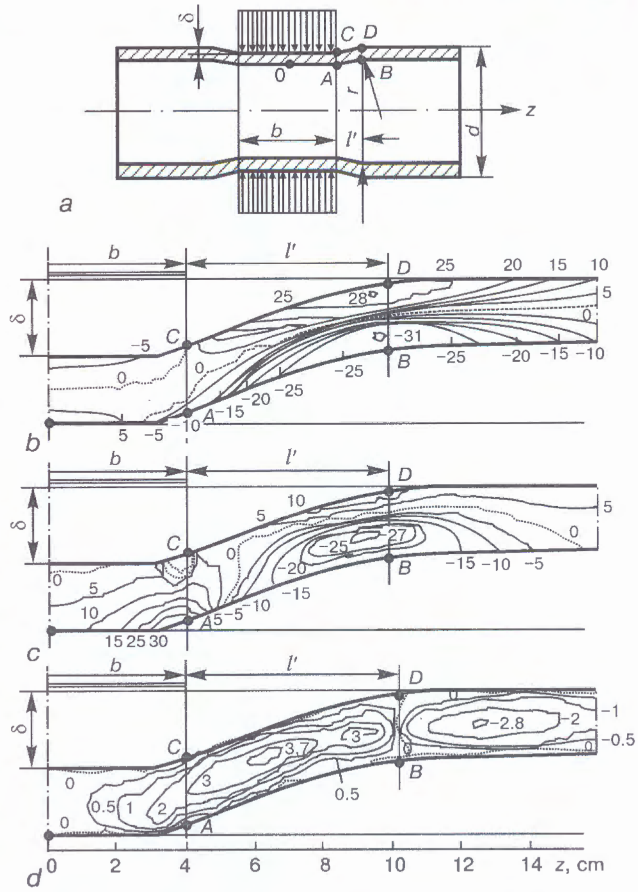

Figure 1. Diagram of pipeline reduction (a) and typical distribution of residual stresses σ_z (b), σ_θ (c) and τ_{rz} (d) (MPa·10^{-1}) during deforming using a cylindrical die (b = 80 mm, δ = 4 mm)

formation of fields of effective residual stresses in the weld zone.

Asymmetric deforming. Let us consider the variants of the asymmetric deforming of the weld zone (Figure 1).

Die with a rectilinear generatrix (cylindrical). Firstly, the effect of two decisive parameters were

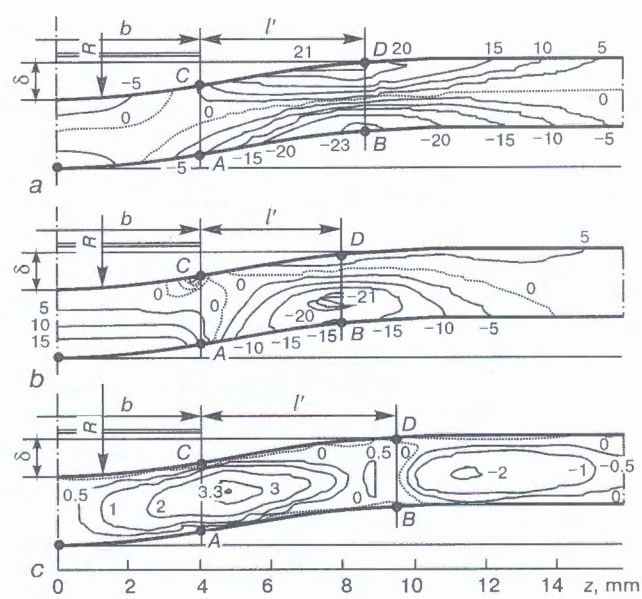

Figure 2. Fields of residual stresses σ_z (a), σ_θ (b) and τ_{rz} (c) (MPa·10^{-1}) in pipeline obtained in reduction using a toroidal die of curvature radius R =1600 mm at b = 80 mm, δ = 2mm

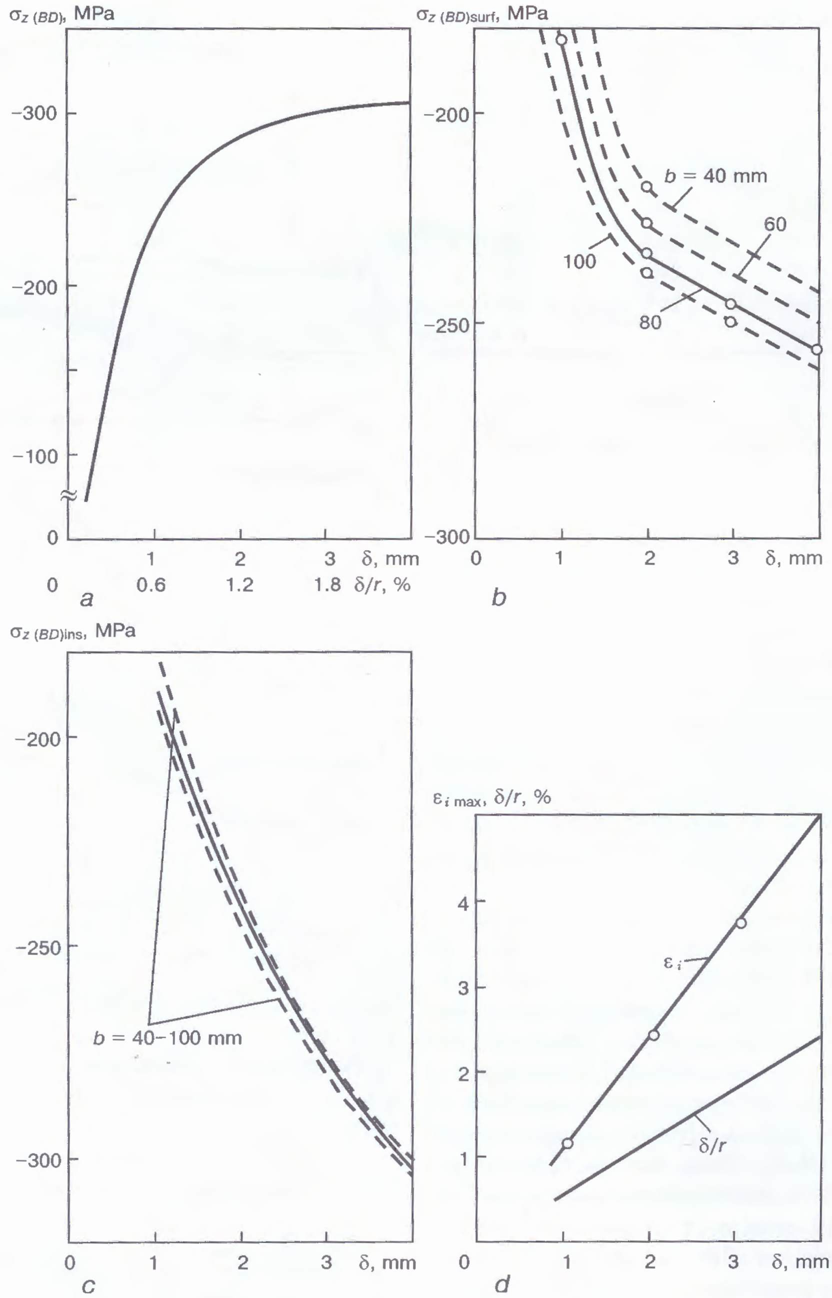

Figure 3. Dependence of residual axial compressive stresses in section *BD* (*a*) and also on inner surface (*b*), inside pipe section (*c*) and intensity of deformation ε_i (*d*) during reduction on the main process parameters *b* and δ

investigated, i.e. radial upset δ and width *b* of a cylindrical die with a rectilinear generatrix. Variants of combination δ = 1, 2, 3 and 4 mm and *b* = 40, 60, 80 and 100 mm were considered. Fields of radial displacements U_1, axial σ_z and circumferential σ_θ residual stresses, as well as the values of deformation intensity ε_i in pipeline section were obtained.

Dependence, presented in Figure 3, *a*, shows that the stable effect of reduction begins from δ = 2 mm and is stabilized at δ = 3 and 4 mm, that corresponds to the circumferential residual deformation $\varepsilon_\theta = \delta/r$ = = 1.2, 1.8 and 2.4 %. Reduction for 1 mm at ε_θ = = 0.6 % does not guarantee the process stability and required level of the residual stresses.

As the results of calculation showed, the values of residual axial σ_z and circumferential σ_θ compressive stresses increase with in increase of upset δ and die width *b* in the weld zone in *BD* section (Figures 3 and 4). On inner surface of the pipe in the weld zone the stresses σ_z and σ_θ are compressive, while on external surface they are tensile (Figures 1, 2 and 5). On inner surface of the pipe the values of compressive stresses are higher than those on the external surface. The effective axial compressive stresses σ_z on the inner surface of pipe are 73 %, and in the pipe section — 86 % of the material yield strength. The circumferential compressive stresses σ_θ in weld zone reach 54 and 79 % of the material yield strength, respectively.

Distance *l′* from the die edge to the zone of maximum unloading of weld on the inner surface in point *B*, as shown in Figure 5, depends mainly on the depth of reduction δ and amounts from 42 (at δ = 1mm) to 60 mm (at δ = 4 mm). Dependencies of pressing force on radial reduction δ and die width *b* are given in

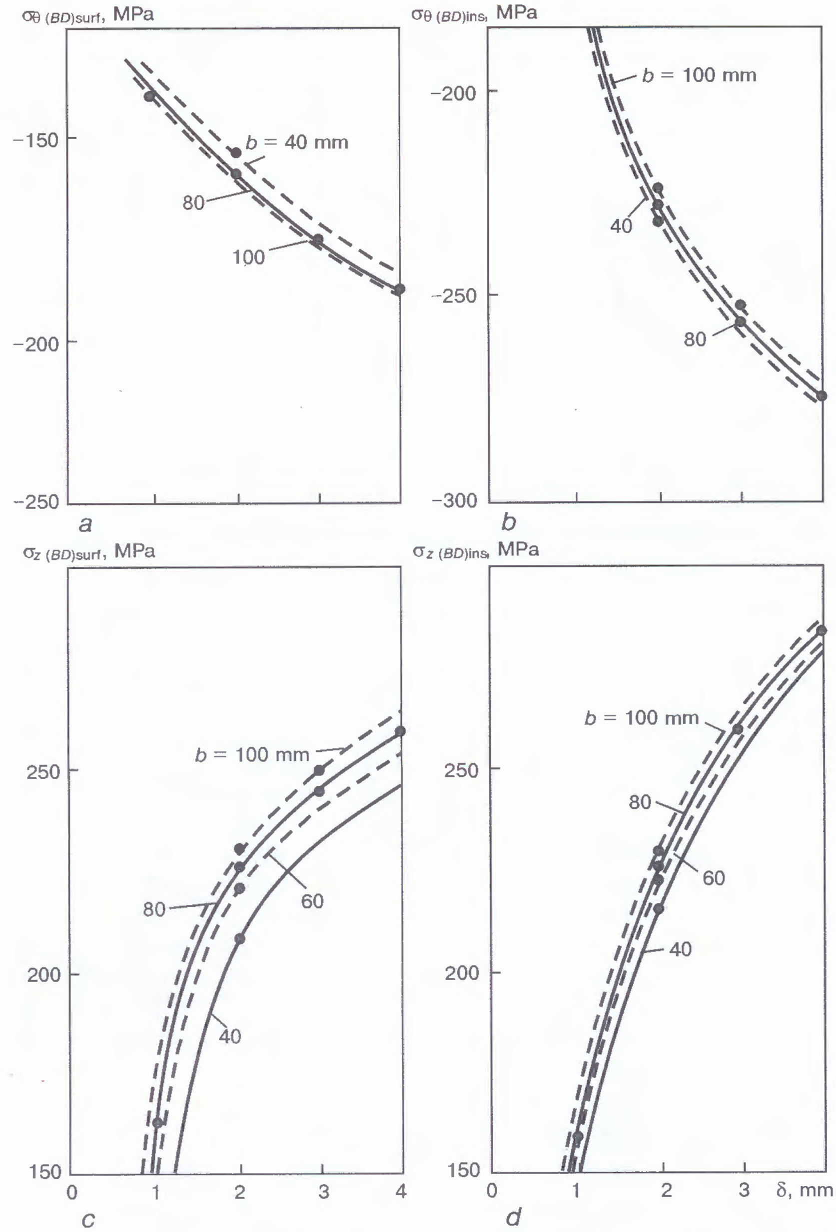

Figure 4. Relations of maximum residual stresses in weld zone in section *BD* during reduction using a cylindrical die: *a*, *b* — circumference residual stresses on inner surface and inside the pipe section; *c*, *d* — axial residual stresses at the same places

Figure 5, *d*. Comparison and analysis of results of experiments show that the depth of a radial upset from 2 to 3 mm at 60–80 mm width of reduction zone can be considered optimum from the point of view of weld unloading.

Dependence of hazardous tensile residual circumferential stresses σ_θ in the die zone on values δ and b is given in Figure 6, *a*. With increase in upset δ these stresses are growing, and with increase in die width b they are decreased. These stresses are very hazardous as their values reach the material yield strength.

In the above variant of combinations of values δ and b the maximum hazardous tensile stress σ_θ is formed on the inner surface of the pipe at the die edge (point A, Figure 1), where intensity of deformation ε_i reaches the highest value. This is explained by the fact that in case of a die with a rectilinear generatrix all the force of pressing is concentrated almost on its edges. The change in distribution of contact pressure in die width makes it possible to decrease the hazardous tensile stresses σ_θ. This aim can be achieved in several ways (for example, by optimizing the die profile, placing of deformable gaskets between the die and pipe, etc.).

The values, given in this work, were obtained for materials with a yield strength $\sigma_{0.2}$ = 355 MPa. The repetition of all the series in the mentioned combinations of upset values in the range from 1 to 4 mm and width of pressing zone from 40 to 100 mm for the material with lower yield strength $\sigma_{0.2}$ = 200 MPa showed that the values of residual stresses, expressed in percents from the yield strength, were preserved almost the same as at $\sigma_{0.2}$ = 350 MPa. This confirms high reliability of the deformational technology providing a stable degree of lowering stresses at deviation of strength properties of the material.

Die of curvilinear profile. The investigations of stressed state of pipeline at a toroidal shape of the

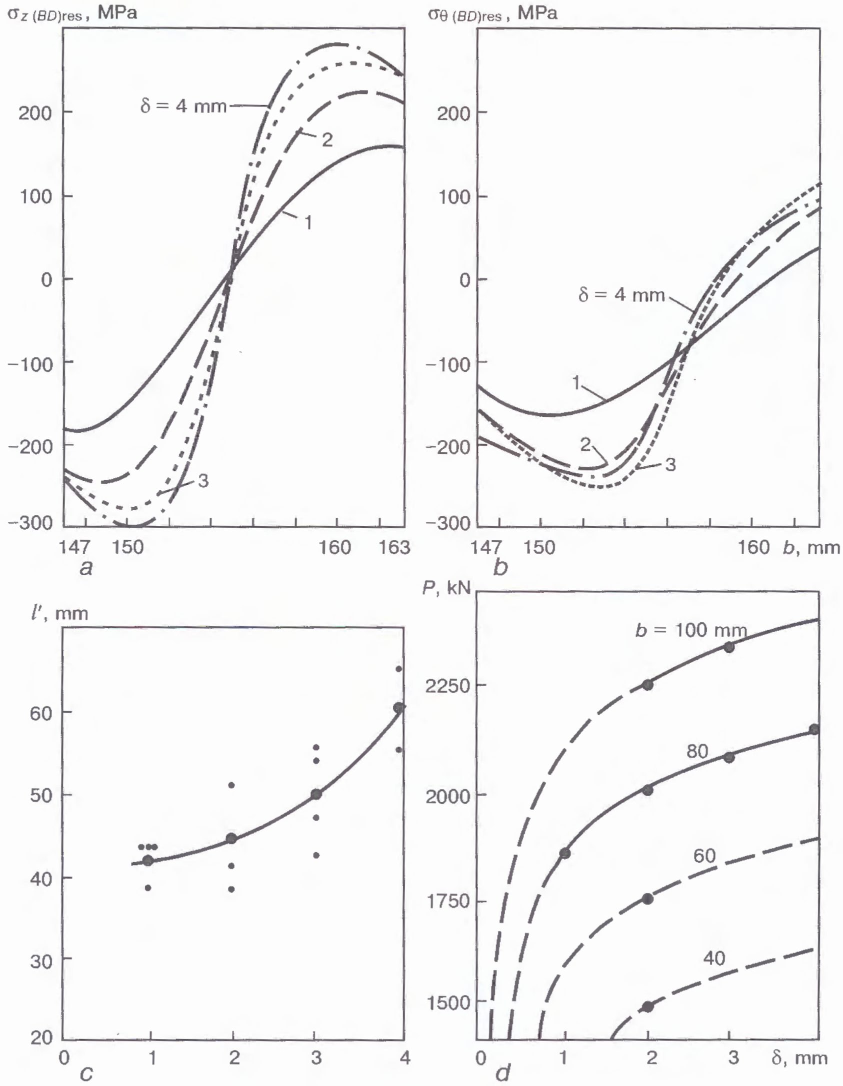

Figure 5. Distribution of axial (a) and circumference (b) residual stresses in weld section BD at b = 80 mm, and also dependence of distance l' from die edge to weld (c) and pressing force P (d) on parameters b and δ

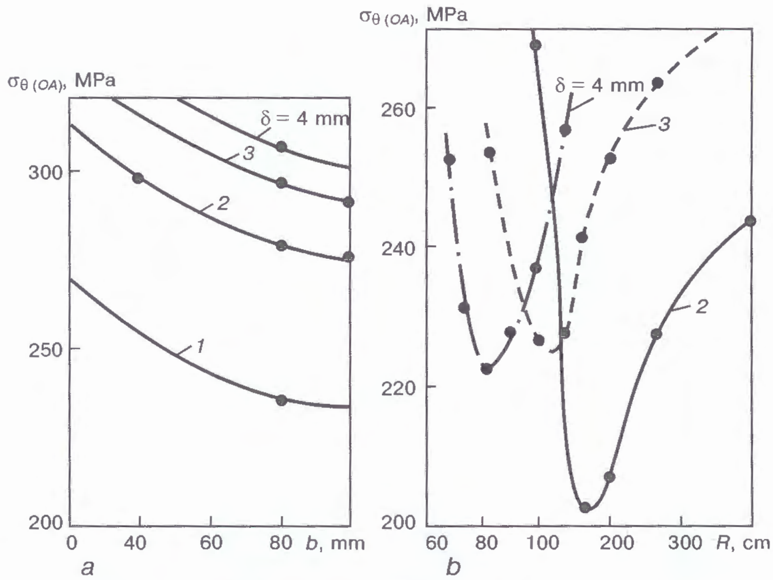

Figure 6. Relations of maximum circumference tensile residual stress σ_θ in region OA located under cylindrical (a) and toroidal (b) dies at b = 80 mm

working surface of die of 60, 80 and 100 mm width and a curvature radius R were carried out. 18 variants of combination of radial upset in the middle of the die were studied: $\delta = 2$, 3 and 4 mm for 27 values of R. The obtained relationships (Figure 6, *b*) showed that minimum tensile stresses σ_θ occur under die of 80 mm width at $\delta = 2$ mm and $R = 1600$ mm, $\delta = 3$ mm and $R = 1000$ mm, $\delta = 4$ mm and $R = 820$ mm. Here, the hazardous tensile stresses σ_θ in point A are decreased by 25–35 % from values corresponding to a rectilinear generatrix of the die. The effective compressive stresses σ_z and σ_θ in the weld zone, and also the distance l' between the weld and die at a curvilinear generatrix, as compared with variant $R = \infty$, are changed negligibly. Calculations, performed for the die of 100 mm width at $\delta = 2$ mm showed that the optimum radius of curvature R is equal to 2000 mm. This guarantees the further decrease in tensile circumferential stresses σ_θ.

Using the data the Table it is possible to establish that the highest degree of lowering hazardous stresses $\sigma_{\theta(OA)}$ is attained at $\delta = 2$ mm and $b = 100$ mm. However, in this case the pressing force occurred to be highest ($P = 2270$ kN) and a heavy technological equipment should be used. Variant of combination $\delta = 2$ mm and $b = 60$ mm is more effective, as the stress decrease is significant and the equipment mass is smallest.

There were some apprehensions that the residual tangential shear stresses τ_{rz}, forming in the weld root zone, can prevent the use of the deformational method of lowering stresses due to a possible brittle shear fracture along circular corrosion cracks.

The investigations showed (see Figures 1 and 2) that the section BD in all the variants of asymmetric loading, passing in the zone of maximum compressive stresses σ_z and σ_θ, is coincided almost always with a zone of zero tangential stresses τ_{rz}. In this zone the stresses τ_{rz} change a sign. This situation is not random, it is stipulated by natural features of fields of residual stresses and fulfilled automatically in the technology considered. The deformational technology ensures occurrence of only favourable stresses and strains in the region of the weld root during all the process of reduction and after die removal. If the achievement of zero tangential stress τ_{rz} is a necessary condition, then the selection of distance l' should be made not coming from values of stresses σ_z and σ_θ, but from field of stresses τ_{rz}. Even a rough violation of an optimum selection of distance l' cannot induce tangential stresses above the level of 5–10 MPa. However, if this is not acceptable, then the use of the method of symmetrical deforming, described below, can provide a full absence of residual tangent stresses on a large width in the weld zone.

Die with gaskets. Maximum concentration of contact stresses under cylindrical die is observed at its edges, where the highest residual stresses $\sigma_{\theta(OA)}$ are also occurred. The deformable gaskets, placed between the die and pipe, can be intensively deformed in the concentration zone, thus levelling the contact and decreasing residual tensile stresses. Two types of gaskets are studied: elastically- and plastically-deformable.

It is assumed in use of gaskets of the first type that the gasket of elastically-deforming material of 5 mm thickness (Poisson's ratio $\nu = 0.25$) is placed between the surface of cylindrical die of width $b = 80$ mm and pipe. The radial upset in the center was 2 mm. Results of seven variants of calculation of elasticity modulus of the gasket, changing in the interval $E = 250$–20000 MPa, showed that in optimum variant at 2000 MPa the tensile stresses decreased by 22 % (Figure 7, *a*).

In use of gaskets of the second type a plastically-deformable gasket of a wavy periodic profile was placed between the cylindrical surface of die of 80 mm width and pipe. The radial upset was 2 mm. Five variants of calculations of yield strength of gasket material, changing from 22 to 350 MPa were made. It was established that the least value of circumference tensile stress is attained at $\sigma_{0.2} = 67$ MPa. The decrease in value σ_θ as compared with a variant of a rigid cylindrical die was 14 % (Figure 7, *b*).

The use of deformable gaskets cannot decrease hazardous stresses to the same extent as in a toroidal die and requires the use of more complicated technologies. The process of manufacture of deformable gaskets with special properties is rather expensive, as the gaskets cannot be reused.

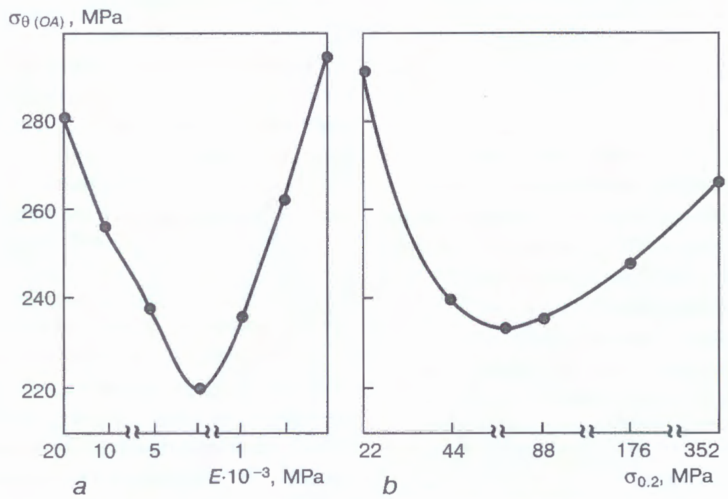

Figure 7. Relations of maximum circumference tensile residual stress σ_θ in region OA located under die using elasto-plastically (*a*) and plastically-deforming (*b*) gaskets of 5 mm thickness

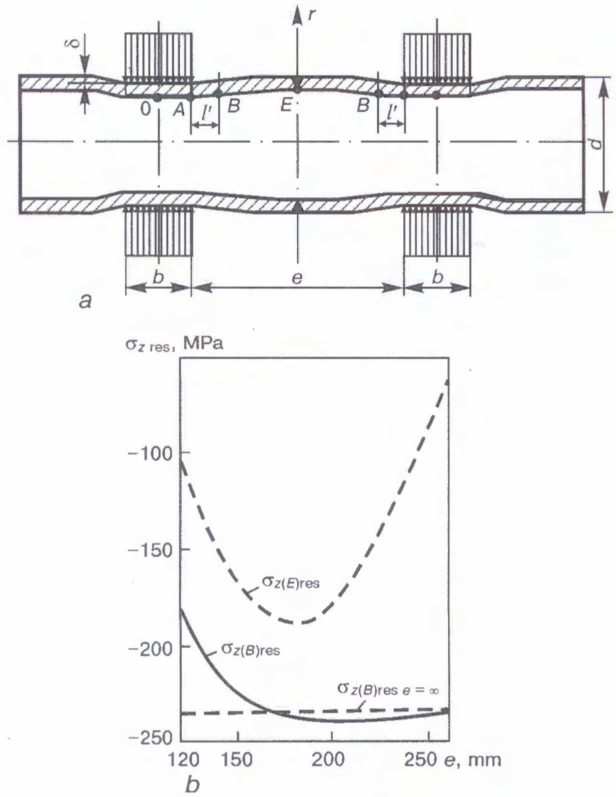

Figure 8. Relations of maximum residual stresses σ_z in point E in the middle between two deforming girths of width b at symmetrical reduction at distance e: $\sigma_{z(B)res}$ — maximum compressive residual stress in the weld zone at asymmetric reduction (a, b are explained in text)

Hydrostatic radial pressure. The hydrostatic radial pressure in the circular zone of width b provides the most uniform distribution of contact forces. The use of the hydraulic pressure represents a variety of a force loading. Here, the optimum deformations cannot be preset directly. They are induced indirectly in the form of local free bendings of pipe wall regions under the action of pressure and depend at least on value of variable (in cube) around the circumference of wall thickness and also on the material yield strength. This leads to the well-known non-uniform deforming around the circumference, distortion of a round section of pipe and local inside wall bulging. At hydrostatic loading there is no feasibility of presetting, monitoring or control of optimum values of circumference radial reduction of pipe. This makes the process of deforming uncontrollable, and the results of unloading of weld from stresses are unpredictable. As the calculations showed, the level of hazardous residual tensile tangential stresses in the reduction zone at hydrostatic loading are significantly higher than those in presetting of a curvilinear profile of radial displacements in the die width. As to the degree of decreasing residual stresses in weld root zone the hydrostatic reduction has no advantages. Hydrostatic reduction is characterized by inadmissibly small distance from edge of loading zone to the weld axis and also by weld entrance to the reduction zone, therefore, the realization of this technological process becomes problematic.

Symmetrical deforming. At asymmetric deforming a system of tangential stresses τ_{rz} is formed in the region of weld simultaneously with the formation of effective axial compressive stresses $\sigma_{z(R)res}$ on inner surface of the pipe. As was shown above, the values of these stresses are low (τ_{rz} = 5–10 MPa), however, it is considered that their effect can decrease the weld strength at the formation of stress corrosion cracks in it. This inspired to develop the technology of deforming, excluding the occurrence of residual tangential stresses in weld zone that makes it possible to use the deformational method of decreasing stresses for welds which passed the period of service with formation of transverse circular corrosion cracks in them. This process can be realized at symmetrical reduction of pipeline relative to weld axis in two girths of width b (Figure 8, a).

Some calculations were made at b = 80 mm and δ = 2 mm to analyze the relations of axial compressive stresses in the weld zone $\sigma_{z(E)}$ in point E at the distance e between the girths of reduction. As it follows from Figure 8, b, with increase in distance e the effective residual stresses $\sigma_{z(E)}$ are maximum increase firstly, and then they are decreased. Distance e = 180 mm can be considered optimum at which $\sigma_{z(E)}$ = 190 MPa.

Curves of distribution of residual stresses on the inner surface of pipeline are shown in Figure 9. It can be noted that the effective stresses in all the cases in point B where weld is usually located at asymmetric loading are always superior to the stresses in point E. Values of favourable axial compressive stresses in zone of weld $\sigma_{z(E)}$ at symmetrical reduction at other equal conditions are lower than those at asymmetric reduction by ≈ 20 %. The conditions of the symmetrical reduction were investigated at circumferential deformations $\varepsilon = d/r$ = 1.2 %. Increase in reduction ratio makes it possible to attain the same decrease in residual stresses $\sigma_{z(E)}$ as at asymmetric reduction. It should be noted that at optimum distance e in case of symmetrical reduction the more uniform distribution of effective residual stresses σ_z in length is observed in weld than at asymmetric loading in point B.

All the earlier results of optimizing parameters of technology of reduction to minimize the tensile stresses under the die as well as the optimum values of width b and radius of curvature of a toroidal surface of die R at symmetrical loading are valid.

Figures 9 and 10 shows the effect of above-described variants of technology on the value of effective compressive residual stresses σ_z and σ_θ in the weld zone and hazardous tensile circumference stresses under die $\sigma_{\theta(OA)}$ in reduction δ = 2mm. The investigation results testify that the favourable compressive stresses σ_z and σ_θ in weld zone depend negligibly on the technology of pipe deforming and are determined by values δ and b. Reduction with a profiled tool of a toroidal profile is the optimum method which provides a maximum decrease of stresses in weld zone and minimum residual tensile stresses under the die. In this case a simple equipment is used and a complete control of preset deformations and process monitoring are attained. Second place by effectiveness is occupied by a variant of using elastic gasket and the third place — by an elastic-plastic gasket. The much higher values

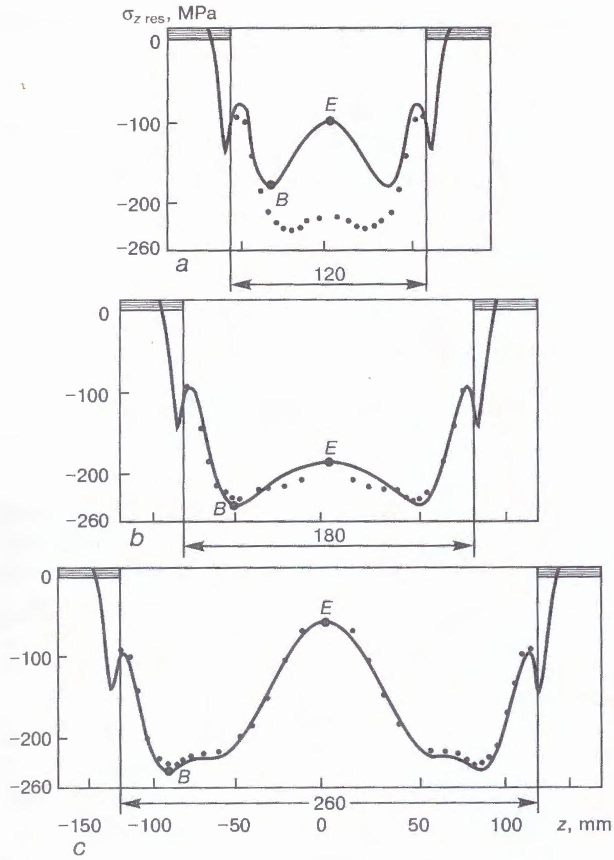

Figure 9. Distribution of axial residual stresses $\sigma_{z\,res}$ in length of inner surface of 325 mm diameter pipeline depending on distance e between two girths of radial upset $\delta = 2$mm at $b = 80$ mm (points show values of stresses at upset in one girth): e = 120 (a), 180 (b), 260 (c) mm

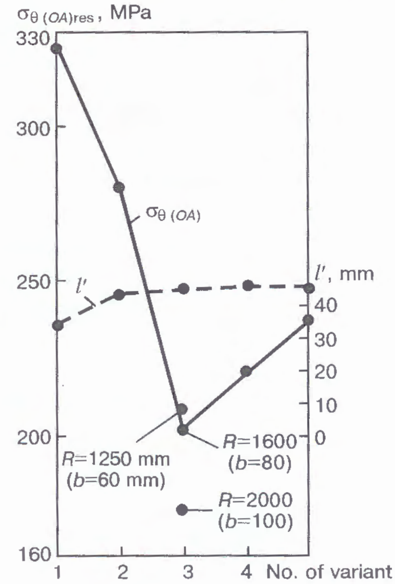

Figure 10. Dependencies of maximum circumference tensile residual stress σ_θ in region OA under die as also distance l' from die edge to the zone of maximum unloading on conditions of reduction in the zone of die of width b = 80 mm at radial upset δ = 2 mm: 1st variant — uniform pressure under die P = 61.8 MPa; 2nd variant — cylindrical die without gasket; 3rd variant — toroidal die; 4th — elastic gasket of 5 mm thickness at elasticity module E = 2000 MPa under cylindrical die; 5th variant — elastic-plastic gasket of 5 mm thickness with $\sigma_{0.2}$ = 67 MPa

of tensile stresses $\sigma_{\theta(OA)}$ are observed under the cylindrical die with a rectilinear generatrix. Maximum values of stresses $\sigma_{\theta(OA)}$ are obtained at uniform hydrostatic pressure in the die region when they reach values of the material yield strength.

CONCLUSIONS

It was stated that use of a die of a toroidal profile of width b = 60 mm at R = 1250 mm and radial reduction δ = 2–3 mm that corresponds to circumference deformation ε = 1.2–2.0 % can be considered as an optimum technological variant. In this case the axial stresses $\sigma_{z(B)}$ in the weld zone are decreased on the inner surface by 250–300 MPa, circumference $\sigma_{\theta(B)}$ — by 200–270 MPa, and tensile stresses under the die $\sigma_{\theta(OA)}$ are equal to 210 MPa.

Two types of deformational effect on the welded joint zone were studied: asymmetric loading when the weld is located at the side of one girth of deformation and symmetrical when the weld is in the middle of two girths of deforming. It is shown in work that at asymmetric loading the weld section located in the zone of maximum compressive residual stresses $\sigma_{z(E)}$ and $\sigma_{\theta(B)}$ is coincided always with a zone of zero tangential stresses in which their sign is changed. Even at a rough violation of optimum distance l' the values of tangential stresses in this zone do not exceed 5–10 MPa. Thus, at asymmetric reduction only favourable stresses are provided during the whole process in the weld root zone. This makes it possible to use the above-mentioned method for joints with circular corrosion cracks.

Symmetrical loading provides a complete absence of tangential stresses in the weld zone. This gives an opportunity to use this variant for welded joints with a corrosion cracks in pipelines which have passed a definite period of service. Main technological parameters of a symmetrical loading were investigated.

The algorithms developed will make it possible in future to calculate the optimum parameters of processes of deformational technology of reduction for different types and sizes of pipelines both at asymmetric and symmetrical methods of reduction. It seems possible to develop parameters of deformational technology of lowering stresses in welds of pipings of reactors and high-pressure vessels.

As the practice showed the preset, controllable and monitorable technological process of reduction of pipeline can be realized only by a tool which ensures optimum preset values of technological deformations. During pipe deforming in a die the preset data of a radial reduction δ and optimum regularity of changing radial displacements U_r in the die width are realized. The preset data of reduction can be attained independently of changing the pipe wall thickness in circumference or yield strength of material of separate regions of pipeline. After deforming the region of reduction has always a round section defined by a shape of a circular die. The deformational loading provides a guaranteed level of welded joint unloading and minimum residual tensile stresses under the die independently of changing the pipe wall thickness in circumference and scattering of values of the material yield strength.

INCREASE IN STRENGTH OF WELDS IN ARC WELDING OF ALLOY 1420 USING THE Sc-CONTAINING FILLERS

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Comparative analysis of the properties of sheet welded joints of alloy 1420, produced by fusion welding with application of serial and experimental filler wires, containing scandium, is performed. It is shown that scandium addition to welding wires creates prerequisites for further strengthening of the weld metal. A heat treatment mode is suggested allowing the production of equivalent joints with an improved system of physico-mechanical properties.

Key words: *welded joints, strength, hardness, filler wire, scandium, artificial ageing, weld, heat-affected zone, heat treatment, hardening, phases*

The industrial Al–Li alloys are characterized by a high degree of alloying, a significant heterogeneity and complicated phase transformations in the process of technological heating, final heat treatment and welding. Their indispensable advantages are the increased specific strength and rigidity. In addition, these alloys possess satisfactory properties at cryogenic temperatures.

The sufficiently high level of properties of heat-hardened alloy 1420 (Al–Mg–Li system) is provided in heating for quenching within the wide interval of temperatures, from 375 to 480 °C. The alloy hardening is reached at the expense of δ′-phase precipitation as a result of the artificial ageing. With decrease in the temperature of quenching the increase in yield strength and ultimate rupture strength at decrease of ductility is observed. At temperatures 400–430 °C a negligible amount of recrystallized grains is appeared in the first minute of heating, which, the same as their size, is not changed at the further soaking. At 460 °C temperature, corresponding to the intensive dissolution of fine and large particles of δ-, β- and *S*-phase, the process of recrystallization is developing actively in the first minutes, and only after 40 min of soaking the texture is disappeared and a collective recrystallization is started. In the conditions of fusion welding the processes of dissolution of strengthening and excessive phases are prevailing in HAZ of alloy 1420, as the time of HAZ metal duration within the 450–500 °C temperature interval does not exceed 1.0–1.5 min.

For welding of alloy 1420 the welding wires of AMg6 or AMg63, not containing lithium, are usually used [1]. The mass fraction of this element in weld metal is decreased to 1.0–1.4 % (it is 1.9–2.3 % in parent metal). The ultimate rupture strength of welded joints is by 20–30 % lower than that of the parent metal. The complete cycle of heat treatment of welded joints including quenching and artificial ageing can increase the mechanical properties, however, it is impossible to reach the level of the parent metal due to change in the weld metal composition.

The aim of investigations was to study the effect of the composition of filler wires, containing scandium, and also conditions of heat treatment on the increase in strength of weld metal, fusion zone and welded joints as a whole.

The 4 mm thick sheets of alloys 1420 (Mg – 6.0; Li – 2.0; Zr – 0.12 wt.%) and alloy 1421 (Mg – 5.3; Li – 2.1; Sc – 0.2; Zr – 0.12 wt.%) were used. After quenching (450 °C, 1 h, air) and subsequent artificial ageing (120 °C, 8 h) they were welded for one pass using the automatic welding with a non-consumable electrode in argon and a consumable electrode in 50 % Ar + 50 % He mixture. Before welding the plates and wires were subjected to the chemical etching using the well-known technology. Directly before welding, the surface layer was removed at edges mechanically for 0.2 mm depth to prevent the porosity formation in the fusion zone in arc methods of welding which is typical of the Li-containing alloys. The non-consumable welding was performed on the forming stainless steel backing with an increased semi-spherical groove of 7.0 mm width and 1.1 mm depth to increase the share of the filler metal in the weld volume to 30 %. The arc was supplied from power source MW-450. The welding current was 200 A, welding speed – 12 m/h, 1.6 mm diameter filler wire feed speed – 130 m/h, argon consumption – 15 l/min.

For the consumable electrode welding the power source TPS-450 was used. The welding of 1420 alloy sheets was performed at 175 A current and 25 V arc voltage. The welding speed here was 40 m/h, wire feed speed – 280 m/h at consumption of argon and helium by 20 l/min each. The method of the consumable electrode welding is characterized by the higher (2–3 times) speed of welding and cooling of the weld metal that contributes to producing the solid solution being more saturated with alloying elements. This is important when the Sc-containing welding wires are used. The high speeds of welding provide a negligible overheating of the near-weld zone, more narrow HAZ, lower deformation and absence of oxide films in welds. At the same time there is a risk of decrease in concentration of main alloying elements due their burnout during consumable electrode welding. The chemical composition of wires used for producing butt welded joints is given in Table 1.

The mechanical properties of welded joints and welds (ultimate rupture strength, impact strength and bending angle) were evaluated on standard specimens. The strength of welded joints was determined at tensile test of flat specimens with a reinforcement and removed back bead, and the weld metal strength was tested on flat specimens with the removed reinforcement and back bead. The change in mechanical properties, peculiarities of fracture of specimens at mechanical tests, the degree of development of weakening of parent metal in HAZ of welded joints were examined. The properties of single-type welded joints made in welding with consumable and non-consumable electrodes were compared.

It was established as a result of examination that in welding of alloy 1420 with non-consumable electrode using filler SvAMg63 the strength of welded joints is ≈ 330 MPa, and that of the weld metal — ≈ 320 MPa (Table 2). The artificial ageing of welded joints (120 °C, 8 h) can somewhat increase their strength (σ_t^w = 370 MPa; $\sigma_t^{w.m}$ = 345 MPa) and decrease the HAZ metal weakening. The use of the full cycle of the heat treatment of the welded joints including quenching (450 °C, 1 h, air) and artificial ageing (120 °C, 8 h) eliminates completely the metal weakening in HAZ. However, the hardness of weld metal will not reach the level of the parent metal that is explained by the decrease in lithium content in the weld metal (Figure 1). Depending on the chemical composition and the share of the filler metal (usually 20–30 %) the content of lithium in the weld metal can be reduced down to 1.3 %.

Table 1. Chemical composition of wires used for welding sheets of alloys 1420 and 1421

Type of wire	*Elements, wt.%*				
	Mg	*Sc*	*Zr*	*Ti*	*Mn*
SvAMg5	5.5	–	–	–	0.12
AMg5 + 0.2 % Sc	5.5	0.2	0.12	0.12	–
AMg5 + 0.5 % Sc	5.5	0.5	0.12	–	–
SvAMg63	6.5	–	0.2	–	0.5
AMg6 + 0.35 % Sc	6.5	0.35	0.12	–	0.2
AMg63 + 0.5 % Sc	6.5	0.5	0.2	–	–

Table 2. Mechanical properties of alloy 1420 welded joints, made by the non-consumable and consumable electrodes using wires of different chemical composition

Method of welding	*Type of wire*	*Ultimate rupture strength, MPa*		*Impact strength of weld metal, a_n J/cm^2*	*Angle of bending of welded joint, α, deg*
		Welded joint, σ_t^w	*Weld metal, $\sigma_t^{w.m}$*		
With non-consumable electrode	SvAMg5	$\frac{305.5–316.6}{311.1}$	$\frac{265.8–280.8}{275.2}$	$\frac{23.3–25.7}{24.8}$	$\frac{71–80}{76}$
	AMg5 + 0.2 % Sc	$\frac{320.5–327.5}{324.0}$	$\frac{295.2–306.9}{302.5}$	$\frac{21.7–23.3}{22.4}$	$\frac{76–79}{77}$
	AMg5 + 0.5 % Sc	$\frac{324.5–329.8}{327.2}$	$\frac{318.9–323.4}{320.5}$	$\frac{15.8–16.6}{16.2}$	$\frac{82–108}{97}$
	SvAMg63	$\frac{324.6–332.8}{328.7}$	$\frac{318.6–323.7}{321.5}$	$\frac{26.0–27.5}{26.8}$	$\frac{90–91}{90}$
	AMg6 + 0.35 % Sc	$\frac{316.6–336.0}{326.3}$	$\frac{315.5–323.6}{319.5}$	$\frac{14.6–17.0}{15.8}$	$\frac{85–87}{86}$
	AMg63 + 0.5 % Sc	$\frac{322.6–328.6}{325.6}$	$\frac{317.2–320.4}{318.8}$	$\frac{26.0–26.1}{26.0}$	$\frac{81–109}{97}$
With consumable electrode	SvAMg5	$\frac{327.1–333.8}{330.5}$	$\frac{311.5–321.0}{315.3}$	$\frac{11.9–12.6}{12.3}$	$\frac{60–65}{62}$
	AMg5 + 0.2 % Sc	$\frac{338.9–346.4}{343.3}$	$\frac{309.9–319.7}{313.8}$	$\frac{11.8–14.1}{13.2}$	$\frac{57–61}{60}$
	AMg5 + 0.5 % Sc	$\frac{335.4–342.1}{337.6}$	$\frac{310.7–321.8}{316.4}$	$\frac{8.2–9.4}{8.7}$	$\frac{43–49}{47}$
	SvAMg63	$\frac{320.9–332.3}{328.9}$	$\frac{309.9–328.9}{321.3}$	$\frac{13.2–15.2}{14.0}$	$\frac{65–66}{65}$
	AMg6 + 0.35 % Sc	$\frac{359.3–366.7}{364.4}$	$\frac{318.5–322.1}{319.7}$	$\frac{9.6–9.8}{9.7}$	$\frac{54–59}{57}$
	AMg63 + 0.5 % Sc	$\frac{354.2–358.4}{356.3}$	$\frac{313.2–328.7}{324.1}$	$\frac{10.3–12.0}{11.4}$	$\frac{55–61}{58}$

Note. Here and further the minimum and maximum values are given in the numerator, while in denominator the mean values from results of testing 3–7 specimens are given.

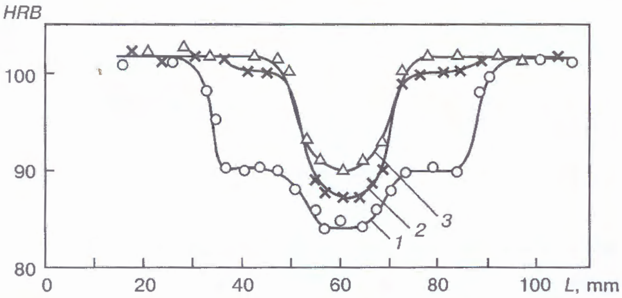

Figure 1. Change in hardness ($P = 600$ N) of welded joints of alloy 1420 produced by the non-consumable electrode using SvAMg63 filler: *1* — quenching + artificial ageing + welding; *2* — quenching + artificial ageing + welding + artificial ageing; *3* — quenching + artificial ageing + welding + quenching + artificial ageing

The use of filler with lithium, close by composition to alloy 1420, provides the strength of welded joints at the level of 315 MPa. After the full cycle of heat treatment of these joints this value is increased up to 405 MPa. In this case the increased porosity is observed, caused by the presence of lithium in the filler wire. In addition, the ductility of welds becomes lower (approximately by 3 times) than that in welds produced using fillers SvAMg6 and SvAMg63.

The use of wires containing 5.0–6.0 % Mg and 0.35–0.5 % Sc provides the strength of welded joints at the level 325, and weld metal — 320 MPa. When scandium is added into the filler, a solid solution of scandium in aluminium (up to 0.35–0.38 %) is formed in weld metal in the process of crystallization. This creates premises for the dispersion-hardening of welded joints due to decay of the solid solution after the heat treatment. With increase in a share of the Sc-containing filler the degree of solid solution saturation with scandium is increased, but, here, its stability is decreased abruptly.

In literature, the processes of decay of the scandium solid solution in aluminium alloys of systems Al–Sc, Al–Mg–Sc, and also Al–Mg–Li–Sc have been studied comprehensively enough [2]. It was established that the alloys of Al–Sc system possess high effect of the artificial ageing. Heating to 300 °C temperature leads to the intensive increase in hardness in the first minutes of soaking, and the maximum hardening is reached in this case after 1 h. The alloy is hardened by precipitation of dispersed uniformly distributed particles of $ScAl_3$ phase, which are coherent to matrix. For the alloy 1420 this heating is not suitable, because it causes almost its complete weakening due to coagulation of the Al–Li phase. The use of conventional conditions of the heat treatment of welded joints is not rational as the temperature of heating up to 450 °C in quenching for the Sc-containing materials is not desirable.

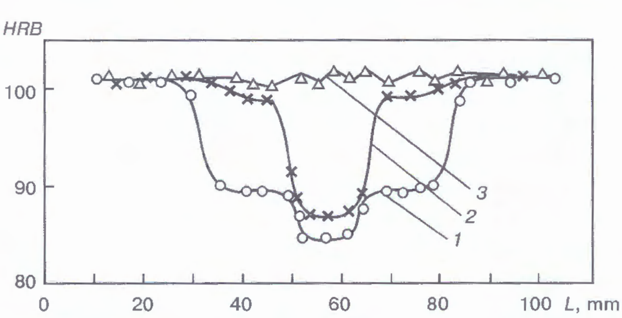

Figure 2. Change in hardness ($P = 600$ N) of welded joints of alloy 1420, produced by the non-consumable electrode using AMg63 + 0.35 % Sc filler: *1* — quenching + artificial ageing + welding; *2* — quenching + artificial ageing + welding + artificial ageing; *3* — quenching + artificial ageing + welding + heat treatment (400 °C, 1 h, air and 120 °C, 8 h)

The heat treatment conditions of welded joints were developed coming, first of all, from the realizing of both mechanisms of metal hardening due to precipitation of particles of main alloying elements of Al–Li alloys and particles of the Al–Sc phases.

Analysis of kinetic curves of changing hardness of alloy Al–Sc at different temperature-time conditions of ageing shows that there is a small interval of time (1/4–1 h) at temperatures above 350 °C (for example, 400 °C), during which the hardening of the alloy is observed and further its weakening takes place. The structural examination of alloys of the Al–Mg–Sc system showed that the coherence of phase $ScAl_3$ with a matrix is disturbed after annealing at 450 °C during more than 10 h [3]. Hence, it follows that the combination of the operation of the high-temperature short-time ageing (to precipitate the Al–Sc phase) with the operation of the high-temperature recovery to a hardened state and subsequent low-temperature ageing (to precipitate the hardening particles of main alloying elements) should increase significantly the hardness not only of the HAZ metal, but also of the weld metal. The 450 °C temperature is an allowable limit during decay of the scandium solid solution in aluminium, from one side, and corresponds to a low-temperature condition of hardening for alloy 1420, from the other side [4]. The application of heat treatment, including heating up to 400 °C during 1 h and artificial ageing at 120 °C during 8 h, made it possible to increase the hardness and strength of the 1420 alloy welded joints. Moreover, the hardness of metals of welds and HAZ in welding with consumable and non-consumable electrodes in case of using fillers, containing 0.35–0.5 % Sc, reaches the hardness level of the heat-hardened parent metal (Figure 2).

The mechanical rupture tests of specimens with a weld reinforcement showed that their fracture both after welding and also after heat treatment occurred in the fusion zone. The ultimate rupture strength of the 1420 alloy welded joints produced using a non-consumable electrode with a filler SvAMg5 was 311 MPa (see Table 2). When the rest filler wires were used, this value increased up to 325 MPa on average. The strength of weld metal made with filler SvAMg5 is at the level of 275 MPa. Adding of 0.25 % Sc promotes increase in strength of the weld metal up to 303 MPa. With increase in a mass share of scandium in filler up to 0.5 % this value is equal to ≈ 320 MPa, the same as in case of using wires with an increased content of the main alloying element. The maximum values of the impact strength of welds

Table 3. Mechanical properties of alloy 1420 welded joints made by the non-consumable and consumable electrodes using wires of different chemical composition after quenching and artificial ageing of specimens

Method of welding	*Type of wire*	*Ultimate rupture strength, MPa*		*Impact strength of weld metal, a_w J/cm²*	*Angle of bending of welded joint, α, deg*
		Welded joint, σ_t^w	*Weld metal, $\sigma_t^{w.m}$*		
With non-consumable electrode	AMg5 + 0.5 % Sc	389.4–390.7 / 389.9	431.2–444.1 / 436.0	9.0–9.3 / 9.2	36–41 / 39
	SvAMg63	383.6–386.5 / 384.6	357.3–361.4 / 360.7	20.0–24.6 / 22.7	60–65 / 63
	AMg6 + 0.35 % Sc	385.9–392.4 / 389.7	442.3–445.5 / 444.0	9.7–11.0 / 10.3	67–72 / 70
	AMg63 + 0.5 % Sc	387.6–390.1 / 388.9	444.1–449.4 / 446.1	14.6–14.7 / 14.7	68–75 / 72
With consumable electrode	SvAMg5	–	380.3–387.7 / 383.9	14.7–15.2 / 15.0	–
	AMg5 + 0.2 % Sc	–	404.3–409.0 / 406.6	10.8–14.7 / 13.2	–
	AMg5 + 0.5 % Sc	–	405.3–414.4 / 409.8	8.0–8.6 / 8.4	–
	SvAMg63	–	389.2–397.4 / 393.3	14.2–15.0 / 14.8	59–73 / 64
	AMg6 + 0.35 % Sc	–	421.9–427.9 / 424.9	8.6–8.9 / 8.8	48–51 / 50
	AMg63 + 0.5 % Sc	–	456.8–460.8 / 459.5	12.1–12.6 / 12.3	64–71 / 68

and angel of bending are provided in welding alloy 1420 using SvAMg63 and AMg63 + 0.5 % Sc.

In the consumable electrode welding the fusion zone is subjected to a lower heat action that provides the higher values of strength of the welded joints. Thus, in welding with wires SvAMg5 and SvAMg63 the ultimate rupture strength is ≈ 330 MPa, and, when the scandium is added, this value reaches 356 MPa depending on the magnesium content. As the filler share in the weld volume in welding with a consumable electrode is about 20 %, then the strength of weld metal, welded with wire SvAMg5, exceeded the similar value for welds made with a non-consumable electrode and was 315 MPa. At the higher content of magnesium in the filler the ultimate rupture strength of the weld metal was increased up to 320 MPa.

After heat treatment of welded joints, i.e. quenching (400 °C, 1 h, air) and artificial ageing (120 °C, 8 h), the values of strength increased significantly (Table 3). The ultimate rupture strength of joints made by the non-consumable electrode with a filler SvAMg63, reached 385 MPa, while 390 MPa was reached using the Sc-containing fillers.

To evaluate the strength of the weld metal the weakening (decrease in thickness of specimens) was made in a weld central part, as it was hardened to such extent that the place of fracture of flat specimens with a removed upper and lower bead reinforcement was shifted in most cases to the fusion zone. For the comparison, the strength of the parent metal after the heat-treatment was evaluated on similar specimens, cut out along the rolling direction. It was 462 MPa (impact strength – 7.6 J/cm, bending angle – 40°).

The ultimate rupture strength of weld metal of the joints, produced by the non-consumable electrode using filler SvAMg63, was 360 MPa. Here, the increase in strength during the artificial ageing (40 MPa) took place only due to precipitation of Al–Li phase. When 0.5 % Sc is added into this filler the ultimate rupture strength of the weld metal after the heat treatment is increased to 446 MPa. Hence, it follows that this value was increased by 86 MPa due to precipitation of Al–Sc phase, i.e. by 68 % of the total increment of this characteristic.

After the heat treatment of samples welded with a consumable electrode using fillers SvAMg5 and SvAMg63, the strength of the weld metal due to precipitation of the Al–Li phase was increased by 70 MPa. The higher increment in the ultimate rupture strength was stipulated by the higher content of lithium in the weld metal (a smaller share of filler) and saturation of the lithium solid solution in aluminium, than in welds made with a non-consumable electrode. When scandium is added into the composition of the welding wire the additional increase in the strength of weld metal after treatment occurs due to precipitation of the Al–Sc phase. The higher scandium content in the wire, the higher increment in the weld metal strength. Thus, in welding of alloy 1420 with a wire containing 0.35 % Sc, the ultimate rupture strength increased by 105 MPa (135 MPa from them were obtained due to Al–Sc phase), and using the wire containing 0.5 % Sc – by 136 MPa (increment

Table 4. Mechanical properties of alloy 1421 welded joints produced with non-consumable electrode using fillers SvAMg63 and AMg63 + 0.5 % Sc

State of welded joints	*Type of wire*	*Ultimate rupture strength, MPa*		*Impact strength of weld metal, a_n, J/cm^2*	*Angle of bending of welded joint, α, deg*
		Welded joint, σ_t^w	*Weld metal, $\sigma_t^{w.m}$*		
After welding	SvAMg63	381.4–388.2 / 383.9	322.5–332.6 / 328.4	8.0–10.0 / 9.0	104–112 / 107
	AMg63 + 0.5 % Sc	382.6–388.9 / 384.2	343.6–354.7 / 349.2	8.0–9.0 / 8.0	85–108 / 98
After quenching (400 °C, 1 h, air) + artificial ageing (120 °C, 8 h)	SvAMg63	412.5–417.1 / 413.1	422.5–439.6 / 431.1	14.8–16.6 / 15.7	50–53 / 51
	AMg63 + 0.5 % Sc	415.3–422.5 / 419.9	462.4–471.0 / 466.7	11.2–13.1 / 12.2	43–46 / 44

was 66 MPa due to Al–Sc phase, i.e. about 50 % of the total increase in the characteristic).

Thus, the offered conditions of the heat treatment of joints after welding make it possible to obtain the strength of the weld metal at the level 445–460 MPa, that is equal to 96–99 % of the parent metal strength. Here, 50–70 % of total increment of strength is reached due to adding 0.5 % Sc into the welding wire composition. The hardening, stipulated by the Al–Sc phase, depends on the filler share in the total volume of the weld metal and rate of its crystallization, which depends on the method of welding.

However, the strength of the 1420 alloy welded joints produced with Sc-containing fillers, after heat treatment amounts to about 80 % of the parent metal strength. One of the effective methods of its increase in the fusion zone of the parent metal with a filler can be scandium adding to the parent metal. This is confirmed by the results obtained at mechanical tests of specimens from alloy 1421 (Table 4). The ultimate rupture strength of welded joints, made with a filler, containing 0.5 % Sc, after the heat treatment is at the level of 420 MPa, that is more than 90 % of the parent metal strength (σ_t = 453 MPa, a_n = = 6.3 J/cm^2, α = 34°). The impact strength of weld metal and angle of bending of welded joints of alloys 1420 and 1421 after the heat treatment exceed these values for the parent metal.

It can be concluded that the strength of the weld metal produced by the argon arc welding of alloy 1420 (initial state: quenching + artificial ageing) using wires of the AMg63 type with 0.35–0.5 % Sc is increased from 319–329 to 446–459 MPa after the heat treatment.

The developed conditions of heat treatment of welded joints of alloy 1420 make it possible to realize two stages of hardening by a precipitation of dispersed Al–Sc phases (400 °C, 1 h) and strengthening particles of the main alloying elements (120 °C, 8 h). The first stage provides the high-temperature recovery of metal to the quenched state with a dissolution of the hardening phases formed by the main alloying elements of the alloy and simultaneous precipitation of the particles of the Al–Sc phase $ScAl_3$ (high-temperature ageing). At the second stage the precipitation of strengthening particles of the main alloying elements of the δ′-phase occurs.

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USING ULTRASONIC WELDING FOR JOINING VARNISH-INSULATED WIRE IN ELECTRIC ENGINEERING APPLICATIONS

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Ultrasonic welded joints between varnish-insulated wire and mating elements of copper and its alloys CuSn6 and CuZn37 were studied. The best results were achieved with estherimide-based varnish insulation, as well as with control of welding cycle by a relative displacement of a waveguide.

Key words: ultrasonic welding, varnish-insulated wire, ultrasonic generator, welding machine, waveguide

High requirements to electric engineering products make manufacturing companies develop and apply new joining methods to provide reliable contacts between varnish-insulated copper wires and various elements. For this it is important to combine operations of removal of an insulating layer and welding in one cycle. Conventional, widely applied joining methods, such as resistance welding or soldering, do not always allow these operations to be combined, as quality of a joint depends to a considerable degree upon technological properties of varnish insulation. The trend to rationalization of production and reduction of costs led to intensification of research on application of new alternative methods for joining varnish-insulated wires. They include also ultrasonic welding (USW). An advantage of this method is in the possibility of mechanically destroying and removing the varnish insulation layer from the contact zone by introducing high-frequency oscillations, followed by formation of the joint in one welding cycle.

Brief review of the state-of-the-art. Varnish-insulated wire takes the leading place among wires used to manufacture windings in electrical engineering products, which is attributable, in particular, to a small thickness of the insulation layer [1]. In making modern insulation varnishes a special consideration is given to the point of combination of high heat resistance with good insulating and mechanical properties, as well as resistance to impact of aggressive chemical environments [2]. The ester-based varnishes, e.g. esterimide- and esterimidamide-based ones [3], find the widest application now for production of insulating coatings. Two-layer varnish-insulated wires, having much better technological properties [2], are most often employed for manufacture of motors and transformers. Such an insulation is usually made using THEIC-poly- or esterimide as the base layer and polyamidimide as the surface varnish layer [4]. Recently the so-called sintering varnishes, making it possible to avoid the use of additional impregnation solutions [2], have received wide acceptance for manufacture of electric motors. A winding made of the wire with such a varnish coating is heated in furnace or by the electric current flow and sintered to form a stable bundle [2, 5].

In up-to-date commercial production the varnish-insulated wires are joined to different mating elements mostly by soldering, resistance welding, mechanical methods (using clamps or clips) or, in some cases, by laser welding. Substantial problems in making such joints are caused by the presence of a layer of the varnish-insulating coating, which prevents formation of a metallic bond between the wire and an element. In the majority of cases this layer is removed from the contact zone mechanically, chemically or thermally prior to or during the joining process. In this case it is necessary to take into account that cleaning

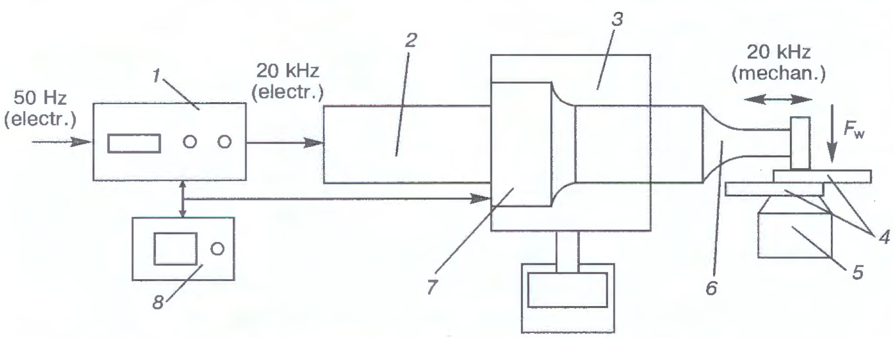

Figure 1. Schematic of the machine for USW: *1* — generator; *2* — converter; *3* — welding press; *4* — parts to be joined; *5* — support; *6* — waveguide; *7* — amplifier; *8* — control device

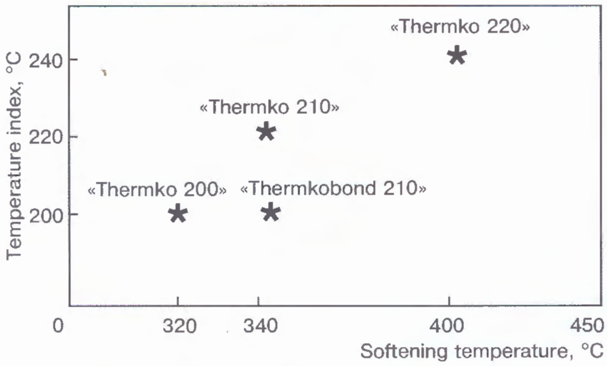

Figure 2. Thermal properties of varnish-insulating materials (test time — 20,000 h)

of the wire prior to welding involves an extra time consumption for performing this operation, difficulties with limitation of the surface to be cleaned and risk of damaging the copper core.

Ultrasonic welding. The principle of USW is based on high-frequency (20–60 kHz) friction of the mating surfaces of parts joined. Electric oscillations formed by an ultrasonic generator are converted into mechanical ones and introduced via amplifier and waveguide into the welding zone (Figure 1). The parts to be welded rest on a stable, rigidly fixed support. The introduced ultrasonic oscillations, as well as the waveguide compression force, lead to a high-frequency horizontal displacement of the part surfaces with respect to each other to form a welded joint [6–9]. In USW of metals the joint is formed in a solid state due to activation of interatomic forces at the interface between the mating surfaces [6]. Temperatures during the welding process are comparatively low, not in excess of 0.4–0.6 of the melting point. In addition to basic welding parameters (frequency and amplitude of oscillations, compression force, welding time) and properties of a material, the following conditions are also important for producing a sound joint: possibility of an unhampered access of the waveguide and support to the contact zone, stable position of the support and insensitivity of a structure welded to a high-frequency dynamic load.

The USW method possesses a number of advantages, owing to which its application is especially promising for electric engineering and electronics [6, 7, 9–11]. One of the most important advantages is that no surface preparation for welding is required in the majority of cases. Contaminants and oxide films present on the surfaces of parts are destroyed directly during the welding process under the effect of ultrasonic oscillations and forced out from the contact zone [6]. Investigations conducted by Soviet engineers in the 1960s proved the feasibility of using USW for joining wires with insulation of the type of PEL and PEH without the need to remove the insulation layer and preliminarily prepare the mating surfaces [12].

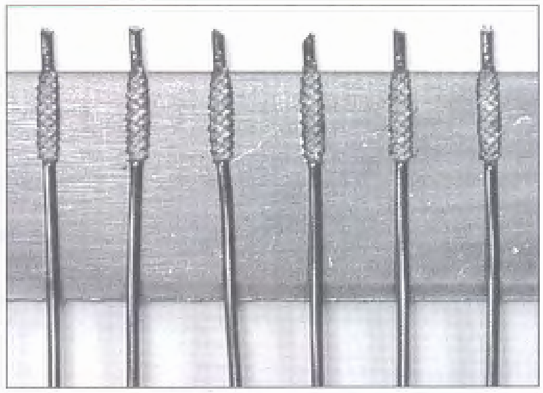

Figure 3. Joining the 0.8 mm varnish-insulated wire to a copper plate by the USW method

Equipment and materials under investigation. A varnish-insulated one-filament copper wire with a diameter of 0.3–2.0 mm, which is most often employed in up-to-date commercial manufacture, was selected for investigations. The insulation materials selected differed in operational characteristics or thickness of the varnish layer (Table).

One of the most important operational properties, exerting a substantial effect on weldability in resistance welding and soldering, is heat resistance of varnish insulation (Figure 2).

Electrically conducting mating elements (busbars, relays, plugs), joined to varnish-insulated wires, are made primarily from copper alloys, which should have a good bending resistance, in addition to high electrical conductivity. Pure copper E-Cu 57 (No.2.0060.08 acc. to DIN 1787), as well as alloys CuSn6 (No.2.1020.26 acc. to DIN 17662), CuSn6Zn6 (No.2.1080 acc. to DIN 17662) and CuZn37 (No.2.0321.30 acc. to DIN 17660) were selected for the investigations as mating materials. Wires were overlap welded to rolled plates (Figure 3) with surface roughness $R_z = 3.2$ nm. The plates welded were 100×15×2 mm in size, while the length of a welded joint was 5 mm.

Welding was performed using the USW machine with a working frequency of 20 kHz (Figure 4). The machine consists of an ultrasonic generator with a power of 3 kV, welding press with the possibility of

Insulation varnishes under investigation

Type of varnish	*Designation*	*Standard*	*Layer*
Polyesterimide	«Thermko 200»	DIN 60317-8	Simple (degree 1)
Polyesterimide and polyamidimide as a coating	«Thermko 210» «Thermko 210 2L»	DIN 60317-13	Same Increased (degree 2)
Polyamidimide	«Thermko 220»	DIN 60317-26	Simple (degree 1)
Base — polyesterimide, polyamidide as a coating; sintering varnish — aromatic polyamide	«Thermkobond 210»	DIN 60317-38	Same (degree 1B)

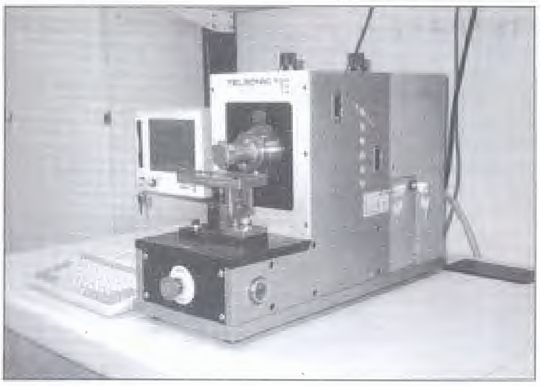

Figure 4. Machine for USW of a varnish-insulated wire

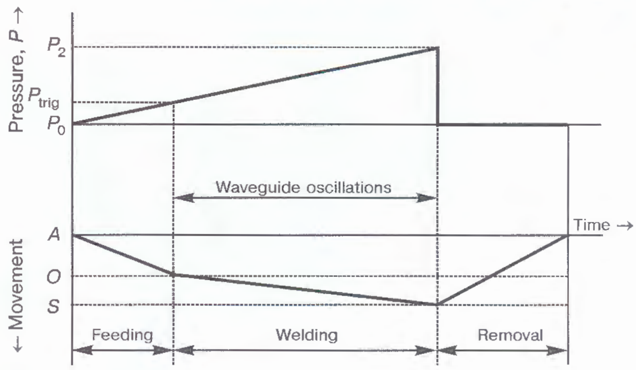

Figure 5. Diagram of the welding cycle (A — initial position of the waveguide)

setting the compression force in a range from 100 to 1700 N, and a microprocessor control and monitoring system.

The joints were welded on a support rigidly fixed by screws to the welding machine frame. Riffles were made on the working surface of the waveguide to improve adhesion of the tool to the wire.

Investigation results. *Selection of optimal welding conditions.* Maximum tensile strength of joints and minimum spread of their strength characteristics served as criteria for selection of optimal welding parameters. In addition, the trend was to minimization of amplitudes of oscillations of the waveguide, welding time and deformation of the wire. While optimizing welding parameters, the special consideration should be given to selection of a proper welding cycle, which should include trigger and welding modes to determine the moment of switching on of ultrasonic oscillations and duration of the welding process, respectively. As shown by the experiments with different welding cycles, it is important to ensure uniform deformation of the wire to achieve high reproducibility of the results. Consistency of deformation was achieved by selecting such welding conditions under which the welding process would start upon reaching the compression force corresponding to pressure P_{trig} and end after the waveguide had passed a preset relative path OS (Figure 5).

As the process of USW of varnish-insulated wire comprises stages of destruction of varnish and subsequent formation of a joint, optimal results are achieved by using a combined force of compression of the waveguide, enhancing during the welding process. Advantages of application of such a programmable compression force can be well illustrated by a pattern of fracture of the joint on the surface of a plate. A lack of penetration region is well seen at the center of the fracture surface of the joint welded at a constant compression force (Figure 6, *a*). Using the compression force that is increased during the welding process provides a welded joint uniformly distributed over the entire contact zone (Figure 6, *b*).

Effect of wire diameter on weldability. Depending upon the diameter of a wire, the optimal results are achieved at amplitudes of oscillations of the waveguide equal to 15 to 35 μm, a compression force within a range of 130–550 N and assigned displacements of the waveguide from 60 to 65 % of the wire diameter. Actual deformation of the wire, i.e. difference between the initial diameter of the wire and height of a region welded, is about 50 % of the initial diameter. The difference in values is attributable to inclusion of height of the riffles and level of deformation of the lower plate into the measured welding displacement.

Strength tests of welded joints showed that pulling forces amount to about 30–45 % and rupture forces — to about 60–70 % of tensile strength of the wire, depending upon the diameter (Figure 7). The tests also showed that the rupture force value depends mostly upon the degree of deformation of a joint and cannot be used as a reliable criterion for assessment of quality of the joint.

It should be noted that welding parameters optimized as a result of the investigations are no more than the initial point for working with actual weld-

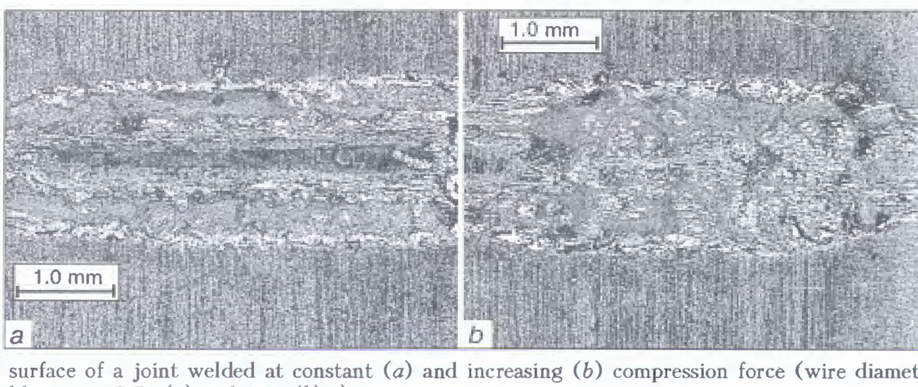

Figure 6. Fracture surface of a joint welded at constant (*a*) and increasing (*b*) compression force (wire diameter 1.4 mm, varnish «Thermko 210», welding time 0.71 (*a*) and 0.69 (*b*) s)

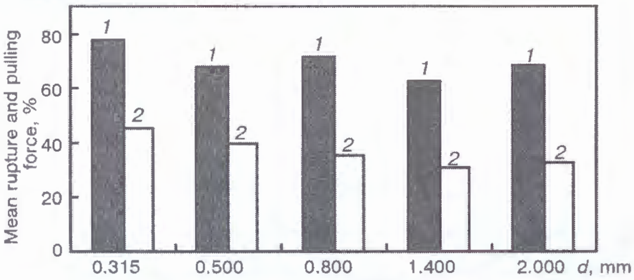

Figure 7. Mean rupture (*1*) and pulling (*2*) force for welded joints (percent of tensile strength), depending upon wire diameter *d*

ments. In the case of variations in boundary conditions, such as design of the backing, etc., it is necessary to refine welding parameters, allowing for peculiarities of a structure to be welded.

Good quality of the joints made was also confirmed by metallography (Figures 8 and 9). Investigations of sections of the welded joints revealed that metal of the contact zone was susceptible to intensive deformation at increased temperature. The process of formation of a welded joint was accompanied by an intensive plastic flow of metal to form local «whirls» and dilution in the subsurface regions.

The degree of plastic deformation in local regions (their width is not large) is so high that boundaries of individual grains are indistinguishable even at high magnification. At a distance of 0.3–0.4 mm from the contact zone the values of microhardness of metal are equal to those of the base metal.

Effect of the insulation varnish on weldability. Independently of a welding method used, destruction and removal of the insulation varnish from the contact zone are the main requirements for formation of a metal joint between the wire and a part. In USW destruction of the varnish insulation occurs primarily due to mechanical friction between the wire and the mating element. The investigations conducted showed that independently of the operational properties of a varnish and thickness of the insulation layer, the achieved values of strength vary almost identically (Figure 10). The process of fracture of the insulation layer starts directly at the moment of introduction of ultrasonic oscillations, and its duration is about 30–40 % of the total welding time. Nevertheless, as shown by a direct comparison of welding parameters, welding of the wire covered by high-temperature

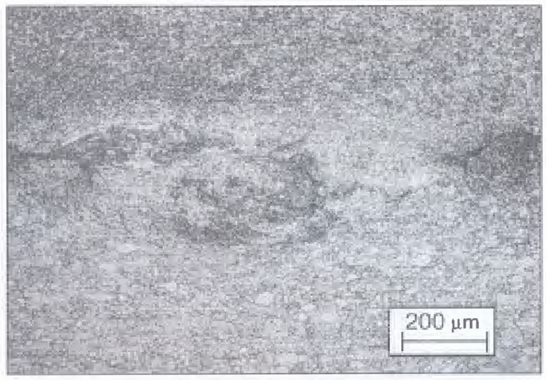

Figure 9. Transverse section of a welded joint (wire diameter 1.4 mm, varnish «Thermko 210»)

polyamidimide requires a higher amplitude of oscillations of the waveguide and a welding time increased by ≈ 100 ms.

Effect of a mating material on weldability. Investigations of the effect of a mating material on weldability to varnish-insulated wires were conducted using a 0.8 mm wire and highly heat-resistant varnish «Thermko 220». It was established that the equal strength characteristics of the joints were observed in the case of using all copper alloys selected for the investigations. In all of them the rupture force amounted to 100 N (≈ 70 % of tensile strength of a wire), and mean values of the pulling force were in a range of 50–60 N, i.e. amounted to 35–40 % of tensile strength of the wire.

Comparison of optimized parameters of the process showed that joining the varnish-insulated wire to plates of alloys CuSn6 and CuSn6Zn6 required the smallest amplitudes of oscillations of the waveguide (22 μm) and joining the above wire to plates of pure copper required the maximum amplitudes (27 μm). A positive effect on ultrasonic weldability is exerted first of all by an increased hardness of copper alloys, which favours the process of destruction of the varnish layer. Welding the wire to pure copper results in a rapid wear of comparatively soft peaks of roughness of the plate surface, which makes the wire slip over this surface. To reduce the time of welding using mating elements of pure copper, it is necessary to increase the energy input or use higher oscillations amplitudes. A good quality of welding between var-

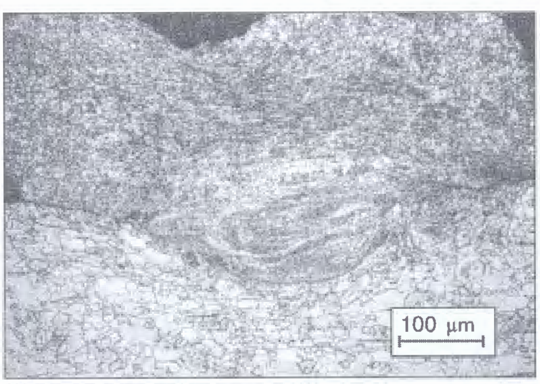

Figure 8. Transverse section of a welded joint (wire diameter 0.5 mm, varnish «Thermkobond 210»)

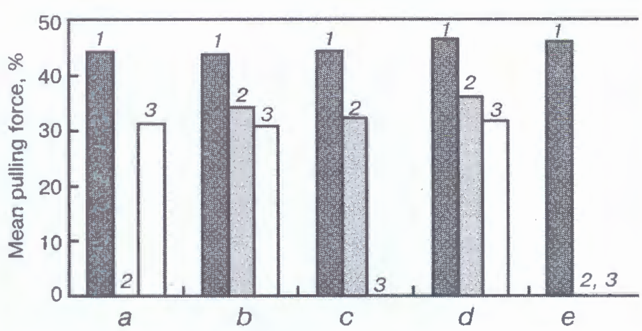

Figure 10. Effect of different types of varnish insulation on values of pulling force for welded joints (percent of tensile strength of the wire) using varnish «Thermko 200» (*a*), 210 (*b*), 220 (*c*), 210-2L (*d*), «Thermkobond 210» (*e*) (thickness of varnish 0.315 (*1*), 0.800 (*2*) and 1.400 (*3*) mm)

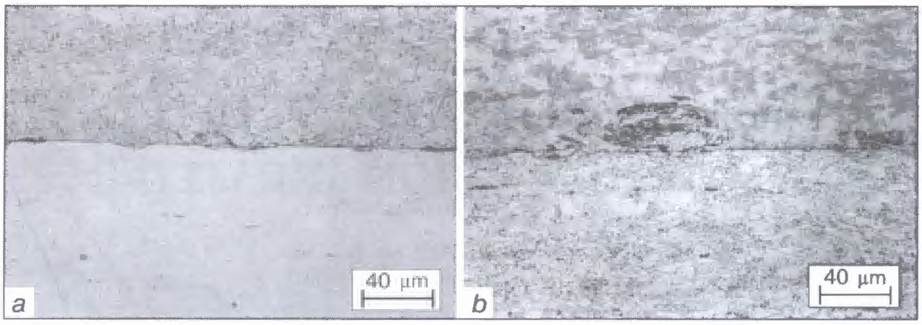

Figure 11. Transverse section of a welded joint (wire diameter 0.8 mm, insulation varnish «Thermko 220», mating material CuSn6 (*a*) and CuZn37 (*b*))

nish-insulated wires and copper alloys under investigation was also proved by metallography of sections of welded joints (Figure 11).

Defects of varnish-insulated wire in USW. The most often defects in USW of varnish-insulated wire include insufficient strength of a joint and damage of a varnish insulation with a probable destruction of the wire. The most important conditions for providing good strength of the joint are welding using optimal parameters and maintaining a constant geometry of a weldment in welding of a large number of pieces.

Damage to varnish insulation is caused by an effective dynamic load, which increases with an increase in the oscillations amplitude and welding time, and with a decrease in the compression force. Exceeding the elasticity limit is accompanied by narrowing of the wire, followed by fracture. In the majority of cases, where wire is supplied in a coiled or other fixed form, its damage can be avoided by selecting optimal welding parameters. The probability of damage will be much higher in welding the wire with free (unfixed) ends. In this case the problem can be solved by adding ultrasonic oscillations in a direction across the longitudinal axis of the wire. This approach can also be employed in the cases where geometry of a weldment does not allow access of the tool to perform welding along the longitudinal axis of the wire.

Conclusions. The USW method can be used to join varnish-insulated wire with a diameter from 0.3 to 2.0 mm to mating elements of copper alloys. The best results were obtained using insulation of an esterimide-base varnish and sintering varnishes. Optimization of welding parameters with regard to static strength of welded joints (pulling and rupture forces), allowing for reproducibility of the results, showed that the optimal welding cycle is that controlled by a relative displacement of the waveguide. To decrease the load acting on the waveguide, it is best to combine the parameters with the minimum possible amplitude of oscillations of the waveguide. In welding the varnish-insulated wire with a diameter of over 0.8 mm the best welding results are achieved in the case of using a combined force profile.

Despite comparatively good strength characteristics of a welded joint, the USW method fails to provide its homogeneity over the entire contact zone, i.e. independently of the technological characteristics of a varnish used for insulation, individual regions with lack of penetration are detected in the welding zone. Nevertheless, the achieved strength values correspond to requirements imposed on the quality of a joint.

In addition, the investigations performed showed that in welding varnish-insulated wires the tool was subjected to a heavier wear than in welding non-insulated wires. In view of a high cost of the waveguide, further investigations aimed at improvement of its wear resistance are required in order to commercially apply the USW method for joining varnish-insulated wires.

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LIMITING THICKNESS OF WELDED JOINTS TO BE EXPLOSION TREATED

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Results of investigation of the efficiency of relieving residual welding stresses in joints of low-carbon steel up to 50 mm thick are given. The effect of some factors (ambient temperature, hardening modulus and strength of a material treated, and loading factor) is described. It is shown that the limiting thickness of a metal welded, that «senses» one-sided explosion treatment using detonation cords or a low-pulse explosive charge, can amount to about 50 mm.

Key words: *submerged-arc welding, welded joints, low-carbon and low-alloy steels, explosion treatment, residual stresses, relieving residual stresses, external load, elastic deformation, elongation, calculations, investigations*

As it was established earlier [1, 2], explosion treatment (ET) using standard explosives allows a sufficiently efficient relief of residual stresses (RS), averaged through thickness of the metal welded, in butt welded joints of low-carbon and low-alloy steels up to 30 mm thick (the main array of experimental data accumulated to date concerns welded joints up to 16 mm thick). This treatment is performed, for example, to avoid corrosion cracking of welded joints, which can be achieved by eliminating the energy basis of this process. Meanwhile, the practice showed the need for widening the range of thickness of welded joints to be subjected to ET, first of all, towards its increase. Foreign researchers also express much interest in this problem.

It is shown in [1] that the degree of decreasing thickness-averaged RS greatly depends not only upon the kind and power of an explosive, but also upon the geometry of a charge and its location relative to the weld. It turned out that decrease in thickness-averaged maximum residual tensile stresses $\Delta\sigma$ was proportional to mass m of an explosive per unit length of the weld with a given method of treatment:

$$\Delta\sigma = \frac{Qm}{pk\delta},$$

where Q is the specific heat of explosion of a given explosive; p is the empirical factor of the efficiency of treatment by a specific method, characterizing power efficiency of the charge per 10 MPa (conditionally accepted value) of maximum residual tensile stresses induced by treatment; $k = \sigma_y/\sigma_1^0$ and $\delta = \delta_1/\delta_1^0$ are the dimensionless coefficients allowing for the effect of strength and thickness, respectively, of a joint treated, the assumed basic values of the parameters being equal to $\sigma_1^0 = 250$ MPa and $\delta_1^0 = 10$ mm (conditionally accepted values) (here σ_y is the yield strength and δ_1 is the weld metal thickness).

Recommended values for p for some loading methods and types of explosives are given in [1]. It is characteristic that the value of p may be different by an order of magnitude in different ET methods, which is indicative of a non-legitimacy of directly relating the efficiency of ET only to the specific (per unit length of the weld) energy of an explosive charge [3].

The purpose of the work described in this article is to generalize the available experimental data on the effect of the treatment parameters used with typical ET methods on the efficiency of relieving RS, averaged through thickness of the weld metal, in butt welded joints of low-carbon and low-alloy steels up to 30 mm thick with a yield strength of $\sigma_y = 240$–350 MPa. This will allow prediction of a limiting thickness of the joints which can be subjected to treatment by explosive charges located on one side of a weldment.

Treatment of welded joints 500×400×δ in size with a weld located along the longitudinal axis and produced by automatic SAW was carried out using methods described in [2]. The methods involved the use of a «serpentine» arrangement of detonation cords (DC), with a specific weight of an explosive equal to 12 g/m, and linear arrangement of the same DC and a low-pulse plate-type explosive charge. Residual stresses were determined before and after ET by a procedure of non-destructive strain measurement suggested in [4], based on measuring increments in elastic strain of the «reference» zone of a sample, induced by applying an external load. Also, control measurements of RS were made selectively. For this, samples were cut into strips 8–25 mm wide. Increments in strains were measured by resistance strain gauges and a mechanical strain meter on a base of 10 mm. In the as-welded state the RS values of the samples amounted to the values of yield strength σ_y. Approaches suggested in [5] were employed to generalize the experimental results. All the below values of RS are averaged on the basis of the results of not less than 5 measurements.

Figure 1, *a* shows dependence of RS induced in welded joints of steel St.3 (C — 0.14–0.22; Mn — 0.3–0.6 wt.%; Fe — balance) upon the number n of linear cord-type explosive charges (DC). It was established that despite a certain spread of the measurement results, associated with procedural errors and

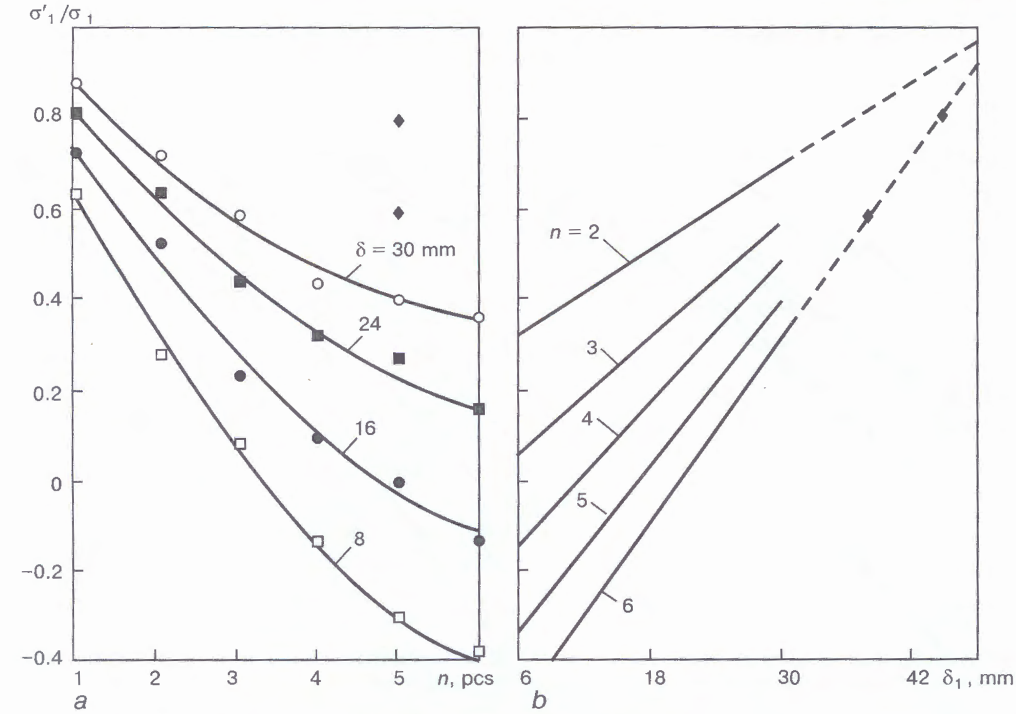

Figure 1. Dependence of maximum resulting tensile RS in butt welded joints of low-carbon steel upon the number n of DC (a) and thickness δ_1 of a welded joint (b): ◆ here and below the results of control experiments are given

variations in diagrams of initial RS in some plates, experimental points corresponding to different thickness of the metal welded fell on the fan-like family of the curves outgoing from a point with coordinates (0, 1).

The curves can be satisfactorily approximated by the family of half-parabolas passing through the point with coordinates (0, 1), the apices of the half-parabolas lying on a straight line with an abscissa of $n = 8$. The family of these half-parabolas is described by the following equation:

$$\frac{\sigma'_1}{\sigma_1} = 1 - a\,(\delta_1)\,\frac{V}{f+1}\,\frac{\sigma^0}{\sigma_y}\,(16 - n)n,$$

where $\sigma_1 = \sigma_y$ are the initial longitudinal RS; σ'_1 are the RS after ET; V is the transverse size of the stress-strain trace (SST) after ET [2, 5]; $f = F_1/F_2$ is the ratio of areas affected by tensile residual stresses F_1 and compressive residual stresses F_2; σ^0 are the stresses in the effective SST [2]. Function $a(\delta_1)$ is determined experimentally. For example, at $\sigma^0/\sigma_y = 2$ and $V/(f + 1) = 5$ the value of this function is $a(\delta_1) = 6{\cdot}10^{-6}\,(50 - \delta_1)$, i.e. $\sigma'_1/\sigma_1 = 6{\cdot}10^{-6}\,(50 - \delta_1)(16 - f)f$.

Figure 2, a shows the calculated curves used for approximation of the experimental data. These data were also used to plot dependencies of the degree of a decrease of tensile RS upon the thickness of an explosion treated welded joint (Figure 2, b). These dependencies have the form of straight lines, which is attributable to a linear character of the decrease in the ratio of depth w of SST to thickness δ_1 of a plate. Extrapolation of the dependencies derived with respect to ordinate $\sigma'_1/\sigma_1 \cong 1$ allows estimation of maximum thickness of a welded joint at which one-sided treatment using standard DC has a marked effect on its stressed state. In this case it amounts to about 50 mm. Results of the control experiments conducted on welded plates 35 and 45 mm thick (see signs ◆ in Figure 2, b) are indicative of an applicability of the approximation used.

Experimental dependencies of variations in the RS values at a different pitch of the «serpentine» arrangement are slightly curvilinear and have asymptote $\sigma'_1/\sigma_1 \cong 1$ (see Figure 2). In a range of rational values of the «serpentine» arrangement pitch ($S = 4$–14 cm) they can be approximated by a bundle of straight lines outgoing from the point with coordinates $S \approx 20$ cm and $\sigma'_1/\sigma_1 \cong 1$. The family of these straight lines is described by the following equation:

$$\frac{\sigma'_1}{\sigma_1} = 1 - \frac{2V}{f+1}\,\frac{\sigma^0}{\sigma_y}\,a(\delta_1)(20 - S).$$

Function $a(\delta_1)$, like before, can be determined as a result of processing of the experimental data. For example, at $\sigma_1^0/\sigma_1 = 3$ and $2V/(f + 1) = 10$, we have the following equation:

$$\frac{\sigma'_1}{\sigma_1} = 1 - 6.7{\cdot}10^{-6}(50 - \delta_1)\,(120 - S),$$

which corresponds to straight lines in Figure 2, a. They also can be used to plot dependencies $\sigma'_1/\sigma_1 = F(\delta_1)$, the extrapolation of which to ordinate $\sigma'_1/\sigma_y = 1$ was used to determine the limiting thickness of the plate reacting to variations in the treatment parameters under consideration. In this case it is ≈45–50 mm. Samples 35 and 45 mm thick were subjected to a series of control experiments on one-sided treatment with the «serpentine» arrangement at a pitch of $S = 4$ cm and the detonation ignition [6]. A decrease in RS of about 20–30 and 15–20 %, respectively, was

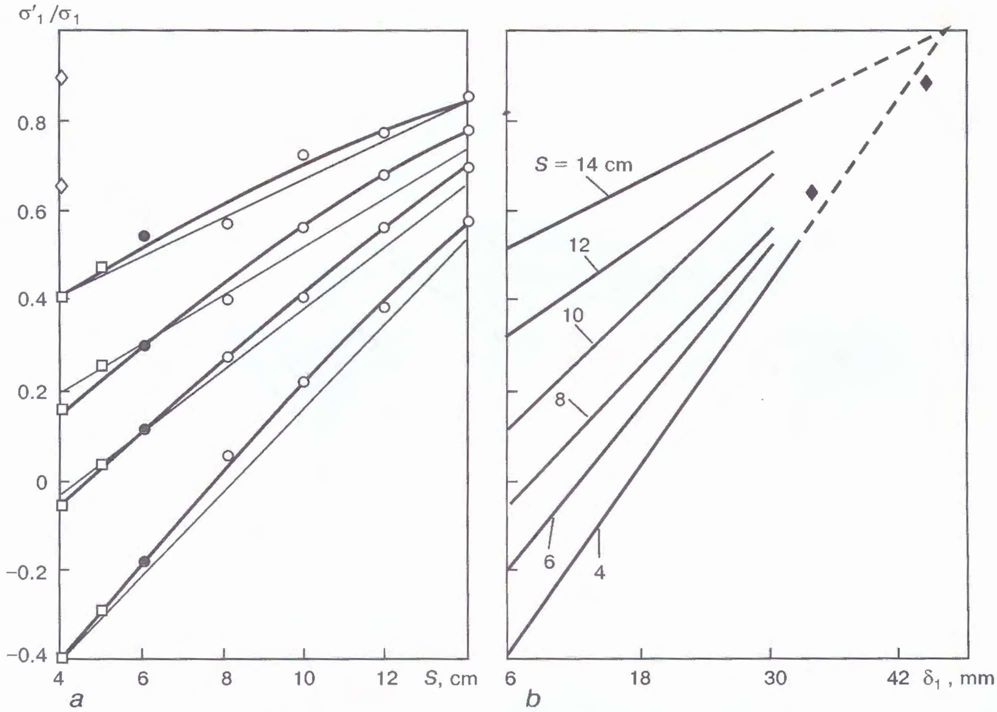

Figure 2. Dependence of maximum resulting tensile residual stresses in butt welded joints of low-carbon steel at ET with the «serpentine» arrangement upon the pitch S of the latter (a) and thickness δ_1 of a welded joint (b): ○ — «serpentine» with one line of DC; ● — two lines of DC; □ — one line of DC with detonation ignition

detected in this case, which is in a satisfactory agreement with the calculation data (see signs ◆ in Figure 2, b). The limiting thickness of welded joints is determined by a certain minimum value of the w/δ_1 ratio ($w \cong 10$ mm is the depth of SST), which is about 0.2 for both methods of ET.

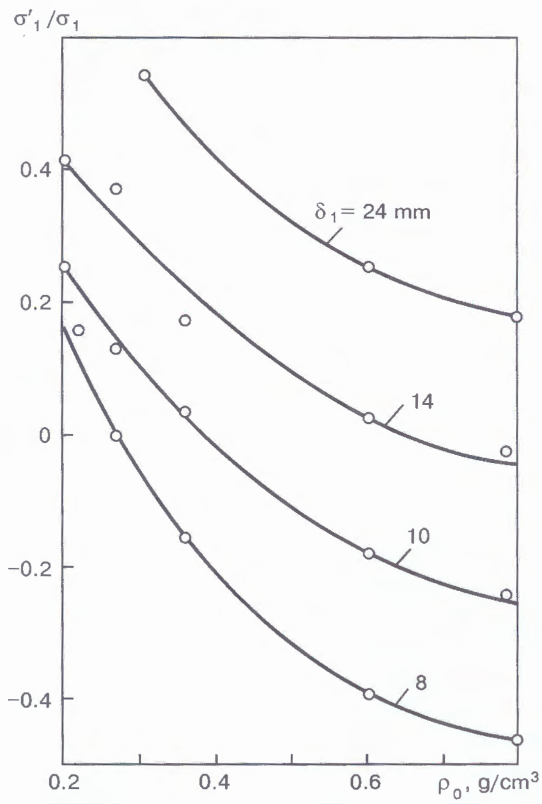

Figure 3. Dependence of maximum resulting tensile RS in butt welded joints of low-carbon steel upon density ρ_0 of a low-pulse strip-type explosive charge

Dependence of relative values of maximum resulting tensile residual stresses upon density ρ_0 of a low-pulse strip-type explosive charge at a different thickness of the plates is shown in Figure 3. The curves describing them converge at a point with coordinates (0, 1). The efficiency of relieving RS continuously grows with an increase in density of an explosive to a maximum value (0.7 g/cm^3). Values of resulting RS depend to a substantial degree upon thickness of a joint. Figure 4 shows dependence $\sigma'_1/\sigma_1 = F(\delta_1)$ obtained in treatment of the plates of steel 09G2S (C – 0.09–0.1; Mn – 1.5; Si – 0.4 wt.%) using a low-pulse explosive charge with a density of 0.5 g/cm^3. Values of resulting RS rapidly grow with an increase in thickness of metal, and at $\delta_1 \cong 40$ mm they remain mostly at a level of the initial values. At $\delta_1 \cong 12$ mm residual stresses in a weld change sign, while at $\delta_1 \cong 8$ mm they amount to about $0.5\sigma_y$. The curves reflecting dependence of RS upon the width of a strip-like charge of a low-pulse explosive are similar to those shown in Figure 3. Like in the case of the cord-type charges, at a fixed value of ρ_0 these curves are close to parabolas of the following kind:

$$\frac{\sigma'_1}{\sigma_1} = a_2(\delta_1)f'(f' + 1) + 1,$$

passing through the point with coordinates (0, 1) and outgoing at different values of δ_1 to the corresponding asymptotes. Here f' is the ratio of width of the strip of a low-pulse explosive to width of the zone of welding thermal-plastic strains and $a_2(\delta_1)$ is the empirical function.

As the stressed state in SST is biaxial, explosion treatment has a favourable effect on transverse RS as well. With all the ET methods investigated, the approximate proportionality persists between resulting longitudinal σ'_1 and transverse σ'_2 RS. The ratio of $\sigma'_1/\sigma'_2 = 2$–4 can be utilized for practical estimation.

Figure 5 shows results of a series of experiments, which allowed establishing the dependence of the RS values measured by the non-destructive strain measurement method [4] on two sides of the plates of steel with $\sigma_y = 260$ MPa after ET («serpentine» with $S = 4$ cm and detonation ignition [6]) upon thickness of the metal welded. The curves which reflect variations in RS on both sides of the plates are of an asymptotic character. With an increase in δ_1 the RS values measured on the surface subjected to ET tend to a limiting value, which is approximately equal to $0.2\sigma_1$, and those on the opposite surface tend to a value of σ_1, i.e. at $\delta_1 \geq 30$ mm they remain almost at the initial level. With a decrease in the δ_1 values these curves converge and intersect at the point with an abscissa of 8 mm. Coordinates of this point characterize the depth of SST and its effective intensity [2, 5].

To illustrate capabilities of the method [4], Figure 5, curve *4* shows dependence of increments, caused by ET, in values (with an opposite sign) of maximum residual tensile stresses upon the distance to the surface treated. As shown by the investigation results, the dependencies obtained are valid in general also for other types of welded joints (and other loading methods), and can be employed a priori for assignment of parameters of their explosion treatment for steels of the strength grade under consideration.

Therefore, one-sided ET of welded joints using typical explosives both with the «serpentine» and linear arrangements is efficient for thickness of a welded joint equal to $\delta_1 \leq 30$ mm. To provide a more complete relief of RS, averaged through thickness of a metal welded, in welded joints $\delta_1 \geq 30$ mm thick, it is necessary to use more powerful explosives or two-sided explosion treatment.

Below we consider the effect of some factors on a decrease in the RS values using mostly the deformation methods of post-weld treatment.

Existing analytical approaches to estimation of the efficiency of relieving RS by application of an external load [7, 8, etc.] relate mostly to a single static loading at room temperature of materials which have a yield plateau. Meanwhile, in many cases the external load can be applied to welded joints made of materials of different strength levels (we will characterize this strength in terms of a yield strength), of hardenable materials, at decreased climatic temperatures or increased deformation rates, including multiple applications of the external load (vibration, high-rate deformation, ultrasonic and electric hydropulse treatment, etc.).

Let us analyze in general the character and degree of the effect of the above concurrent factors on the end results of ET, using an approach suggested in [9].

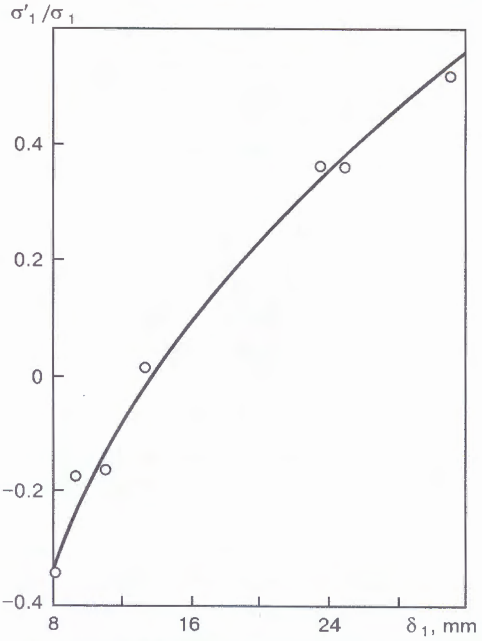

Figure 4. Dependence of maximum resulting tensile RS upon thickness δ_1 of a welded joint in the case of treatment using low-pulse explosive charges

In this case we will proceed from the fact that if the end result of ET is determined by a combined action of two non-competing factors (relaxation of tangential stresses and selective plastic deformation of metal), in realization of other deformation methods of relieving RS the main contribution in their decrease is made by plastic deformation. Therefore, to generalize considerations, the analysis conducted is focused on studies of plastic strains induced in metal by the external load.

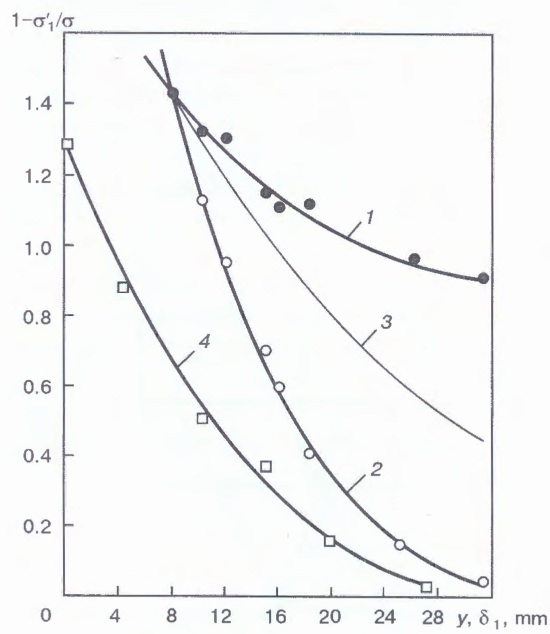

Figure 5. Dependence of maximum resulting tensile RS after ET upon thickness of a welded joint: *1* — RS on the sample surface subjected to ET; *2* — RS on the opposite side of the above surface; *3* — values of RS averaged through thickness of a joint; *4* — dependence of increment (as a result of ET) in maximum RS upon the distance to the surface treated; *y* — coordinate of the axis directed downward through thickness of metal

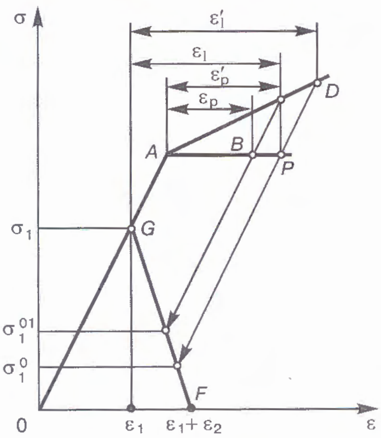

Figure 6. Constructions on the σ–ε diagram illustrating the effect of hardening on a decrease in RS (value with a prime characterizes a material with hardening)

Below we will use the following notions: if σ_y is the yield strength of a material, then ε_y is the strain corresponding to it; σ_1 are the initial residual stresses; ε1 is the elastic strain of a stretched zone of a weldment; ε_2 is the residual elastic strain of the compressed zone; ε_l is the total load strain of a weldment caused by application of the external, e.g. tensile load; ε_p is the plastic part of the load strain; $k = \sigma_1/\sigma_y$, M is the hardening modulus; E is the Young modulus; $q = M/E$ and $m = \varepsilon_l/\varepsilon_y$.

Many structural steels, some non-ferrous metals and their alloys have a tension diagram without the yield plateau [8, 10]. Approximate the initial region of such a diagram by a fragment-linear function (Figure 6) with angles of inclination of the elastic region and hardening region, and accordingly determine E and M. According to [9], the initial state of a weldment is shown by triangle 0GF. After application of the external load to a weldment, causing its elongation by a value of ε_l, providing that $m > 1 - k$, plastic strain equal to a length of section AP is formed in the stretched zone, i.e.

$$\varepsilon_p = (k + m - 1)\,\varepsilon_y.$$

For a hardenable material, the value of plastic strain will correspond to the length of section AB. In a non-hardenable material $BP = qm\varepsilon_y$, whereas for a material with hardening $BP = (1 - qm)\varepsilon_y << \varepsilon_y$. Upon relieving the load, tensile residual stresses will decrease to a value of

$$\sigma_1^{01} = \sigma_1 - (1 - qm)\,\frac{E\varepsilon_p}{1 - f}, \qquad (1)$$

larger than in the case of a material without hardening by

$$\Delta\sigma_1^{01} = (1 - qm)\,\Delta\sigma_1^0,$$

where $\Delta\sigma_1^0$ is the decrease in RS in a material with the yield plateau. By equating (1) to zero, find a condition for a full relief of RS. In a case of $k = f =$ $= 1$, we have that $m_{max} = 2/1 - q$. Using evident geometrical constructions (see Figure 6), we can determine the value of a load strain leading to the same decrease in RS, as in the case of the absence of hardening $m' = m(1 - q)$. It is not difficult to note that for a hardening material the plastic strain induced by external loading is lower by

$$\Delta\varepsilon_p = \frac{M}{E}\,\varepsilon_p.$$

An adjustment that allows for hardening is usually insignificant. So, it is about 10 % for some structural steels at $M \cong 0.1E$.

It is well known that a decrease in temperature and increase in the strain rate are accompanied by an increase in the yield strength. According to [11], a decrease in the test temperature from +20 to −80 °C leads to an increase of 75 % in the yield strength. The yield strength is affected to a larger degree by an increase in the strain rate. Transition from static ($\dot{\varepsilon} \cong$ $\cong 1\cdot10^{-3}$ s^{-1}) to high-rate ($\dot{\varepsilon} \cong 1\cdot10^{5}$ s^{-1}) deformation leads to an increase in the yield strength by a factor of 2.5–3.0 and more [12, 13].

Note that if a given deformation method for relieving RS (high-rate deformation, explosion treatment, etc.) features high values of the loading rate within a certain range, the corresponding dynamic strength characteristics of a material of the welded joint should be directly introduced into calculation and empiric dependencies describing the process [14]. It should be noted that under some conditions of ET of welded joints the strain rate is about $\dot{\varepsilon} \cong 1\cdot10^{5}$ s^{-1}, in this case the yield strength grows (e.g. for steel St.3 it grows to 700 MPa [14]). If this value is introduced into the calculation formulae, this will enable a reliable prediction of optimal loading parameters. In ET the pressure at the shock wave front is by an order of magnitude higher than static yield strength [12–15]. Therefore, the effect of decreased temperatures is mitigated, whereas at a static application of load it is very high.

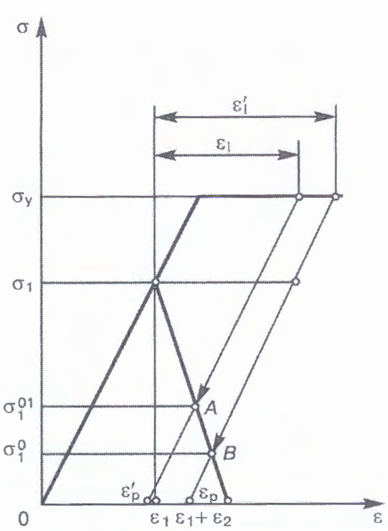

Figure 7. Constructions on the σ–ε diagram illustrating the effect of temperature-rate sensitivity of yield strength and strength of metal on a decrease in RS

Increment in yield strength associated with the effect of increased strain rates and (or) low temperatures can be taken into account by introducing coefficient R, which is the ratio of yield strength at a given temperature and (or) strain rate to that at room temperature and under static loading. If the ε_l value is left unchanged, an increase in yield strength to σ'_y will lead to a decrease in plastic strain ε_p (Figure 7) caused by external loading due to a proportional decrease in values of the m and k parameters:

$$\varepsilon'_p = \varepsilon_p - (R - 1)\,\varepsilon_y.$$

After relief of the load RS decreases to a level of

$$\sigma_1^{01} = \frac{R-1}{f+1}\,\sigma_y,$$

and a minimum value of load strain, providing a complete relief of residual stresses, will be equal to $m + k + R$.

Find the load strain value necessary to decrease RS to a level which corresponds to static deformation at a normal temperature. It follows from Figure 7 that

$$\varepsilon'_l = \varepsilon_l + (R - 1)\,\varepsilon_y. \tag{2}$$

Adjustment (2) can be substantial. For example, according to study [11], yield strength of low-carbon steel at −80 °C increases by a factor of 1.75. In this case $\Delta\varepsilon_l = 0.75\varepsilon_y$.

If a value of strain in the first loading cycle meets condition $m > 1 - k_1$, plastic strain $\varepsilon_p = (m + k_1 - 1)\varepsilon_y$ is formed in the stretched zone of a weldment (here and below indices i = 1, 2, ... designate the states which correspond to the first and next loading cycles). Residual stresses decrease to $\sigma_1^0 = \sigma_1 - \left(1 - \frac{f}{1+f}\right)E\varepsilon_p$. This leads to a change in the value of coefficient k_1 which will be equal to $k_2 = k_1(1 - f/1 + f)E\varepsilon_{p1}/\varepsilon_y$ before the second loading. The second loading (at constant m) causes plastic strain

$$\varepsilon_{p2} = (m + k - 1)\,\varepsilon_y = \frac{f}{1+f}\,\varepsilon_{p1} \tag{3}$$

and a change in RS to a level of

$$\sigma_{12}^0 = \sigma_1 - \left[1 - \left(\frac{f}{1+f}\right)^2\right]E\varepsilon_{p1}. \tag{4}$$

Extrapolation of the values considered with respect to the N-th loading cycle yields

$$k_N = k_1 - \left[1 - \left(\frac{f}{1+f}\right)^N\right]\frac{\varepsilon_{p1}}{\varepsilon_y};\quad \varepsilon_{pN} = \left(\frac{f}{1+f}\right)^N \varepsilon_{p1};$$

$$\sigma_{1N}^0 = \sigma_1 - \left[1 - \left(\frac{f}{1+f}\right)^N\right]E\varepsilon_{p1}.$$

Coming to a limit of $N \to \infty$, we find

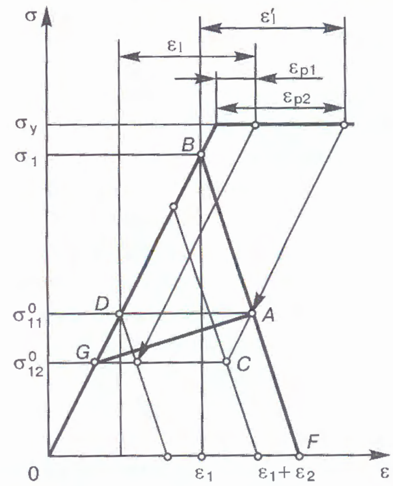

Figure 8. Constructions on the σ–ε diagram illustrating the effect of the loading factor on a decrease in RS

$$k_\infty = 1 - m;\quad \varepsilon_\infty = 0;\quad \sigma_{1\infty}^0. \tag{5}$$

In Figure 8 triangle $0BF$ characterizes the initial stressed state of a weldment, and point B — residual stress and elastic strain of its stretched zone. The first loading will change the weldment into a state that corresponds to point A, but with stress and elastic strain of its stretched zone which correspond to coordinates of point D.

Repeated loading at the same value of m will cause, according to formula (3), a lower plastic strain, compared with the previous loading, and a substantially lower decrease in the level of RS (the second term in brackets of expression (4) is a diminishing function at any $f > 1$).

It is not difficult to see that all points of «elastic recoils» of a weldment at repeated loading cycles will fall on straight line AG. RS and elastic strain of its stretched zone at $N = w$ and ε_l = const correspond to coordinates of point G.

Therefore, at a multiple application of the external load to a weldment the values of RS in it will monotonously decrease following the law of an exponential function, asymptotically approaching the limiting value of (5).

The efficiency of treatment varies in a similar way when coming to joints characterized by a higher strength. Such constructions are similar to those shown in Figure 7, if yield strength of the joints considered in this case is designated as σ_y^0 and σ_y^{01}. The character of the effect of strength on the RS value can be expressed through formula $\Delta\sigma_1 = \sigma_y^{01} - \sigma_y^0 = q\Delta\sigma_y$.

CONCLUSIONS

1. The limiting thickness of welded joints that reacts to the effect of one-sided explosion treatment, using cord and strip-like low-pulse explosive charges (which shows up as a change in RS), is ≈50 mm.

2. Widening of the range of thickness of welded joints, which can be effectively explosion treated,

requires the use of two-sided loading or higher-power explosive charges.

3. The method for analysis of interaction of natural stresses and strains, as well as those induced by external loading, in a weldment, suggested in [4, 14, 15], enables prediction of the effect of a number of actual factors on the end values of RS.

4. Application of the external load to weldments of hardening materials at decreased climatic temperatures and (or) at high strain rates leads to a marked decrease in the efficiency of relief of RS, which requires adjustment of parameters of the force effect.

5. In multiple application of the external load to weldments the main contribution to a decrease in RS is made by a few of the first loading cycles.

6. Explosion treatment conducted to relieve residual stresses in welded joints is almost insensitive to the effect of the considered factors, due to high-intensity loading of metal.

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WELDING AND ALLIED TECHNOLOGIES AT THE ESSEN FAIR

A representative Ukrainian delegation (about 80 members) took part for the first time in the International Fair «Welding and Cutting 2001» (12–18 September, 2001, Essen, Germany) which is a traditional parade of world achievements in the field of welding fabrication, held once every four years. The delegation included the researchers and specialists of «E.O. Paton Electric Welding Institute» REC, M.V. Frunze SMPO, SELMA, VELMA, Kakhovka Plant of Electric Welding Equipment, «Zaporozhstekloflus» OJSC, etc. This Fair surpassed all the previous ones in its scale: more than 1000 companies from 41 countries of the world took part in it and the exposition occupied 12 pavilions of 104,000 m² area. The total number of visitors was more than 93,000. The Annual Conference of the German Welding Society was held in Essen at the same time, in which more than 150 specialists participated and about 70 presentations were made.*

The material given below is based on the impressions of the delegation members of «E.O. Paton Electric Welding Institute» Research-Engineering Complex about the exposition. It is based on the contributions of Prof. I.K. Pokhodnya («Welding consumables»), Prof. V.K. Lebedev («Arc welding power sources»), Prof. S.I. Kuchuk-Yatsenko («Pressure welding»), Prof. L.M. Lobanov («Diagnostics, NDT»), Prof. O.K. Nazarenko («Beam welding processes»), Dr. V.V. Stesin («Robotic work stations»), Dr. V.I. Zelenin («Plasma processing of materials»), Dr. P.P. Protsenko («Training and certification of personnel for welding productions»).

Welding consumables. Companies from Germany, France, Great Britain, USA, Italy, Sweden, Japan, Austria, etc. were the best represented manufacturers of welding consumables, raw materials and equipment for their production. Five companies from Russia participated in the Fair, and Ukraine's achievements were demonstrated by the E.O. Paton Electric Welding Institute and Zaporozhje Plant of Welding Fluxes and Glassware. The Fair, on the whole, was very impressive; the number of companies-exponents had increased; information approaches, used in arranging the displays, had changed – many developments were demonstrated directly in the Internet, using modern video systems; material catalogs were presented on CD discs. Expert systems of welding consumables were also proposed.

In 1997–2000 welding consumables manufacture in the developed countries was continuously improved by restructuring the production, upgrading production facilities and fitting them with modern equipment, and increasing the share of advanced welding consumables. Reduction of coated electrode output is found everywhere in the USA, EC and Japan (coated electrode share currently is 20, 19 and 19 %, respectively). Coated electrodes are replaced by materials for gas-shielded welding, namely solid and flux-cored wires. In the general volume of welding consumables output, the share of the former, as estimated by experts, in EC is about 70 %, that of flux-cored wires is up to 5 %; in the USA these figures are 52 and 25 %; and in Japan 40 and 30 %, respectively. Self-shielded flux-cored wires take up just a minor part of the market, while the share of consumables for submerged-arc welding has stabilised and is between 5 and 10 % in different countries.

According to estimates by leading experts, Germany now manufactures between 100,000 and 120,000 t of welding consumables, including 20 % electrodes, 70 % solid wires and 4–5 % flux-cored wires (of them, 3 % for shipbuilding and 5 % for SAW).

Such a situation in the consumables market is attributable to the structure of industry in different countries. Shipbuilding has been developing intensively in Japan lately, which widely uses flux-cored wires, as well as metal-core wires for automatic and robotic welding. Some Japanese companies (primarily, Kobelco), have set up modern production of flux-cored wires for welding low-carbon and low-alloyed high-strength steels, as well as stainless and high-alloyed chromium-nickel steels. Manufacturing capacity of this company is about 3,000 t per month. In Holland the same Company set up production of flux-cored wires for welding high-alloyed chromium-nickel steels of up to 800 t annual capacity. On the whole, in 1998 Japan manufactured 11180 t of consumables for welding high-quality chromium-nickel steels, this type of flux-cored wires taking up about 50 % of the market. Part of this wire is supplied to European companies, which sell in under their trade names in Europe.

* Information on «E.O. Paton Electric Welding Institute» REC participation in the Essen Fair was published in «Avtomaticheskaya Svarka», 12, 2001.

Manufacture of solid wires for gas-shielded welding is well-established in Western Europe with Italian companies taking the lead. High quality of the wires, comparatively low prices, as well as efficient production of Ar-based gas mixtures, and their timely delivery, result in predominant application of gas-shielded solid wire welding.

Welding consumables of such companies as ESAB, Böhler Thyssen, AIR LIQUIDE–OERLIKON, Lincoln Electric, Kobelco, KISWEL (South Korea), INNOWELD and ISAF (Italy), and Sandvik (Sweden) were the most widely represented in the Essen Fair.

It should be noted that corporatisation and specialisation of welding consumables production has been going on over the last years. Major companies (AIR LIQUIDE–OERLIKON, Böhler Thyssen, Lincoln Electric, etc.) formed transnational alliances and acquired a great number of medium-sized and small companies, currently controlling and funding their industrial production (within the alliances). This leads to widening the product range, improvement of product quality and lower manufacturing costs. Practically all the major companies have developed and introduced product quality assurance systems to ISO 9000. Familiarisation with the companies' displays and catalogs reveals the following tendencies in welding consumables development.

Coated electrodes. A number of companies are developing electrodes for welding high-strength low-alloyed steels with the yield point of 500 to 690 MPa and higher. Special attention is given to searching for new systems of alloying and microalloying the weld pool metal, reducing the weight fraction of sulphur and phosphorus impurities to 0.01–0.15 % and less. A very important trend is development of coatings, providing a low absorption of moisture and low content of hydrogen — 3–5 ml per 100 g of the deposited metal. Range of electrode types for welding high-alloyed chromium-nickel steels is becoming wider. When weld metal composition is selected, the known Shaeffler–DeLong diagrams are used to predict the weld metal structure and its susceptibility to solidification cracking. Methods of δ-ferrite determination are improved. A number of companies developed electrodes for welding advanced heat-resistant steels with 9–12 % weight fraction of chromium, used in power engineering. Basic electrodes for «downward» welding of the main pipelines, as well as with cellulose coating for welding X65, X70, X80 steels, are improved. A lot of attention is given to new kinds of hermetic packing. The range of electrodes for welding aluminium and aluminium alloys has become wider. A new geometry of the electrode tips in the form of a sharpened end is of interest, as their application allows prevention of «starting» porosity in welding with basic electrodes.

Solid wires. The range of such wires, used for coated-electrode manufacture, as well as for submerged-arc and gas-shielded welding, is extremely broad. Special attention is given to the quality of the initial wire rod. Its content of sulphur and phosphorus, amount of scale, tolerance on alloying element content, diameter and ovality are limited. Mechanical cleaning of wire rod from scale and additional etching of the remaining scale allows reducing the content of inclusions in the wires and improving the arcing stability. Good preparation of the wire surface enables forming it at a higher rate during drawing, thus eliminating waviness.

The surface of almost all the wires for gas-shielded and submerged-arc welding of carbon and low-alloyed steels is Cu-plated. Additional drawing after Cu-plating improves the strength of the copper layer adhesion to the wire surface, reduces the tolerances on diameter, thus allowing the wire to be accurately wound on the coils or metal frames, by compact winding method. These operations are performed in the automatic and semi-automatic units. The main diameter of the wire, used in gas-shielded welding ($Ar + CO_2$, CO_2) is 1.2 mm. The wires are checked for «feedability», this being important for semi-automatic welding.

A number of companies advertise and supply wire in cardboard barrels and boxes, fitted with special unwinding devices (Marathon type unit). Wire wound by this method is used for automatic and robotic welding.

Flux-cored wires. The number of wire grades offered by Lincoln Electric, Böhler Thyssen, AIR LIQUIDE–OERLIKON, ELGA, Kobelco, INNOWELD, COREWIRE, METRODE, KISWEL, etc. for gas-shielded welding is growing continuously. A lot of wire grades with a metal core, as well as a rutile core, have been introduced for welding low-carbon and low-alloyed steels, including high-strength wires for welding stainless steels.

Two technologies are used for manufacturing the wire, namely from a strip and a welded tube, the first being much more widely accepted. The most used wire diameter is 1.2 mm, shielding gases being CO_2 and $Ar + CO_2$.

The number of wire grades, designed for welding high-strength steels, is comparatively limited. Highly promising are flux-cored wires for welding stainless and high-alloyed chromium-nickel steels, with Kobelco and Böhler products leading the market. A number of manufacturers (ESAB, AIR LIQUIDE–OERLIKON) promote a great number of flux-cored wire grades for SAW. The advantages of their application, when small quantities of wires of a broad range of types are required, are emphasised.

The share of self-shielded wires in the overall range is comparatively small. Their leading manufacturer is still Lincoln Electric, which produces wire under Innershield trade mark. The Company offers two wire grades for main pipeline construction: NR-207-H for semi-automatic welding of X42–X60 steels and NR-208-H for X65–X80 steels.

It should be noted that although these wires are advertised as being low-hydrogen, hydrogen content in the deposited metal of up to 8 ml/100 g is admissible, this being rather high to allow high-quality welding without preheating.

Equipment for welding consumable manufacture. Equipment for manufacturing solid wires was exhibited by SAMP STEEL, TRAFILERIE DI CITTADELLA (Italy), ESAB (Sweden), VASPO (Czechia), etc.

SAMP STEEL mills for dry drawing of wire are of interest. They provide a drawing speed of up to 30–35 m/s, have a perfect electronic drive, non-polluting closed-cycle cooling system, rotating dies and drive synchronising. The mills are fitted with drums with a horizontal or vertical axis of rotation. They are supplied as a set with automatic lines for wire winding on spools or frames by the compact winding method and lines for wire Cu-plating (maximal speed of 20 m/s). The Company also supplies complete automatic lines for drawing, copper plating and winding of welding wire.

The equipment for welding electrode manufacture was exhibited only by a few little known companies, mainly, in the form of models and catalogs.

The most perfect electrode-making presses of different capacity with the appropriate ancillary equipment (stripping machine, briquetting press, feed mechanism, etc.) were exhibited by Maschinenfabrik Berner (Germany). Laboratory press B25 and its head were displayed separately in the booth. Fitting the extrusion head with die movement sensors with adjustment for thickness difference and a water-cooling system, as well as design features of the head proper are notable.

Equipment of Collin Technology (Germany) is also characterised by a high level of technology. The Company offers two electrode-manufacturing lines, fitted with presses of 640 and 900 kg/h capacity, mixers, straightening and cutting machines, charging scales, furnace and some laboratory equipment.

Siderarco (Italy) demonstrated a series of three vertical electrode-manufacturing presses of different capacity, straightening-and-cutting machine, conveyor oven for electrode baking and weighing-packing machine. The equipment is not particularly attractive in appearance, while the maximal working temperature of the oven is only 120 °C, so that it allows a complete baking cycle of just electrodes with cellulose and rutile-cellulose coatings.

A rather wide range of equipment was on show in the booths of VASPO (Czechia), formed on the base of a repair shop of the former Zelizarny-Vamberk Works. It included two extrusion presses with stripping machines and a multi-position briquetting press, mixers, a chamber and two conveyor furnaces (one of them a tunnel furnace) and a packing machine. One of the presses looks like our OSZ-3 press, and the second is similar to the known Messer Griesheim press. On the whole, the engineering level of the equipment is approximately on a par with that of the Ukrainian manufacturers of similar equipment, except for some units (for instance, packing machine).

The Russian Welding Institute exposition included a complete set of equipment of Rotex-K Company of the capacity of 100, 1,000, 3,000 and 5,000 t of electrodes per year. The advantages and disadvantages of this equipment are well-known in the territory of the CIS countries.

It should be noted, that equipment for making wires for mechanised welding was mostly exhibited, although many visitors from developing countries were interested also in equipment for electrode manufacture.

Raw materials. Five companies offered raw material components for welding electrode coatings: two of them from Germany and one from Great Britain, Italy and Turkey each.

The broadest range of raw materials, covering practically all the electrode coating components known to us, was demonstrated in the booth of Mineralmühle Leun Rau (Germany), which also represented a number of other companies (German PMC Tec and Bremthaber Quarziturerk, Austrian Alusil, US F.W.Winter). Catalogs list powders of 28 minerals, 9 fused and agglomerated and 12 chemical products, 12 metal powders, 9 kinds of ferroalloys, more than 7 types of various metal alloys, etc. (their specification is not given). Of interest are materials, that are new for us, or where import into Ukraine is problematic, namely lithia mica and feldspar; calcium mica; wollastonite; potassium, sodium and calcium titanites; water-soluble silicate powders; most of metal powders and ferroalloys.

A number of companies demonstrated a quite broad range of metallurgy products — powders of ferroalloys, metals and various binary and ternary alloys. One of them is Thyssen Krupp Metallurgie (Germany), which displayed about 32 products; London + Scandinavian Metallurgical (Great Britain), also representing German Elektrowerk Weis Weiler and Gesellschaft für Elektrometallurgie (18 products); Pometon (Italy) (about 14 powders, chiefly, metals and binary alloys) and GENSA (Turkey) (14 kinds of powders of the traditional ferroalloys). Compared to those used in Ukraine, the proposed raw materials are characterised by a lower content of impurities (sulphur and phosphorus) and carbon (for instance, in ferromanganese), as well as a wide range of the majority of products in terms of the granulometric composition of powders. In addition, some powders, for instance, ferrosilicium, are supplied with a passivated surface.

Of greatest interest among the above products are powders of Al–Mg–Si alloy (silusnal), ferroaluminium, Ni–Al–Ti and Ni–Mg alloys, that are not produced in CIS countries, but are promising for use in Ukrainian factories.

GENSA (Turkey) produces, under a licence from OERLIKON, dry charges for manufacture of known Supercito, Overcord S and Overcord N electrodes.

The latter is the charge for electrodes with ilmenite coating (ilmenite is supplied by Ukrainian companies). Considering the need to develop inexpensive general-purpose electrodes, it is expedient to study the technological capabilities of these electrodes.

Arc welding power sources. Arc welding remains to be the most widely spread process in welding fabrication and still does not give ground to its closest rival — laser welding. Therefore, most of the exposition consisted of power sources for manual arc welding, and to a greater extent of those for mechanised and automatic gas-shielded welding.

The last decade of the past century did not bring about any significant changes in arc welding technology that would affect the power sources design. Their improvement lay in the electrical engineering domain, use of modern means of power electronics and automatic control. Transition to power sources with a high-frequency intermediate link, namely an inverted converter, can be regarded as completed. The latter are now based on bipolar transistors with an insulated gate of IGBT type, designed for operation at up to 20 kHz frequency and MOSFET-type transistors, used in power units of up to ≈ 50 kHz frequency.

Small weight is the first and one of the major advantages of inverter power sources. Therefore, they have found application primarily for performance of installation and repair operations, where this advantage is the most pronounced. Ability to carry out fast control and this way gain additional benefits in terms of technology, can be regarded as the second advantage, this being very important, especially for mechanised and automated gas-shielded welding. The third advantage is resources saving, consisting in a many-time reduction of the consumption of such materials, as copper or aluminium, as well as transformer steel. Finally, the fourth advantage is power saving, due to a higher efficiency and power factor, than in the power sources of the traditional design.

As could be anticipated, inverter power sources prevailed in the Fair, although the market still has a demand for the regular ones. Therefore, many companies, in addition to the inverter sources, also produce traditional units, used for heavy-duty operation under stationary conditions.

The great variety of power sources, demonstrated in the Fair, need not be described. Let us dwell on the exhibits of the prominent and prospering Carl Cloos Schweiβtechnik, whose activity in the field of arc welding equipment manufacture is well-known world wide. The Company catalogs list several dozens of power sources for various purposes, including inverter sources, based on IGBT and MOSFET-type transistors.

Several types of power sources are designed for consumable and non-consumable electrode manual arc welding. The smallest of them is a single-phase source, designed for the maximal current of 140 A at 40 % duty cycle, its weight being just 4.3 kg. The range of welding current variation is 5–140 A, and open-circuit voltage is 90 V (its reduction to 20 V during the pauses is envisaged). A more powerful source of the same type is designed for the maximal current of 160 A at 60 % duty cycle. The three-phase modification of the source is designed for 240 A with 45 % duty cycle at 15 kg weight. All of them are fitted with ammeters and supplied with air-cooled torches for non-consumable electrode welding. Use of power transistors and quite perfect control system provides a «hot start», stable arcing at low currents, ability to excite the arc by the non-consumable electrode directly touching the item, while electrode sticking during arc ignition is prevented. All this greatly simplifies the welder's task and promotes higher quality of welded joints.

One of the most recent developments in the mobile unit area is a computer-controlled multifunction power source. It is designed for the maximal current of 300 A, its weight being 30 kg. Computer memory stores one hundred working programs, of which any can be selected by rather simple means, and corrected, if required. If the power source is used by several operators, each of them can have a key, by which the source «recognises» the operator and provides the required program.

The second group of inverter sources includes four units with the following rated currents: 170 (at 60 % duty cycle), 200, 250 and 300 A (at 40 % duty cycle). They are designed for non-consumable electrode and consumable electrode manual arc welding. Depending on the rated current, the weight of the units varies in the range of 26 to 41 kg, their power factor being equal to 0.9 and efficiency to 0.8. All the power sources, except for the first one, are fitted with water-cooling devices. The main feature of the units in this group consists in that they are applied both at direct and alternating current, while the output voltage curve is of a rectangular-wave shape. Reverse polarity current can be adjusted in a very broad range, this allowing effective use of these power sources for non-consumable electrode welding of items from aluminium and aluminium-base alloys. Welding current frequency is adjustable in the range of 50 to 200 Hz. The unit has the capability of a smooth current increase at the start of welding and its smooth drop during crater welding-up, as well as a time delay before switching on the current for filling the system with the shielding gas. A «hot start» is provided in consumable electrode manual arc welding and electrode sticking during arc excitation is eliminated. The arc runs in a stable manner, beginning from 5 A. Open-circuit voltage is not more than 110 V.

Carl Cloos Schweiβtechnik regards as its special success, a series of four all-purpose computer-controlled power sources (from GLS 353 Quinto Profi for 300 A up to GLS 603 Quinto Profi for 600 A), which was displayed in the Fair. The inverter operates at 50 kHz frequency and this ensures a very high operating speed of the control system, in particular, provides a reliable ignition of the arc in welding with thin aluminium wire. Reliable ignition is further promoted by the so-called soft start. Inverters can also be applied in pulsed welding at 20 to 40 Hz pulse frequency. The control system of the power source and the feed mechanism is based on 16-bit processor 80C166. User-friendly control, incorporating a liquid-crystal display, allows to quite easily set up the required welding mode. Computer memory stores 63 programs, identified by names of up to 12 characters and including parameters of the initial, main and final stages of the process; correction of these programs is allowed, if required. The control system can be connected to a PC, that may be used to perform monitoring or documenting. It should be noted that application of sufficiently perfect automatic control systems increases the power source price several times, compared to the regular sources. Therefore, their use is justified in not all the cases by far, and for this reason their sale is limited. Company also makes the simplest power sources for mechanised welding with step control, application of which is quite rational in many enterprises.

Lincoln Electric, just as it did four years ago, displayed an inverter power source, performing automatic control of metal transfer with short-circuiting of the arc gap in CO_2 welding. Automatic control used in them minimises the molten metal spatter, but this control has so far not become accepted in welding fabrication to any noticeable degree. This is, probably, related to the fact that welding in Ar-based gas mixture, when this problem is non-existent, has almost completely ousted welding in pure CO_2. This time, however, the Company demonstrated samples of CO_2 welding of a position butt on a large-diameter pipe. In this case the advantages of using CO_2 and automatic control of metal transfer are evident, and it is quite possible that the new technology, developed by the Company, will help solve one of the problems in arc welding of position butts of pipes. Unfortunately, the first work of the E.O. Paton Electric Welding Institute on controlling short-circuiting metal transfer, completed as far back as in 1987–1988 in the laboratory variant, still remains unrequited so far.

Several companies had comprehensive displays of mobile electric welding plants. The greater part of the units are designed for powering not only the welding arc, but also other power consumers, predominantly of alternating current, three- and one-phase. This can be lighting load, as well as mechanisms with three-phase motors of general industrial purpose. This accounts for the limit on the used frequency of the combustion engine rotation of 1500 or 3000 rpm. Almost all the units are designed so that the welding load power is smaller, than the power that can be used for powering the electric motors and lighting. Such an approach to the use of self-sufficient welding plants is, probably, dictated by the conditions of their service in construction sites and repair operations. Diesel engines are used more often, than petrol engines, as prime movers. The prevailing types of generators are electric synchronous generators with built-in energiser and asynchronous generators (the latter are more numerous). Thyristor valves are most often used for alternating current rectification and producing the required characteristics. Plants for powering several welding stations (most often two) are manufactured.

Modern requirements to product quality assurance, defined in special European standards, are aimed at a precise and accurate following of the specified technologies, that requires instrumentation and documenting devices. In this respect welding fabrication, similar to many others, did not have the required instruments. With the recent advances in electronics, the situation has changed, this being reflected in the changes in design of power sources, described above.

Welding equipment also requires special measuring instruments. HKS Prozeβtechnik demonstrated a set of transducers for automatic and semi-automatic arc welding machines. It includes a sensor of wire feed speed with measurement range of 0–25 m/min, sensor of gas flow from 2 up to 25 l/min and a combined sensor of the welding process. Weldlogger system acquires and processes information and documentation in the analog and digital form. The printed out protocol, in addition to the date and time, also includes the weld identification number, time of its performance, current and voltage. In the analog variant these data are presented in the graphical form. Measuring instruments adapted to the special features of welding processes with indubitably be developed in the future.

Pressure welding. *Resistance welding*. Equipment for spot, projection and seam welding was exhibited by several dozen companies. The design of the mechanical part of these machines did not feature any cardinal changes. The greatest number of various improvements were made possible due to development of small-sized welding transformers, combined in one block with rectifiers and converters of frequency and phase number.

Converters allow supplying direct current to welding machine electrodes. The inverter transforms three-phase mains voltage into single-phase voltage of 600–1000 Hz frequency and this voltage is applied to a single-phase welding transformer with a rectifier, built into its secondary circuit. While in the US exhibitions in 1999–2000 only individual samples of machines with inverter power sources were on show, in Essen such equipment was demonstrated in the booths of many companies, and not just for stationary machines, but also for various portable tongs. Many companies, producing electronic control systems for welding machines (Bosch, TECNA, Cisomatic, Miyachi, Taylor-Winfield, etc.) displayed separate modules, that consisted of converters combined in one block with the welding transformer and rectifier. Exhibited inverter power sources were designed for secondary circuit currents from 10 up to 320 kA at 8–15 % duty cycle. It should be noted that the above duty cycles pertain to such operating modes, when duration of current pulses and pauses between them does not exceed fractions of a second, this being characteristic of spot welding. Converters are not designed for long-time loads, counted in minutes, therefore, their use in resistance butt welding machines is not rational.

In addition to providing a uniform load for the three-phase mains, inverted converters enable:

• a considerable reduction of welding transformer dimensions, this being particularly significant for equipment, used for multi-spot welding, as well as various tongs, incorporated into robotic work stations;

• lowering secondary circuit losses at the expense of lowering its direct current resistance;

• providing a more accurate adjustment of current in the welding circuit and a considerable increase of the regulators operating speed.

The above advantages of the inverters are particularly obvious in welding parts that require very accurate control of the weld spot formation, for instance, in welding sheets with coatings of high-strength aluminium alloys. Stabilisation of the spot nugget dimensions is also required in welding critical parts, made of low-alloyed steels. Requirement of a three-phase load of the mains in resistance welding (at least in more than 50 kW machines) is becoming mandatory for many European countries and is introduced into the respective standards.

Wide introduction of the inverter power sources of the above types is significantly restrained by their high price. The cost of the first spot welding machines, incorporating such inverters of 100 kW power, was 3 times higher, than the cost of similar machines of a standard modification. By the data of the representatives of TECNA (Italy), that displayed a range of inverted converters in Essen, the cost of spot welding machines, using modern inverted converters will be 1.5–1.7 times higher, than in case of a regular modification. These experts predict a lowering of the price later on.

One of essential advantages of inverter power sources is the capability of precise control of the main process parameters, opening up new technological perspectives. Despite that, a comparatively small number of automatic systems of welding parameter adjustment, making full use of these capabilities, were on show. Such regulators will certainly become available in the near future.

Resistance butt welding and flash-butt welding. Equipment for this type of welding was exhibited only in the booth of IDEAL (Germany). For decades it has specialised in manufacturing equipment for welding wire and thin strip. The exhibited series of machines is designed for welding 0.35 to 1.50 mm thick and up to 120 mm wide strip. Flash-butt welding is performed by rigidly set programs that in most cases are fulfilled by mechanically-driven devices. Among the advertised innovations, note those made in the mechanical part of the machines, use of a spring upset drive with a high accuracy of adjustment, as well as the ability of accurate alignment. The majority of improvements pertain to electronic control systems, chiefly, for postweld heat treatment of the joints (use of contactless sensors for temperature measurement, thyristorized voltage regulators for automatic control of the heat treatment process). Welding machines are supplied with all kinds of ancillary equipment for cutting and scraping the parts to be welded prior to welding and accurate alignment of the strips in the welding machine clamps.

A series of machines of BAS type for welding carbon steel strip 0.35–1.50 mm thick and 25–120 mm wide, was represented by nine types of 3.5–45.0 kW units. They allow welding bimetal, as well as tungsten and stainless steel strip.

The same company exhibited as a new product, a unit for non-consumable arc welding of thin (0.5 mm) strip that, in the opinion of company representatives, can compete with resistance welding machines in joining 0.5 mm and thinner plates.

IDEAL is also known as manufacturer of machines for resistance welding of wire. The main improvements in this field chiefly concern the electronic systems for controlling the process of resistance welding and heat treatment in the machine jaws. All the types of equipment for welding wire and strip run at commercial frequency of 50 Hz and one-phase load on the mains.

Machines for welding 0.5–0.8 mm diameter wires (with a pneumatic drive for clamping and upsetting and electronic control of the welding and heat treatment cycle) were also exhibited by German-Turkish COSKUNÖZ Company. The same Company produces general-purpose monitoring systems with sensors of current, voltage, pressure (with displaying of the main parameters) and current regulators.

It should be emphasised that the equipment for welding wire and strip is continuously in demand in the world market, this being evident from a rather broad range of various machine types (up to ten). Mechanical part of the machines did not undergo any significant changes over the last decade, while the electronic part, control and monitoring systems are being continuously perfected by incorporating new components. It should be further noted that alongside the rather complicated control systems, manufacturing equipment with simple control systems also goes on, thus satisfying the requirements of a broader range of customers, interested in purchasing inexpensive equipment.

Resistance microwelding. Welding in instrument-making and electronics was represented on a very limited scale in Essen. It is possible that companies working in the field, prefer displaying their equipment in specialised industrial shows.

SPATZ display was interesting. The Company demonstrated precision machines for resistance microwelding with the largest electrode force of 20 and 150 N. They are fitted with piezoelectric linear motors of electrode displacement, that allow making up to 5 welds per second, while being readily and accurately controllable. Maximal acceleration of electrode movement, created by these motors, is 250 m/s^2. A second feature of such machines is that they are powered by an inverter, operating at 20 kHz frequency. Its output is connected to the transformer, in which the secondary windings are connected to diodes, forming a single-phase rectifier with a neutral terminal. Welding current is varied by changing the angle of the transistors switching, i.e. by pulse-width modulation. The power block of energy conversion is made as a module, separate from the welding machine, and is connected to it by rather long (about 1 m) flexible cables. High frequency of welding current allows reproducing complex cycles of its variation within small time intervals, this being highly important in microwelding. The same approach is used to solve one of the main problems of resistance microwelding, arising from prevalence of contact resistances in the welding circuit impedance. Operation in the modes of stabilisation of welding current, voltage on the electrodes and power, is possible. Many technological processes require resistance stabilisation, controlling the heating rate and other process parameters, this being quite practicable with numerical control.

Automatic control of resistance welding processes. Matuschek Meßtechnik advertised its MASTER control system in the Fair, developed for resistance welding in the car-making industry. In this automatic control system, designed for machines with an intermediate link of a higher-frequency, two quantities are used for feedback, namely welding current and voltage drop across the electrodes. A mode, producing a joint of the required quality, is selected before welding. Then, the current and voltage, as functions of time, are memorised as standard values. During the subsequent welding cycles, the current values of these quantities are compared to the standard, and the system generates the control action. It also allows for the variation of the thickness of the plates being welded and the electrode surface condition, in particular, as a result of electrode wear (under the impact of welding). Promotion material contains a lot of experimental data, confirming the rationality of applying this system.

Bosch Rexroth displayed its PS 6000 system, designed for spot welding and using ultrasonic vibration. The system is characterised by originality of introducing the ultrasonic signal into the item, receiving the echo-signal and its processing. Many companies demonstrated their achievements in the field of measurement of the resistance welding process parameters, processing and documenting of the measurement results.

Friction welding. Such companies as TOMPSON (Great Britain), MTI (USA) and KUKA (Germany) have become established as the main equipment manufacturers in the field of friction welding in the world market. Of these companies KUKA had the most representative booth in the Fair. The Company now offers to its customers seven types of friction welding machines with the upset force from 5 to 2500 kN. A number of specialised machines have also been put on the market for installation in the automated production lines (twin-head machines for welding car axles; machines with a vertical spindle). All the machines are fitted with a canonical drive (without flywheels). In this respect they are inferior to the US and British models, which have an inertia drive, providing a number of technological advantages. Company representatives substantiated such an approach to machine design by the canonical drive making it easier to implement the modular principle of assembling all the machines. This was dictated by the fact, that KUKA is working chiefly for the automotive industry, where the machine clamping devices have to be adapted to the variety of the parts being joined. On the other hand, most of the joints are made on steel not belonging to the difficult-to-weld category, therefore application of the inertia drive in this case does not have any significant advantages. A common design feature of all the large KUKA machines (with up to 300 kN upsetting force) is a large-sized frame with symmetrical guide and clamps, providing a high precision of alignment and sufficient rigidity. The clamps accommodate complex-shaped parts, including cast parts, by changing the number of pawls and their location on the casing. The drive allows the rotation speed to be varied in a broad range. Layout of the main machine components (clamping assemblies) enables them to be used in combination with robots.

The welding technology proper does not have any novel features. Rigid programs of changing the compression pressure and rotation speed are used. The main parameters (displacement, speed, pressure) are recorded by modern instruments in the graphical and numerical form. Preliminary diagnostics of operation of the main machine components is also performed.

Visitors to the Fair showed interest in technology and equipment for friction stud welding, demonstrated by RAM STUD (USA). A set of manual and modular tools (in the form of a hand drill) was offered. The tools are mounted in complementary centering devices and are designed for welding parts (pins, bolts and bosses) of 8–14 mm diameter and up to 200 mm length, to a flat surface. The weight of one tool is up to 25 kg, its dimensions being 160×400 mm, and the rotating spindle speed is 8000 rpm. The design uses a pneumatic or hydraulic drive. In the opinion of the developers, such a welding process has a number of advantages:

• practically no preparation of the sheet surface prior to welding is required (element to be welded on is sharpened to a cone);

• dissimilar materials can be welded, for instance, aluminium to steel and titanium, copper, stainless steel, as well as aluminium rods to ceramics;

• its can be performed under the water;

• no protective means are required;

• it can be carried out in an explosive atmosphere, using a special protective cover;

• it allows welding studs to thin sheets due to a small heat input during the process.

All the equipment, produced by the Company, has been patented. Special emphasis should be made on totally new capabilities, which, in the opinion of the company experts, are offered by applying the friction stud welding process under the water. In this case the welding zone is located within a chamber. Metal heating is accompanied by intensive evaporation of water. Special modular heads (mounted with additional mechanisms) have been developed for welding under the water. Such heads of 190×530 mm size have the weight of up to 45 kg, and are designed for welding rods of 5 to 35 mm diameter. Welding can be performed at the depth of 600 m and deeper. The heads are fitted with a computerised control system, that reacts to pressure change in the system with the increase of the immersion depth.

Friction stir welding (FSW). This process was demonstrated in the expositions of The Welding Institute (TWI) and ESAB, Sweden. The first of them that is the inventor of the process, presented a small laboratory unit for illustration and demonstration of the very principle of FSW and its main advantages, as of a solid-phase welding process, over the known fusion welding processes. Low alloys several millimetres thick were used for the purpose. ESAB, which is the world's leading producer of FSW equipment, demonstrated two laboratory units. One of them is designed to make circumferential and rectilinear welds of thin blanks, made of aluminium, copper and its alloys. The other unit allows joining blanks of aluminium alloys up to 25 mm thick, when welding from both sides. It is fitted with a powerful system of hydraulic clamps, providing a reliable assembly and fastening of the parts during welding, as well as an up-to-date system of the work tool displacement, that allows making curvilinear welds. Preassembly by FSW method of a panel, consisting of individual extruded blanks of a tee cross-section, was an example used to demonstrate the main advantage of this welding process in large-size structure fabrication, namely, minimising the residual strains.

Factors, restraining wide application of FSW, currently are a narrowly specialised purpose of the welding machines and their comparatively high cost, amounting to $0.5 to 1.5 mln for the laboratory and commercial units, respectively.

ESAB's extensive promotional information presented case histories of application of equipment, developed for shipbuilding, automotive industry and electrical engineering, including the newest samples of welding machines, supplied to Boeing for making longitudinal and circumferential welds in fabrication of fuel tanks of Delta family missiles. With the purpose of reducing the required shop area one of the units allows vertical welding of the longitudinal welds of tank shells. As a new development of ESAB, the so-called coil technology was demonstrated in the promotional visuals, i.e. welding from both sides with two simultaneously rotating tools. The technology allows improving welding efficiency and mechanical properties of the joints, this being especially important for head-hardenable aluminium alloys.

The only development in the field of magnetically-impelled arc butt (MIAB) welding, was presented in the KUKA booth. The demonstrated twin machine for welding back axles of trucks, is designed for application as part of an automated line. It allows welding two complex-shaped brackets of high-strength cast iron to the central steel pipe at the edges. Pipe diameter is 100 mm, and wall thickness in the welding area is about 6 mm. Welding is performed in a shielding atmosphere. Heat treatment to reduce material hardness in the HAZ is conducted in a separate position. This operation takes 30 s, using 1000 Hz inductor. Similar to friction welding, quality control is performed by recording the appropriate parameters, which during welding are changed by rigidly set programs. Company representatives did not explain, why in this case MIAB process was preferred to the traditional friction welding that is used for fabrication of similar assemblies of steel parts. From our experience we know, that friction welding of steel to cast iron is made more difficult by the low deformability of cast iron. From Company information, friction welding is the preferred process for steel parts of a similar shape. For MIAB process one of the limiting factors also is the thickness of the parts being welded that should not be higher, than 5 to 6 mm.

It may be concluded that MIAB method can be successfully used, providing a high quality of the joints under the condition of mass production of the most critical parts, such as the rear axles of heavy trucks. Parameter recording in welding is the main method of process control.

Beam welding processes. *Electron beam welding (EBW).* This section of the Fair, in addition to the booth of the E.O. Paton Electric Welding Institute of the NAS of Ukraine, traditionally included the displays of leading EBW equipment manufacturers, namely Steigerwald Strahltechnik and PTR (Germany) and TECHMETA (France).

It cannot be said that anything new was on show, either in the field of technology or the equipment for this welding process. It can just be stated that out-of-vacuum EBW is becoming still wider accepted in fabrication of load-carrying car body parts of aluminium. Steigerwald Strahltechnik and PTR are active in this field, and some research centres, in particular, the Institute of Welding in Aachen are working in the field of welding technology.

A modern unit for out-of-vacuum welding is a sophisticated complex, consisting of the following components: module for item transportation to the assembly position; fixture for item assembly and mounting on a two-position table; chamber around the welding zone for protection from X-ray radiation; mechanisms for item positioning and displacement during welding; welding system proper with an assembly for protection and cleaning of the outlets from metal vapour deposition. Its cost can be estimated at not less, than $2 mln and it is only cost-effective in the case of a three-shift operation.

Laser welding. It should be noted that laser welding developments were exhibited by more than thirty companies, in particular Rofin-Sinar Laser, MWM, TRUMPF Lasertechnik, KUKA, LASERVALL, Fronius, etc. A large number of booths were devoted to laser application for automatic control of various welding heat sources along the butt being welded and visualisation of the welding zone (in particular, the booths of VISOTEK and META Vision Systems).

Laser cutting in laser pressing dies was traditionally widely represented, especially in the exposition of TANAKA (Japan). A quite well substantiated conclusion can be made about the beginning of a rather wide acceptance of laser welding in aluminium structure fabrication, in particular, in car-making and shipbuilding, where aluminium application is continuously expanding. The main cause for using the above welding process and its competitor — out-of-furnace EBW is the need to achieve the maximal welding speed.

There is no doubt that the most interesting in this area are the results, presented by Fronius, on application of a tandem (hybrid) process of laser-arc welding of ship containers from an aluminium alloy: a short video was demonstrated, as well as samples of equipment.

The processing system includes: ABB robot; laser-arc head; mechanism for feeding 1.2–1.6 mm filler wire of an aluminium alloy; complete 4 kW solid-state laser, made by HAAS-LASER, with a light guide, connecting the optical radiation generator to the welding head; switch-mode arc welding power source MW 1700 (2200, 2600, 3000).

A typical mode of welding a fillet weld on EN AW-6082T6 aluminium alloy 2 mm thick with filler wire EN AW-Al Si5 is characterised by the welding speed of 8.1 m/h at the heat input of 730 J/cm. Part of welded joints are made at the welding speed of 9 m/min. Company representatives state that the hybrid process allows a 10 times increase of the arc welding speed. By their information, this process is already used in such companies as Volkswagen (4 units) and Audi (6 units).

TRUMPF was practically continuously demonstrating in the Fair the process of welding large-sized panels-radiators of an aluminium alloy — weld depth of about 10 mm was achieved at beam power of 5 kW. Under a name of «Long-Range Laser Welding System» Rofin-Sinar Laser displayed a unit for laser welding of doors in an Audi car, with the laser head removed from the welding area for a considerable distance of 650 mm. This significantly improves the operating conditions for the applied laser optics due to a low thermal impact and small amount of metal vapour deposition, thus markedly enhancing the technological capabilities of the equipment. The laser beam is focused by a lens, mobile in the longitudinal direction, and is program-controlled by three-coordinate displacement, using a metallic mirror. VA TECH exposition was devoted to another interesting example of laser welding application in car-making, namely in fabrication of Volkswagen Polo door. Laser technology used in production of tailored blanks of car bodies was mostly just mentioned, as this process has already become widely accepted by industry.

TRUMPF, as indicated by its comprehensive and diverse display, maintains a strong position in development of laser equipment proper, as well as fitting it into sophisticated processing systems. The exhibited TRUMPF Linear Welder TLW 60 is a module, including a laser radiation generator of 0.7 to 20.0 kW power and a system of feeding the radiation to the working position, where continuous welding of pipes or shaped sections is performed. Development and manufacture of such lines is conducted by TRUMPF together with the respective specialised plant. A rather long focal distance of the generator of 150 to 300 mm should be noted as an indubitable achievement. Maximal deviation in automatic guiding of the laser beam to the butt of the edges being welded is equal to ±2 mm. Welding speed varies from 10 (for 0.5 mm thick metal) up to 28 m/min (for 3 mm), laser radiation of 1.5 to 20.0 kW being used. The exhibited welded samples of tubular blanks, formed from a strip, had practically no flash.

A self-sufficient laser technology system, fitted, in addition to the laser generator proper, with all the required peripheral equipment (gas stations, mechanisms of item transportation, welding manipulators, system of gas shielding, operator protection, etc.) was presented by Weil engineering. It is also designed for laser welding of a broad range of tubular structures and is made as a closed monoblock with a sealed working chamber, so that the welding process is observed through large viewport glasses. High-speed laser butt welding (8 m/min) of coiled thin strip (0.15–2.00 mm), including bimetal strip, that had been cut up also by the laser beam, was presented in IDEAL booth. A broad demonstration of the capabilities of various complete laser systems to solve specific production tasks was combined with presentation of a multitude of optical quantum generators: gas, diode and regular solid-state, based on aluminium-yttrium garnet and neodymium glass, both with the traditional and diode pumping (TRUMPF and Rofin-Sinar Laser booths).

TRUMPF prepared information booklets on new laser systems Trumatic L3050 and TLF 20.000, while HAAS-LASER (TRUMPF division, Germany) provided specifications of HLD 1003 (4506, 3504) lasers with diode pumping, having a very high efficiency (about 10 %).

TRUMPF, Rofin-Sinar Laser and Laserline displayed powerful diode lasers, which were quite similar in their engineering design and were fitted with an optical output head, connected to the generator directly or via a light-guide of a practically unlimited length.

When prices are discussed, all the diode laser manufacturers give approximately same sums: the cost of a 1 kW compete laser system is \$75,000, and that of a 6 kW unit is \$250,000–300,000.

An interesting and, evidently, a quickly developing field is microwelding and microsurfacing by a pulsed laser with manual feed of small-diameter wire (from 0.1 to 0.3 mm), demonstrated in the booth conditions with two sleeves for manual control of the item displacement and wire feed. Operator observes the technological process through a binocular microscope, moves the item with one hand, using the joystick and feeds in the wire with the other hand. This allows forming a deposited metal bead less than 1 mm wide and performing precision surfacing of dies, jewelry, sheet metal welding, etc.

Two companies, namely MOBILLASERTEC and SLV (Halle) simultaneously exhibited equipment for semi-automatic laser welding and results of its application. In this process, the operator either moves the laser welding head himself (MOBILLASERTEC), or mounts and fastens in the fillet weld zone small-sized devices, which accommodate mechanisms for moving the head along the butt of the edges being welded (SLV, Halle). Up to 4 kW laser radiation, transported through optical fibre, is used, and the welding speed is up to 90 m/h. MOBILLASERTEC expert said that the cost of a complete 2 kW semi-automatic welding machine was 450,000 DM.

Results of functioning of job-shops on laser welding and cutting of mass-produced items were extensively presented by LASERZENTRUM Schorcht. Products of manufacturers of spare parts for laser units (lenses, mirrors and other accessories), were also exhibited, in particular, those of MWM.

Thus, the following main areas of work on laser welding application, presented in the Fair, can be mentioned:

- high-speed welding of mass-produced casing items of aluminium alloys; strip blanks, including bimetal blanks; car body blanks; longitudinal welds on small-diameter pipes;
- mobile welding;
- precision surfacing and welding with manual feed of small-diameter filler wire and semi-automatic displacement of the item.

Advances in the field of diode lasers are also notable.

Robotic work stations (RWS). RWS were presented in a greater number and variety, than the traditional machine tools and machines for automatic welding.

Automatic lines, based on processing robots, typical, primarily, of automotive industry, were demonstrated only in video films. Conceptual material was provided by VA TECH that presented a model of a shop, fitted with several automatic assembly-welding lines, based on processing robots.

Prevailing in the exposition were robots with manipulation systems, traditionally made in the polar system of co-ordinates, sometimes with expanders along one or two rectilinear co-ordinates. Manipulators, operating in the rectilinear or combined system of co-ordinates, are normally used for cutting up the blanks.

Arc welding robots usually have a load-carrying capacity of 3 to 20 kg and positioning accuracy of 0.03 to 0.15 mm, and those for resistance welding and handling – up to 400 kg and between 0.3 and 1.0 mm, respectively. An increase in their maximal load-carrying capacity is observed, that allows heavier and more diverse actuators to be used. Accuracy and uniformity of motion, achieved in some robot models, allows such a high power density heat source as the laser beam to be efficiently used as the end effector.

Design of the new generation robots is characterised by application of self-sufficient electric mechanisms with short kinematic chains, located directly near the actuator link.

Robots that are incorporated into RWS, making weldments, are equally applicable for performing both the welding, and auxiliary operations (assembly, transportation, etc.). For this purpose, for instance, resistance spot welding heads are made as quick-change processing devices and are used during the operating cycle alternatively with various grips, clamps, benders, etc.

Popular are RWS, consisting of two or three simultaneously operating robots with their sets of replaceable end effectors, one of the robots being a welding robot, while the others act as manipulators of the base part and elements welded to it. Such a solution allows:

- widening the range of the main and auxiliary operations, performed by RWS in each work cycle;
- performing several processing programs without readjustment of RWS mechanical equipment;
- reducing the need for auxiliary programmable manipulators of the item;
- greatly simplifying the non-standard technological fixtures and associated costs for their development and fabrication;
- shortening the time for technological preparation to manufacturing new items.

The range of welding technologies that can be implemented, using RWS, has become broader, and in the traditional resistance spot and arc welding the range of processing parameters has become wider.

Higher load-carrying capacity of the manipulation systems enabled:

- applying, as replaceable end effectors, powerful heads for resistance spot welding at up to 20 kA current, and up to 0.5 m electrode extension;
- using replaceable grip modules, assembled in a turret head;

• using the manipulation system to perform such operations as bending or positive positioning of the parts to be welded.

RWS are used to perform capacitor-type and argon-arc welding processes with and without filler wire feed, characteristic of instrument-making industry. The achieved high accuracy of the robot manipulation systems allows implementing such fine technological processes, as laser welding without filler material feed. Of special interest are Linde achievements in welding Zn-plated parts in shielding gases with up to 20–30 % helium.

RWS are used to implement such new varieties of electric arc welding technologies, as:

• high-speed gas-shielded Tandem welding with two consumable electrodes (Lincoln Electric achieved the welding speed of up to 240 m/h);

• welding by a rotating-arc that is also used as a sensor (Carl Cloos Schweiβtechnik);

• plasma-powder welding (Carl Cloos Schweiβ–technik);

• combined welding simultaneously by a laser and a consumable electrode (KUKA).

The following examples of resistance seam welding technologies application in RWS can be given:

• one-side welding of flat structures, implemented, using a manipulator of orthogonal displacements and a device for the welding head rotation about a vertical axis, passing through the point of contact of the roller and the item (CEMSA);

• welding from both sides, performed with a replaceable four-roller head, interchangeable with a spot welding head (NIMAK).

Designs of powerful resistance welding heads are made in two variants – with a pneumatic or electromechanical drive of electrode compression (NIMAK).

Program-controlled systems for cutting up sheet metal, using plasma and laser cutting, were extensively represented in the Fair. Their working envelope dimensions are as follows: width of 1.5 to 10 m; length of 3 to 80 m; cut metal thickness is 1 to 50 mm, and the accuracy of cutting the blanks with the laser is 0.2 mm. Of interest is a HGG Profiling Equipment robot for making blanks of a standard length with different geometry of the edges from rectangular sections (pipe, channel bar, double T-shapes).

Various modifications of all-purpose assembly fixtures, containing setting elements and clamping devices were offered. Full-scale exhibits and video material led to the conclusion that even highly automated RSW for automotive industry are fitted with all-purpose assembly devices predominantly with manual clamps for parts fastening. On the other hand, various clamping elements of assembly fixtures with pneumatic or even electromechanical drive were widely displayed.

Plasma processing of materials. A wide range of plasmatrons, differing both in their power and purpose, and the kind of atmosphere and cathode material, used in them, were exhibited. Familiarisation with the exhibits showed that their designs were not particularly novel. The number of robotic systems and quality of equipment manufacturing were very impressive.

Sophisticated multifunctional systems, demonstrated by leading companies (such as ESAB, HITACHI, CTS, etc.) permit cutting and other kind of plasma processing to be conducted by special pre-developed programs, designed for in-line processing of hundreds and thousands of parts. The main attention is given to computerised control, allowing engineering tasks of plasma processing to be performed without man's participation by pre-composed programs with a high accuracy. When the statement of work for the proposed action is written, the required technical parameters are assigned in a special format, which is followed by the computer creating the required technological sequence, using the data available in the base, which is immediately implemented through the robotic system.

The second, not less important area of plasma technologies development, is related to safety and environmental protection. Diverse filtering cleaning systems were exhibited. A lot of attention is given to this work by such companies as Krupp, THYSSEN, and KEMPER. Technology of metal cutting in a water medium, demonstrated by OERLIKON, was also of interest.

Special methods of metal structure assembly. A series of machines for mechanised underwater cutting of pipes for their subsequent assembly and welding, exhibited by KISTLER, is notable. Machines of RSM-2000, 400, 800 models can perform both cutting of the end portions of pipes at different angles, and cutting out of holes in the pipe to connect a branch pipe to it. Edges bevelling for welding is done simultaneously. Cutting parameters are established by a program, where the initial data are entered, depending on the component design and geometrical dimensions of the elements. When one pipe is joined to another one, it is necessary to enter the diameters of the main and adjacent pipe and angle of inclination of the latter. If joining is performed with shifting of pipe axes, this parameter is also entered into the program.

The main purpose of the above machines is fabrication of general-purpose tubular structures, as well as pipeline components, such as T-bends, elbows, etc. Their use for construction of off-shore platforms is limited, as the maximal pipe diameter does not exceed 800 mm.

Machines have the following technical characteristics: cutting speed of up to 2 m/min, depending on pipe wall thickness; three-phase current source has the following parameters: 400 V voltage, 50 Hz frequency; and 12 kW·A consumed power.

Gas-oxygen severing. Both manufacturers and sellers of gas-cutting equipment from 16 countries had their booths. The main exposition was presented by companies MESSER, GREGGERSEN, IBEDA, Vulkan (Germany), UNIWELD PRODUCS, GENERICO, SMITH EQUIPMENT (USA) and ARROWELD ITALIA, CONTESSI, PERGOLA (Italy).

Gas mixing in the torch is applied in the design of practically all the specialised cutters for manual severing. Steel thicknesses, cut by them, vary from 5 up to 700 mm, but the majority of the presented cutters were designed for cutting steels up to 100 mm thick. Preheating is performed, using acetylene, and synthetic gases that are acetylene and propane substitutes. Cutters are fitted with systems of remote firing of the combustible mixture.

A number of leading gas-cutting equipment manufacturers offer all-purpose kits for gas-oxygen cutting and welding. They consist of an all-purpose handle with the stop valve and injector for gas mixing, a cutter and a set of torches for gas welding and soldering. A lever (sometimes a valve) for feeding the oxygen, used for cutting, is mounted on the cutter. The set also includes a range of various nozzles and tips for cutting steels up to 100 mm thick and safety valves for combustible gas and oxygen, preventing the flashback. Other variants of the kits are also offered.

Manufacturers presented cutters not only for manual, but also for machine cutting of steels up to 1 m thick by oxygen of high, medium and low pressure. Acetylene, synthetic gases and propane are used as preheating gas. No significant changes in the design of this type of cutters were noted.

CONTESSI exhibited a system for cutting metals and other materials, using oxygen lance, that was fitted with a specialised holder and cartridges for electric ignition of the lance.

Gas welding and soldering. Equipment in this area was rather widely represented. A common feature for all the exhibited torches was use of acetylene and its synthetic substitutes as combustible gas. The latter are put on the market in disposable bottles of up to 0.5 l volume, as well as more than 10 l reusable bottles. Propane in combination with oxygen, is used in the preheating systems as combustible gas.

Torches for welding and soldering are, as a rule, sold as a kit with safety valves, wrenches and all-purpose tools for removal of scale and metal spatter from the inner and outer surfaces of the nozzles. The kit may also include a set of torches for welding up to 0.5 mm thick steel. Torches for microwelding and soldering, applied in jewelry making were also exhibited. A number of companies demonstrated small-sized mobile welding systems, fitted with bottles of different volume, reducers, hoses, cutters and torches. The units, the weight of which varies between 10 and 50 kg, are mounted in suitcases or special fixtures, that, together with the bottles and regulating valves can be placed on wheels or in the form of a backpack on the welder's back.

Stop, gas-regulating and safety valves. A large number of companies started making reducers and stop valves, designed for the bottle working pressure of 30 MPa. It should be noted that a number of upgrades have been made recently in the safety valve design, resulting in their higher operating reliability and smaller dimensions. A number of companies are making reducers, where the surface has a larger heat exchange area, and a rotameter can be added to the set. A great variety of recording and reducing systems were also exhibited, providing the feed of oxygen and other gases into the factory gas supply systems, and they were complemented by stop valves, safety valves, mounting elements and other fixtures for various piping diameters. The majority of the manufacturers of gas-cutting and gas-welding equipment, presented in the Fair, are working under ISO 9001 quality system.

Analysis of the equipment and technology for gas severing and welding leads to the conclusions, that these processes currently are still in demand, despite development of a whole number of other, more advanced technologies. This is attributable, primarily, to the relatively low cost of the equipment and ease of its operation. The cost of gas-oxygen severing of general-purpose steels remains to be the lowest, compared to the cost of other technological processes. Oxy-gas welding of steels is still in a rather high demand as a technology, considering its high mobility, as well as a low cost of the equipment and consumables.

Underwater welding and cutting. Equipment and electrode materials for underwater welding and cutting were shown in three expositions. ARCAIR (USA), exhibited samples of 4 mm coated electrodes for wet underwater welding and 8 mm tubular electrodes for underwater oxy-electric cutting. The latter are made of a thick-walled steel tube with the inner diameter of 3.1 mm, through which «cutting» oxygen is supplied. A coating and thick plastic surface waterproofer are applied on the electrode surface. Total length of the electrode is 305 mm, and that of the working part is 350 mm. In addition to electrode materials, the company offers holders for oxy-electric cutting and welding.

M.O.S. Speciality Welds (Great Britain), demonstrated coated electrodes for welding low-carbon and low-alloyed steels in air and under the water. Electrode diameter was from 3.2 to 5.0 mm. Ultimate tensile strength values of the weld metal in welding under the water and in air are practically the same (564 and 540 N/mm^2, respectively). However, in welding under the water the ductile properties of the welded joints drop significantly (from 26 % in air to 10 % under the water). Weight fraction of the deposited metal components, by the data of the developer, is independent on the welding conditions, being, %: C — 0.05; Mn — 0.5; Si — 0.45; S, P $\leq$ 0.025. In addition to coated electrodes, the company offers electrode holders of a novel design and small-sized systems for monitoring and switching the arc processes in welding under the water.

TERMMEI (China) exhibited 4 to 12 mm electrodes for oxy-electric underwater cutting. They are of a standard length of 305 mm, and their cost is significantly lower, than of those made in the USA or Europe. The company did not provide any other additional information, for instance, about the cutting parameters.

Alternative joining technologies. Interesting technologies of making permanent joints by the method of perforation, that are an alternative to resistance spot welding, were presented in the Fair. They include perforation with a semi-tubular rivet, for instance, of BOLLHOF, as well as with a die (TOX PRESSO-technik).

Compared to resistance spot welding the perforation methods have the following advantages: power saving (≈ 3 times); ability to join dissimilar materials in any combinations; preservation of the integrity of coating on the metals being joined; sound formation of combined glue-mechanical joints in view of a low heating of the metals in the deformation zone; non-polluting nature of the process. Equipment with hydraulic and pneumatic drives was widely exhibited.

Diagnostics, non-destructive testing methods. It should be noted, that the modern methods of technical diagnostics were not presented in the Fair. About ten leading companies (KRAUTKRÄMER, Rich. Seifert, MPV, Förster, Vogt Werkstoffprüfsysteme, etc.) demonstrated equipment for non-destructive testing methods. Up-to-date systems for non-destructive testing of the welded joint quality both under the shop conditions and in site were widely exhibited. A new generation of equipment for ultrasonic testing has been introduced, which allows detection and characterisation of defects in three-coordinate planes in the automatic mode with computer processing of measurement results.

The following devices are of the highest interest:

1. All-purpose ultrasonic system for flaw detection and thickness measurement of KRAUTKRÄMER USN family. It is designed for performance of all the ultrasonic testing tasks, including measurement of defect co-ordinates and item thickness with up to 0.01 mm resolution. The weight of the instrument with nickel-cadmium accumulators is 1.6 kg, its working temperature range being between −20 and +55 °C.

2. Portable ultrasonic dialogue flaw detectors of KRAUTKRÄMER USN family. They are used for laboratory studies and practical control. They have a smaller inertia and capability of representing the maximal signal during the scanning process, and establish defect co-ordinates and item thickness with the resolution of up to 0.01 mm. Weight of the instrument with the accumulator is 3 kg.

3. KRAUTKRÄMER digital ultrasonic thickness gauges for point measurement and measurements of the residual wall thickness. They represent a new generation of ultrasonic instruments, designed for measurement of item thickness and residual wall thickness of pipes or vessels of all kinds, developing inner wear. Access to the back side of the controlled object wall is not required. Measurements can be taken in items under load. Instrument processors allow storing measurement results and transferring them for further processing in the computer.

The following modifications of thickness gauges have been developed:

• DN-4 is an ultrasonic instrument, compact and simple to operate; applied for measurement of wall thickness of equipment that is being manufactured or is operating. The instrument can be used to take measurements on items of various materials, including coated items. It has DUAL MULTI mode for measurement of the parent material thickness, excluding the coating thickness. Measurement range for steel is equal to 0.5–500 mm, the resolution being 0.01 (for thicknesses up to 100 mm), and 0.1 mm (for more than 100 mm);

• DHS2 is reliable and easy to operate, being especially convenient when working with laminated materials and coated items. It also has DUAL MULTI mode to exclude the coating thickness from measurement results. Measurement range for steel is 0.2–635 mm; resolution being 0.01 or 0.10 mm; working temperature from −10 up to +50 °C.

4. KRAUTKRÄMER instruments for hardness measurement by resonance-impedance (UCI) and rebound methods. They provide measurement results, independent on the probe position in space, even in the overhead position. Measurement results are recorded automatically by special processing of signals. These include hardness meters:

• HIC 10, being the most compact and-light weight, is used for fast analysis by UCI method; can be used for hardness measurement of items of practically any shape and size, with a fine-grained structure, especially in local study of material properties; allows evaluation of hardness values in *HV, HB, HRC, HRB* scales and determination of material rupture resistance;

• Dyna POCKET hardness meter is the most compact, designed for fast analysis and uses the rebound method; combines a striker and indicator with electronics in one block; can be used for determination of ultimate tensile strength and hardness measurement of materials in *HV, HB, HRC, HRB* scales in large-sized items with a coarse-grained structure, including cast products, and items of a complex configuration with difficult access.

A wide range of pickup probes and a wide selection of fixtures enhance the capability of materials hardness measurement by two methods, namely impedance and rebound method. Supports are proposed for precision hardness measurements, measurements on camshafts and other parts.

Vogt Werkstoffprüfsysteme exhibited units for automated ultrasonic testing. Acoustic contact between the ultrasonic transducer and object of control is provided by the immersion method (performed in an immersion bath) and slot method (running liquid fills the slot between the item surface and ultrasonic transducer, sliding along the contacted item).

MPV (Hess und Prüftechnik) demonstrated portable mechanisms of GECCOSCAN series for ultrasonic transducer displacement in quality control of vessels, columns and large diameter pipes. They have magnetic wheels, providing the instrument displacement along inclined and vertical surfaces at the speed of up to 150 mm/s. Positioning accuracy is ±1 mm, while the maximal determining size is equal to 240 mm.

Rich. Seifert demonstrated a number of new developments for X-ray inspection method, namely a commercial automated X-ray system ERESCO HF2 DP series isovolt mobil; commercial automated X-ray systems of DP series with image displaying; DP-51 and 354 type systems for controlling the quality of car wheels; completely automated systems of X-ray image processing; three-dimensional computer tomography systems.

Professional training and certification of personnel in the field of welding. It was presented only in the booth of the German Society of Welding and Allied Technologies (DVS).

Programs of professional training and certification of personnel are regulated by the appropriate DVS Directives, updated every two years. The current directives include more than forty training programs and comprehensive data on the training plans and scope, allowing assistance to be rendered to all the interested persons, as well as providing a complete idea about all the kinds of training and the standards currently in force. The contents of the training programs and duration of each training course are being continuously perfected in keeping with the changing requirements of welding productions.

Training is conducted only in the educational establishments that have DVS certification; approximately 500 educational establishments over the entire territory of Germany form one network, completely satisfying the production requirements and providing uniform conditions for mastering the profession.

DVS is currently offering various training programs, depending on the requirements of the German and international economy. They include the following qualification levels of welding personnel training.

Practical training courses. Training programs in the four main welding processes, namely gas (DVS Directive 1113), manual coated-electrode arc (DVS Directive 1123), gas-shielded consumable metal electrode (DVS Directive 1133) and gas-shielded non-consumable metal (tungsten) electrode (DVS Directive 1132), are divided into separate training stages (modules) going one into another. Training is focused on acquiring practical skills (80 % of training time). The theoretical course (≈ 8 % of training time) provides only basic knowledge on fundamentals of welding. A broad range of manuals, handbooks and reference books, issued by DVS publishing house, are proposed to gain a broader and more profound theoretical knowledge.

The first stage of training that envisages obtaining basic qualification in each of the training courses is the basis for further professional training in the next stages. After successful completion of the course a person receives a document, stating the basic qualification, namely a Certificate of DVS Welder. It is a unified confirmation of the qualification and a mandatory condition for further training in other modules and getting certification. Welders' certification is conducted by evaluation of practical task performance — depending on the requirements in the manufacturing field, controlled by the government, they are certified to DIN EN 287 or DIN EN ISO 9606. After successful certification the welder, in addition to DVS Certificate, receives an additional one, valid in all the countries-members of the European Welding Federation (EWF), thus guaranteeing acceptance of the qualification level of this specialist by foreign plants and authorised certification bodies.

In addition to the above arc welding processes, DVS, depending on the requirements of industry and service sector, offers training in various specialised courses (underwater welding; welding of sheets, reinforcing-bar steel, cast iron, etc.).

At the start of 1990s EWF accepted the welder training system, developed by DVS, as the European system. All the above DVS Directives have been approved as EWF Directives in a slightly modified form.

Training courses for supervising personnel. With the appearance of the first codes, defining the requirements to welded joints, welding fabrication plants faced the need to have qualified personnel, supervising the welders and the production. With this purpose programs for training welding engineers, welding technicians and welding specialists were developed in the DVS training system. These programs later on formed the basis within the EWF training system for development of unified programs of training supervising personnel for welding production. The professional activities of this personnel, their responsibilities and job description are defined in EN 719.

Currently offered training courses for the above personnel are conducted in keeping with the requirements, set forth in the following Directives: DVS-EWF 1173 (for welding engineers), DVS-EWF 1172 (for welding technicians), DVS-EWF 1171 (for welding specialists).

The International Institute of Welding (IIW) accepted the EWF system of supervising personnel training as the international system in the year 2000. In connection with the high requirements to training, it is conducted only in the DVS Training-Research Institutes (SLV), having European certification. All the programs are unified, taking into account Europe's specific features, and can be divided into three parts (theoretical fundamentals; practical updates; main course). The last part is divided into four programs: welding processes and equipment; materials and their behaviour in welding; design and calculation; production and technology. Training process is organised so that the three parts of the course can be mastered separately, but the entire training program must be completed within three years. Training ends up by qualification certification, including a written and oral examination. After successful certification, for instance in the welding engineer program, the trainee receives DVS Certificate in German, as well as EWF Diploma of European Welding Engineer and IIW Diploma of International Welding Engineer in English. EFW and IIW certificates confirm mutual acceptance in the counties-members of these organisations, that is a prerequisite for worldwide recognition.

Special refresher courses. A broad variety of training programs, covering special issues of the equipment and technology of welding, cutting and coating is a distinctive feature of DSV special courses, offered for welding instructors (DVS Directives 1151, 1152, 1154–1156); supervising personnel for welding reinforcing-bar steel (DVS Directive 1175) and cast iron (DVS Directive 1176); brazing parts of copper alloys (DVS Directive 1183); automatic (DVS Directive 1184-1) and robotic (DVS Directive 1184-2) welding, etc.

DVS courses on welding and adhesion bonding of plastics. To meet industry's demand DVS offers programs on training welders of plastics (DVS Directive 2212), practical specialists on adhesion bonding of plastics (DVS Directive 2221), as well as supervising personnel for these technological processes (DVS Directives 3301, 3305, 3308). All the proposed courses envisage mandatory certification by a common system jointly with the Engineering Inspection Society (TUOV).

Series of DVS courses for quality assurance personnel. Global quality policy, dominating in the world market, requires the manufacturer to fully comply with all the user (customer) quality requirements, as well as provide confirmation of the professional qualifications of the personnel in keeping with ISO 9000 series standards.

Interindustry program of professional development, offered by DVS under the requirements of ISO 9000 standards, is designed for three different training levels (DVS Directive 1177):

• training of quality assurance personnel (personnel, having fundamental knowledge);

• training of persons, responsible for quality assurance (personnel with special engineering knowledge);

• training of source inspectors (personnel with special technical knowledge, capable of supplier evaluation).

Training and certification in the respective course leads to receiving a European Certificate.

The proposed DVS training courses, meeting the requirements of the European and international standards, satisfy any needs of the customer for professional training and certification of personnel in all the possible fields of application of welding, cutting and coating deposition.

PLASMA-POWDER CLADDING OF INTERNAL COMBUSTION ENGINE VALVES

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Development of surfacing materials, technology and equipment for plasma-powder cladding of internal combustion engine valves is described.

Key words: *plasma-powder cladding, valve, powder, penetration, installation for cladding*

The industrial technology of a plasma cladding of valves of internal combustion engines (ICE) was developed almost at the same time in the USA and USSR at the beginning of the 1960s [1]. Since that time different versions of the plasma cladding using rods, rings, powders and other materials as filler materials have been developed. A plasma cladding on a fixed filler in the form of cermet rings was most widely spread. It is used in mass production of exhaust valves of cars, but its application is limited due to difficulties in industrial manufacture of filler rings and lack of advanced automated cladding equipment.

At the E.O. Paton Electric Welding Institute a technology of plasma cladding has been developed with use of powders of the filler material, which can be produced from any alloy, suitable for the valve cladding, not depending on hardness, ductility, degree of alloying and other properties, thus making it possible to widen significantly the range of alloys of cladding.

The valve cladding is most rational with use of plasmatrons and filler wire feeding into the arc. As the thermophysical calculations and experimental investigations showed the more favourable conditions are created in these plasmatrons for heating the filler material with a plasma [2]. Depending on the design of plasmatrons, and also valves and seats to be clad, the powders of particles from 45–63 to 125–200 μm are used. As a rule, they are produced by sputtering of molten metal with inert gas. The nominal composition of some grades of powders developed at the PWI in collaboration with industrial enterprises is given in the Table.

The powders indicated in the Table were used for cladding valves and seats of different types and sizes. The real efficiency of cladding depends to a great extent on type and size of the product, thickness of a deposited layer, granulometric composition of powders and other factors and lies within the ranges from 0.5 to 3–4 kg/h, thickness of deposited layer being from 1.5 to 4–5 mm. Penetration into the parent metal is negligible, if optimum ratio between current of

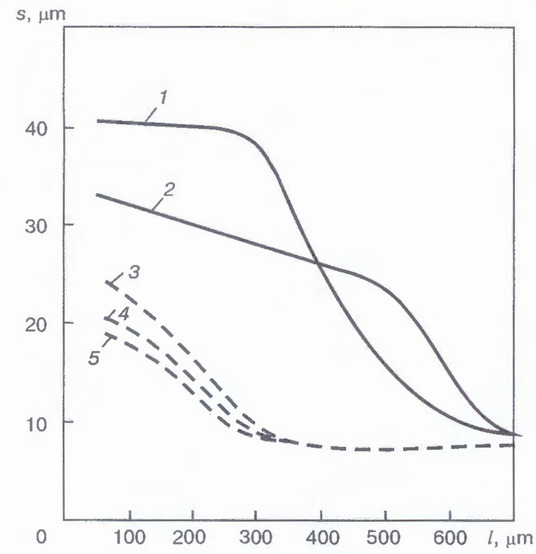

Figure 1. Change in grain size s in induction (*1, 2*) and plasma-powder (*3–5*) cladding of valves using different alloys: *1* — K60Kh30VS (V3K); *2, 4* — EP-616A; *3* — stellite 6; *5* — K25Kh25N20V12 (stellite F) (l — distance from fusion line)

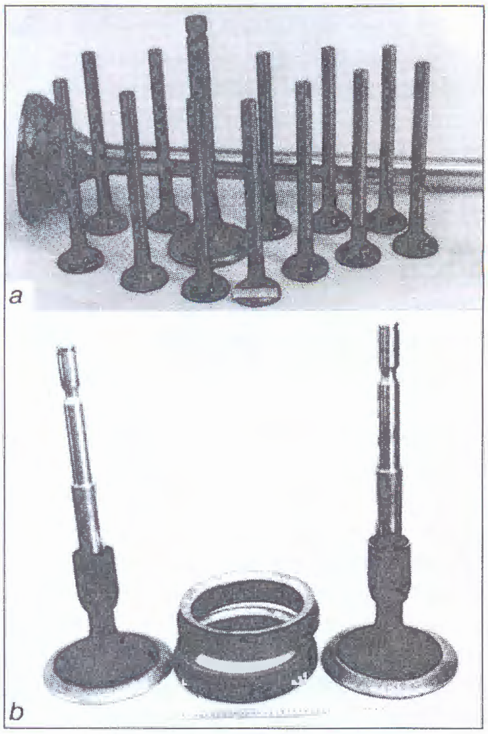

Figure 2. As-deposited prefabrications of valves and seats of benzine and diesel (*a*) and also large ship (*b*) engines

Chemical composition of powders and hardness of deposited metal

Powder	*Elements, wt.%*							*Hardness* HRC_e
	C	*Cr*	*Si*	*Fe*	*Ni*	*Co*	*Others*	
EP-616A	0.85	26	2.2	3	Base	–	1.3 B	35–42
PR-N73Kh16S3R3	0.7	16	3.2	≤ 3	Same	–	2.5 B	45–52
PR-N40Kh25V6	1.5	27	0.5	25	»	–	6.0 W	30–35
PR-K60Kh30VS	1.1	30	2.2	≤ 3	≤ 3	Base	4.5 W	38–44
PN-AN34	0.8	30	1.7	≤ 3	≤ 6	Same	4.5 W 0.8 B	42–47
PN-AN35	1.5	30	1.7	≤ 3	≤ 3	»	4.5 W	42–47
Pr-K25Kh25N20V12	1.8	26	1.0	≤ 2	22	»	12.0 W	42–45

plasma arc and powder feed is maintained. The feasibility of deposition of thin layers at a low thermal action on the parent metal is the most important advantage of the plasma-powder cladding. Zone between the parent and deposited metal in cladding of nickel alloys is 50–100 μm, and that of cobalt alloys – 100–150 μm. Width of overheating zone with a coarse austenitic grain in plasma-powder cladding is 0.2–0.3 mm. This differs it greatly from induction cladding where the parent metal is inevitably subjected to a high overheating with a formation of a vast coarse-grain zone (Figure 1) which can be a cause of the fatigue fracture of valves during service.

As a rule, the plasma-powder cladding is effective in manufacture of new valves and seats of ICE, more often instead of thermal cladding with rod fillers or the manual arc cladding, providing a significant, as compared with them, increase (from 30 % to 3–5, sometimes by 5 times) in efficiency, reduction in consumption of cladding materials and improving the quality of the deposited metal. In many cases the plasma-powder cladding is competed successfully with the induction cladding (freezing-upon). The most important field of application of the plasma-powder cladding is also repair of worn-out valves and seats, in particular of large ship diesels (diameter of a packing surface is 300–450 mm).

Figure 2 presents as-deposited prefabrications of automobile and ship engine valves. Versatile installations of plasma-powder cladding can be used for manufacturing and repair cladding of valves and seats of different types and sizes, and in serial production the specialized installations with a microprocessor control of the cladding cycle can be used.

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ADAPTIVE ALGORITHM OF QUALITY CONTROL OF RESISTANCE SPOT WELDING USING NEURAL NETWORKS

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Adaptive algorithm is suggested for quality control of the resistance spot welding of low-carbon galvanized steel taking into account the change in thickness of parts being welded. Algorithm was verified experimentally for (0.8 + 0.8), (1.2 + 1.2) and (2.0 + 2.0) mm packs. The adaptation of control algorithm from the results of spot welding of a limited number of samples provides an error in prediction of nugget diameter using a neural network of not more than 10 %.

Key words: *resistance spot welding, diameter of spot nugget, quality control, neural networks, adaptation*

Neural networks are used for a real time quality control of spot welding [1]. Artificial neural networks and appropriate controllers provide the evaluation of sizes of the weld spot nugget diameter and a force of its fracture at mechanical tests using data about the process parameters. Teaching of the neural network model is performed during welding of parts, made from steels of definite grades and thicknesses with allowance for other specific features of the process. Here, the change in working surface of electrodes, due to their wear, possible fluctuations in mains supply voltage and clamping force of electrodes are taken as main disturbing factors.

Depending on the thickness of parts welded from steels of the same grade, the welding condition parameters (welding current, diameter of working surface of electrodes, electrode voltage) are changed significantly. Therefore, the taught neural network model for a definite thickness of parts welded, which predicts the nugget diameter with an error, for example, 5–7 %, can reach error of 25–30 % at thickness change.

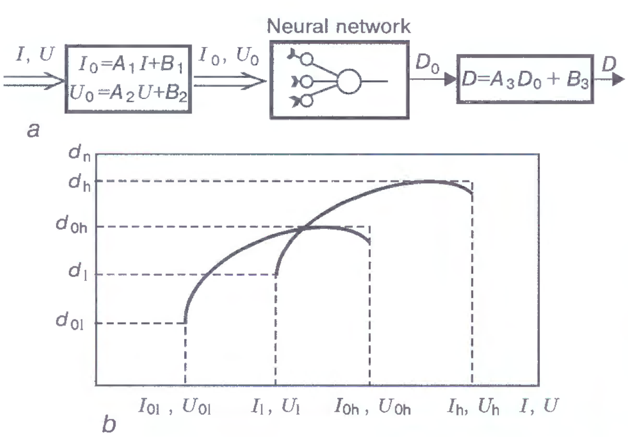

Figure 1. Schematic diagram of adaptive algorithm of quality control using neural network (*a*) and changing the region of definition and existence of mathematical model of process by varying welding conditions (*b*)

The taught neural network model includes a nonlinear model of the spot welding process in its structure. In the course of teaching of the neural network model the required values of weights and thresholds are selected on the basis of experimental data [1]. Consequently, to obtain the minimum error in prediction it is necessary to perform experiments and to specify weights and thresholds at neurons for each thickness of the parts. Moreover, the number of experiments can reach several dozens, that is inadmissible in the conditions of manufacturing.

Physical similarity of processes in spot welding can allow feasibility to produce algorithm for recalculation of coefficients at input and output variables of mains.

Below, such adaptive algorithm is described, according to which the coefficients are recalculated at input and output variables of the taught neural network depending on thickness of parts being welded. Weights, thresholds and structure of the basic model remain constant. It is assumed that a kind of relation between inputs and outputs, i.e. its monotony, convexity, presence of maximum in the interval between optimum values of weld spot diameter d_n and its critical value $d_{n.cr}$, at which splashes are occurred, is remained.

The principle of adaptation is as follows. Let us construct and teach the neural network for a definite thickness of parts being welded. We shall call it basic. From the experiment results, the ranges of changing input variables (in our case), values of welding current I and voltage U between electrodes, at which the model provides evaluation of quality with a minimum error, are known. A certain range of changing d_n corresponds to this region. The region of model definition is selected so that to include deviations of welding condition parameters, possible in manufacturing, at which the diameter of the weld spot nugget is changed from minimum admissible $d_{n\,min}$ until appearance of a splash $d_{n.cr}$.

In transition to welding of a pack of parts of another thickness the algorithm of the quality control should be reset, because in general case the region of both input condition parameters and also output value of quality (diameter of weld spot) is changed. In addition, the input variable networks are recalculated so that the old basic region of model definition was preserved at its input (Figure 1). The recalculation of each variable is realized by a linear law

$$I_0 = A_1 I + B_1; \quad U_0 = A_2 U + B_2, \qquad (1)$$

where I_0, U_0 are the values, respectively, of welding current and voltage between electrodes for a basic region, substituting to the neural network input; I, U are the measured values of the same variables.

Coefficients and absolute terms in relations (1) are calculated coming from admissible deviations of input variables of basic and new conditions of welding

$$\begin{aligned} A_1 &= (I_{0h} - I_{0l})/(I_h - I_l); \quad B_1 = I_{0h} - A_1 I_h; \\ A_2 &= (U_{0h} - U_{0l})/(U_h - U_l); \quad B_2 = U_{0h} - A_2 U_h, \end{aligned} \qquad (2)$$

where I_{0h}, I_{0l}, U_{0h}, U_{0l} are the high and low values of range of changing welding current and voltage between electrodes of a basic condition; I_h, I_l, U_h, U_l is the same for a new condition.

At such recalculation of measured parameters the data in the range I_l, I_h and U_l, U_h will be always substituted to the input of network in the region of I_{0l}, I_{0h} and U_{0l}, U_{0h}, i.e. the network will be used in the same region of input variables for which it was taught. It is evident, that the network will give the output values of a basic condition. To make the algorithm of quality control of welding to determine the value of spot nugget diameter according to the new condition it is possible to use the similar linear transformation for the network output:

$$\begin{aligned} D &= A_3 D_0 + B_3; \; A_3 = (D_h - D_l)/(D_{0h} - D_{0l}); \\ B_3 &= D_h - A_3 D_{0h}, \end{aligned} \qquad (3)$$

where D_l, D_h are the measured values of the nugget diameter, respectively, at input variables I_l, U_l and I_h, U_h; D_{0l}, D_{0h} are the output values of network in substituting I_l, U_l and I_h, U_h, recalculated by equations (1) to its input.

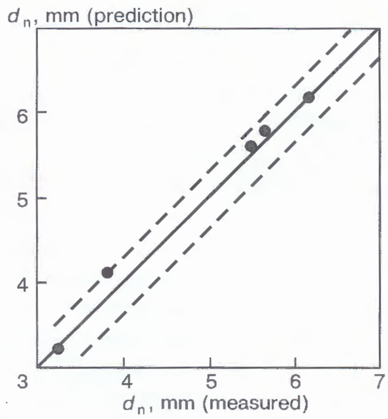

Figure 2. Neural network prediction of nugget diameter in welding steel of (1.2 + 1.2) mm pack thickness

When relations (3) are used, it is necessary to take into account that experimental data about the weld spot nugget diameter have random errors of experiment reproduction. Taking this into account, expression (3) is rational to construct as a linear regression of values D, obtained in experiments from values calculated by network D_0 in substituting corresponding input variables [2]:

$$\begin{aligned} D &= MD + A_3 (D - MD); \\ A_3 &= \sum [(D_j - MD)(D_{0j} - MD_0)] \,/\, \sum [(D_{0j} - MD_0)^2], \end{aligned} \qquad (4)$$

where MD and MD_0 are the mean values of weld spot nugget diameter, measured, respectively, on samples-witnesses and calculated by a network; D_j and D_{0j} are the measured and network calculated values of nugget diameter in j experiment.

It follows from expression (4) that to obtain very precise evaluations of parameters of recalculation algorithm it is necessary to design experiment so that output values of a basic network had as much as possible changes relative to their average value. It can be assumed for this that input variables I, U should take values in the entire region of the network definition at which the output value of the network (nugget diameter) is changed from minimum admissible to critical. In practice it is reasonable to narrow the

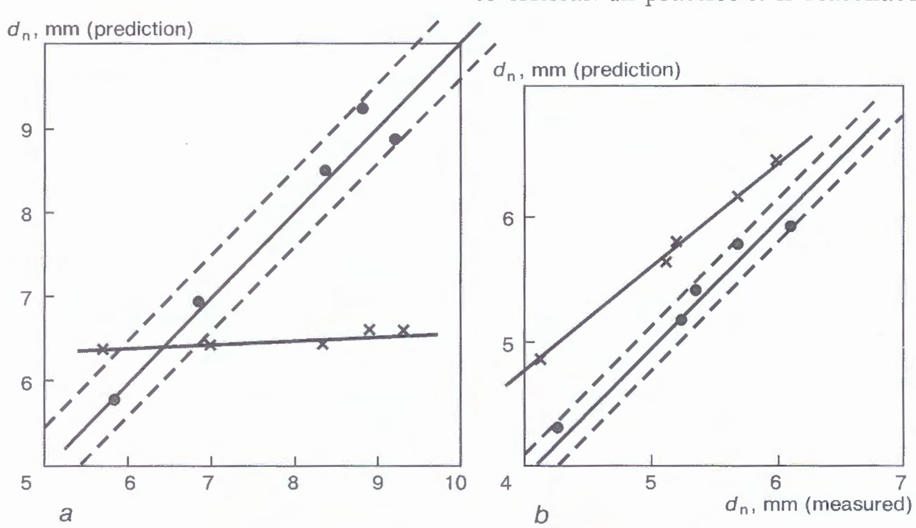

Figure 3. Neural network prediction of nugget diameter in welding steel of thickness of pack (2.0 + 2.0) (*a*) and (0.8 + 0.8) (*b*) mm with adaptation (●) and without it (×)

range of changing input variables by values at which the nugget diameter will take value from minimum admissible to optimum, to which the preset welding condition corresponds. This interval for the quality control presents the greatest interest.

The experimental verification of adaptive algorithm of the quality control was performed from the results of welding of the galvanized low-carbon steel. The neural network which was taught for welding parts with a (1.2 + 1.2) mm pack thickness was selected as basic. The welding condition parameters were selected taking into account the recommendations of International Institute of Welding: welding current I_w = 9 kA, time of welding t_w = 10 periods, welding compression force F_{com} = 350 daN. Electrodes of chromium bronze had initial diameter of the working surface d_e = 5 mm. Nugget diameter at optimum condition was d_n = 5.5 mm. During experiments the voltage supplying welding machine was changed by +5, −20 %, welding compression force — by ±20 %, diameter of working surface of electrodes — up to +40%. Here, the diameter of weld spot nugget was changing from $d_{n.cr}$ until lack of penetration. Input variables of the network were the mean values of current and voltage between electrodes at four intervals of time of welding: first three intervals by 2 periods and the last — 4 periods. The three-layer network had 8 input neurons, 3 neurons in a latent layer and 1 at output. The maximum error of prediction of nugget diameter of the taught basic neural network was 5–7 % (Figure 2).

To weld the same material with a pack thickness (0.8 + 0.8) mm the following condition was selected: I_w = 7.2 kA, t_w = 8 periods, F_{com} = 280 daN, d_e = = 5.0 mm, d_n = 4.5 mm, and for pack (2.0 + 2.0) mm: I_w = 12.0 kA, t_w = 12 periods, F_{com} = 600 daN, d_e = = 7.0 mm, d_n = 7.0 mm. During quality control of spot welding of parts of (0.8 + 0.8) and (2.0 + + 2.0) mm using a basic neural network the error in evaluation of nugget diameter was up to 30 %, that was inadmissible.

Then the algorithm of the quality control was adapted using the same data during experimental welding of packs of (0.8 + 0.8) and (2.0 + 2.0) mm thickness. Here, the error in prediction of the nugget diameter by the adaptive algorithm of the quality control for these thicknesses was less than 10 % (Figure 3) that is quite admissible under the manufacturing conditions.

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EXPRESS-METHOD FOR DEVELOPMENT AND VERIFICATION OF PRESSURE BRAZING TECHNOLOGIES

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The article describes experiments on development of an express-method to determine the possibility of producing joints and performing the process of pressure brazing or braze-welding of samples of specified materials. The above method allows selection of an appropriate braze alloy, flux, activators, technological modes of pressure brazing or braze-welding without having to make the joints on full-scale samples.

Key words: *welding, brazing, braze-welding, weldability, express-method, pressure, deformation, procedure, tests*

The issue to which extent a given material out of an assigned range of structural materials is suitable to make weldments or structures is very important for technologists involved in production of permanent joints by such methods as welding, soldering, pressure brazing, joining of bimetals and metals to non-metals. In this case it is desirable that experiments and technological tests be conducted on standadized small-size samples.

The express-method suggested allows a substantial reduction of costs of making such samples, compared with the use of samples of full-scale parts. This is economically and technically viable, for example, in a case where the required class of welding equipment for conducting experiments is unavailable. Reported is the use of such samples to control shear resistance of brazed joints [1, 2]. The use of standardized samples is indicated for the express-method intended for development of the technology of pressure brazing, i.e. plastic deformation of the near-weld zone of base metal (shortly — braze-welding)*. At present this technology finds an increasingly wide application [3–8].

The fundamental difference of the method of braze-welding from the other known joining methods lies in a combination of existing technologies and corresponding processes: brazing, induction welding, diffusion bonding and resistance butt welding.

The braze-welding process is performed as follows. To produce a butt joint with strength equal to that of the base metal, edges and surfaces of parts are subjected, if necessary, to simple machining using a highly efficient induction heating, which is carried out only until a melting temperature of the braze alloy and filler metals (activators) is reached. A joint is formed through displacement of a low-melting point phase and adhesion of crystalline lattices of the base metal. Strengthening of a weld is provided by pressing the molten braze alloy into microdefects.

Braze-welding provides for application of pressure to affect the joining line of the parts upon reaching a plastic deformation in the joining zone under the effect of heating, the temperature of which is mostly

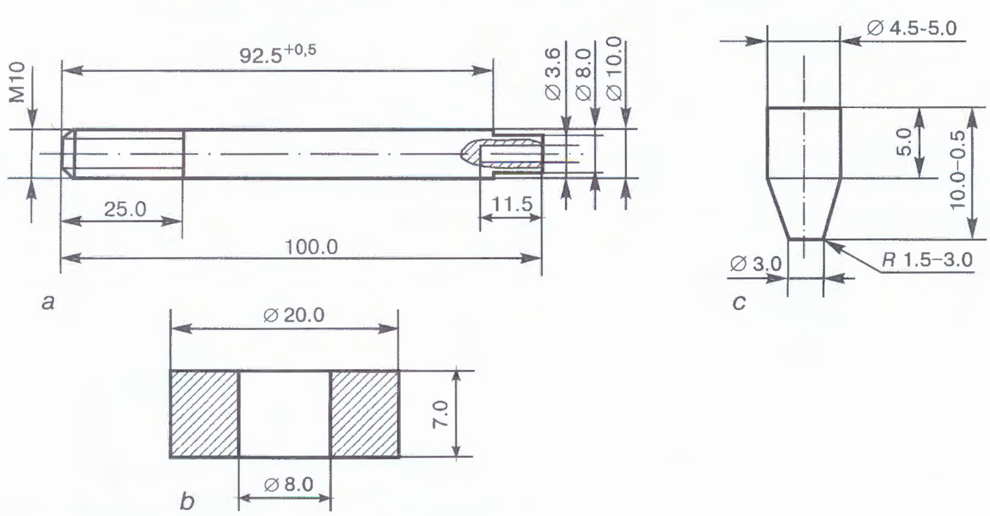

Figure 1. Schematic of the pin (*a*), washer (*b*) and cylindrical wedge-shaped insert (*c*)

* The term «braze-welding» has not yet been validated in the scientific literature and is open for discussion. The term used in this article is fundamentally different from that given in GOST 17325–79 «Soldering, brazing and tinning. Main terms and definitions» (used instead of GOST 17325–71), introduced 01.01.1981. Moscow: Izdatelstvo Standartov, 1980.

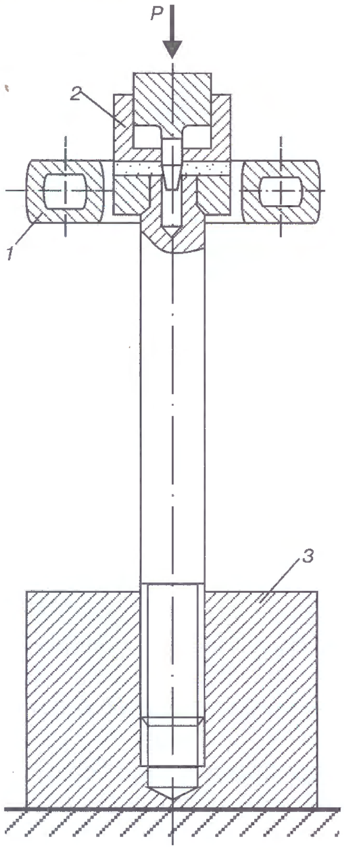

Figure 2. Schematic of assembly of a sample for heating: *1* — inductor; *2* — pressing-in device; *3* — support

lower than the level of a liquidus–solidus state of metal of the Fe–C system.

The use of upsetting (pressure) and resulting deformation of the parts being joined to a preset size is determined by the following factors: design parameters of a joint, degree of heating of the parts to a state at which it is possible to provide inelastic deformation and heating, allowing transformation of the braze alloy or an activator into the liquid state. In this case, further increase in temperature should not lead to a variation in quality of the braze alloy or activators in the joining zone.

In the latter case the moment of application of pressure onto the parts joined is determined by the melting point of the braze alloy and its flow into the gaps in the joint, as is the case of brazing. However, in any case the application of pressure should lead to plastic (inelastic) deformation and, eventually, to contact crushing of the joining line and decrease in thickness of the weld.

The braze-welding method is a sort of a complement to the existing principles of brazing and has much in common with this process. Nevertheless, it has some differences from the latter: the joint can be made permanent, depending upon its shape, owing to application of pressure and contact crushing; thickness of the fusion line is substantially different, which leads to a decrease in flow of the braze alloy along the grain boundaries and limits the probability of formation of lack of fusion; there is a insignificant distortion of geometrical dimensions of the parts joined, this being comparable with formation of a projection of the weld or external flash in welding, which can be either removed or not removed, depending upon the type of a welded structure and its application.

The so-called «Method of Tensile Tests of Brazed Joints» [1, 2] has been used as the basis for the suggested express-method, the general shape and sizes of samples used for it being preserved, although with a minor modification. The latter involves drilling of an axial hole of a certain diameter in the tip of a pin (sample component) (Figure 1, *a*). After assembly of the pin and a washer (Figure 1, *b*) and subsequent heating of the sample (Figure 2), a cylindrical wedge-shaped insert with a cone pointing (Figure 1, *c*) is pressed into the above hole. The ratio of diameters of holes in the pin and cylindrical insert is determined on the basis of assigned values of tightness and contact pressure between the sample components.

The required contact pressure P_c between the parts joined is set with a certain degree of accuracy using the known formula [9]:

$$P_c = \frac{\delta/d_c}{\frac{1}{E_1}\left(\frac{1+K_1^2}{1-K_1^2} - \mu_1\right) + \left(\frac{1+K_2^2}{1-K_2^2} - \mu_2\right)},$$

where δ is the preset tightness; d_c is the diameter of the contact surface; E_1 and E_2 are the elasticity modula; $K_1 = d_1/d_c$, $K_2 = d_2/d_c$ are the different thickness factors; μ_1 and μ_2 are the Poisson's ratios (here indices 1 and 2 designate that parameters belong to the external washer and the pin surface, respectively). The required values of outside diameters of

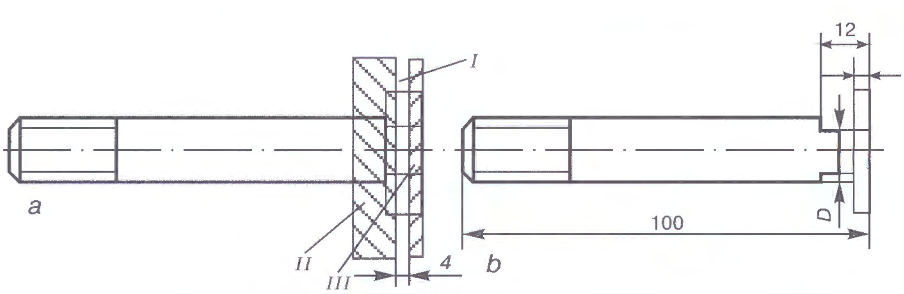

Figure 3. Schematic of samples produced by the braze-welding method: *a* — samples prepared for machining; *b* — samples after machining; *I* — zone 1 mm wide, which is to be removed by machining; *II* — zone 8 mm wide, which is to be turned to a diameter of 8 mm (an increase in the width of turning towards thread); *III* — braze-welded joint

the washer, d_1, and pin, d_2, are determined from the above formula.

Therefore, optimization of the known method and a sample used for it allowed realization of elements of the technology of pressure brazing and braze-welding using standardized specimens.

The affordable and informative express-method has been developed on this basis to determine the possibility of formation of joints using brazing which involves plastic deformation of the base metal in the joining zone (braze-welding). The use of this new express-method makes it possible to solve the following problems:

- determination of the feasibility of the brazing process involving plastic deformation of the base metal on samples made from the base metal;
- assignment of a contact pressure (with a certain degree of accuracy) between the samples joined over the entire joining area to induce deformation of the base metal at a location of the joint;
- use (selection) of the existing and new braze alloys, fluxes and activators;
- development of the laboratory technology using standardized small-size samples of materials of billets instead of full-scale samples and parts (pipes, flanges, rods, etc.). In the latter case this method belongs to the methods of incomplete physical modeling;
- determination of structure of the weld metal and near-weld zone in making sections from a given sample.

The necessary conclusions on the required degree of deformation, weldability of a material, suitability of this or that braze alloy, flux and activator are made on the basis of a character of deformation and fracture of samples during the tests.

Application example. Figure 3 shows schematics of samples produced by the above method using the braze-welding process. In this case the wedge-shaped insert with a diameter of 5 mm was pressed into the hole with a diameter of 3.6 mm at the pin tip.

Practical application of the suggested express-method is as follows. A pin and a washer are made from the material investigated. The washer (see Figure 1, *b*) is placed on the pin (see Figure 1, *a*). The braze alloy and a flux in the form of an inserted element or a powdered mixture of the braze alloy and the flux, as well as other activators, are placed on their joining surface (cylindrical surface). Placement of the braze alloy and flux powdered mixture on the common horizontal end face of the pin and washer is permitted, therefrom it gets into the gap between the pin and the washer under the effect of capillary suction. Then the sample thus assembled (see Figure 2) is heated to a preset temperature. At the moment of achievement of this temperature the cylindrical insert is pressed (see Figure 1, *c*) into the end face hole of the pin.

Then the joints produced are subjected to machining, according to Figure 3, which results in standardized samples for mechanical shear tests (Figure 4, *a*) or for determination of physical-chemical and metallographic properties of the circumferential weld and the near-weld zone (Figure 4, *b*).

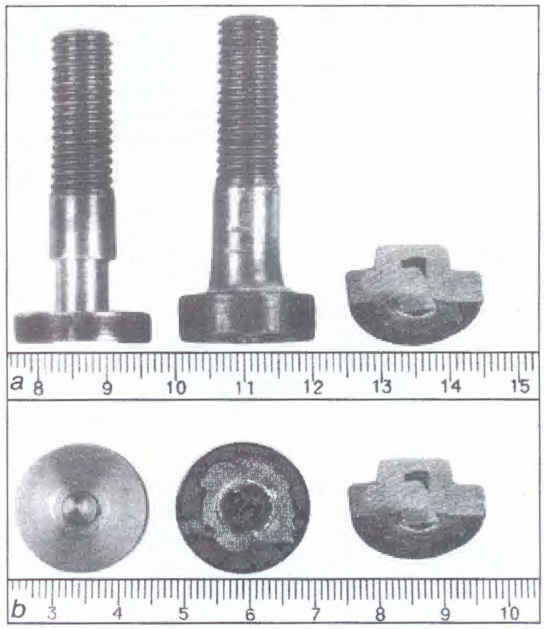

Figure 4. Standardized sample: *a* — general view; *b* — end face of the sample

As it can be seen, practical application and verification of the suggested express-method are performed in compliance with the procedure described previously. In addition, this provides the possibility of inducing plastic deformation of the weld zone. The latter is achieved by adding extra process elements, such as a cylindrical insert and a hole for it made in the pin (see Figure 1, *a*). This allows the required plastic deformation to be induced in the cylinder wall between the process hole and its outside diameter, caused by a difference between the insert diameter and diameter of the hole in the pin.

The cylindrical insert generates a separating force and pressure in the zone of the joined cylindrical surfaces of the pin and washer over the entire area of their contact. Its pressing in leads to a flow of metal and tightness of the cylindrical surfaces being joined.

This express-method is especially convenient for modeling of the braze-welding process for manufacture of flanges and flange joints in pipes [8].

The method suggested enables selection of the process parameters for braze-welding, such as heating temperature, upsetting pressure, deformation of the base metal in the weld zone, using standardized samples made from materials subject to joining, to meet requirements for quality of the joints, as well as selection of the process material, such as braze alloy, flux and other activators, to suit the braze-welding process.

Application of the express-method developed makes it possible to avoid making joints on full-scale samples and manufacture of standard test specimens, which substantially reduces the cost of the research process and development of a technology.

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