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PATON EVGENY OSCAROVICH

On March 5, 2000, 150 years have passed since the birthday of Paton Evgeny Oscarovich (1870–1953), the outstanding scientist in the field of metal structures and welding, academician of the Academy of Sciences of UkrSSR (1929), Honoured Scientist of UkrSSR (1940), laureate of Stalin prize of USSR (1941), Hero of Socialist Labour (1943), founder and permanent director of the Institute of Electric Welding (1934–1953), vice-president of Academy of Sciences of UkrSSR (1945–1953). E.O. Paton went down in history of science as the author of classical manuals on bridge construction, the designer of unique projects of bridges, the head of a scientific school on the problems of welding which is recognized all over the world.

Evgeny Oscarovich is well characterized by his own words: «I have never been attracted by the work directed to the solution of subjects abstracted and isolated from practice. I tried to make my works and the works of my staff to the useful for the national economy. The best award for the man is to see the embodiment of ideas and results of works into the life». Different scientists including those involved in engineering estimate their achievement in different ways. Some of them are satisfied with receiving unique formula and consider their mission finalized. But such an achievement for E.O. Paton is only a step on the way to the main aim.

All life he was tireless at his work. He taught students, wrote manuals, improved methods of design of bridges, created unique projects and participated in their realization. He invited students to these works, fascinating them with his ideas, imparting the habits of a creative approach to the solution of technical problems.

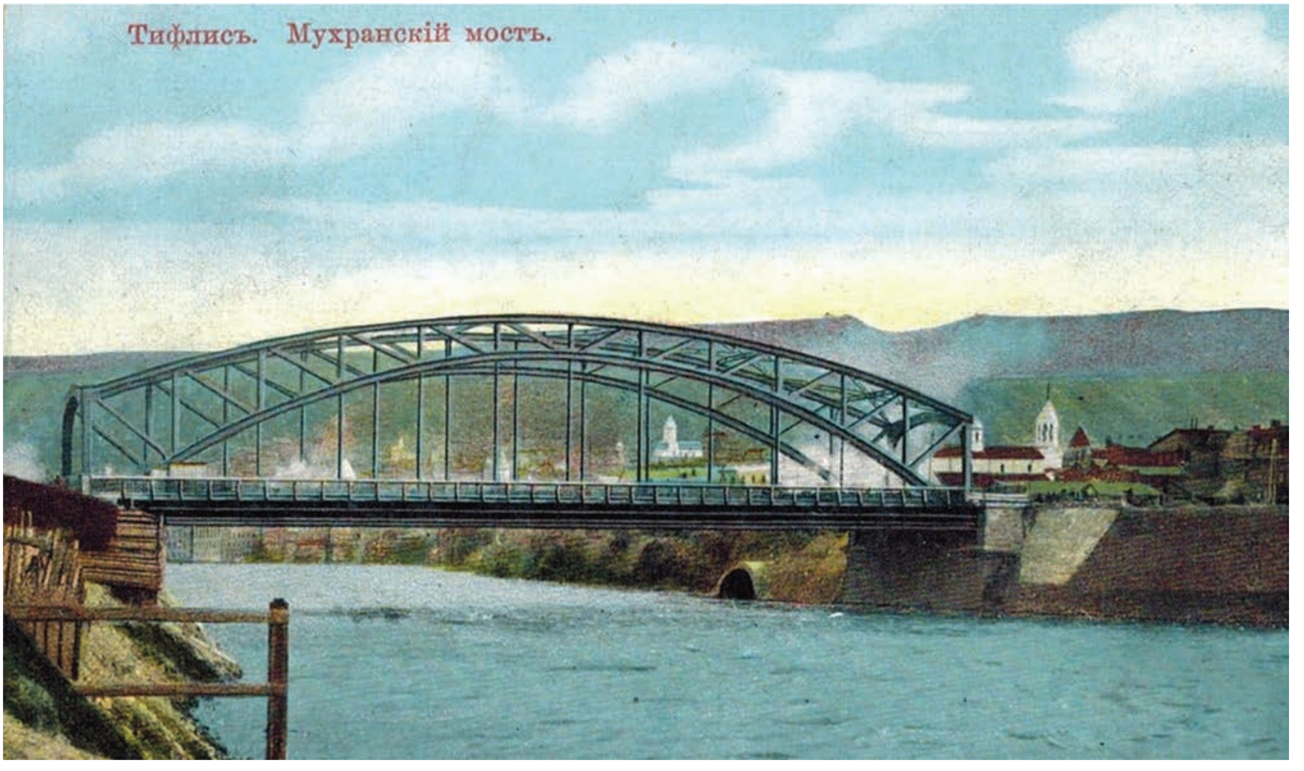
In the 20s E.O. Paton realized that the technology of fabrication of metal structures will be based on an electric welding and decided to study this technological process. He founded the Electric Welding Laboratory which in 1934 was transformed to the Institute of Electric Welding. Evgeny Oscarovich considered the development of a high-efficient method of welding suitable for manufacture of critical structures as one of the important aims of the Institute. By the end of the 30s the Institute managed to develop such method as the submerged-arc welding. The Second World War began. By the request of Evgeny Oscarovich the fall 1941 Institute was evacuated to the Urals where the mass production of tanks was organized. In the severest conditions it was necessary in the shortest terms to create the technology of welding of hard-to-weld armoured steels, to set the manufacture of welding automatic machines and flux. At that time Evgeny Oscarovich and his colleagues accomplished a really heroic deed in realizing all this. The famous tanks T-34, welded by the automatic machines, were continuously leaving the plant conveyor. The submerged-arc welding was also mastered at other defense plants owing to the efforts of E.O. Paton and his staff.

In postwar years the Institute was working in collaboration with hundreds of plants. New technologies of manufacture of ship hulls, large-diameter pipes, power, petrochemical and other equipment were created. At the same time Evgeny Oscarovich returned to his main idea, i.e. to the construction of all-welded bridges. The program of research works was scheduled and successfully fulfilled. This program envisaged the specifying of requirements to steel for welded structures, creation of rational welded joints and study of their strength, development of technology of welding both under shop and site conditions. At that time a method of welding vertical welds with a forced weld formation was also developed. The works of that period made a good start for a thorough study of materials science problems of welding, problems of strength of welded joints for different conditions of service, contributed to a wide application of mechanized methods of welding in site conditions. The first long all-welded bridge designed and constructed under the direct supervision of Evgeny Oscarovich and named after him was put into service in Kyiv in 1953.

E.O. Paton paid a great attention to the works made from the orders of the industrial enterprises. He considered an agreement with a customer as a certificate of recognition of usefulness of the research works. At a present transition to the market principles of organizing the economy, the progressiveness of the vital positions of the outstanding scientist becomes more evident.

E.O. Paton left us the property, the Paton traditions, which are followed now at the Electric Welding Institute headed by Paton Boris Evgenievich. In spite of hard times in the country economy, the Institute, which bears the name of its founder, PATON EVGENY OSCAROVICH, is still one of the most authoritative research centres in the field of welding and allied technologies. This is proved by its wide-spread relations both with Ukrainian enterprises, and with R & D centres and companies of many foreign countries.

Given the great contribution of the Electric Welding Institute to the world treasury of knowledge and technology in welding and allied technologies, International Welding Institute in 2000 founded the «Eugenij PATON Prize».



Mukhrani Bridge across the Kura river in Tiflis, built in 1908 by E.O. Paton's design


Grand opening for traffic of Evgenia Bosh Bridge, designed by E.O. Paton. Kyiv. May 10, 1925

Opening ceremony of the E.O. Paton bridge, November 5, 1953

Memorial sign with which
the American Welding Society commemorated
the E.O. Paton Bridge in 1995 as a prominent
welded structure of the twentieth century

E.O. Paton bridge today

Designing the Kyiv pedestrian bridge at the end of Petrivska alley, well-known to all the Kyivites, gave me a lot of creative joy. e remains of a slope on the hilly bank of the Dnipro, which had not yet slid down, were an obstacle to continuation of the Petrivska alley. First, a project was put forward, which consisted in running a tunnel through this land mass. Such a solution seemed uninteresting and dull to me. is wonderful corner of Kyiv could be decorated by a light, beautiful bridge. It would look extremely aractive against the background of endless Dnipro expanses and magnicent Kyiv parks. I suggested making a deep recess in the slope and spanning it by a light pedestrian bridge with crescent laice trusses. They liked the idea, and it was approved.

E.O. Paton

Arched bridge over Petrovskaya Alley in Kyiv,
built in 1912 by E.O. Paton's design

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USE OF STEELS OF THE STRENGTH CLASS C350–C490 IN THE PRODUCTION OF BUILDING WELDED STRUCTURES

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The effect of thermal cycles of arc welding on the structure and mechanical properties of metal of the heat-affected zone of welded joints of microalloyed structural steels of the strength class from C350 to C490 was investigated. It was established that as a result of the action of thermal cycles of welding, metal structure of the heat-affected zone of most microalloyed steels of the strength class from C350 to C490, except for steel 09G2SYuch, remains stable bainite in a wide range of cooling rates, and mechanical properties do not change significantly. As a result of welding, at moderate cooling rates the structure of the heat-affected zone metal in the steel 09G2SYuch can change from bainitic to baini-to-martensitic and martensitic as the metal cooling rate increases. As a result of that, the values of static strength and impact toughness of the metal are increasing and its ductile properties are reduced. 12 Ref., 5 Tables, 7 Figures.

Keywords: *structural steels, thermal cycle of welding, metal structure, mechanical properties, welded building structures*

One of the main tasks in the modern development of industry is to increase the technical and economic performance of machines, mechanisms and engineering structures on the basis of reducing their specific metal consumption, increasing service reliability and life. In world practice, this is achieved through the use of high-strength steels with the yield strength of 350 MPa or higher during manufacture of welded metal structures.

In particular, low-alloy high-strength steels of the strength class C355–C490 are widely used in bridge construction, in the production of tanks for storage and processing of gas and oil, in the manufacture of building structures, etc. As far as the vast majority of the mentioned metal structures are welded, such steels have certain requirements, namely, they should be well welded, provide high ductility and equal strength of welded joints, as well as the values of impact toughness at the level of the requirements, which are regulated by the state building standards, which have undergone some changes in recent years. These changes, first of all, relate to the values of impact toughness and relative reduction in area of rolling surface in the Z-direction. According to the modern requirements, steels and, respectively, weld metal and metal of heat-affected zone (HAZ) of welded joints should have impact toughness $KCV^{-20} \geq 25$ J/cm^2 for steels with $\sigma_y = 290$–390 MPa and $KCV^{-40} \geq 25$ J/cm^2 for steels with $\sigma_y \geq 390$ MPa and relative reduction in area in the Z-direction (ψ_z) of not less than 35, 25 and 15 % for the first, second and third groups of structures, respectively.

Until now, during the manufacture of building structures in the CIS countries, low-alloy steels of the strength class C350–C390, such as 09G2S, 10KhSND, 15KhSND and other are still widely used, which were developed in the times of the USSR (Table 1). All the mentioned low-alloy structural steels, listed in Table 1 completely meet the modern requirements to the static strength and ductile properties of steels along and across the rolling surface (Table 2). In most of them the impact toughness is also at the level of these requirements. But in order to maintain the required level of *KCV* of HAZ metal, the cooling rate of welded

Table 1. Requirements to the chemical composition of increased and high-strength steels for building structures

Steel grade	Mass fraction of elements, wt.%									
	C	Si	Mn	Cr	Ni	Mo	V	Al	Cu	S	P
09G2S	≤0.12	0.5–0.8	1.3–1.7	<0.3	<0.3	–	–	–	<0.3	<0.035	<0.03
15KhSND	0.12–0.18	0.4–0.7	0.4–0.7	0.6–0.9	0.3–0.6	–	–	–	0.2–0.4	<0.035	<0.03
17G1S	0.15–0.20	0.4–0.6	1.15–1.6	<0.3	<0.3	–	–	–	<0.3	<0.035	<0.03
10G2S1	≤0.12	0.8–1.1	1.3–1.65	<0.3	<0.3	–	–	–	<0.3	<0.035	<0.03
10KhSND	≤0.12	0.8–1.1	0.5–0.8	0.6–0.9	0.5–0.8	–	–	–	0.4–0.6	<0.035	<0.03

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Table 2. Requirements to the mechanical properties of increased and high-strength steels for building structures (not less than)

Steel grade	σ_y, MPa	σ_t, MPa	δ_5, %	KCU^{-40}, J/cm^2
09G2S	350	500	21	34
15KhSND	350	500	21	29
17G1S	350	500	22	29
10G2S1	390	520	19	29
10KhSND	390	530–660	19	29

Table 3. Requirements to the mechanical properties of new microalloyed steels of increased and high-strength for building structures (not less than)

Steel grade	σ_y, MPa	σ_t, MPa	δ_5, %	KCV^{-40}, J/cm^2
06GB, 390	390	490	22	98
06G2B, 440	440	540	22	98
09G2SYuch	450	570	19	29
10G2FB	490	565	22	29

joints in the temperature range of 600–500 °C ($w_{6/5}$) should be in the range of 15–20 °C/s. This requires a significant limitation of welding modes, which complicates the technological process and makes its efficiency low. In addition, ψ_z in such steels does not exceed 15 %, which limits their use in welded elements operating in the direction of the thickness of a rolling surface.

Since the 1990s, some changes occurred in the metallurgical industry due to significant economic and technical transformations. The mass transition of enterprises to economic independence contributed to the creation of steels, the production of which is most economically advantageous for specific economic conditions of the combine plants. The intensive integration of domestic metallurgy into the world economy caused a necessity in the revision of the standards to steel quality evaluation. First of all, it concerns the evaluation of their impact toughness. In addition to the approach to determination of impact toughness, generally accepted in the domestic industry, based on the results of examination of specimens with a U-shaped notch, the specimens began to be used, that have a V-shaped notch. Their use during tests provides a more accurate evaluation of the ability of steels to resist fracture. At the same time, such an approach revealed certain defects in domestic steels. In this regard, a need arose to modernize the existing steels and create the new steels that would satisfy the ever-increasing requirements of production. As a result, in recent years domestic metallurgical plants mastered the production of new steels of increased and high strength that are manufactured by domestic and international standards and completely meet the Eurostandard requirements.

High strength, ductility and impact toughness (Table 3) are obtained by modern high-strength structural steels due to formation of fine-grained structure of a certain composition in the metal. This is achieved both due to alloying of steels (as a rule, they contain manganese, silicon limited to 0.5 %, carbon — to 0.15 %, nitrogen — to 0.012 % and microalloyed separately or in combination with vanadium, aluminum, niobium, cerium), as well as due to controlled rolling or special heat treatment of rolled steel (Table 4).

Taking into account that the mentioned high-strength structural steels, which are manufactured at Ukrainian metallurgical enterprises, have exceptionally high mechanical properties, all of them were recommended and included in the State Building Regulations as those that can be used in the manufacture of building metal structures. To ground such possibility, at PWI the comprehensive investigations were carried out, which showed a good weldability of these steels and allowed determining the conditions of welding at which joining of the mentioned steels would fully meet the modern requirements to metal structures.

Evaluation of steels weldability consists in determining the optimal welding conditions, at which the probability of cold cracks formation in the joints and in the metal of the heat-affected zone of the structures is eliminated, that will facilitating the reduction in the strength, ductility and cold resistance of the metal.

In contrast to rolled steel, the formation of structure in the HAZ metal of welded joints of high-strength steels is significantly affected by the thermal

Table 4. Requirements to the chemical composition of new microalloyed steels of increased and high strength for building structures

Steel grade	Mass fraction of elements, wt.%										
	C	Si	Mn	Mo	Al	Nb	V	Ce	Cu	S	P
06GB, 390	0.04–0.08	0.25–0.50	1.1–1.4	≤0.08	≤0.05	0.01–0.03	0.02–0.05	–	<0.3	<0.01	<0.025
06G2B, 440	0.04–0.08	0.25–0.50	1.3–1.6	≤0.10	0.02–0.05	0.03–0.05	0.03–0.07	–	<0.3	<0.01	<0.025
09G2SYuch	0.08–0.11	0.3–0.6	1.9–2.2	–	0.035–0.065	–	–	0.002–0.005	0.3–0.6	<0.015	<0.02
10G2FB	≤0.15	≤0.35	≤1.7	≤0.3	0.02–0.03	≤0.08	≤0.1	–	–	<0.01	<0.02

cycle of welding (TCW) [1–9]. The most significant changes in the structure of steel during welding occur in the region of overheating of the HAZ metal, i.e. in that area, which is located in the immediate vicinity to the weld and is heated to the temperature of 1300–1150 °C. During arc welding, TCW parameters depend on many factors. The most important among them are heat input of welding, initial temperature of the metal and its thickness and type of welded joint. With increase in the heat input of welding and initial temperature of the metal, the rate of cooling the HAZ metal in the temperature range of 600–500 °C ($w_{6/5}$, °C/s) decreases, and with increase in the metal thickness — it grows. Based on these considerations, we selected namely the index $w_{6/5}$ as a criterion that will allow comparing the reaction of steels to TCW and determining how the conditions of heating and cooling of the metal affect its structure and mechanical properties.

The investigations, the results of which are given in this article, were performed with respect to the thermal cycle of welding specimens and the specimens produced from the deposits on the plate. The effect of thermal cycles of welding on the HAZ metal structure was studied by dilatometry examinations and optical microscopy [10]. The mechanical tests on static tension and impact bending were performed using the standard specimens: type II according to GOST 6996–66 and type IX according to GOST 9454–78.

To determine the effect of chemical composition and cooling conditions of the metal on its structure, the austenite transformation diagrams were used, which were plotted taking into account the processes that occur during welding. At the same time, in order to provide a high austenite resistance typical for welding, such heating conditions (w_h) were selected when plotting the transformation diagrams, under which the individual features of steels with respect to the susceptibility of grain growth became to be quite clearly revealed. Usually, during dilatometric investigations, the specimens heating rate is set within 150–300 °C/s [11]. In our investigations, it was 150 °C/s. The cooling rates of dilatometric specimens were selected on the basis of the need to provide such cooling conditions in the temperature range of the least austenite stability that will be as close as possible to the conditions of cooling the metal at the overheating region of the heat-affected zone of the joints produced on the conditions characteristic for arc welding processes.

The heating rate was controlled by changing the current according to the set program, which passed through the specimen and the cooling rate was controlled by cooling the devices that transmit the current from the heating machine to the specimen by water, blowing the specimen with inert gas.

Due to the rigid fixing of specimens in the heating machine, the processes of development of inner deformations are simulated on them in the region of uniform heating, which according to the value and nature of changes are close to the longitudinal inner deformations formed at the region of HAZ metal overheating in arc surfacing of metal layer on the edges of plates.

The dependencies plotted on the basis of the austenite transformation diagram related to changes of structural components occurring at different cooling rates at the region of HAZ metal overheating of new high-strength microalloyed steel structures, are presented in Figure 1.

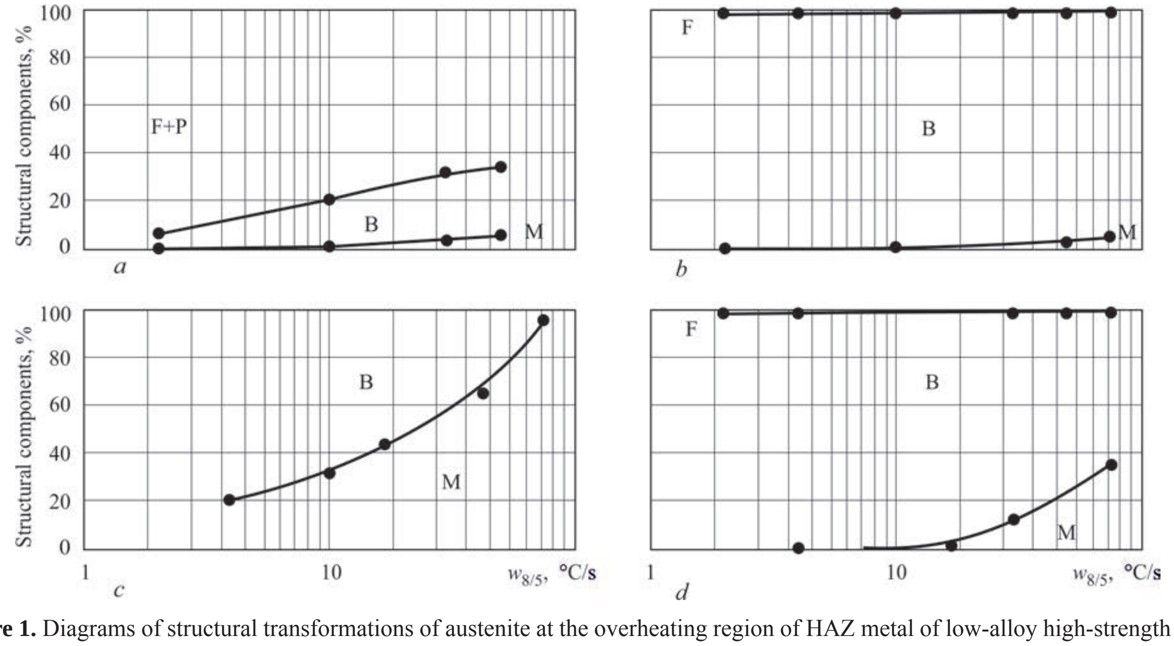

Figure 1. Diagrams of structural transformations of austenite at the overheating region of HAZ metal of low-alloy high-strength steels of type 06GBD (*a*); 06G2B (*b*); 09G2SYuch (*c*); 10G2FB (*d*)

Unlike low-alloy steels 09G2S, 10KhSND and 15KhSND, in which the transformation of austenite largely depends on the cooling rate of the metal and can occur in ferrite (at a moderate, up to 10 °C/s, cooling rate) and in bainite and martensite regions at higher cooling rates, in microalloyed steels of grades 06GBD, 06G2B and 10G2FB, it occurs in a significantly different way. In almost all the investigated range of cooling rates, the austenite transformation at the overheating region of HAZ metal of steels 06G2B and 10G2FB occurs mainly with the formation of bainite, and in steel 06GBD — with the formation of ferrite, pearlite and bainite [1, 2].

An exception among the investigated microalloyed structural steels is the steel of grade 09G2SYuch [5]. In it, as in most low-alloy high-strength structural steels, the transformation of austenite occurs with the formation of bainite and martensite.

Further let us consider how the conditions of cooling metal under the influence of TCW affect its mechanical properties.

To obtain the information on the effect of TCW on the values of static strength and plastic properties of HAZ metal of welded joints, standard tensile specimens are used made from the investigated metal bricks preliminary treated according to the thermal cycle of welding. This is associated with the fact that the sizes of HAZ and its separate components are usually much smaller than the sizes of specimens being tested. Therefore, in this case, the investigations related to changes in the yield strength, tensile strength, elongation and reduction in area occurring in the HAZ metal of steels under the influence of TCW were obtained using the abovementioned approach. During the investigations, 13×13×150 mm bricks were used which were treated according to the thermal cycle of welding in the MCR-75 installation, designed at PWI [12].

For modelling TCW, the specimens were heated by a passing current to the temperature of 1250 °C (heating rate is 150 °C/s), and then cooled according to a set program. By regulating the intensity of blowing specimens with inert gas, their cooling rate in the temperature range of 600–500 °C was varied from 3 to 50 °C/s. The mode of heating-cooling specimens was controlled by 0.5 mm diameter chromelalumel thermocouple, and the cooling rate was evaluated according to the results of processing oscillograms, which were recorded in the oscilloscope 117/1 in temperature-time coordinates.

For testing on static (short-term) tension, from the bricks treated over TCW, the specimens of type II were mechanically manufactured according to GOST 6996–96 (2 specimens for each cooling rate). The tests were performed in accordance with GOST 6996–66 at a temperature of 20 °C. The results of the investigations are shown in Figure 2.

They indicate the fact that when the metal on the HAZ overheating region is cooled at a cooling rate $w_{6/5}$, which does not exceed 10 °C/s, it can be softened. This is manifested in the fact that the values of its yield strength are decreased by 10–25 % in re-

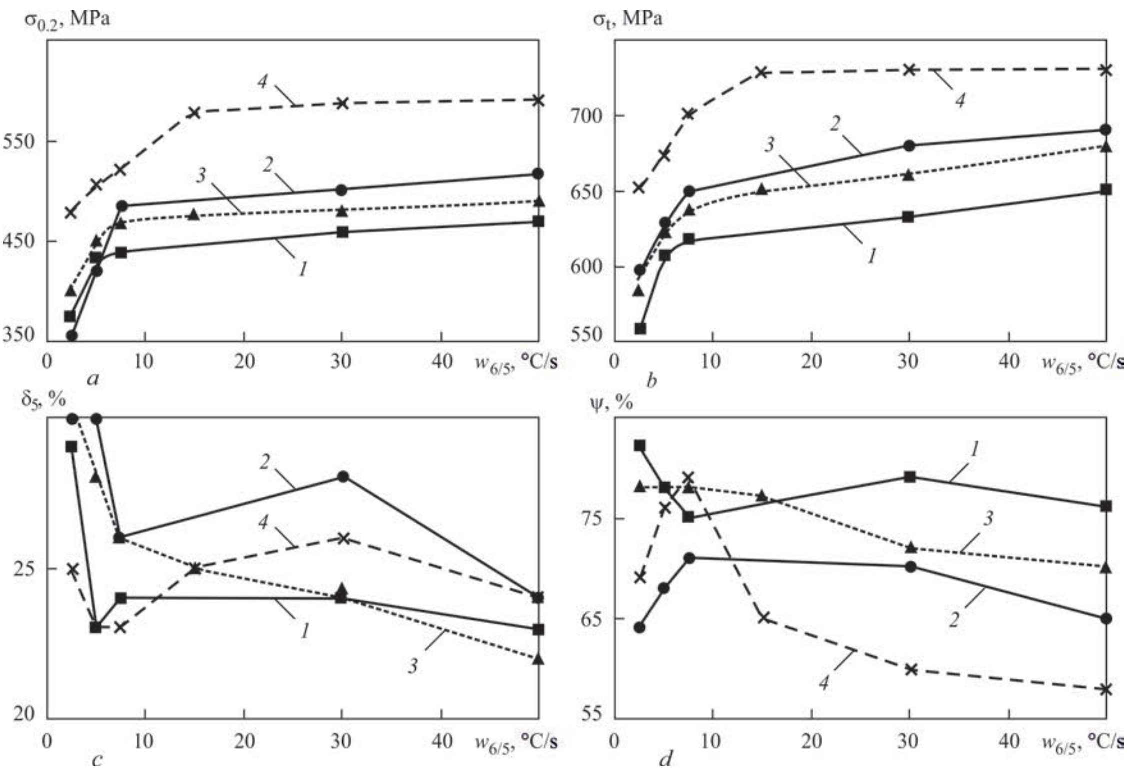

Figure 2. Effect of cooling rate $w_{6/5}$ on the values of yield strength (*a*), tensile strength (*b*), elongation (*c*) and reduction in area *(d)* of HAZ metal of steels: 06GBD (*1*); 09G2SYuch (*2*); 06G2B (*3*); 10G2FB (*4*)

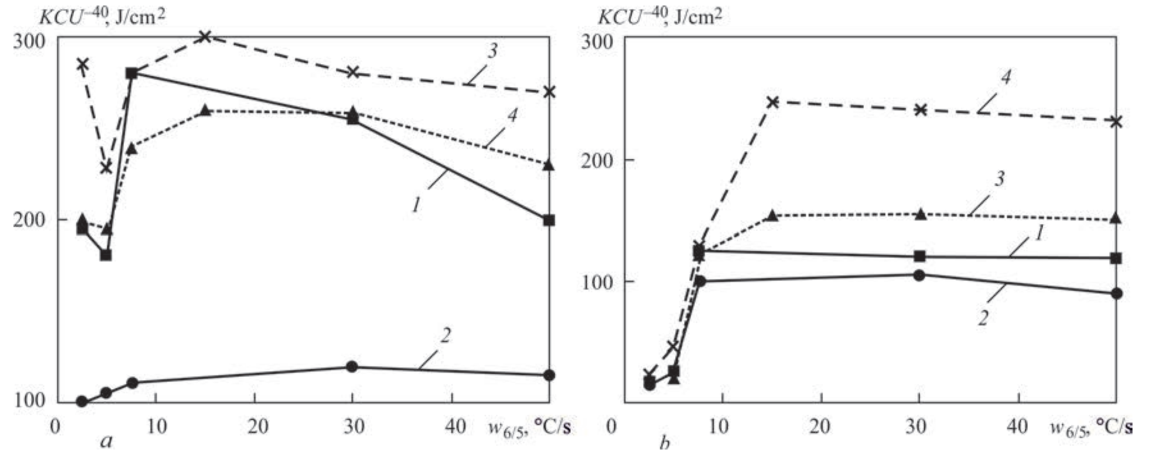

Figure 3. Effect of cooling rate $w_{6/5}$ on the values of impact toughness of HAZ metal of steels 06GBD (*1*); 09G2SYuch (*2*); 06G2B (*3*); 10G2FB (*4*)

lation to the base metal. In the range of rates from 3–10 °C/s, the values of $\sigma_{0.2}$ and σ_t of the HAZ metal are rapidly increased and subsequently they grow rather slowly. This is quite natural, since as the data in Figure 2 show, the HAZ metal structure of high-strength microalloyed structural steels is stable over a wide range of cooling rates. The ductile properties of HAZ metal in these steels are also somewhat decreased, but remain quite high and stable over a wide range of cooling rates.

The effect of thermal cycles of welding (TCW) on the values of impact toughness of the HAZ metal of the investigated structural steels was studied using a «bead test» according to GOST 13585–68.

To provide the conditions of cooling welded joints with the metal of different thickness characteristic for processes of manual, mechanized in shielding gases and automatic submerged-arc welding, namely in the range from 3.0 to 50 °C/s, the plates with a thickness of 20 mm were produced using the wire of solid cross-section with a diameter of 4.0 mm under the layer of flux in the modes, shown in Table 5.

To determine the impact toughness, from the «bead sample» the billets were cut, which were made of specimens with a cross-section of 10×10×55 mm (type VI with a round notch and type IX with a sharp notch). The tests of specimens were carried out at the temperature of –40 °C.

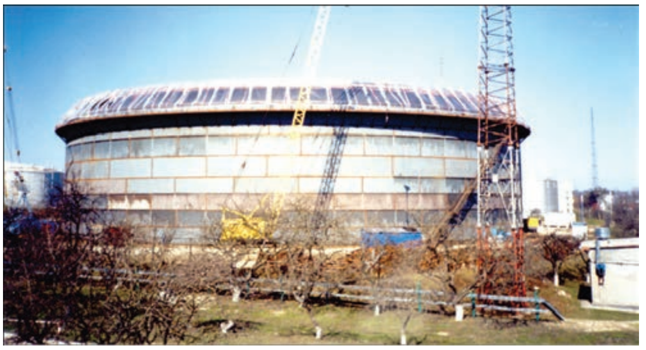

Figure 4. Tank for oil storage with a capacity of 75000 m³ of rolled steel 06G2B-440

The investigations, the results of which are given in Figure 3, showed that under the conditions of cooling HAZ of welded joints at a rate $w_{6/5}$ which is higher than 5 °C/s, the impact toughness of the metal KCV^{-40} on the overheating region is provided at a level significantly exceeding the current requirements to building metal structures. At a slower cooling, the values KCV^{-40} can be reduced to critical levels.

In general, the carried out investigations showed that the new microalloyed structural steels of the strength classes C350–C490 as to their mechanical properties are superior to low-alloy structural steels of the strength classes C350–C390, which were developed in the USSR, are more technological and allow providing a complex of properties of welded joints at the level of modern world requirements to metal building structures. Namely this was the impetus to the fact that since the beginning of this millennium, such steels began to be gradually introduced into production in Ukraine for the manufacture of welded metal structures for the needs of building industry in bridge construction, mechanical engineering, etc.

In particular, the technological processes of arc welding developed in 2003 on the basis of the above-mentioned results of investigations, were introduced in the manufacture of unique building structures during construction of the tank in Brody for the stor-

Table 5. Modes on which surfacing on the plates was performed

I_w, A	U_a, V	v_w, m/g	Q_w, kJ/cm	$w_{8/5}$, °C/s
580–600	34–38	9.8	62.7	3
580–600	34–38	14.7	41.8	6
580–600	34–38	17.3	35.7	10
580–600	34–38	21.7	28.6	20
380–400	30–32	15.2	23.0	30
380–400	30–32	20.1	16.7	50

Figure 5. Construction of the Podilskyi Bridge crossing in Kyiv, the arches of which are made of steel 06GBD of the strength class C390

Figure 6. Olimpiyskyi NSC in Kyiv

age of oil with a capacity of 75000 m^3 of rolled steel 06G2B of the strength class C440 (Figure 4).

In the future, the experience gained during this work was used in the manufacture of steel structures of tanks with a capacity of 50000 m^3 during modernization of the tank farm in Mozyr (Republic of Belarus) on the region of main oil pipelines. The metal structures were made of rolled steel 06GB of the strength class C390 with a thickness of 20–30 mm with the use of mechanized welding in mixture of gases (82 % Ag + 18 % CO_2) with a solid cross-section wire.

In 2006, steel 06GBD of the strength class C390 and technology of its welding were used in the manufacture of metal structures for the Podilskyi bridge crossing over the Dnipro River in Kyiv at the I.V. Babushkin Dnipropetrovsk Metal Structure Plant (Figure 5).

During preparation for the European Football Championship EURO-2012 in Ukraine, the technologies of automatic submerged-arc welding, mechanized welding, welding in shielding gases and manual arc welding of steel S 355 J2 (analogue of steel 10G2FB of the strength class C355)) with the thickness of 16–100 mm were developed and certified. In 2010–2011, they were introduced during the manufacture and assembly of box-like metal structures for the fence roof over the Olimpiyskyi NSC (Kyiv) during its reconstruction. Welded metal structure with a total weight of 40 thous tons consists of 80 lower and facade columns with the length from 23 to 25.5 m, weight from 25 to 30 tons each, as well as beams of the lower and upper compressed rings (Figure 6).

Figure 7. Repair of blast furnace DP-2 at the OJSC «Azovstal Steel Plant» using rolled steel 06G2B of the strength class C440

The experience gained during the reconstruction of the Olimpiyskyi NSC contributed to the successful fulfilment of a new task in 2013, namely, in the development of welding technology for manufacture and assembly of metal structures of tubular cross-section of steel 10G2FBYu of the strength class C490 for the football stadium with 45000 spectators.

New structural high-strength steels become increasingly used in Ukraine in the construction and major repair of engineering structures of metallurgical enterprises. In particular, steel of grade 06G2B of the strength class C440 and welding technologies developed at the PWI were introduced during the repair of the blast furnace DP-2 at the OJSC «Azovstal Steel Plant» (Figure 7), as well as at the Yenakiieve and Kryvorizhsky metallurgical plants.

Conclusions

1. Unlike most structural low-alloy steels, the transformation of austenite into vanadium- and niobium-alloyed steels of the strength class from C350 to C490 at a continuous cooling over the thermal cycle of welding occurs mainly in the bainite region.

2. As a result of structural transformations occurring in steels under the effect of thermal cycles of welding, the values of static strength of the metal of the heat-affected zone of the welded joints increase and the ductile properties decrease.

3. A significant decrease in the values of impact toughness in the metal of the heat-affected zone of

welded joints of microalloyed structural steels is observed at $w_{6/5} \leq 5$ °C/s. As the cooling rate increases, the impact toughness of the metal of the heat-affected zone grows rapidly, and in some steels it almost reaches the level of the base metal.

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DEVELOPMENT OF WELDED STRUCTURE OF SIDE FRAME OF FREIGHT CAR BOGIE OF INCREASED RELIABILITY

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The accidents occurring on railway track of 1520 mm are often associated with the fracture of cast load-carrying elements of three-element freight car bogies. The level of quality and endurance of such bogie elements as side frame and bogie bolster, which are traditionally manufactured by casting technology, are insufficient, so it is advisable to use welding technology to manufacture the mentioned parts of sheet rolled metal in order to increase the fatigue resistance characteristics. The development of a new all-welded structure of side frame of a three-element freight car bogie with an axial load of 23.5 ts was carried out on the basis of widespread use of mathematical modelling to determine the stress-strain state of welded elements of the bogie under the action of a regulated range of loads and to evaluate the strength according to the valid standards and modem global approaches. The technology of assembly and welding, as well as the appropriate specialized equipment for manufacture of a developed design of welded side frame were created. Two test specimens were manufactured and accelerated fatigue tests were carried out, the results of which showed a significant increase in endurance and vitality under operational cyclic loads as compared to designs of existing cast side frames. Taking into account high values of reliability, availability and manufacturability, ability of a significant reduction in unsprung weight and increase in dimensional accuracy, the welded structure of the side frame of a three-element freight car bogie is very promising for its implementation on railway track of 1520 mm. 9 Ref., 2 Tables, 6 Figures.

Keywords: freight car bogie, side frame, welded structure, technology of production, fatigue resistance, life, vitality, mathematical modelling, calculation, fatigue testing

It is known that on railway track of 1520 mm the accidents occur related to the fracture of cast load-carrying elements of three-element freight car bogies [1–3]. This is caused by the presence of casting defects in the areas with stresses of 0.75–1.0 from permissible stresses, which lead to a significant decrease in the characteristics of fatigue resistance and, according, to premature fracture within 2–23 years of operation [3]. To increase the reliability of side frames and bogie bolsters is possible by improving the casting process and initial nondestructive testing or by manufacturing the mentioned parts by using alternative technologies. For example, the mentioned parts can be manufactured from sheet rolled steel 09G2S by using welding technologies in order to improve the characteristics of fatigue resistance [4]. It should be noted that the use of welding is more technologically attractive, since all the detected defects at the manufacturing stage are easily eliminated, unlike cast parts.

At PWI a considerable amount of works on designing a new all-welded structure of the side frame of three-element freight car bogie with an axial load of 23.5 ts and manufacturing technology were carried out [5]. The development was carried out on the basis of widespread use of mathematical modelling to determine the stress-strain state of welded elements of the bogie under the action of a regulated load spectrum and evaluation of strength in accordance with current standards [6] and modern world approaches [7].

The fatigue resistance of the designed structure of the all-welded side frame of the bogie was calculated in compliance with the Standards [6] according to the coefficients of fatigue resistance for different evaluation zones (base metal and welds) taking into account the distribution of the coefficient of vertical dynamics over the operational speed ranges. Moreover, taking into account the additional spectrum of loading from the longitudinal compressive forces through the autocoupling, it was demonstrated that the designed all-welded structure of the side frame is serviceable under varying loads and satisfies the requirements of the Standards [6] with the coefficient of fatigue resistance [n] = 2 both under the condition of nonexceeding the calculated stresses of the values of the allowed stress amplitudes and under the condition of damage accumulation.

The coefficient of fatigue resistance of the structure is evaluated by the formula [6]:

$$n = \frac{\sigma_{\mathrm{a},N}}{\sigma_{\mathrm{a,e}}} \geq [n], \qquad (1)$$

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where $\sigma_{a,N}$ is the endurance limit (according to the amplitude) at a symmetric load cycle based on the tests $N_0 = 10^7$ cycles; $\sigma_{a,e}$ is the calculated value of the amplitude of the dynamic stress of the conditional symmetric cycle, equivalent to the damaging action of the real mode of operational stresses over the life of a part; [n] is the permissible minimum value of the fatigue resistance coefficient [n] = 2 is selected in accordance with the Standards [6] for a repeatedly designed bogie.

The endurance limit (according to the amplitude) for a symmetric load cycle is determined according to [6]:

$$\sigma_{a,N} = \frac{\overline{\sigma_{-1}}}{\overline{K_\sigma}}(1 - z_d v_\sigma), \quad (2)$$

where $\overline{\sigma_{-1}}$ is the average value of endurance limit of a smooth standard specimen; z_d is the quantile of the distribution of $\sigma_{a,N}$ as a random value; v_σ is the coefficient of variation of the endurance limit; $\overline{K_\sigma}$ is the average value of the coefficient of reduction of the endurance limit of a part relative to the endurance limit of a smooth standard specimen.

The calculated value of the dynamic stress amplitude of the conditional symmetric cycle, equivalent as to the damaging effect of the real mode of operating stresses over the life of the part, is calculated taking into account the distribution of the coefficient of vertical dynamics over ten ranges of operation speeds [6]:

$$\sigma_{a,e} = \max(\sigma_a)\sqrt[m]{\frac{T_p f_e}{N_0}\sum_{i=1}^{10} P(v_i)k_i^m}, \quad (3)$$

where m is the exponent in the equation of the fatigue curve in the amplitudes; T_p is the total time of dynamic loads over the calculated life of the part service; f_e is the effective frequency of the process of changing dynamic loads for spring-suspended parts; $f_e = \sqrt{4c/m_b}$ (c is the vertical rigidity of coil spring group under the gross tonnage of a car; m_b is the weight of the loaded body); N_0 is the base number of cycles of dynamic stresses; i is the number of speed ranges; $P(v_i)$ is the fraction of time that falls into operation in the i-th speed range (v_i is the average value of speed in the i-th range); k_i is the coefficient of vertical dynamics in the i speed range; $\max(\sigma_a)$ is the maximum amplitude of stresses during a symmetric load cycle.

From the formulas given above, the permissible maximum stress amplitudes according to the fatigue resistance criterion are expressed as follows:

$$\left[\max(\sigma_a)\right] = \frac{\sigma_{a,N}}{[n]\sqrt[m]{\frac{T_p f_e}{N_0}\sum_{i=1}^{10} P(v_i)k_i^m}}. \quad (4)$$

In the case of welded structure of the side frame, several values of permissible stress amplitudes are calculated for different evaluation zones of the base material and the welded joint metal according to the fatigue resistance criterion. To evaluate the fatigue resistance of the side frame, the loads were applied corresponding to the normal movement of a car in the train set:

● vertical force reduced by the value of the gross tonnage of the car body;

● transverse component of the longitudinal quasi-static force.

The value (amplitude) of loads is determined by the coefficient of vertical dynamics in the range of speeds of movement to the design one (120 km/h). The coefficient of vertical dynamics is accepted to be the same for the movement on straight and curved regions of the track. The calculated loading spectrum [6, 8] is given in Table 1.

Applying the numerical method based on MCE the maximum stresses at quasistatic loading with a vertical force of 210.6 kN and wedge thrust force of 30.1 kN [8] were determined relative to which the load spectrum was specified (Table 1). The vertical dynamic loading F_{lz} acting on the side frame is applied to the supporting surface of the central spring suspension, the wedge thrust force F_{3x} — to the vertical

Table 1. Normative loads for calculation of fatigue resistance of side frame of the bogie with an axial load of 23.5 ts

Interval of movement speed, m/s	Average speed of interval, m/s	Probability of movement in the speed range $P(v_i)$	Side frame		
			Coefficient of vertical dynamics k_d	Vertical dynamic load amplitude F_{lz}, kN	Amplitude of wedge thrust force F_{3x}, kN
0–12.5	6.25	0.03	0.063	13.27	1.90
12.5–15.0	13.75	0.07	0.138	29.07	4.15
15.0–17.5	16.25	0.09	0.298	62.77	8.97
17.5–20.0	18.75	0.12	0.333	70.14	10.02
20.0–22.5	21.25	0.16	0.368	77.52	11.07
22.5–25.0	23.75	0.19	0.403	84.89	12.13
25.0–27.5	26.25	0.16	0.438	92.26	13.18
27.5–30.0	28.75	0.10	0.473	99.63	14.23
30.0–32.5	31.25	0.06	0.508	107.01	15.29
32.5–35.0	33.75	0.02	0.543	114.38	16.34

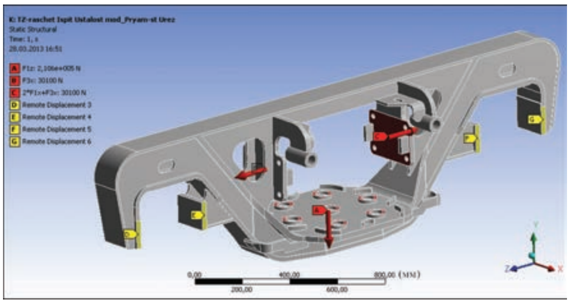

Figure 1. Vertical load F_{1z} = 210.6 kN (A), uniformly distributed over the area of spring suspension on the support surface of the central spring suspension, and the wedge span force F_{3x} = 30.1 kN (B), which are applied to the vertical posts of the central spring hole

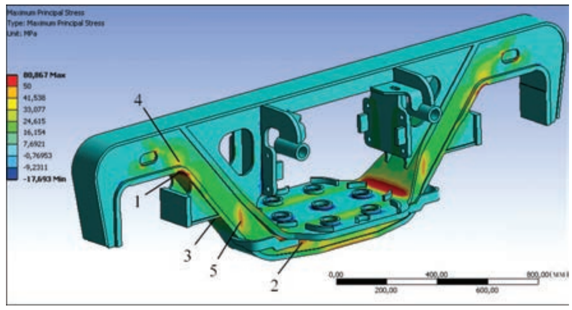

Figure 2. Distribution of main stresses in the structure of welded side frame under the action of loads regulated by the Standards [6] (description 1–5 see in Table 2)

posts of the central spring hole (Figure 1). The results of calculations of the distribution of maximum main stresses from the applied quasistatic load are shown in Figure 2 and in Table 2.

The calculation of fatigue resistance of the all-welded structure of the side frame, carried out in accordance with the Recommendations of the International Institute of Welding (IIW) [7] on the condition of a fatigue fracture (macrocrack) initiation in different evaluation zones of the structure (zones of welded joints) taking into account the specified load spectrum during operation [6] showed that the designed variant of the all-welded structure of the side frame has a sufficient level of fatigue resistance of welded joints with a safety factor γ_M = 1.1–1.4.

The Recommendations of IIW summarize a considerable volume of experimental investigations for typical welded joints, which allowed formulating a procedure on determining the range of nominal stresses allowed under a regular load for each joint in the form of:

$$[\Delta\sigma] = \frac{FATf_1(R)\,f_2(N)\,f_3(\partial)\,f_4(T)}{\gamma_M}, \qquad (5)$$

where *FAT* is the class of a joint and its permissible stress range based on $2\cdot10^6$ regular load cycles (constant load cycle parameters) at $f_1 = f_2 = f_3 = f_4 = \gamma_M = 1$; γ_M is the safety factor. In [7] there is a table of *FAT* values for different typical welded joints. The factor $f_1(R)$ takes into account the influence of the asymmetry of the load cycle $R = 1 - \frac{\Delta\sigma}{\sigma_{max}}$ and also the level of residual stresses in the joining zone. In case if the residual stresses do not exceed $0.2\sigma_y$, where σ_y is the yield point of the material (for steel 09G2S $\sigma_y \approx$ ≈ 390 MPa), then according to [7]:

$f_1(R) = 1.6$ for $R < -1.0$;

$f_1(R) = -0.4R + 1.2$ for $-1.0 \le R \le 0.5$;

$f_1(R) = 1.0$ for $R > 0.5$.

The factor $f_2(N)$ takes into account the limited fatigue. In the range of $10^4 < N < 10^8$ cycles, $f_2(N)$ according to [7] (Figure 2) is determined by the dependence:

$$f_2(N) = \left(\frac{C}{N}\right)^{\frac{1}{m}},$$

where N is the life of welded joint; $C = 2\cdot10^6$, $m = 3$ at $10^4 < N < 10^7$ cycles; $C = 5.8\cdot10^6$, $m = 5$ at $10^7 < N <$ $< 10^8$ cycles.

The correction for the thickness of the adjacent element in which a fatigue crack arises, $f_3(\delta) = 1.0$ if the thickness is $\delta < 25$ mm. At higher thicknesses:

$$f_3(\delta) = \left(\frac{25}{\delta}\right)^{0.3}.$$

Table 2. Comparison of amplitudes of permissible stresses and calculated maximum stresses in different zones of structure of side frame in accordance with the acting Standards [6] and Recommendations of IIW [7]

Area of structure of side frame	Standards [6]		IIW [7]	Calculation/ measurement
	Coefficient of reduction of endurance limit $\overline{K}_\sigma$	Maximum permissible amplitude of stresses max(σ_a), MPa	Permissible amplitude of stresses [σ_a], MPa (γ_M = 1.0/1.4)	Maximum value of main stresses σ_a, MPa
1. Main material in the zone R55 of axial hole	1.5	150	–	81
2. Longitudinal fillet welded joint of the side wall and the supporting surface of the springs	3.0	78	40/50	56
3. Transverse fillet welded joint of support in the thrust hole	3.0	78	40/50	37
4. Longitudinal fillet joint in the area R55 of the thrust hole	3.0	78	40/50	53
5. Cross butt welded joint of the side wall	4.7	51	44/56	33

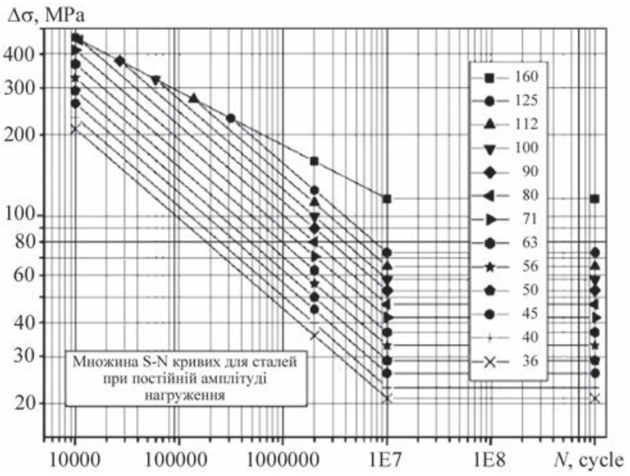

Figure 3. Generalized Weller curves for different classes of *FAT* welded joints (material — steel) for normal rated stresses at $N < 10^9$ cycles [7]

For the considered joints of the structure of the side frame with a thickness of elements of up to 25 mm $f_3(\delta) = 1.0$ can be taken.

The factor $f_4(T)$ takes into account the operating temperature T of the joint service. According to [7] at T <100 °C, $f_4(T) = 1.0$ can be taken.

When setting the value of the safety factor γ_M, it is necessary to take into account that *FAT* is recommended based on 0.95 of nondestruction probability (experimental data). Therefore, in [7] it is recommended to choose γ_M within the range of 1.0–1.4. Moreover, the value of the safety factor $\gamma_M = 1.4$ corresponds to the case when a threat to human life exists.

The load spectrum for the calculation of fatigue resistance is determined by the coefficient of vertical dynamics and the probability of movement in the range of speeds to the design speed (120 km/h).

Taking into account the abovementioned, for the considered evaluation areas of the structure of the side frame (zones of welded joints) at regular load the dependence (5) can be represented as:

$$\left[\Delta\sigma\right] = \frac{FAT}{\gamma_M}\left(\frac{C}{N}\right)^{\frac{1}{m}}. \tag{6}$$

Accordingly, the fatigue limit $[N]$ at a regular load with a range $\Delta\sigma$ is expressed as follows:

$$\left[N\right] = C\left(\frac{FAT}{\Delta\sigma\gamma_M}\right)^m. \tag{7}$$

Taking into account the load spectrum of ten regular cycles according to the Standards (Table 1), the life N_{spec} is determined by linear summation of damageability (Palmgren–Miner method):

$$\sum_{j=1}^{10}\frac{n_j}{N_j} \le 1, \tag{8}$$

where n_j is the number of j-cycles with a range $\Delta\sigma$; N_j is the ultimate life at a regular load with a range $\Delta\sigma_j$ for the spectrum element. The value of N_j is determined by the formula:

$$N_j = C\left(\frac{FAT}{\Delta\sigma_j\gamma_M}\right)^m. \tag{9}$$

Table 2 summarizes the permissible stress amplitudes (fatigue strength) in accordance with the Standards [6] and recommendations of IIW [7] in different zones of welded structure of the side frame, taking into account the specified [6] load spectrum based on 10^7 cycles during long-term operation. The comparison shows the insufficient conservatism of the Standards during evaluation of the fatigue strength of welded joints.

Also Table 2 represents calculated values of maximum stresses in different areas of the side frame due to the action of maximum design forces on a bogie with an axial load of 23.5 ts. The carried out calculations (Table 2, items 2, 4) show that in order to provide a sufficient level of fatigue strength in the most dangerous zones of welded structure of the side frame, it is advisable to use a general heat treatment for residual stress relaxation and impact ultrasonic treatment along the fusion line of longitudinal fillet welds.

It is important that designing of the welded side frame was also performed taking into account the technological capabilities of assembly and welding of all its parts, providing high demands on the quality and load-carrying capacity of the product. For this purpose, a minimum number of welded joints, especially transverse joints was used and they were placed in the least loaded areas, providing a complete penetration of all welded joints and, if possible, performing double-side welding with edge preparation. Technological instructions for assembly and welding of the side frame were developed, as well as corresponding specialized equipment was designed that provides the accuracy of assembling structural elements and low levels of residual deformations, performance of high quality welding, additional treatment and nondestructive testing of the most dangerous regions of welded joints, reducing overall labour costs and time for manufacture of the product.

Two experimental specimens were manufactured (Figure 4) and accelerated fatigue tests (Figure 5) were carried out according to the requirements of standards existing in Ukraine [9].

The results of fatigue tests showed that in the specimen of the welded side frame No.1 after N_{i_mp} = 8.8 mln cycles of vertical load (amplitude P_{ai} = 245 kN = 25 ts, a constant average load cycle P_m = 363 kN = 37 ts), the first macrocrack was formed in the base metal on the side wall between the lower belt and the spring supporting surface. During the continuation of regular loads, the crack was slowly propagated in the lower belt and almost was not propagated on the spring supporting surface. At 11.6 mln cycles in the zone of a transverse welded joint of the side wall, the second macrocrack was formed, which led to the fracture at N_{i_p} = 13 mln cycles (Figure 5, *b*). The opening of both cracks were performed. Visual analysis of the surface of the first crack did not reveal welding defects, all welded joints were produced with a complete penetration (Figure 5, *c*). The analysis also revealed that the second crack was formed as a result of a defect of discontinuity, namely a partial penetration of the transverse welded joint (Figure 5, *d*). In the specimen No.2, after N_{i_mp} = 5.0 mln cycles, a macrocrack formed in the axial opening in the zone of radius blend R55 after N_{i_p} = 5.4 mln cycles the fracture occurred. Visual analysis of the fracture revealed that the crack was formed in the zone of longitudinal fillet joint, but welding defects were not revealed (Figure 6).

In general, the cyclic life of two test specimens of the welded side frame exceeded the cyclic life of cast frames by 2–4 times, even those strengthened by HMP technology under the same loading mode. At the same time, the established life of welded frames

Figure 4. Equipment for assembly and welding of side frame structure (*a*) and two manufactured test specimens (*b*)

exceeds the calculated permissible number of cycles before fracture by ten times, which for the load 37 ± ± 25 ts for cast frames is $[N_c] = 0.345 \cdot 10^6$ (according to the data of investigations carried out by UkrNDI

Figure 5. Test specimen No.1 of all-welded side frame during accelerated fatigue tests (*a*) and fracture in the area of transverse welded joint of side wall (*b*), fracture in the zone of a first crack (*c*) and in the fracture zone (*d*)

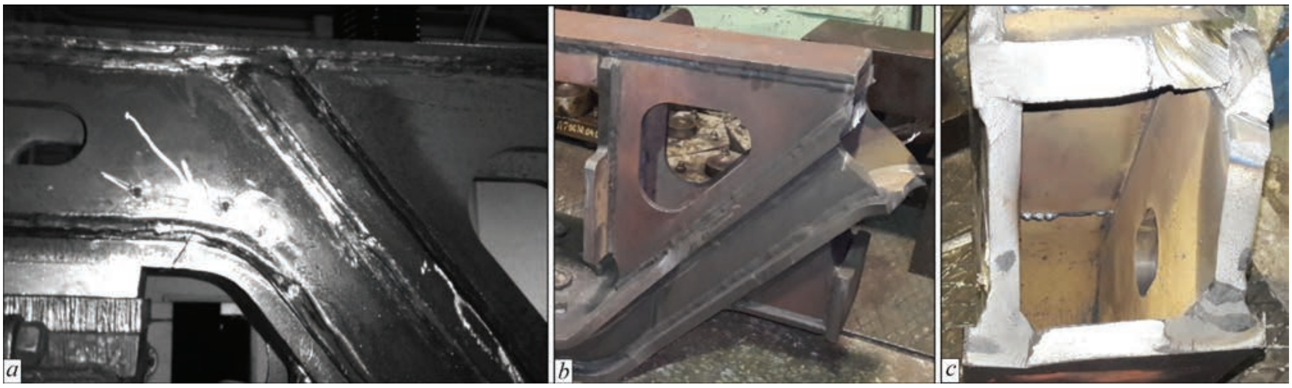

Figure 6. Fragment of fracture of test specimen No.2 of all-welded side frame after macrocrack formation during accelerated fatigue tests (*a*) and after fracture in the radius blend zone R55 of axial hole (*b*, *c*)

«Vagonobuduvannya», Kremenchug). It should be noted that the specimen of the welded side frame No. 1 showed a high value of relative survivability $Zh = (N_{i\_p} - N_{i\_mp})/N_{i\_p} = 0.32$, and according to the absolute value the survivability of the welded specimen exceeds several times the life of the standard cast frame (without additional strengthening treatments).

Thus, the high values of fatigue resistance of the structure of all-welded side frame of a freight car bogie with an axial load of 23.5 ts designed at PWI, which gives grounds to recommend this design for implementation on the railways of 1520 mm track.

Conclusions

1. The calculation of fatigue resistance of the structure of all-welded side frame of the freight car bogie of sheet rolled metal (09G2S steel) with an axial load of 23.5 ts designed at PWI was performed taking into account the specified load spectrum. As a criterion of fatigue fracture the origination of a fatigue macrocrack was considered. The maximum permissible stress amplitudes in different zones of the investigated frame were established in accordance with the standards acting in Ukraine and the recommendations of IIW. It is shown that designing of the side frame structures should be carried out according to the recommendations of IIW as they are more conservative.

2. It was proved that with the use of the developed technology and equipment it is possible to produce all-welded side frame of the railway car bogie with providing a high quality of welded joints and geometric shapes of products.

3. The fatigue test of two specimens of all-welded side frame at a load of 37 ± 25 ts was carried out. It was experimentally established that the cyclic life of welded frames is 2–4 times higher than the cyclic life of cast frames, even strengthened by the technology of high-frequency mechanical peening. In this case, the life of welded frames is ten times higher than the calculated number of cycles before fracture at a specified loading mode.

4. High values of fatigue resistance of the structure of all-welded side frame of the freight car bogie with an axial load of 23.5 ts designed at PWI give grounds to recommend this structure to be introduced at 1520 mm rail tracks.

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WELDING IN POWER ENGINEERING INDUSTRY OF UKRAINE

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Review of some PWI works on creation of advanced technologies of welding the equipment for enterprises of power engineering sector of Ukraine is presented. Approaches to producing welded rotor structures, and combined joints of high-temperature components of equipment of thermal power plants are described. Information on improvement of the technology of welding thick-walled pipe elements from 10GN2MFA steel for NPPs is generalized. The gained experience forms the basis for solving new problems in the power engineering sector of the country. 12 Ref., 3 Tables, 9 Figures.

Keywords: welding rotors, automatic submerged-arc welding, narrow gap, combined joints, manual arc welding, connection of steam generator with the main circulation pipeline, automatic argon-arc welding

Started in 1959, PWI department «Physical and Structural Strength of Welded Joints from Higher Strength Steels» conducted fundamental and applied investigations, aimed at solving the urgent problems of ensuring the quality and reliability of critical welded structures from complex-alloyed steels in heavy, power and nuclear engineering. Today this direction remains to be one of the main and urgent for power engineering and power generating enterprises.

Over more than 50 years, the Department has conducted numerous works, solving rather complicated, extraordinary scientific and production problems. Research activity included studying physico-metallurgical fundamentals of weldability and technological strength of medium-alloys steels of different structural classes, development of efficient technological processes of manual and automatic gas-shielded and submerged-arc welding, development and study of welding consumables, development and improvement of the technologies of repair welding of equipment and pipelines of thermal and nuclear plants.

Given are examples of some works performed by the Department in cooperation with partner-organizations that were of certain actual importance for industrial companies.

Automatic welding of thick-walled turbine rotor structures. Urgent for the industry increase of the capacity and working parameters of power generating equipment necessitates an increase of the overall dimensions and weight of its parts. However, production of castings and forgings of large-sized rotors runs into problems of quality assurance, particularly when alloyed steels are used [1].

First welded turbine rotors in ex-USSR were produced using manual arc welding. However, this method, despite its flexibility and simplicity, features a low productivity, that was particularly obvious in welding thick elements.

The technology of automatic submerged-arc welding of rotors of steam and gas turbines using separate elements — discs, was introduced with the participation of PWI specialists at Kharkiv turbine plant (former name of JSC «Turboatom») in order to replace manual welding process, in 1967–1968 for the first time in the practice of power engineering in the USSR. Important advantages of such a measure are simplification of component elements, while ensuring their proper quality, reduction of finished structure weight, possibility of combining steels with different alloying in one large product, according to different thermal conditions of operation of individual parts of this product [1].

At optimization of the technology in the experimental facilities of Kharkiv Turbine Plant with PWI participation, first pilot-production operations were performed, using rings of D_{out} = 1000 mm and thickness of 100 mm from 35KhM steel; and a model of a rotor from this steel of D_{out} = 1200 mm with 200 mm deep edge preparation for welding, was made (Figure 1). Welding was performed using flux/welding

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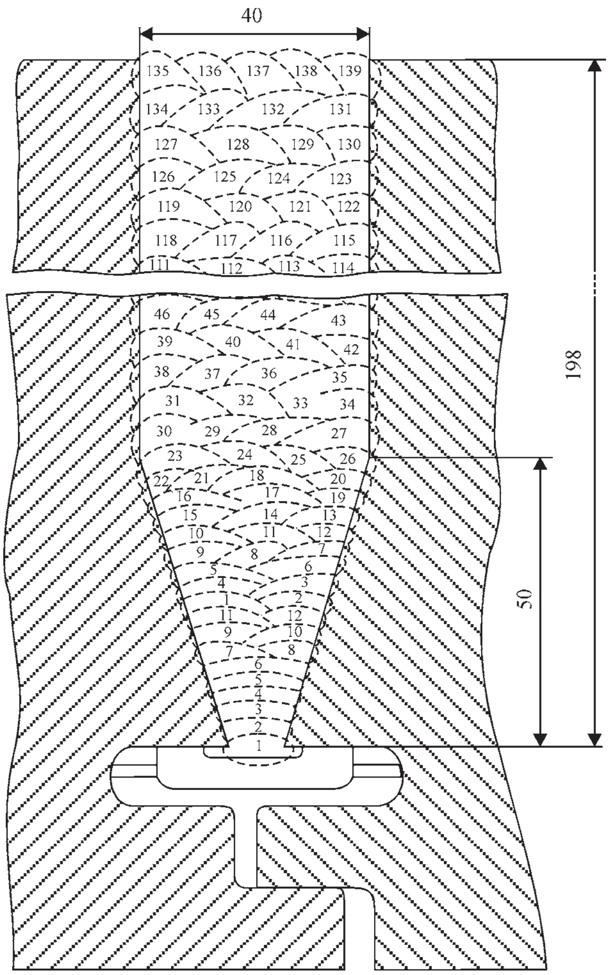

Figure 1. Scheme of automatic welding of a rotor model

wire: AN-22+Sv-10KhM, AN-22+Sv-08KhGMSF and AN-17M+Sv-08KhGMSF. One of the important results was establishing the nature of deformation development in a thick-walled joint and determining the conditions for their minimizing.

After a thorough study of the mechanical properties and quality control of welded joints, the technology was used in manufacture of standard rotors of GT-35, K-160, PVK-150, K-22-44, and K-500-65 types. Used at this stage was automatic machine U-738 with mechanical (by means of a follower) control of the welding nozzle.

Industrial technology tried out for the first time, allowed performance of automatic welding of horizontally placed rotors of more than 500 mm diameter with wall thickness from 30 to 250 mm and up to 36 t weight. The productivity of the process of welding one rotor increased 4 to 5 times, compared to manual welding, average duration of manufacturing one rotor was 3–5 days.

Later on, powerful rotors of up to 200 t weight began to be manufactured. They were made using forged discs from 25Kh2NMFA and 20KhN2MFA steels, which combine appropriate strength, high ductility and low critical brittleness temperature [2, 3].

In order to replace the first model of the welding machine, new modifications of automatic machines were developed with PWI participation, for submerged-arc welding of ring sections of powerful turbine rotors with automatic bead arrangement by a specified program [3].

It should be noted that in order to eliminate the drawbacks, characteristic for welding with the traditional wide edge preparation, progressive narrow-gap welding was introduced that allowed [3−5]:

- reducing the labour content of fabrication of structures with great thickness of elements and improve the welding conditions, eliminating the involvement of welding operator in the welding process;
- saving welding consumables and power;
- reducing the volume of deposited metal;
- lowering the level of residual stresses in the welded joints and the probability of crack formation at post-weld tempering.

Note that compared to electroslag welding (ESW) which is used for producing very thick products, automatic submerged-arc welding also has considerable advantages as a result of technology simplification. In submerged-arc welding, much narrower groove can be used (for comparison — for the above metal thickness of 500 mm at ESW the groove width was 90 mm), and just one kind of heat treatment is performed, namely tempering; whereas after ESW of alloyed steels application of a complex heat treatment is required, namely double normalizing at high temperature (950 °C) with subsequent tempering [3].

In submerged-arc welding the groove width depends both on the possibility of placing the welding nozzle inside the gap without the risk of the nozzle shorting to the edge, and possibility of grinding the defective areas at different depth of the joint, using metal-working tools. It is established that for up to 500 mm thickness, it is convenient to perform the repair operations using a manual tool at not less than 36 mm gap width; at 24–28 mm gap the defective areas can only be cut out using machine tool equipment [5].

It is experimentally determined that sound fusion of the beads and the base metal is possible in welding with both two and three beads in the layer. Trials of welding technique by both the variants with different groove width showed that the optimum width in welding with two beads is equal to 25 mm on average, and with three beads it can be 30−36 mm (Figure 2).

At the same time, narrow-gap welding ran into difficulties of slag removal and weld formation. Proceeding from comparative analysis of different grades of welding consumables, it is found that the best separation of slag in a deep groove and minimum content of impurities (S, P — to the level of approximately

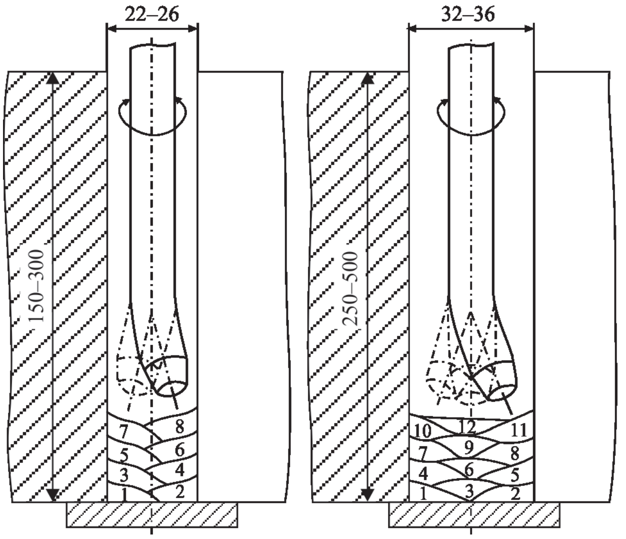

Figure 2. Examples of bead arrangement by the optimized technology of narrow-gap welding

0.03 wt.% each) are achieved when using AN-17M, AN-43 fluxes, in combination with Sv-08KhN2GMYu wire. In order to avoid slag crust jamming, provide sound fusion of the beads with each other and with the base metal, prevent formation of undercuts and slag inclusions along the weld in the groove, requirements were developed regarding welding mode parameters, bead width and positioning of welding wire (of 2 and 3 mm diameter) relative to the groove walls.

In order to eliminate the risk of cold crack formation, welding is performed with preheating/concurrent

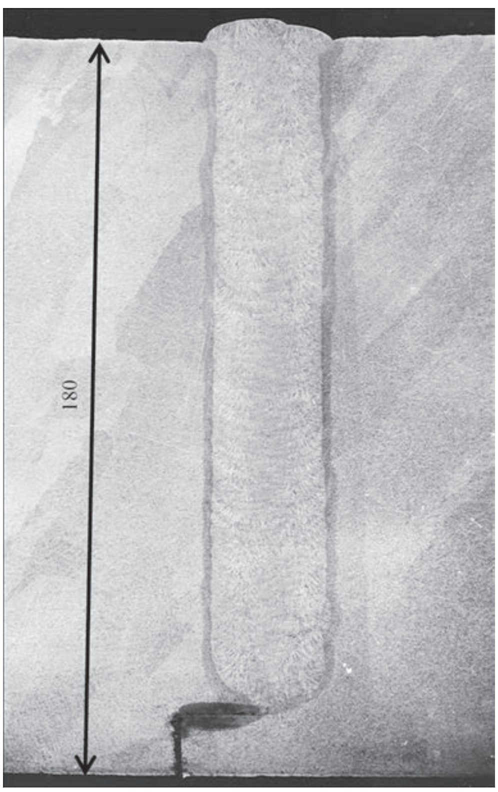

Figure 3. Cross-section of a model joint of a rotor section from 25Kh2NMFA steel of K-1000 steam turbine of 1000 MW power

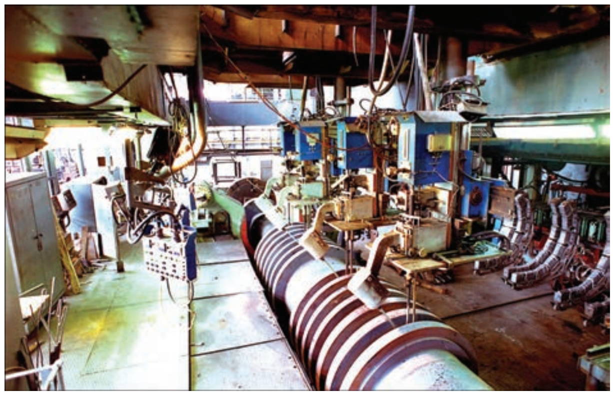

Figure 4. Welding of a rotor in a specialized stand at JSC «Turboatom»

heating to approximately 350 °C. Welding is followed by high-temperature tempering (630 °C) to lower the level of residual stresses and produce the structural state that provides the required performance. Application of the defined technological measures ensures easy (independent) separation of the slag from the groove during the entire cycle of continuous welding and producing tight defectfree welds (Figure 3).

Welding of rotor structures was performed in a specialized unique stand, where mounting and fastening of rotor parts and preheating/concurrent heating are performed (Figure 4). At the current stage, automatic welding machines of a new design A1569M (manufactured by PWI EPPE) with processor control of rotating nozzle position, have been introduced (Figure 5) [2].

An essential achievement over the recent years was mastering the technology of manufacture of welded composite large-sized rotors by JSC «Turboatom» with PWI participation [6, 7]. Their design envisages use of elements from two steel grades, namely 25Kh2NMFA and 20Kh3VMFA, each of which operates under different temperature conditions. The combined new generation rotor is shown in Figure 6.

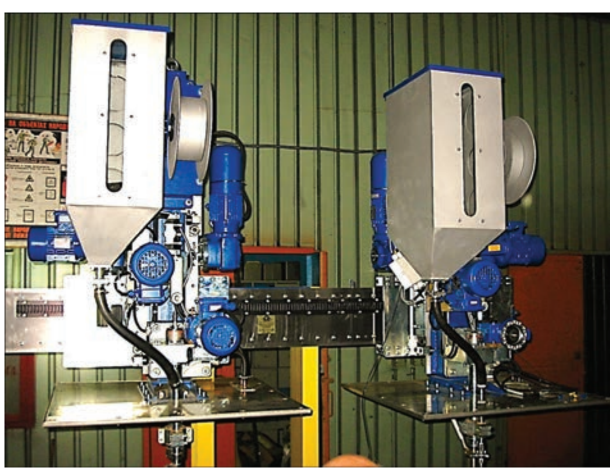

Figure 5. General view of dual automatic welding machines A1569M for narrow-gap submerged-arc welding of cylindrical products

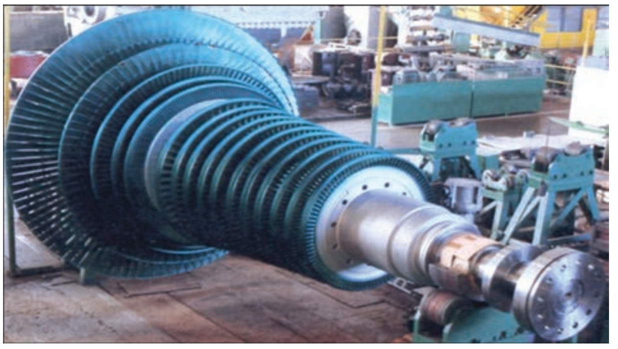

Figure 6. Composite rotor with mounted blades of medium-pressure cylinder of a new generation steam turbine of 325 MW power (JSC «Turboatom»)

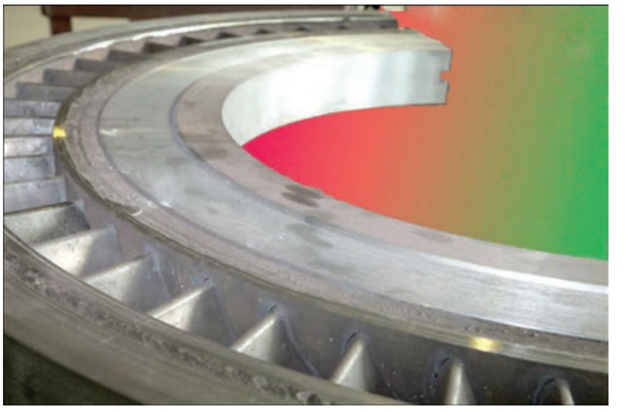

Figure 7. Element of welded high-temperature diaphragm of a steam turbine (JSC «Turboatom»)

Upgrading (reconstruction) of high-temperature elements of boiler-and-turbine equipment. One of the urgent tasks in power generation sector is improvement of the design of some elements to increase the reliability of the equipment a whole. Proceeding from the experience of turbine equipment operation and calculations by finite element method, the specialists of JSC «Turboatom» showed that the critical components in the flow sections of steam turbines are welds in the joints of blades from 15Kh12VNMF and 15Kh11MF steels with the rim and body of high-temperature diaphragm from steel 15Kh1M1F. Traditionally, such joints were welded by electrodes, which provided low-alloyed deposited metal (of 09Kh1MF type). A decision was taken as to improvement of weld performance through application of electrode metal with higher chromium content. With the participation of PWI experts, electrodes were selected, which provided deposited metal of 0.16C–Cr11–W0.5Ni0.5Mo0.9V0.2 type. A comprehensive study on optimization of the thermal mode of welding was conducted, in order to ensure high technological strength of welded joints [8]. The question of high-temperature tempering of the resulting welded joints was solved that ensured the required level of impact toughness of weld metal ($KCV \geq 44$ J/cm^2) at their strength higher than that of the base metal (Table 1). The technology was introduced at JSC «Turboatom» in manufacturing of high-temperature turbine diaphragms (Figure 7).

Extremely urgent is radical upgrading of facilities of thermal power generation of Ukraine [9] with application of new steels with a higher level of long-term strength. However [10], at the initial stage the plan of reconstruction and upgrading of thermal power plants and combined heat and power plants in power generating companies in the period up to 2020 envisaged just reconstruction of the currently existing power units with continuation of their operating life for 15–20 years. In keeping with the above-mentioned plans, JSC «Turboatom», together with PWI, performed work on development of the technology of welding a steam pipeline from new martensitic high-chromium steel Kh10CrMoVNb91 (R91) to the steam turbine body from 15Kh2MFBS steel (P3) [11]. The possibility of welding with electrodes, providing low- and high-chromium deposited metal with 2 and 9 % Cr (0.07C−Cr2−Mo1−V0.2 and 0.1C−Cr9−Mo1−Ni0.8VNb alloying systems), was studied. Temperature of preheating (concurrent heating) in order to avoid delayed fracture of such combined joints and

Table 1. Mechanical properties of welded joints of 15Kh1M1F+15Kh12VNMF type (after high-temperature tempering at 720 °C)

T_{test}, °C	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	*KCV*, J/cm^2	σ_t, MPa	ψ, %	Fracture site
	Weld metal					Welded joint		
20	555.75	704.2	22.75	56.45	93	561.65	53.1	HAZ
570	319.65	388.3	29.75	82.5	190.7	375.65	67.9	HAZ

Table 2. Mechanical properties of combined joints of P3+R91 type (after high-temperature tempering)

Weld metal type	T_{test}, °C	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	*KCV*, J/cm^2	σ_t, MPa	Fracture site
		Weld metal					Welded joint	
9 % Cr	20	601.8	727.2	18.5	52.5	96.3	615.6	HAZ
	570	361.4	401.0	22.5	81.3	–	360.3	HAZ
2 % Cr	20	620.1	716.7	20.4	68.7	193.9	667.8	HAZ
	570	410.6	451.0	20.5	80.5	–	390.0	HAZ

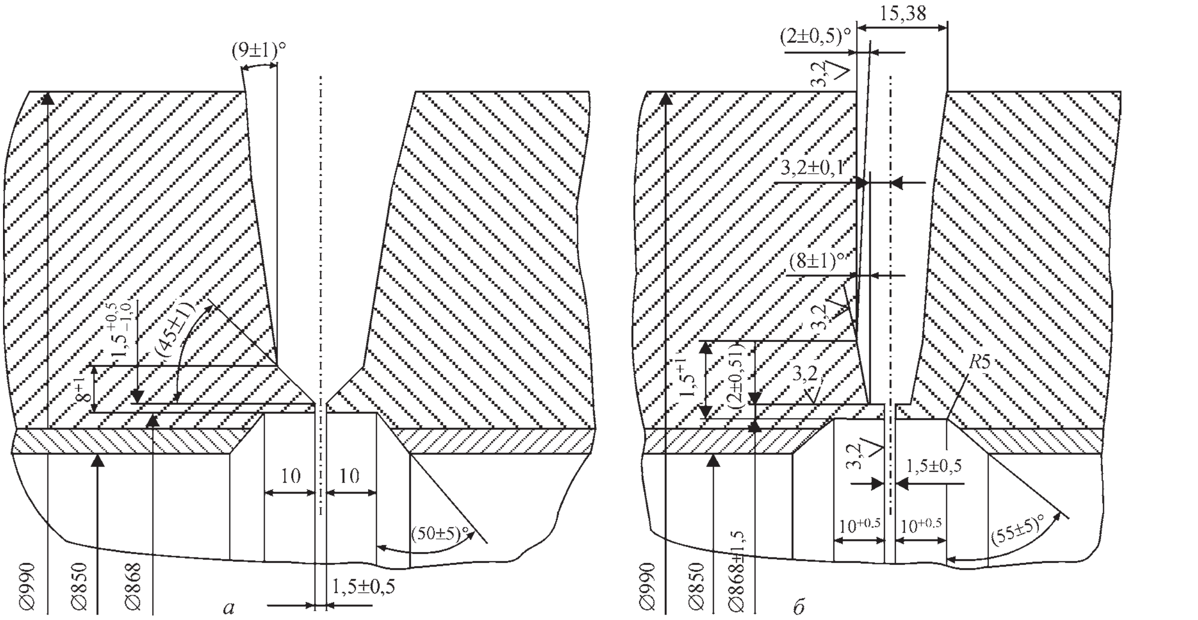

Figure 8. Edge preparation: *a* — standard; *b* — proposed

the mode of their post-weld tempering were determined experimentally. In both the welding activities the weld metal strength was higher than that of the base metal: failure of transverse samples at room and working temperatures occurred in the base metal; weld toughness level corresponded to the required condition $KCV \geq 51$ J/cm^2 (Table 2). The technology was accepted by industry.

Welding of MCP Dy850 elements of nuclear power units. One of the technology problems was improvement of the technology of steam generator welding to the main circulation pipeline (MCP) in site. Elements, which are welded – steam generator nozzle and MCP — are made from 10GN2MFA steel, clad by an austenitic corrosion-resistant layer inside; inner diameter is 850 mm, wall thickness is 70 mm. For welding the main (load-carrying weld) by the current technology, application of the argon-arc process (AAW) with Sv-08G1NMA wire and standard edge preparation with a wide groove (Figure 8, *a*) are recommended. However, it was anticipated that automatic narrow-gap welding can be more productive; the advantages of such a technique, in addition to a significant lowering of labour content of the work, is reduction of the quantity of the deposited metal, lowering of the level of residual stresses, and, which is essential, reduction of the dose of radiation exposure of the personnel. Such an approach became possible due to development of specialized portable machining equipment, which allows making edge preparations with a narrow groove on the abutted elements (Figure 8, *b*) [12]. Autotig 600 PC equipment (Polysoude Company, France) for narrow-gap AAW in the mixture of 70 % He + 30 % Ar was accepted to produce butt joints. The work on experimental verification and mastering of the technology was performed by the specialists of PWI, and SE «Atomremontservis».

Thorough verification of the new technology was performed [9] by the procedure, determined by the rules and norms in power engineering, as narrow-gap welding was not envisaged by normative documents. Prior studies led to optimization of the technology of horizontal welding of butt joints with 0.9 mm Sv-08G1NMA wire and determination of optimum mode parameters (I_w = 150 A, U_a = 11 V; v_w = 6.0 m/h, wire feed rate v_w = 152.0 m/h, gas mixture consumption of 1000–1200 l/h; preheating/concurrent heating to approximately 170 °C). After filling of the main weld, deposition of the removed cladding layer and nondestructive testing of the entire joint were performed. Then, high-temperature tempering by a standard mode (at 650 °C) and repeated nondestructive testing of both the main weld and the cladding zone were performed. The proper quality and absence of defects in the welded joint were confirmed. Resulting mechanical properties of the load-carrying weld metal

Table 3. Mechanical properties of weld metal in welded joint of 10GN2MFA steel (results of experimental verification)

$T_{test.}$, °C	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	*KCV*, J/cm^2	σ_t, MPa	Fracture site
	Weld metal					Welded joint	
20	615.0	690.0	24.2	73.3	290.0	556.0	BM
350	522.0	617.0	22.0	70.8	240.0	505.0	BM

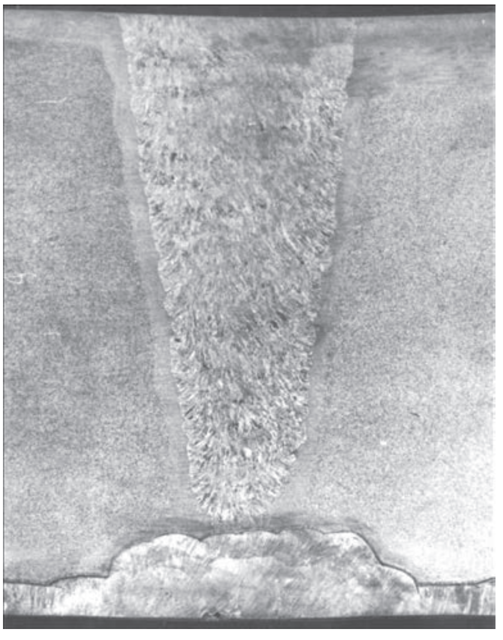

Figure 9. Cross-section of a certification joint from 10GN2MFA steel

exceeded the established requirements both at room and at working temperature.

Developed recommendations were used to perform experimental certification of the technology under laboratory conditions at SE «Atomremontservis» by welding and testing a circumferential joint of 990 mm diameter and 70 mm thickness, which confirmed the suitability of the proposed technology for further production certification. Characteristic mechanical properties are given in Table 3. Critical brittleness temperature was −70 °C, weld metal structure was tempered bainite with *HV* hardness of 235–240.

Final certification testing of the technology was performed in the South-Ukrainian NPP (see weld cross-section in Figure 9). After obtaining positive results of all the verification checks the new technology was coordinated with the State Nuclear Regulatory Committee of Ukraine and recommended for application at repair of MCP Dy 850, as well as for joining MCP elements with nozzles of PGV-1000M steam generator at its replacement in NPP power units with WWER-1000 reactors.

In conclusion, we note that in addition to general theoretical investigations, in keeping with the profile of the Institute's activity, the main focus in the specialists' work are applied scientific developments due to the needs of the production sector. As one can see from the given examples, only cooperation of science and production enables obtaining significant results. The thus accumulated experience forms the basis for solving new problems that may be generalized as follows: past achievements are the key to future development.

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WELDED STRUCTURES FROM ALUMINIUM ALLOYS

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Examples of modern lightweight structures from aluminium and its alloys are given. Their applications in different mechanical engineering sectors are shown. The structure diversity reflects the technological capabilities and forms of realization of unique properties of this material. Trends in world production and consumption of such structures have been analyzed. It is noted that appearance of more advanced alloys with the respective set of physico-mechanical and technological properties, as well as rational selection of the processes of their permanent joining, provide a high quality of welds and welded structure reliability. Presented examples clearly illustrate the fact that the effectiveness of lightweight structures is determined by functional requirements to products, weldability of the selected aluminium alloy and level of its joining technology, provided the expenses and production time are minimum. 20 Ref., 2 Tables, 6 Figures.

Keywords: aluminium and its alloys, welding methods, welded joints, light weight welded structures, physico-mechanical and technological properties, weld quality, reliability, service conditions

Products from aluminium and its alloys have now filled the goods market. They are widely used in many sectors of mechanical engineering, as well as civil and industrial construction [1–9]. Aluminium-based structural materials are traditionally used in flying vehicles. Their application sector is military, passenger and transportation aircraft. They are also used in rocket and space engineering (up to 80 % by weight). Aluminium alloys have a special status in the structures of land vehicles (car- and carriage building), river and marine shipbuilding. Irrespective of the welded structure application area common characteristics are used, which determine their service life (Table 1).

In **aircraft construction** the effectiveness of aluminium alloy application is well-known**.** Comparatively inexpensive, readily workable, strong aluminium alloys have proven themselves in aviation of the previous XXth century. They remain to be the main aviation structural materials both at the present stage and in the future. Creation of new models of flying vehicles in aerospace engineering is inextricably linked to solving three main problems of mechanical engineering: weight and cost reduction, and improvement of service properties. Weight reduction allows decreasing material content of the vehicle structure, promotes increase of the payload, and improvement of tactical performance at reduction of material costs for manufacture and service [10–12]. This motivates searching for alternatives to the main aerospace aluminium-based materials — D16, D19, V95 and V96, 1201, which are traditionally used in the airframe structure of civilian fleet aircraft. It has been estimated that reducing the civil aircraft mass by 1 kg allows saving 125–165 l of fuel annually, and during its entire service life the consumption savings are equal to 3.0–4.8 mln USD [9]. A new class of high-strength aluminium alloys, containing lithium, opened up broad possibilities in this direction.

Modern aircraft operate mostly under the conditions of intensive and extreme loading, so the main requirements, made of their materials, include the complete spectrum of aerodynamic conditions, environmental im-

Table 1. Characteristics determining the welded structure serviceability

Service properties	Types of tests	Studied characteristics
Deformability in the cold state	Tension	Relative elongation, uniform elongation
Weldability	Process samples (fishbone, cruciform samples, etc.)	Hot cracking susceptibility, fracture surface
Delamination resistance	Tension in the direction of thickness	Narrowing of sample cross-section
Fracture (brittle or tough)	Impact outward bending of notched samples	Work of deformation
	Outward bending of the weld	Fracture surface, bend angle
	Tension or outward bending of notched samples	Crack initiation temperature
	Fracture mechanics testing	$K_{1C}(K_C)$, $\delta_{1C}(\delta_C)$, J-integral

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pact, flight safety and cost. In flight, use is made of the load-carrying surfaces of the structure to create the lifting and control forces in the air environment, as well as the power unit which maintains the aircraft flight using the energy of fuel on board the aircraft.

Correct selection of the material of structure elements can essentially improve the weight and tactical characteristics of the flying vehicle. Particular attention is given to satisfying the requirements on ensuring the needed strength and rigidity of the structure at minimum mass, mass efficiency of the material, which is determined by the ratio of σ_{add}/ρ to the cost of 1 kg of material. Increase of mass effectiveness of the welded structure depends on the perfection of prefabricated components and type of the joints of its elements that is determined not just by design goals, but also by technological potential of the material. In addition to weldability, structure designers make to the material the requirements of ensuring a high specific strength and ductility of its welded joints at maximum fracture toughness. This is exactly what allows continuing fulfillment of the flight tasks in case of damage. In view of the increasing speed of the aircraft and the accompanying increase of external panel temperature, aluminium alloys should also have high thermal stability and thermal cycle fatigue under service conditions. Creation of oriented space expresses, space shuttles, cosmoplanes is related to the need for materials, which, alongside good weldability and heat resistance, also have high quality at superlow temperatures.

Air-tight compartments of flying vehicles are stamp-welded structures, which consist of the sheath 1.5–3.0 mm thick with butt welded frames and flanges, produced by machining the 3D stampings with the preset direction of grain flow [13–16]. Parts from forgings are used in exceptional cases. This is related to the fact that on the frame caps, which are welded to the sheath, and on the flanges the metal thickness is just 2–3 mm. At unfavourable direction of grain flow of the semi-finished product, this zone can be not tight, that under the complex service conditions can lead to premature failure of the entire structure. The following alloys are used for these structures:

- V96 (7075), designed for parts which should have high static strength;
- D16-T (2024) — for parts, which should have high fatigue strength;
- special-purpose alloys (7175, 7050, 7150, 7475, 2124, 2224, 2324), i.e. almost all the available structural aluminium alloys.

Created in the last decade new aluminium alloys, together with other structural materials, opened up the way to appearance of structures with more perfect aerodynamic shapes [17–19]. Here, the welded structures are not only light and strong, but are also characterized by high reliability and safety of flying vehicle operation. Modern models of aircraft and rockets allowed mastering new tactical characteristics, which ensure the required cost-effectiveness of civil air transport, and high effectiveness of military aircraft. The general tendency of further development of such vehicles is associated with mastering the areas of high flight speeds and working temperatures of the structure. In the near future creation of supersonic flight vehicles is envisaged, which will have flight speeds M = 5–7–10 km/min.

Different concepts are being verified in order to solve these tasks. For instance, in order to create all-welded structures, the possibility of further improvement of the quality, reliability and service life of the product is envisaged due to application of new high-strength light alloys, welding methods, modern methodology of design and manufacture of welded components. Realization of such a concept is based on fabrication of welded finned panels of the wing, having considerable rigidity and minimum specific weight, fuselage elements, landing gear, etc. This envisages a significant saving of metal, reduction of the structure weight at replacement of mechanical joints by welded ones.

Traditionally used aluminium-based materials are replaced by those having improved composition and properties. As the main task of perfecting the aircraft structures for the next few years consists in weight reduction, improvement of the life and durability at the respective levels of strength, durability and cost-effectiveness, investigations are continuously going on, which will allow opening new reserves for performance improvement, and, thus, increase of their competitiveness, compared to other structural materials.

A vivid example of the policy of active upgrading of the structure is Boeing 777X aircraft. It collected the most promising developments in the field of materials science, technological processes and operations. A high-strength aluminium alloy, developed by Boeing and Alcoa companies— 7055-T77 alloy with yield limit of 640 MPa, is used for the upper surface of the wing, where static strength characteristics are the most important indices. The lower surface of the wing is made from 2324-T39 alloy of improved composition, with high strength and fatigue values. 2524-T3 alloy with high values of strength, fatigue and crack resistance is used in the fuselage.

At present, A-380 aircraft, which was developed in Europe (Figure 1), is a leader in application of new promising materials. It is designed for 555 passengers, which is by one third more than in its main competitor — Boeing 747. The world's first two-level (or two-deck) aircraft has four engines. Its length is 73 m, wing range is 79.8 m, and height is 24 m. The airliner is capable of flying 15 thou km without landing or refueling. High-strength 7055-T77 alloy is used for the upper surface of wing structure, and 2324-T39 alloy of improved composition is applied for the lower surface. 2524-T3 alloy is used for the upper part of the fuselage, and in the lower part weldable corrosion-resistant 6013-T6 alloy is applied. Empennage of the aircraft and wing center section are made from composite materials. Material replacement allowed reducing the structure weight and improving its adaptability to fabrication.

In Russian aircraft structures alloys of two alloying systems are extensively represented — Al–Cu–Mn and Al–Zn–Mg–Cu. D16-T alloy is used for the fuselage outer sheath and load-carrying side and lower surfaces of the wing, exposed to fatigue loading, and V96 (7075) alloy is applied for fuselage load-carrying elements (keys, stringers) and sheath of the upper load-carrying surface of wings, to which shrinkage stresses are applied. At present, developments based on the traditional alloys are performed, in order to improve their strength, toughness and fatigue properties.

Perfect production technology is one of the important prerequisites, in order to reduce the machine mass. In addition to thermal, mechanical and plastic treatment, it includes effective welding processes. Although they feature low productivity, high equipment cost in manufacture of flying vehicles, at the same time they provide high reliability of the joint and ability to resist stringent service conditions. Gas-shielded consumable electrode arc welding belongs to such processes for joining typical elements from aluminium alloys. It did not become widely applied in aerospace industry, as it does not provide sufficiently high mechanical properties of the joint and the required level of reliability. Nonetheless, this method of joining aluminium alloys is the main one in welding outboard compartments for fuel and oxidizer in rockets of various classes.

For instance, in manufacture of the structure of Saturn-V rocket tank from 2014 and 2219 aluminium alloys, gas-shielded tungsten electrode arc welding had the greatest advantage. Welded structures of rocket engine bodies and rocket fuel tanks from aluminium alloys were made using arc welding technology. The reliability of the joints was ensured by providing effective heat removal behind the arc that greatly reduced the residual stresses and deformation of the joints [5].

When manufacturing elements of Space Shuttle reusable vehicle, the technology of plasma welding (Figure 2) with alternating polarity of the arc was widely applied, which was optimized at Hobart Brothers Company. The method was specially developed for welding thick profiles from aluminium alloys, which are used for outboard fuel compartments of Shuttle type vehicles (Figure 3). The thermal cycle in the following mode turned out to be the most effective: reverse polarity current pulse of 15–20 ms, straight polarity current pulse of 2–5 ms; straight polarity current here was by 30–50 A higher than the reverse polarity current. This creates the conditions for concentrated heating of the base metal that allowed reducing the angular deformation of the welded joint.

Figure 1. A-380 aircraft at takeoff

In aircraft of Airbus 318 and 380 series laser technology is used as an alternative to riveted joints for joining stringers to the sheath [15]. In welding the fuselage of F-22 fighter plane, electron beam welding was used instead of the riveted structures [10]. Diffusion and electron beam welding, as well as the combined process of friction stir welding are the most extensively used [17–19]. The main requirements to technology are the high joint quality, ensuring minimum risk under the product service conditions, and admissible production cost.

Integrated technology of treatment of aluminium elements and their joints allowed the Boeing Company to manufacture a tank for liquid oxygen and fuel compartment of booster of Delta series carrier

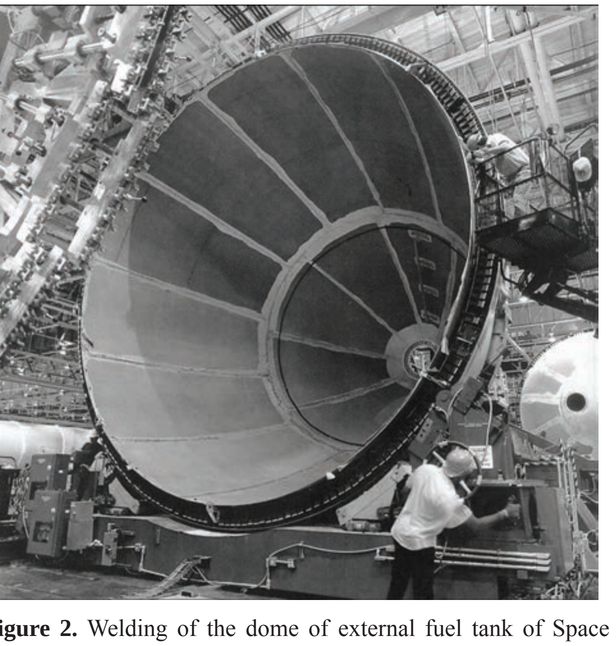


Figure 2. Welding of the dome of external fuel tank of Space Shuttle vehicle (USA)

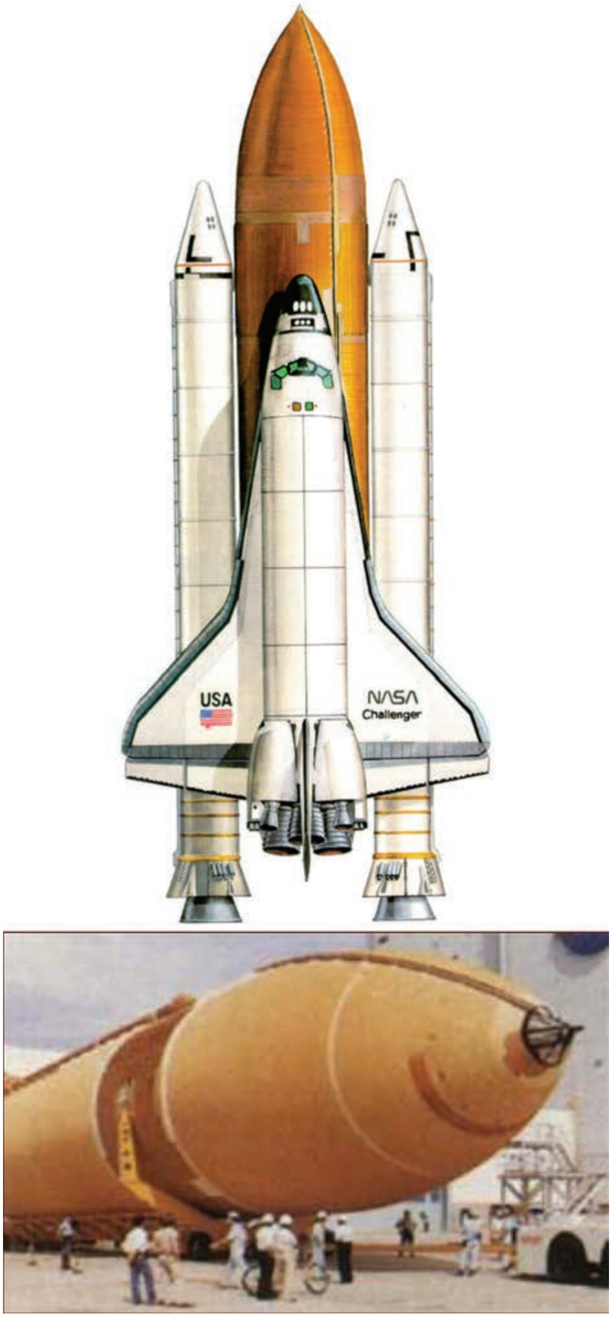


Figure 3. Appearance of base fuel compartment of vehicles of Space Shuttle type

rocket. The structure of the tank, which is loaded by cryogenic fuel, takes up a considerable part of flying vehicle overall dimensions. The booster compartment consists of two types of tanks of 12 and 8.4 m length, as well as intermediate cylinder of 4.8 m length and 2.4 m diameter.

Now preparations for launching Delta-VI rocket are underway. It is planned to make the tanks for it for aluminium alloy 2598. As the tank has considerable dimensions, it is envisaged to weld it in the vertical position. Here, the tank will move relative to the platform with the welding unit. Boeing Company developed such a technological process and anticipates an increase of commercial launches of satellites using rockets of Delta series and plans to produce 100 tanks per year. In addition, the Company conducts wide-scale investigations of service properties of welded joints and new technological documentation is being developed. Such a production strategy is due to expansion of the sphere of application of advanced welding processes for manufacture of welded structures in the civil and military factories.

Work on welding curvilinear joints is also actively pursued. In order to make superlight outboard compartments of reusable aerospace vehicle of Space Shuttle type, NASA (Figure 3) used the technology of friction stir welding for joints of 2 to 5 mm sheets of 2198 alloy of Al–Li system. Such elements of the structure are used for containing the fuel components, and usually they are of 47 m length and 8.38 m diameter. Results of studying the quality of welds confirmed that this technology can completely replace the plasma and electron beam welding methods when working with aluminium alloys [12, 13]. The low value of welding energy input creates the thermophysical conditions, required for weld formation, i.e. conditions are in place, under which a solid solution is deformed, that has a positive effect on the values of physico-mechanical properties of the joints, degree of metal softening in the heating zone and welded item deformation.

The method of friction stir welding was verified also for joining new aluminium-lithium alloy — C458 (Al–1.8Li–2.7Cu–0.3Mg–0.08Zr–0.3Mn–0.6Zn), which is characterized by a lower density (0.026 kg/cm^3), compared to other aluminium-lithium alloys and high modulus of elasticity, than 2219 alloy. Obtained results of investigation of weldability and physico-mechanical properties of welded joints allow predicting that owing to replacement of the traditional alloys by new alloy C458 in the structure of reusable vehicle fuel tank, it is possible to save from 2 to 4 mln USD for 400 flights, in terms of production and maintenance costs.

Prospective analysis (up to 2020–2030) of application of aluminium-based materials in flying vehicles is indicative of the fact that these alloys will retain their leadership in the structures of planes, for instance airframe, of about 80 %. The main tendency of their development, based on increase of strength and decrease of the alloy specific weight, will continue to grow. At the same time, it should be noted that increase of the above characteristics is usually based on complication of the alloy chemical composition, need to optimize the heat treatment modes and other technological measures, including also the welding processes, which cause lowering of the material ductility and life properties. Therefore, fabrication of sound permanent structures from new aluminium-based materials is a major scientific and technological problem, which necessitates large-scale investigations and mastering new methods of welding aluminium alloys, taking into account the fact that the welded joints should be able to perform with a high reliability under the complicated service conditions.

A similar tendency promising for application of new welding processes is also observed in the **ship-building sector**. The main structural material in construction of high-speed vessels for operation under the conditions of sea and river basins are aluminium alloys of 5XXX group of Al–Mg–Mn alloying system. Compared to steel, they have essential advantages — high corrosion resistance in sea water. In addition, aluminium hulls are not overgrown by shells that allows preserving the flow around the ship and increases the passage speed in the overhaul period, thus lowering the operating and painting costs. This way, the conditions required for operation in aquatic environment are created (Figure 4). Earlier, different fusion welding processes, particularly consumable electrode welding, were widely used in ship-building. Over the recent years, a considerable increase of the interest to introduction of friction welding technology is observed in this mechanical engineering sector. Here, all the types of welded joint are used: butt, tee, fillet, etc. This welding process became the most developed in the Scandinavian countries of Europe.

The wide introduction of friction stir welding technology was facilitated by successful development of welding equipment by ESAB Company, Sweden, under a license purchased from The Welding Institute, Great Britain. In keeping with the data provided by ESAB Company, development of a series of SuperStir units is based on application of standard machines of modular type. Such a production strategy allowed development of a typical line of welding equipment for joining different groups of aluminium alloys. The units of modular design cover the entire range of working space parameters for overall dimensions of the welded panels from 0.5×1.5 up to 10×20 m. The equipment set includes special clamping devices with gear mechanism for movement, welding machine and computer control system. Welding is performed in the automatic mode. Welding process parameters are recorded due to a built-in operational control system.

One of SuperStir units was tested by a Norwegian shipbuilding Marine Aluminium Company, when making the hulls of high-speed launches and large hull ferries from aluminium panels of 6×16 m size. Here, evaluation of service properties of welded joints of 6082 and 7108 alloys was performed, and the possibility of application of aluminium panels produced by friction stir welding for sea vessel sheathing was determined. Obtained results showed that after clean-

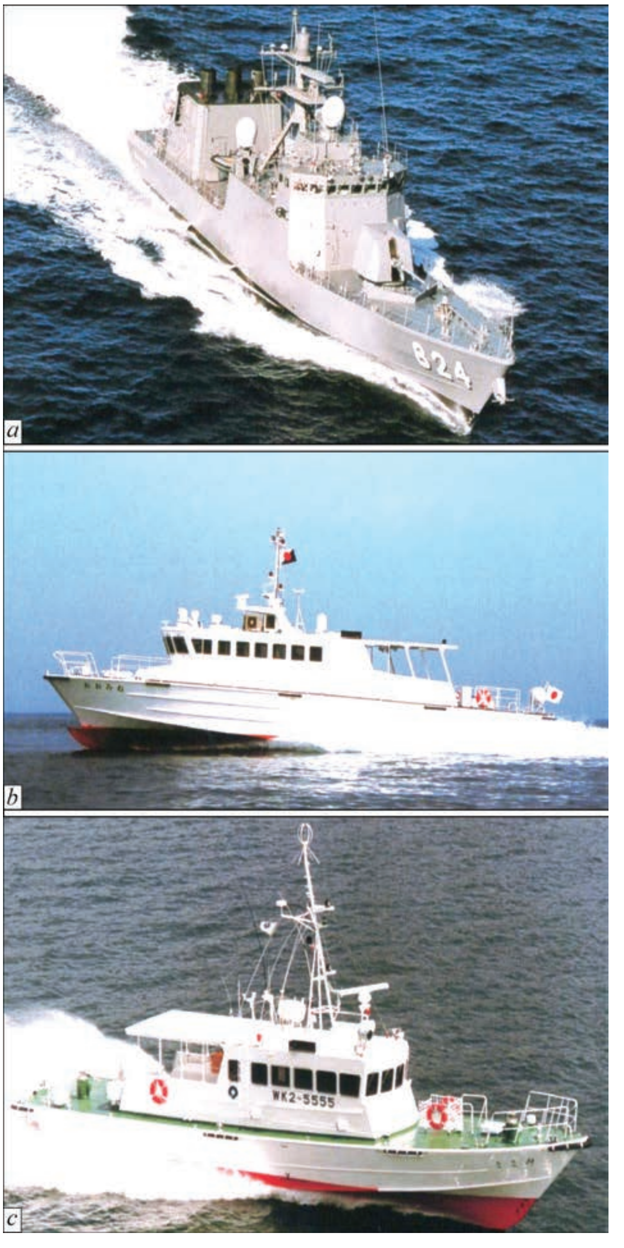


Figure 4. Examples of aluminium alloy application in shipbuilding structures (Japan): *a* — border guard boat; *b* — pleasure boat; *c* — small fishing boat

ing from corrosion products and further tension, the welded samples had high anticorrosion resistance under the conditions of cyclic testing in a chamber with sea environment for 1000 h at the humidity of 98 %, as well as 50 °C and higher temperature. Welded joints of 2519-T87 alloy made by friction stir welding, demonstrated high properties at ballistic testing. They allowed General Dynamics Land Systems Company in cooperation with the Edison Welding Institute, welding aluminium plates of 1219×121×31.8 mm size to create a new generation of amphibious marine armoured vehicles [15].

Swedish Company SAPA together with The Welding Institute (Great Britain) developed and put into production welded panels for quick freeze refrigeration units [14]. Higher requirements of weld tightness are made of welded joints of these panels as they are containing cold substances, dangerous for man and environment. The sample company, using friction stir welding, mastered manufacture of welded panels for stations of fish mass precompression before freezing. The structure of such a station consists of 17 panels of up to 30 mm thickness with total weld length of 16 m. Equipment of SAPA Profil Plant, Sweden, allows welding from pressed profiles the extended and wide panels of 14.5×3.0 m size for fabrication of ship decks, covers and side parts of carriages of railway and metro trains.

In the **automotive sector**, the attractive qualities of aluminium alloys for designers are: reduction of the car weight and fuel consumption, accordingly; replacement of deficit copper and corrosion-resistant steel; wider raw material possibilities, compared to other metals; high efficiency of processing (recycling) of aluminium fragments and parts after vehicle life is over. Specialists have calculated that each kilogram of aluminium used in the car structure, allows saving 7–10 l of fuel during the car life.

Figure 5. Examples of aluminium alloy application in passenger cars: *a* — Feardi Z33; *b* — Skyline V35

Analysis of the dynamics of growth of the volumes of application of aluminium and its alloys in cars of EC countries and the USA show that already in 2000 the total weight of aluminium components and parts was equal to 120–150 kg or around 10 % of the car total weight. An example of promising applications of aluminium alloys is Porsche 928 car, which has almost 300 kg of aluminium parts in its design that is equal to approximately 20 % of the car total weight. Ford Motor Company developed a new model of Synthesis-2010 car, the structure of which is mainly made from aluminium that ensures its practically complete recyclability. Welded aluminium load-carrying body has the weight, which is by 46 % smaller than the respective body made from steel. The car has a three cylinder engine with an aluminium cylinder block.

Aluminium alloys are widely used in the structure of bodies of cars of Audi-A8, Lotus, Expedition (Ford), Navigator, and other classes. The above-mentioned car models belong to the high class of sports cars or the so-called SUVs (Figure 5). The volume of manufacture of such cars does not exceed 0.1–0.2 % of the total car output in the world.

The most widely accepted components and parts of cars from wrought and cast aluminium alloys are the frame, heat exchangers (radiator and heater), bumper, doors, trunk and hood covers, body, wheel discs, cylinder block, pistons, profiles of the car exterior and interior, cab bodies and sides of trucks, fuel tanks (Figure 6). In foreign car brands of frame structure extruded aluminium alloy profiles are used for frames and other elements. So, AOS/APC Car Company reported wide introduction of friction stir welding method into manufacture of a welded car frame from aluminium profile.

Table 2 gives the main types of welded joints and welding processes, which became widely accepted in fabrication of elements of the car structure from aluminium and its alloys. Their realization in car manufacture was due to solving a whole number of production processes. They include: absence of aluminium alloys of an optimum composition for manufacturing bodies of trucks and cars; low yield limit of the alloys, compared to steel; absence of a serial technology of stamping automotive blanks, particularly thin-walled items, preparation of aluminium semi-finished products for welding (laser, contact, arc) and further deposition of protective coatings. Today, new design-technological, metallurgical and organizational measures are being developed, which are mainly aimed at further reduction of the body weight and fuel consumption, improvement of ecological indices, high reliability and extended service life, as well as high level of comfort and safety during car operation.

Analysis of modern tendencies of development of automotive industry shows that today three main directions are noted in application of aluminium alloys in manufacture of car bodies. First, these are parts and components of the body in the cars with monocoque bodies. Second, these are add-on parts and components of hoods, boot lids, hatches, removable wings, doors, fuel tanks, front and rear bumper power beams, exhaust systems, etc. Third, these are parts and components of cars with frame design of the body. The last direction was particularly widely accepted in the USA and Europe. Aluminium alloys of Al–Mg, Al–Mg–Si, Al–Zn–Mg alloying systems, alloys 5083, 5456, 5556, 6061, 6013, 7033 are widely applied for this purpose. In Russia, their analogs are used: AV, AD33, AD37, AMg2, 1515, 1523. Alloys of Al–Mg and Al–Mg–Sc systems: 1535, 1545, 1570, AMg6 are widely used for load-carrying structures and components of cars; for exhaust systems these are 1419, SAP-3, 1151 alloys; and for load-carrying levers of torsion bars, rods — 1970, AK6, 1460, 1933, 1973 alloys.

Aluminium and its alloys are also used in agricultural vehicles, including manufacture of animal transport trucks, refrigerators, flour trucks, specialized bodies of cars and trailers for transportation of mineral fertilizers. In addition to reducing the car body weight and increasing the payload that lowers the transportation costs and saves fuel, a high hygroscopicity and extension of operating life are ensured. Welded structures of all-aluminium flatbed and tipper platforms have also been introduced, which are used in international transportation of passenger cars have also been introduced. Structures of semi-trailers with sideboards and bars for awnings from aluminium profiles, general purpose box semi-trailers, refrigerated semi-trailers of different capacity have also been developed.

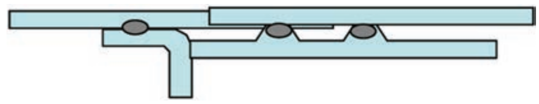
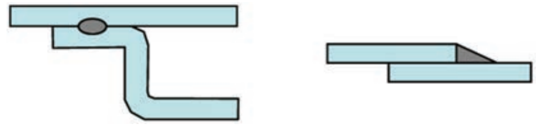
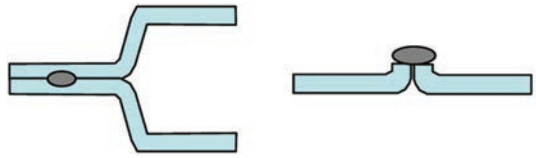
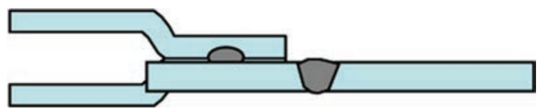
Welding technology arsenal is constantly growing. Alongside welding of plates from aluminium-magnesium alloys 0.5–1.5 mm thick by CO_2-laser (up to 5 kW power) and Nd:YAG-laser (up to 6 kW power), hybrid laser-arc technologies (laser + MIG) began to be used, which allow reducing power consumption and requirements to the accuracy of fit-up of the butts between the structure elements. The requirements to the quality of edge preparation, accuracy of butt fit-up for welding of aluminium alloys include the following: presence of strictly rectilinear edges without burrs at not more than 0.04 mm waviness. The gap in the butt between the edges of 0.5–3.0 mm thickness should not be larger than 0.08 mm. Some USA plants and companies operate new units for realization of the technology of electron beam welding without vacuum

Figure 6. Examples of aluminium alloy application in trucks: *a* — Toyota FCHV; *b* — superlight truck FU with aluminium frames; *c* — aluminium alloy body of a dump truck

[19]. In Japan studies are under way on application of welding of sheet (0.8–1.5 mm) aluminium and its alloys for automobile production. Selection of the process of welding at organization of production is based on analysis of their technological capabilities. Cost is an important consideration, depending on type and volume of production.

In **railway transportation** aluminium and its alloys are used in the form of stamped and extruded blanks when making carriage axle-boxes [20]. The axle-box weight is here reduced two times. Damping properties of aluminium promote 10 % reduction of the load on the rails and elements of the carriage structure. Owing to high corrosion resistance and good weldability of aluminium, it is used with success in manufacture of tank cars for transportation of concentrated nitric acid, milk, wine materials, mol-

Table 2. Main types of joints and processes of welding aluminium alloys in fabrication of car structure elements

Structural element	Alloy	Thickness, mm	Welding process	Main type of joints
Front and rear wings of a car	AMg2, alloys of Al–Mg–Sc system (1523)	1.0–2.5	Laser; resistance (spot or seam)	
Doors	AMg2, AD37, AMg4, 1523, 1535	1.0–2.0	Laser, resistance (spot or seam), spot arc, manual arc	
Hoods, lids	AMg2, AMg4, AD37, alloys of Al–Mg–Sc system (1523, 1535)	1.0–2.5	Laser, resistance (spot or seam), spot arc, manual arc	
Fuel tank	AMg2, AMg4, AMg6, alloys of Al–Mg–Sc system (1523)	1.5–2.5	Laser, resistance (spot or seam), spot arc, manual arc, automatic argon-arc	
Gas exhaust system	1419, 1151, SAP	1.2–1.8	Laser, resistance (spot or seam), spot arc, manual arc, automatic argon-arc	
Load-carrying elements, spar, bumper	AMg4, AMg6, AD37, alloys of Al–Mg–Sc system (1535, 1545, 1570)	1.5–3.0	Laser, resistance (spot or seam), spot arc, manual arc, automatic argon-arc	

ten sulphur and other chemicals. Profiles and other semi-finished products are widely used in the interior of passenger cars. Pipes with inner cladding from corrosion-resistant aluminium alloy are used for the systems of water supply and heating of the carriages. Their service life is ten times larger than that of monometal ones, that eliminates the need for system repair during the operating period. At present, the possibility of application of large-sized panels from aluminium alloys up to 800 mm wide as load-carrying structural elements in the carriage structures is considered. Aluminium shipping containers of all types, have considerable advantage over the steel products. Their weight is two times smaller than that of the steel ones, and corrosion resistance is much higher, they are more durable and cost-effective in service, as they accommodate higher payload and require no painting.

In **building of civil and production facilities** the base for application of aluminium alloys of Al–Mg, Al–Mg–Si, Al–Mg–Zn, Al–Cu–Mg system are the high strength, absence of cold brittleness threshold, low density, high ductility, good corrosion resistance, absence of sparkling upon impact, antimagnetic properties, high seismic resistance, bactericidal activity, as well as good appearance of the structure [15–18]. Aluminium building structures are not like steel ones. Flat plates turned out to be the most cost-effective, sometimes 3D parts and extruded rods, which together make up spatial systems.

Nonconsumable and consumable electrode arc welding, and automatic arc welding over a layer of flux became widely accepted. Over the recent years wide application of pulsed-arc welding is observed, at which the voltage and current change by a certain law, that allows producing sound welds in different positions in space, during fabrication of structures of a complex shape.

It should be noted that despite the advantages of aluminium structure application, search for rational engineering solutions of their fabrication increases the design costs several times, compared to steel ones. This is due to the need for thorough verification of the design schematics and cross-sectional shapes of the elements and conducting full-scale testing of individual samples, in order to determine the life and corrosion properties of the products. At the same time, considerable design costs are paid off by operating life of such structures, as the minimum cost of the welded product, incorporating individual elements from aluminium alloys, is inversely proportional to the costs of project optimization.

Operation of aluminium structures has its special features. The main expenses are to ensure systematic observation of the condition of structure element surface and areas of their joining to the parts from other materials, which it is desirable to properly insulate from aluminium. In the absence of aggressive environments (haloids or alkali), the aluminium structures do not require any funds for repairs for 20 to 50 years.

Application of weldable aluminium alloys is particularly effective in facilities, located in the Arctic, Antarctic, mountain regions and deserts. This is related to the ability of the alloys to increase their strength under the conditions of low and cryogenic temperatures, while preserving the ductility which they have at room temperature (20–25 °C).

Considerable cost effect is obtained from aluminium alloys in construction or reconstruction of bridge overpasses. In the latter case, it is possible to not only preserve the architectural appearance of the bridge, but also increase the traffic flow. Despite the considerable difference in the structure of aluminium and concrete, aluminium and ferrocement which are used, the base is a comparatively low modulus of elasticity of these materials that allows their use in the designs of spatial ferrocement and concrete structures.

Thus, the presented examples of mastering welded lightweight structures in different engineering sectors in the world are indicative of the diversity of technological capabilities and forms of realization of unique properties of aluminium and its alloys. They reflect the tendencies of world production and consumption, which widen the spectrum of their application by improvement of the welding processes and development of new joining technologies. The structure effectiveness is determined by functional requirements to products, weldability of the selected aluminium alloy and level of its joining technology at minimum costs and fabrication terms. Appearance of more perfect alloys with the respective physico-mechanical and technological properties, alongside the rational methods of their permanent joining provides the high weld quality and welded structure reliability.

A similar process also takes place in Ukraine. However, the pace of its realization is very slow. Intensification of lightweight structure fabrication requires mastering the recent high technology achievements, including welding, by industry. This will ensure higher productivity of welded structure fabrication at reduction of manual labour, lowering of labour content, improvement of ecological conditions in manufacture of typical structural elements, that will open up the prospect for creation of new samples from aerospace engineering to land and water vehicles, as well as effective building and bridge structures with wide application of welded parts and components from aluminium alloys.

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BRAZING AS A PROMISING METHOD OF PRODUCING PERMANENT JOINTS

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The paper presents practical results of developments and investigations in the field of brazing different materials: aluminium, copper, high-temperature nickel and titanium alloys, as well as promising materials based on Ni_3Al and γ-TiAl intermetallics and steels of different grades. Data on reactive-flux brazing of aluminium thin-walled structures in a controlled gas environment are given. A lot of attention is paid to producing brazed joints from dissimilar materials: Mo+C (stainless steel), W+Cu, hard alloy material (VK 20)+steel, Al+steel, etc. Effective application of the developed technologies of brazing high-temperature nickel and titanium alloys in fabrication of critical structures for high temperature applications and results of mechanical testing of brazed joints are shown. The developed brazing filler metal and technologies of high-temperature vacuum brazing were applied to produce joints from new generation alloys based on nickel and titanium aluminides, which have been successfully tested for long-term strength under the conditions of higher temperature and continuously applied stresses. 17 Ref., 1 Table, 14 Figures.

Keywords: brazed joints, brazing filler metals, vacuum, reactive-flux, flame brazing, high-temperature nickel, titanium alloys, long-term strength, dissimilar materials, aluminium, copper alloys

Nowadays, brazing occupies an important place among the different methods of producing permanent joints and is widely used in different industries: aircraft, space, instrument making, automotive during manufacture of refrigeration and cryogenic engineering, at jewelry enterprises and other [1, 2]. The advantages of brazing over welding consist in the ability of combining different materials without their melting, which provides preservation of the initial structure of base metal, provided that the temperature and time parameters of brazing process and chemical composition of the brazing filler material are correctly selected. A great importance belongs to the application of brazing process for joining materials characterized by poor weldability, because of cracking in the heat-affected zone and in the weld [3]. One more factor in favor of brazing is the ability of combining the heat treatment mode of the base metal with a thermal mode of brazing and automation with a simultaneous producing of several elements of a complex geometric configuration [4]. The decisive factor in brazing is the ability of producing joints in hard-to-reach areas where it is impossible to join base materials with the use of conventional welding methods. In such cases, brazing is the only possible method of producing joints.

However, notwithstanding such positive characteristics of brazing process, there are some peculiarities and problems that need to be solved in order to provide the operational properties of the brazed structures. They include chemical composition and form of a used brazing filler metal. Currently, there are many brazing filler metals on different bases: tin, aluminium, copper, silver, nickel, titanium, iron, etc. They are applied in the cast state, in the form of powders, wires of different diameters, plastic tapes, produced with the use of traditional methods of metallurgical processing or by ultrafast hardening, etc. [4, 5]. The choice of chemical composition of brazing filler metal is predetermined by physical and chemical properties of the base metal and performance characteristics of brazed products. One of the indices of brazing filler metal compatibility with the base metal is the ability of brazing filler metal to wet the base metal and spread over its surface at the brazing temperature [6, 7]. The use of brazing filler metals with a wide interval of melting leads to the development of chemical heterogeneity and liquation processes in the weld metal, as well as porosity. The use of eutectic brazing filler metals allows a brazed joint to solidify at a constant temperature, but at the same time an eutectic structure is formed, which often contributes to embrittlement of the weld metal. Therefore, each pair of materials to be brazed requires an individual approach and a specific chemical composition of brazing filler metal with a predetermined temperature interval and mechanical properties.

At PWI for many years systematic investigations in the field of brazing has been conducting, the physicochemical processes have been studied that occur during heating to brazing temperature, the relationship between mechanical properties of brazed joints, structure of brazed joints, chemical composition of brazing filler metal and base metal have been studied. Based on the results of the investigations, brazing filler metals were created that are compatible with the base metal, brazing technological processes were developed to provide the brazed joints with the necessary service properties. This paper presents some results of the carried out investigstions and the examples of practical applications in different industries.

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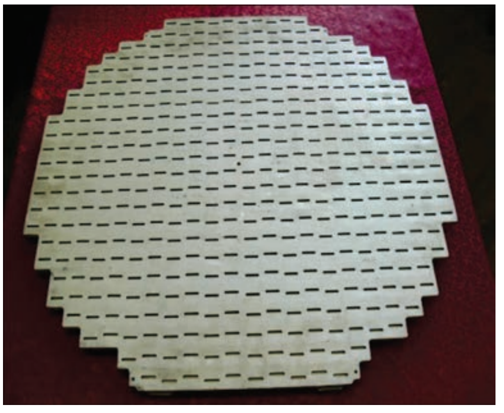

Figure 1. General view of brazed antenna array

Aluminium brazed joints. At PWI the technology of brazing aluminium alloys was developed and a method for furnace brazing of aluminium thin-walled structures was proposed (Figure 1) in a controlled gas environment (nitrogen, argon). This method is environmentally friendly and less energy intensive as compared to existing brazing methods (for example, immersion in salt melts).

For high-temperature brazing of aluminium alloys of series 1000 ((90.3–99.98) A1) and 3000 (Al–Mn systems), brazing filler metals of Al–Si system and non-hygroscopic reactive flux of the salt system K, Al, Si/F are used, which provide the equal strength of brazed joints in the conditions of multiple shocks, vibration according to TU U 14307274-009:2016.

The melting point of brazing filler metal and flux should be lower than solidus temperature of the brazed aluminium alloy, which determines the upper limit of the brazing temperature interval. The antenna arrays with the overall dimensions (640×640×26 mm) were manufactured. The weight of the antenna is 2.07 kg. It should be noted that during the manufacture of this antenna it is necessary to produce brazed joints about 6000 mm in length. However, the flux consumption are insignificant and amount to ≤50 g, which favorably differentiates the cost of this method as compared to the existing ones.

The thin-walled aluminium waveguides made in the controlled gas medium (Figure 2) are characterized by a large total area of a brazed joint, which is about 1562 mm^2. The consumption of brazing filler metal per a unit of product is 1.1–1.5 g, flux — 2–3 g.

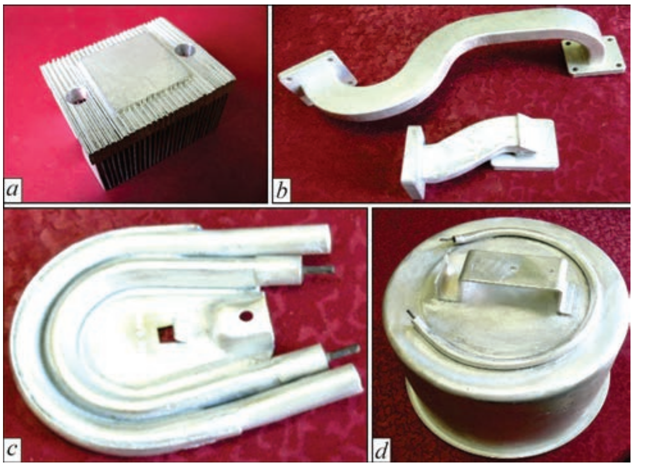

Figure 3. Brazed products of aluminium alloys: *a* — plate aluminium heat exchanger; *b* — element of ultra-high frequency module; *c* — tubulat heating elements for household appliances (*d*)

The produced brazed weld of a thin-walled structure is characterized by the presence of a smooth fillet and the absence of defects (Figure 2, *b*).

The technological process of reactive-flux brazing is used in the manufacture of plate-type aluminium heat exchangers of the electrothermal module of the rolling stock used for preparation of water, microwave antenna elements and a number of other products of the national economy (Figure 3).

The overall dimensions of such heat exchangers are 145×160×82 mm, the number of plates is 82 pieces and the total area of a brazed joint is 1740 mm^2. The flux consumption is negligible and is ≤ 20 g.

In this case, brazing proceeds with the use of reactive fluoride flux, which melts during heating to brazing temperature and interacts with aluminium and forms a liquid phase of the Al–Si system, which is close to the eutectic composition and serves as a brazing filler metal [8]. The produced brazed joints are characterized by the presence of brazed welds, whose width is much smaller than the width of the welds produced with the use of flux with brazing filler metal (Figure 4).

Dissimilar brazed joints. The choice and use of dissimilar metals as structural materials is determined by the service requirements and economic indicators specified to the finished products. Most high-tech

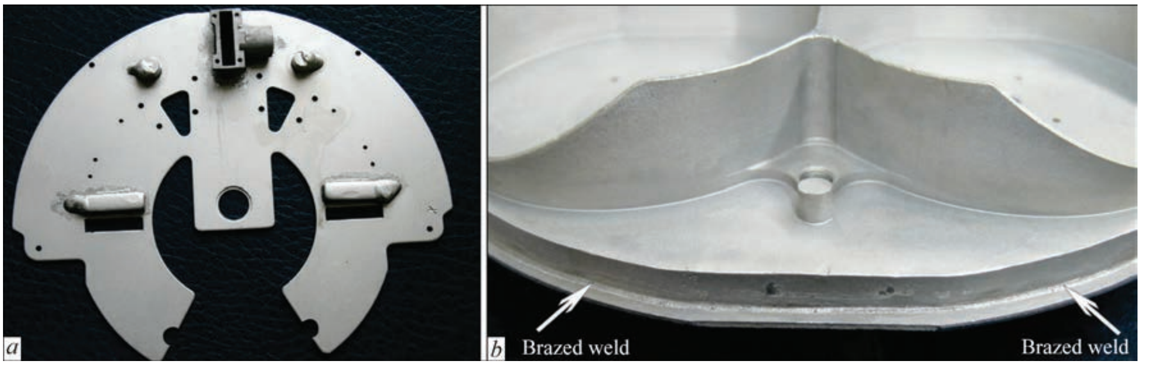

Figure 2. Appearance of thin-walled aluminium waveguide (*a*), brazed weld along the perimeter of the structure (*b*)

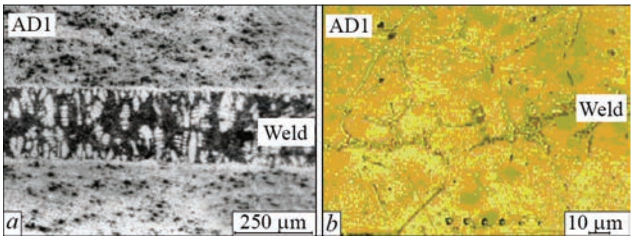

Figure 4. Microstructure of brazed weld of aluminium brazed joint produced using brazing filler metal and flux (*a*) and with flux without brazing filler metal (*b*)

equipment contains separate assemblies of dissimilar materials that are produced by brazing. It should be noted that during brazing of dissimilar materials, the problems arise caused by different physical and chemical properties of base materials. The quality of brazed joints is significantly affected by the difference in the coefficients of thermal expansion, which contributes to the arising of inner stresses. Reducing the effect of inner stresses provides a correct choice of brazing filler metal composition and temperature-time parameters of the brazing process.

The developed technology of flux induction brazing of steel-aluminium pipe adapters (SAPA) with an inside diameter (10−300 mm) in an argon medium (for cryogenic engineering) was developed. As far as the coefficients of thermal expansion of the basic dissimilar materials (corrosion-resistant steel 12Kh18N10T and aluminium alloy of the series 3000 (AMts)) differ, during brazing in the brazed joint residual stresses occur. Their level is much lower as compared to the welded joints produced with the use of existing arc welding methods. The brazed steel-aluminium pipe adapters (Figure 5, *a*) were successfully tested for strength and sealing according to the requirements of TA.

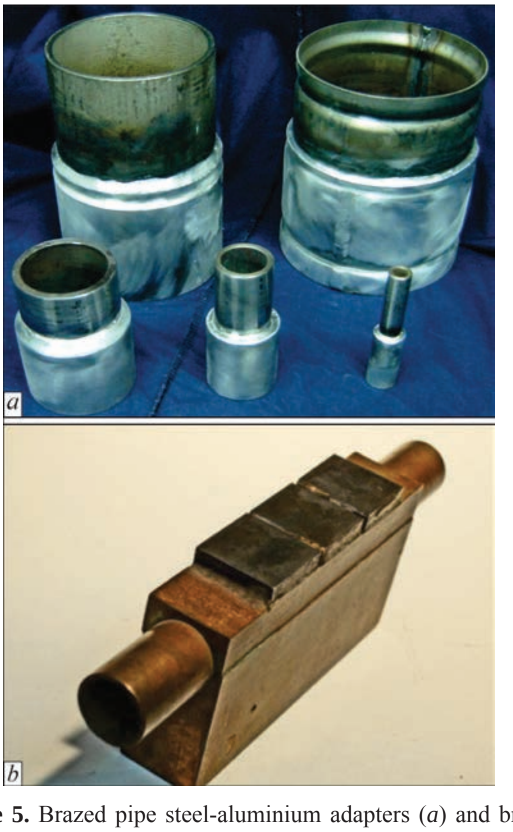

Figure 5. Brazed pipe steel-aluminium adapters (*a*) and brazed model of Cu−W diverter assembly for thermocyclic tests (*b*)

The obtained results of thermocyclic tests show that under the conditions of working pressure of 1 MPa/cm^2 brazed steel-aluminium pipe adapters can withstand 50 cycles at the temperature variation from 35 to −196 °C preserving sealing and without fracturing. They are characterized by a high strength, which amounts to 0.95−0.98 of the strength of the AMts alloy.

Brazing a pair of dissimilar materials copper-tungsten represents a particular interest and considerable difficulties. They find application in the manufacture of plasmatrons, powerful X-ray tubes, individual units of the thermonuclear fusion diverter, etc. On the basis of systematic investigations the technological process of vacuum brazing of dissimilar joints copper–tungsten, designed for application in rigid conditions of thermocyclic loading and neutron irradiation, was developed. For such tests, by means of brazing the models of diverters copper-tungsten were produced (Figure 5, *b*). Under the action of a pulsating heat flux, in the model an uneven temperature distribution is generated. The heat flux power and the duration of its action were determined in such a way that the maximum temperature on the surface of the tungsten coating and in the zone of brazed weld at the interface with the copper base corresponded to the design temperature at a constant flux with the power $Q = 10$ MW/m^2. The results of thermocyclic tests showed good thermal fatigue properties on the base of $1\cdot10^3$ cycles (Table).

After neutron irradiation with the dose of $5\cdot10^{21}$ neutr/cm^2 at a temperature of 100 °C, an increase in the tensile strength of the brazed joints from 200 (in the initial state after brazing) to 250 MPa, which is associated with the processes of ordering the solid solution in the brazed weld, the specimens preserve a sufficient strength also at 400 °C (Figure 6).

The technological process of vacuum high-temperature brazing of dissimilar joints molybdenum–carbon alloys (stainless steel), which are serviceable under rigid conditions of thermal loads (Figure 7, *a*, *b*), was created.

The brazed tubular joints molybdenum–stainless steel with tight brazed welds were produced, where cracks and a formed structure of solid solution were absent (Figure 7, *c*).

The dissimilar joints kovar–titanium alloy are widely used in instrument making. To produce them by brazing, a special technology of preliminary treatment of the base metal (titanium alloy) was developed and applying vacuum radiation heating individual brazed assemblies were manufactured (Figure 8). The carried out tests on sealing gave positive results and testify to the quality formation of brazed welds.

The flux brazing of hard-alloy plates for sawing discs and holders were worked out during the manu-

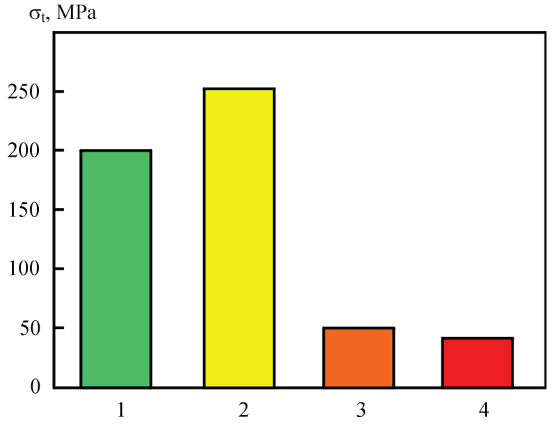

Figure 6. Strength of brazed Cu−W joints: in the initial state after brazing (*1*); after neutron irradiation in the SM-2 reactor at T = = 100 °C and a dose of $5{-}10^{21}$ neutron/cm^2 (*2*); at T = 310 °C, in the SM-2 reactor, dose of $5{-}10^{21}$ neutron/cm^2 (*3*); in the BOR-60 reactor at T = 400 °C, dose of $5{-}10^{22}$ neutrons/cm^2 (*4*)

facture of circular saw blades for woodworking and metalworking tools.

The brazing process is used in the manufacture of cylindrical elements for semiconductor devices consisting of dissimilar materials, such as metallic 22XC ceramics and kovar (or copper).

The brazing of dissimilar materials of hard-alloy cutters for body blades (made of steel) during manufacture of drill bits was mastered [9]. In addition, during operation of drill bits a partial fracture of the surface of hard-alloy cutters occurs and spallings are observed (Figure 9, *a*), which deteriorates their serviceability.

Therefore, it becomes necessary to perform defect restoration and repair works with the use of flux brazing of dissimilar steel materials with hard-alloy cutters, as well as in the use of strength carbide-containing coatings. It allows continuing drilling with the recovered drilling tool (Figure 9, *b*) with a considerable saving of material resources.

Results of thermocyclic tests of brazed models of Cu−W diverter

Loading type	Pulse/pause duration, s	Heat flow capacity, MW/m^2	Number of cycles, N
1	0.3/18−25	26−28	1000
2	0.5/26−28	26−28	200
3	10/13	13/14	1000

Brazing of copper and its alloys. Brazing filler metals based on copper-phosphorus system were developed, flux and vacuum brazing (repair) of copper alloys, including bronzes of different grades (dispersion-hardening type BrKhTsr), dispersion-hardening alloys (of type Glidcop), 0.25 $A1_2O_3$), cupronickels (MNZhMts31-1), cunials (Cu−Ni−Al), non-silbers (MNTs15-20), etc. were worked out. Corrosion-resistant cupronickels are used in the manufacture of seawater desalting plants, medical tools and marine shipbuilding.

In the production of refrigeration and heat exchange (Figure 10, *b*) equipment, capillary brazing of copper pipelines is used. Heat exchangers (of copper, cupronickel — MNZhMts3-1) are used in shipbuilding.

In diesel locomotive building and in the production of gas columns heat exchangers are used (Figure 10, *b*), whose components are brazed elements of copper (or brass). The carried out investigations of strength of brazed joints made of copper M3 and alloys MNZh-5-1 and MNZhMts 30-1-1 under static and cyclic loads gave

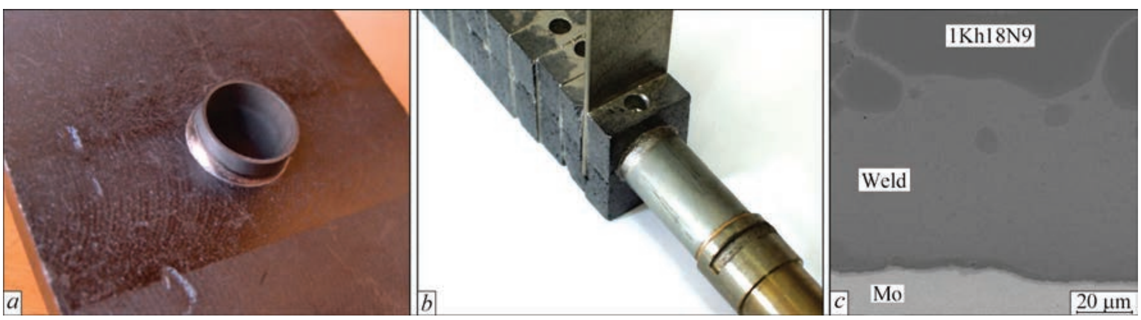

Figure 7. Brazed assembly graphite–molybdenum (*a*) and model of diverter device (**b**) containing brazed elements Mo−C (stainless steel) produced by vacuum high-temperature brazing for thermocyclic tests; microstructure of brazed joint molybdenum–stainless steel (*c*)

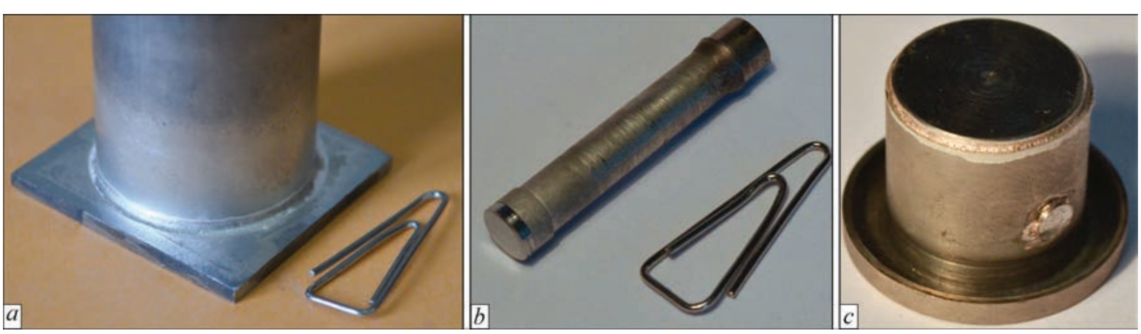

Figure 8. Brazed specimens of dissimilar materials kovar–titanium alloy: model specimen for tests on sealing (*a*); tubular element (*b*); brazed assembly with plug (*c*)

Figure 9. Matrix drill bit of 215.9 mm diameter for surface drilling during oil and gas production before (*a*) and after repair (*b*)

a positive result and provided a reliable operability of telescopic and collar-pipe tubular structures.

Copper-phosphorus brazing filler metals are used to braze copper joints, which consist of tubular elements and plates applied in solar collectors for heating water (Figure 10, *a*). Solar collectors are a great way to save energy resources. Due to the free solar energy, it is possible to provide hot water for economic needs (for at least) 6−7 months a year and in other months also to support the heating system [10]. In the manufacture of solar collectors, the process of brazing steel components can also be applied.

Different heating for brazing copper tubular structures, including flame arc or plasma methods can be effectively used, where as a filler material copper-phosphorus brazing filler metals by additional alloying with different elements are applied.

Vacuum brazing of high-temperature nickel alloys. The creation of permanent brazed joints in the manufacture of critical structures from nickel cast, dispersion-solid, intermetallic alloys based on Ni_3Al, which are operated at high temperatures, is an important task today, and its solution determines the possibility of using these materials in the manufacture of parts of the hot passage of gas turbine engines, power plants, jet engines and heat engineering equipment.

For brazing high-temperature nickel alloys, commercial nickel-based brazing filler metals are widely used, in which as depressants silicon and boron are applied. These elements, on the one hand, reduce the melting point and improve spreading and on the other hand, they form low-melting brittle (eutectic) phases in brazed welds and in the base material [11−13], which cannot be dissolved even at a long-term isothermal holding, which adversely affects the mechanical properties of brazed joints during a long-term operation under the conditions of high temperature and permanent stresses. The use of brazing filler metals containing silver, copper, nickel does not provide the required level of heat resistance.

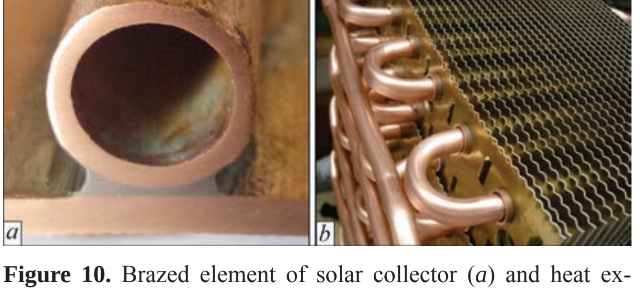

Figure 10. Brazed element of solar collector (*a*) and heat exchanger (*b*)

In this regard, the fundamental investigations of physico-metallurgical processes occurring during vacuum brazing of high-temperature dispersion-solid nickel alloys (IN 718) were carried out and regularities of the structure formation of brazed joints were determined. It was established that producing single-phase structure of a brazed weld provides stable results of short-term strength of brazed joints at a room and elevated (550 °C) temperature, respectively (Figure 11, *a*), as well as high values of long-term strength (132 h without fracturing) at a temperature of 550 °C and set stresses of 785 MPa (Figure 11, *b*). The obtained data of long-term strength more than twice exceed the similar data obtained with the use of industrial brazing filler metal. This technology is used in the manufacture of a closed centrifugal wheel (Figure 11, *c*).

Brazing of intermetallic alloys. For today, the traditional metal alloys providing solid-soluble and carbide strengthening are almost obsolete in terms of radical improvement of properties, especially for high-temperature applications. Some reserve for the near future is constituted by dispersion-strengthened, single-crystal and eutectic alloys. The increase of temperature in gas turbine engines is achieved due to intensive cooling of the blades, which, in turn, leads to decrease in efficiency. A real alternative to metal alloys is represented by alloys based on intermetallics, which are designed for high-temperature applications and contribute to expanding the field of using cooled blades with providing a high heat resistance without the use of coating [14].

The brazing filler metals together with the technological process of vacuum brazing (repair) of heat-temperature nickel alloys of different grades were created: casting alloys (ZhS6U), perspective heat-temperature nickel alloys based on intermetallic Ni_3A1 (Ni–8A1–14Mo–0.05V), operating under the conditions of high temperature, aggressive environment and continuous loads. They are used for the manufacture of individual parts and assemblies in the hot sections of gas turbine engines (Figure 12, *a*, *b*). The produced brazed joints of nickel alloy based on Ni_3A1 are characterized by a high long-term strength at an elevated temperature of 900 °C and permanent stresses of 150 MPa (Figure 12, c).

The class of promising intermetallic alloys includes titanium alloys based on TiAl. They are prominent representatives of high-strength and heat-resistant intermetallic alloys of the new generation, which are promising for the use in aircraft construction in the manufacture of a number of parts of the hot sections of gas turbine engines. In terms of heat-resistant

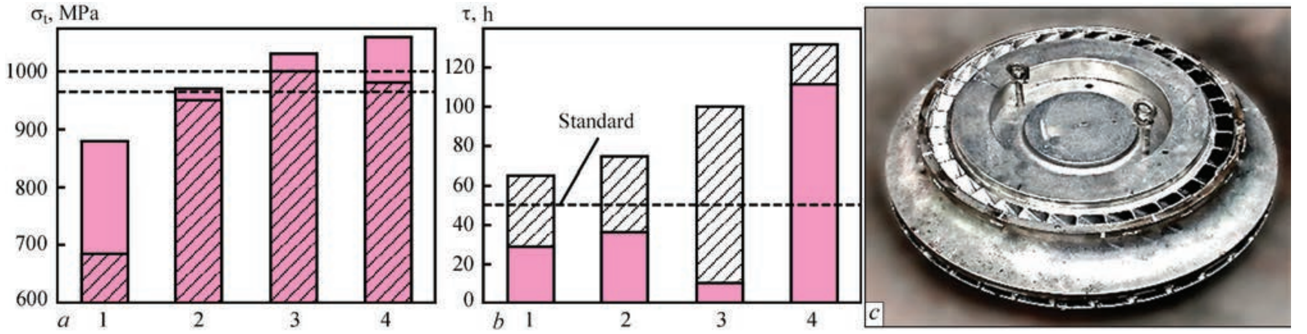

Figure 11. Tensile strength of butt brazed joints (*a*) produced using filler metals of the system: Ni–Pd–Cr–Si (*1*); Ni–Pd–Cr–Co–Si (*2*); Ni–Pd–Cr–B (*3*); Ni–Pd–Cr–Ge (*4*); long-term strength (*b*); double shrouded centrifugal wheel of axial flow compressor of gas-turbine engine (*c*)

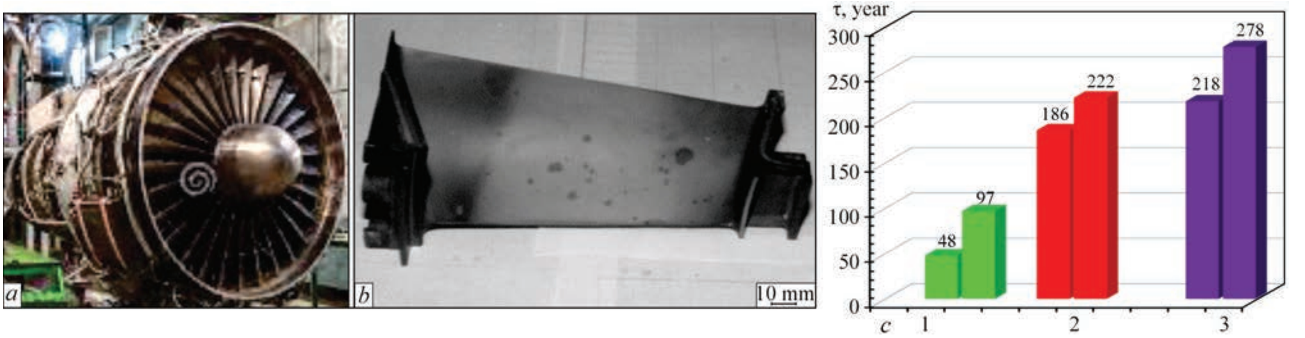

Figure 12. Gas-turbine engine (*a*), blade (*b*), long-term strength of butt similar brazed joints Ni_3Al+Ni_3Al produced using multicomponent nickel brazing filler metal without heat treatment (*1*), with heat treatment (*2*) and dissimilar joints Ni_3Al+ZhS6U with heat treatment

characteristics at a temperature of 700–750 °C, they can compete with highly alloyed nickel alloys due to a low specific weight of 3.8 g/cm^3 (8.9 g/cm^3 in nickel). This will provide a reduction in the weight of the gas turbine engine by 30 % and an increase in its operating characteristics. As a classic example of intermetallic titanium alloys Ti–48A1–2Cr–2Nb (at.%) can be, the main structural component of which is an ordered γ-phase (TiAl), on the boundaries of which a small amount of α_2-phase (Ti_3A1) is evolved in the form of lamellar grains. Due to such layered structure, this alloy has a good balance of ductility at a room temperature, strength at a high temperature and resistance to oxidation. The alloys, in which the volume fraction of α_2-phase is at the level of 10–15 %, have the maximum level of ductility [15]. The γ-TiA1 alloy (47KhD) has a high strength both at a room temperature (650–700 MPa) as well as at elevated temperature (at 700 °C, 320–350 MPa).

At PWI the investigations on joining intermetallic titanium alloys based on γ-TiAl (Ti–45Al–2Nb–2Mn + 0.8 vol. % TiB_2) with the use of vacuum heating and adhesion-active brazing filler metals based on titanium-zirconium system were carried out [16]. The pro-

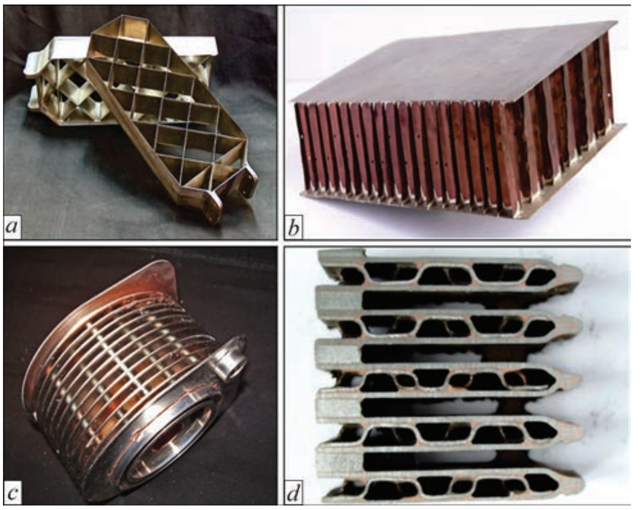

Figure 13. Brazed thin-walled stainless steel structures: rocket rudders (*a*); plate heat exchanger (*b*); automotive oil cooler: exterior (*c*) and vertical section (*d*)

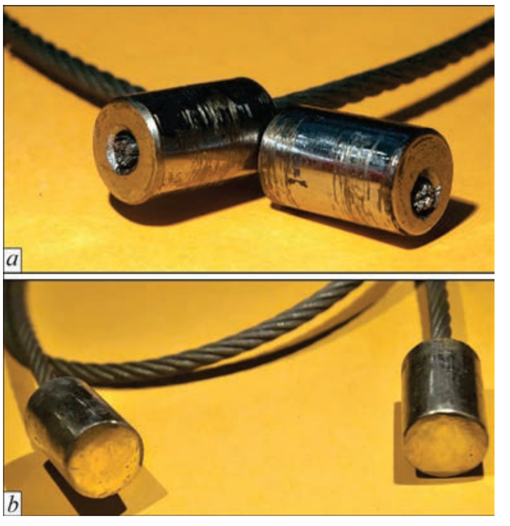

Figure 14. Brazed elements of high-strength austenitic steel and steel 45 before (*a*) and after brazing (*b*)

duced joints successfully passed mechanical strength tests at a room, elevated temperature and showed a good long-term strength at an elevated temperature and a constant stress.

Brazing of stainless steel. Stainless steel structures are often operated under the conditions of aggressive environments and elevated temperature. The technological process of vacuum brazing of stainless steel relating to thin-walled products such as: rudders of rockets, faceted structures [17], automobile heat exchangers (Figure 13) was worked out.

The car heat exchangers of stainless steel (Figure 13, *c*, *d*) are designed to maintain the optimum temperature conditions in cars, tractors, combines and other machines.

In industry, brazed assemblies of steels of different grades are widely used. The brazing process can be performed in a vacuum, in the environment of shielding gas and in the air. An example is a brazed assembly of high-strength austenitic steel and plugs of steel 45 (Figure 14), characterized by a uniform strength and used in a laboratory bench to test structures of rolling stock (rail cars) on rail transport.

A special attention should be paid to the experiments on brazing in outer space: in the conditions of zero-gravity and a significant temperature gradient, which affect the process of brazed joints formation and differ significantly from the earth's conditions. Only the first steps were made in this direction, and to study the physical and metallurgical features of the formation of brazed joints in more details, the further systematic investigations are needed.

Conclusions

In this paper some aspects of practical application of investigations results and created scientific and technological developments in the field of brazing of dissimilar materials are briefly covered such as: aluminium, copper, steel, high-temperature nickel, titanium alloys and advanced materials of the new generation based on Ni_3A1 and γ-TiAl intermetalics. A particular attention should be paid to the considerable volume of experimental investigations while producing brazed joints, designed for operation in severe conditions of high temperature and continuously applied stresses. The examples of the application of brazed joints of dissimilar materials, differing in physicochemical properties and requiring a complex approach during the selection (development) of chemical composition of a brazing filler metal and the technological process of brazing, are shown. The practical solutions mentioned in the work are of great importance to many industries and extend the scope of brazed structures applications.

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ENGINEERING CENTER OF ELECTRON BEAM WELDING OF E.O. PATON ELECTRIC WELDING INSTITUTE

The Department 57 of «Physical Processes, Machinery and Equipment for Electron Beam and Laser Welding» of the E.O. Paton Electric Welding Institute of the NAS of Ukraine and the Engineering Center of Electron Beam Welding for many decades have been specialized in the development of electron beam welding (EBW) technologies for many advanced structural alloys, as well as in the development of equipment for EBW and related processes for aerospace industry, power and chemical engineering, instrument manufacture and medicine.

Main directions of activity:

● development of technology and processing methods of EBW of materials and products with a thickness of welding edges from 0.5 to 250 mm;

● study of physical processes in welding pool during joining different metals and alloys of up to 250 mm thick;

● development of repair technologies for aircraft engine components and gas turbines;

● development of additive technologies for manufacture of products of a set shape by using the methods of layer-by-layer filler electron beam surfacing in vacuum with the use of powder materials (EBM — Electron Beam Melting) and wire (DM — Direct Manufacturing), manufactured in Ukraine;

● development and production of equipment for implementation of additive technologies in industry;

● improvement of welding guns and power sources for EBW;

● development of software for control of EBW installations;

● development, manufacture, putting into operation, warranty and post-warranty maintenance of electron beam equipment in accordance with the customer specifications and designated purpose of products on the territory of Ukraine, Europe, America and Asia;

● using of the own production facilities for manufacturing experimental batches of parts and assemblies for which the use of EBW is the optimal solution.

In recent years, a new generation of electron beam installations developed by the E.O. Paton Electric Welding Institute on the base of a model-oriented control has been mastered at twenty enterprises of aerospace and power industries, as well as at mechanical engineering enterprises in the USA, China, South Korea and India.

All the installations developed and delivered by the Department can be divided into several types according to the volume of a welding chamber: «small», «medium», «large» and «superlarge». At the same time, a characteristic feature of the installations, developed for EBW of large-sized parts is intrachamber mobile electron beam gun, which has from 3 to 5 axes and positioning accuracy of not worse than 0.08 mm.

General appearance of production area

Small-sized electron beam installation

This, of course, allows maximizing the capacity factor of internal volume of the vacuum chamber.

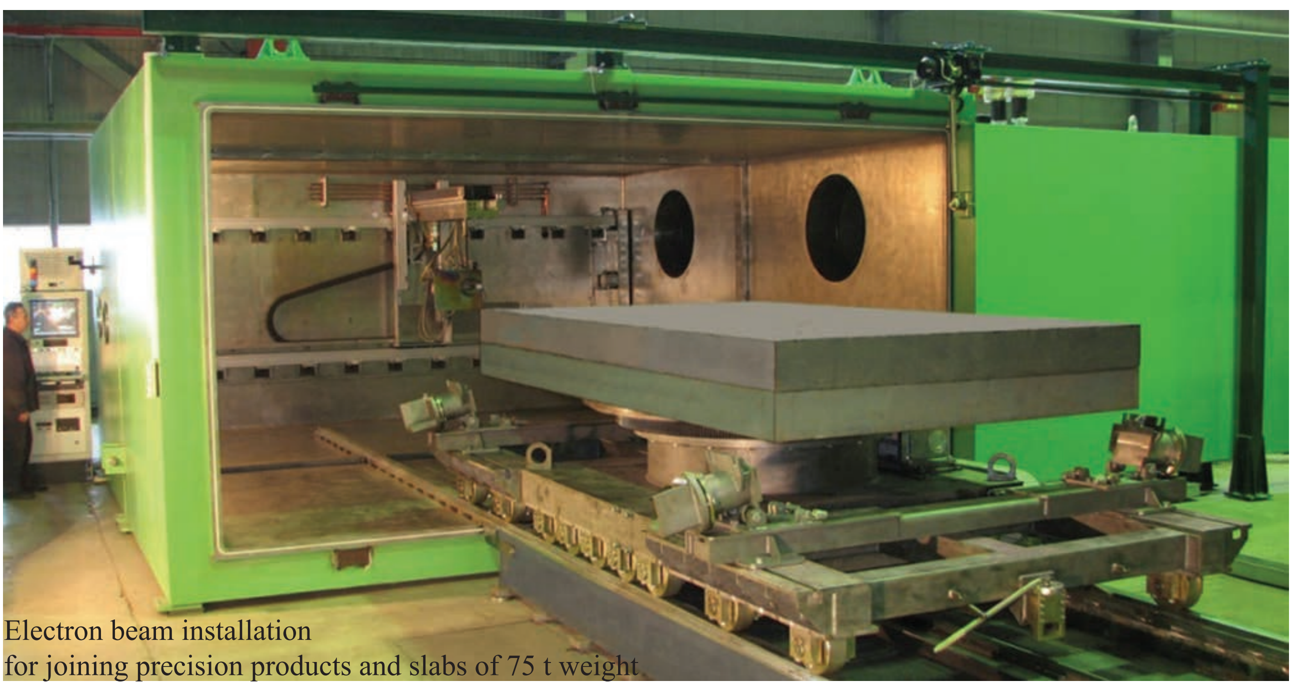
The presence of the 2000 m^2 production area, equipped with a gantry crane with a lifting capacity of 5/30 tons allows performing assembly and adjustment of installations for EBW with a volume of vacuum chambers of up to 100 m^3. If dimensions or mass of the vacuum chamber are beyond the admissible limit for transportation, then it is divided into sections with corresponding connecting flanges. The use of a box-like structure of walls and doors instead of a conventional T-shape strucutre provides a two times higher moment of inertia for the same thickness and, as a result, lower bending of the wall during pumping of the chamber. This, in turn, increases the accuracy of movement of the welding gun.

To control electron beam installations, distributed computer systems were developed and successfully used, for communication of whose elements industrial interface buses are used. For real-time monitoring and tracking of a joint, in the installations secondary emission RASTR electron systems are successfully used. The power complexes of electron beam installations have high-voltage power sources and welding guns of up to 120 kW at an accelerated voltage of 60–120 kV.

In addition to the typical nomenclature of installations for specific tasks of the Customer, namely, dimensions and shape of components to be welded, type and location of welded joints in the component, PWI designs and manufactures many variations of dimenisons of welding chambers, configurations of vacuum system, mechanism for moving electron beam gun and parts to be welded. Moreover, besides the equipment itself, the technology of welding structures is developed. It means that the Customer purchases the equipment together with the technology for EBW of specific parts.

By 2020, more than 150 sets of electron beam equipment have already been developed and delivered to different countries of the world. Our customers and partners are: Airbus Industry (France), Boeing (USA), British Aerospace (United Kingdom), Hitachi Works (Japan), MHI (Japan), GKN (USA), Halla Industrial Co. (South Korea), BIAM (China), The Harbin Institute of Technology (China), Doosan Heavy Industries & Constructions Co. (South Korea), Harbin Boiler Plant (China), SC SPKG «Zorya–Mashproekt», Lutsk Repair Plant «Motor», SE «Ukroboronprom», JSC «Motor Sich», PJSC «Poltava Machine-Building Plant», SE «Makarov Production Association Yuzhny Machine-Building Plant», SE Plant «Generator», etc.

Using the scientific potential of scientists of the National Academy of Sciences of Ukraine, the E.O. Paton Electric Welding Institute of the NAS of Ukraine is constantly improving the equipment and electron beam technologies in accordance with actual orders of industry.



Electron beam installation
for joining precision products and slabs of 75 t weight

RESEARCH AND PRODUCTION CENTER «TITAN» OF E.O. PATON ELECTRIC WELDING INSTITUTE

НВЦ ТИТАН
ІЕЗ ім. Є.О. Патона

State Company «Research and Production Center «Titan» of E.O. Paton Electric Welding Institute of the NAS of Ukraine» was established in 1996, in keeping with the decision of academician Borys E. Paton, PWI Director, for research and production development of technologies and equipment in the field of electron beam melting of metals and alloys and their further introduction in the Ukrainian enterprises, as well as for intensification of research and experimental design work in the field of titanium metallurgy under self-financing conditions.

In the production facilities of SC «RPC «Titan» six electron beam installations are in operation, including: three electron beam installations, each of the annual capacity of 500 t; specialized electron beam installation of 1500 t annual capacity; electron beam installation for surface flashing of ingots of both round and rectangular cross-section; laboratory electron beam installation for development of new alloys, based on iron, nickel, titanium and other metals, as well as optimization of their production technologies.

The installations are fitted with axial electron beam guns Paton-300 of 300 kW nominal power, which have differential pumping that allows conducting the melting process in a stable uninterrupted mode.

In order to produce titanium alloy ingots, the following can be used as the initial charge: titanium sponge (briquetted, loose, unbroken blocks), titanium scrap, and alloying components in the form of master alloys.

SC «RPC «Titan» has introduced the technology of electron beam melting of high-quality ingots of titanium alloys, which contain inclusions of low and high density, of a guaranteed composition.

In order to reduce metal losses, SC «RPC «Titan», instead of machining, uses the technology of flashing the side surface of ingots of both the round and rectangular cross-sections. Application of the technology of electron beam melting of the ingot side surface allows removing the surface defects without machining the ingot surface that increases the metal yield up to 15 %, depending on ingot weight.

Each ingot is subjected to visual control and ultrasonic testing.

Electron beam installation UE5812

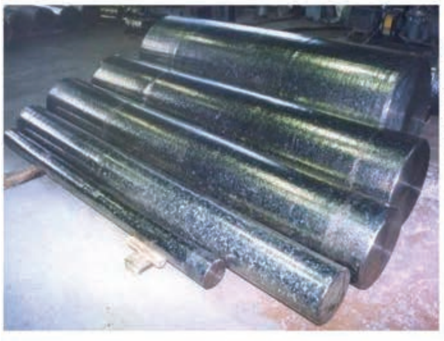
All-purpose electron beam installation UE5810

Electron beam installation UE121

Electron beam guns Paton-300

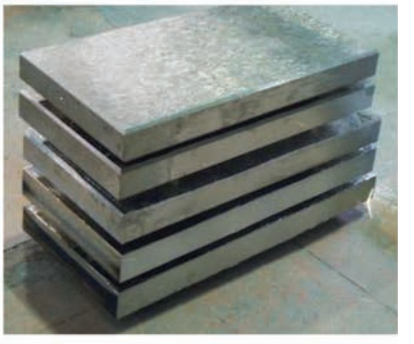
Remelting sponge titanium briquettes into 400 mm diameter ingot of Grade 2

Producing 165×950×2500 mm slab-ingot of PT-3V titanium alloy



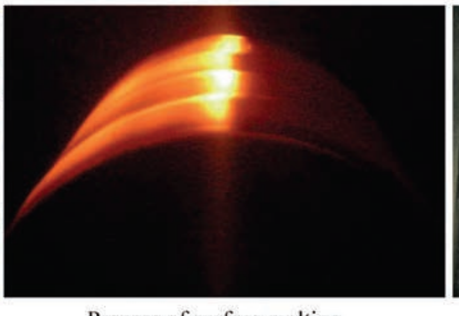
Titanium ingots of 100–600 mm diameter

Titanium ingot of 1100 mm diameter

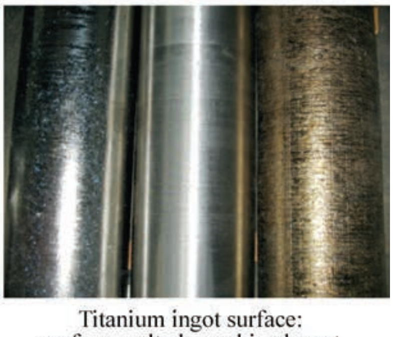


Titanium slab-ingots of 165×950×1500 mm dimensions

Electron beam installation UE185 for melting the ingot surface



Process of surface melting of titanium ingot of 1100 mm diameter



Titanium ingot surface: surface-melted; machined; cast

Product range of SC «RPC «Titan»

Range	Alloy grades
165×950×4000 mm; 150×530×4000 mm; diameter 80, 110, 150, 195, 300, 400, 500, 600, 830, 1100 mm, up to 4000 mm length	VT1-0, VT1-00, VT3-1, VT5, VT6, VT8, VT14, VT20, VT22, PT3V, PT7M, PT1M, 3M, ET3, Grade 1, Grade 2, Grade 5

Chemical composition of the ingots meets the requirements of national and foreign standards (DSTU, ASTM, AMS, etc.) Other alloy grades can be produced by agreement with the Customer.

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INTERNATIONAL CENTER FOR ELECTRON BEAM TECHNOLOGIES OF E.O. PATON ELECTRIC WELDING INSTITUTE

Technology of electron beam evaporation (atomization) and further physical vapour deposition in vacuum (EB-PVD) for producing thick films and massive condensates with specified structure and properties began to be developed at PWI under the leadership of Borys O. Movchan at the start of 1960s. Created during 1975–1991 at PWI, EB-PVD technologies and equipment (15 industrial multichamber units) were introduced in many enterprises of the Ministries of Aviation, Shipbuilding and Gas Industries for deposition of heat- and corrosion-resistant and thermal barrier coatings with an outer ceramic layer on gas turbine blades for various applications.

State Self-supporting Company «International Center for Electron Beam Technologies of the E.O.Paton Electric Welding Institute of the NAS of Ukraine» (ICEBT) founded in 1994, continues systematic research for creation of new materials and protective coatings, which are produced by application of EB-PVD technologies. Scientific fundamentals of EB-PVD technologies of producing amorphous, nanocrystalline, dispersion-strengthened, microlaminate, porous and gradient materials and coatings; specific technologies and new examples of EB-PVD equipment, which gained international recognition, are protected by numerous patents (USA, Europe, China), in particular joint patents with customers.

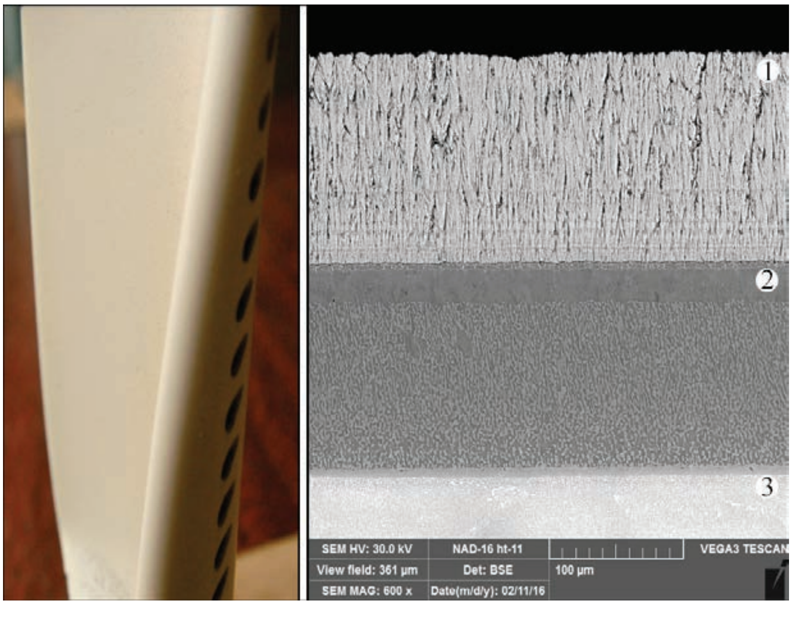
Developed at ICEBT technologies for deposition of gradient protective coatings provide a higher level of repeatability of the composition, structure and fatigue life, compared to coatings which are produced by the traditional multistage technology. For instance, the graded thermal barrier coatings of NiCoCrAlY(AlCr)/YSZ type for protection of gas turbine blades (see Figure), with ceramic layer thickness of approximately 160 μm have a low level of heat conductivity (approximately 1.2 W/(m.K), and their thermal cyclic fatigue life is 2–3 times higher than that of the traditional thermal barrier coatings.

Technology of deposition of multilayer damping/erosion-resistant nanostructured coating for protection of parts from titanium- and aluminium-based alloys was developed.

The main ICEBT customers for fulfillment of research contracts are foreign companies and research centers of the USA (General Electric, Pratt&Whitney, Honeywell, Pennsylvania State University), Canada, Japan and India.

Active cooperation was established with the enterprises and organizations of the People's Republic of China. Here, both the equipment and advanced technologies are proposed to all the customers. Over the recent years, 4 licenses for the right of industrial use of patents for deposition of thermal barrier coatings were sold to PRC, together with 6 electron beam units, and training and upgrading of the qualifications of Chinese engineers and technicians was performed.

It should be noted that the first EB-PVD unit, designed and manufactured at ICEBT at the end of 1990s, was supplied to Beijing (Beijing Institute of Aeronautics and Astronautics). All together, ICEBT designed, manufactured and supplied to Chinese customers 13 EB-PVD units, which are operating both at research organizations (Beijing Institute of Aeronautics and Astronautics,



Appearance and microstructure of gradient thermal barrier NiCoCrAlY(AlCr)/ZrO_2–8 % Y_2O_3 coating on a blade of gas turbine engine:

1 — outer ceramic layer of ZrO_2–8 % Y_2O_3;

2 — heat-resistant NiCoCrAlY layer with AlCr gradient zone;

3 — high-temperature alloy

EB-PVD units developed and manufactured at ICEBT, are operating in PRC, USA, Canada and India

Beijing Aeronautical Manufacturing Technology Research Institute, Beijing Institute of Aeronautical Materials), and at industrial enterprises in the cities of Xi'an, Guizhou, Shenyang, Chengdu.

In 2019 the license for the use of the technology of high-rate EB-PVD of corrosion-resistant alloys for deposition of protective coatings was purchased by SC SPKG «Zorya−Mashproekt» (Mykolaiv), and joint research is continued on improvement of composite coatings of metal/ceramic type, which are used in this enterprise.

ICEBT is developing variants of hybrid EB-PVD technologies, which combine the physical and chemical processes of deposition of inorganic materials in vacuum. EB-PVD hybrid nanotechnology and the respective equipment are a real basis for further progress of science and technology and economy, in order to produce protective coatings in different sectors of modern mechanical engineering.

Over the recent years, a new direction began to be developed at ICEBT, alongside the above-mentioned traditional areas of technology, namely EB-PVD technology of deposition of nanostructured coatings («islet» and continuous) on powders and granules of various materials.

All together, over the 25 years of ICEBT existence 17 EB-PVD units for various applications have been manufactured and supplied, and 6 licenses for the right of industrial use of patents for protective coating deposition have been sold to foreign customers (PRC, USA, Canada, and India). The new generation units proposed to customers, are fitted with modern Western vacuum components, improved electron beam projectors with cathode life extended up to 100 h, stabilized high-voltage power source that corresponds to the European standard CEI 61000-3-4, and modern industrial computers for the control system.

http://www.paton-icebt.kiev.ua/

A potential ad actum

PATON TURBINE TECHNOLOGIES

Paton Turbine Technologies LLC (PTT), being the assignee of «Pratt & Whitney-Paton» (PWP) marked its twenty-fifth anniversary in 2018.

At the start of 1990s, United Technologies Corporation (UTC), one of USA largest financial-industrial groups, addressed B.E.Paton with the initiative to create a scientific-research center for further advance of scientific developments in the field of EB-PVD technology, started earlier at PWI under the leadership of such well-known scientists as B.E. Paton, B.O. Movchan, I.S. Malashenko, V.O. Timashov, and oth.

The main specialization of the established Joint Venture consisted in improvement and adaptation of the production of thermal barrier coatings (TBC) for the world market (Figure 1). TBC application is one of the ways to improve the service life of components of the turbine hot section and more efficient operation of gas-turbine units (GTU). In combination with internal cooling, TBCs provide a lowering of temperature on the base alloy surface, and, hence, allow raising the turbine inlet gas temperature, thus increasing its efficiency, and also promote protection from external erosion impact and prevent metal degradation under the impact of the external gas environment, thermal and residual stresses. International experience of the last decades, particularly in the aviation industry, confirmed the rationality of application of electron beam physical vapour deposition (EB-PVD) in vacuum, in order to produce thermal barrier ceramic coatings with a columnar rather dense structure of formed crystallites. This is exactly the structural feature that ensures a fatigue life margin of the ceramic coatings at varying thermal cyclic loading in operation (Figure 2).

The process of formation of electron beam thermal barrier coatings on a heat-resistant bond coat was mastered at PWI. Further successful development of the technology led to formation of a regular thermally grown oxide layer (TGO) on the boundary with the metal interlayer during ceramics deposition. It was developed and certified due to the efforts of Ukrainian and USA specialists of Pratt & Whitney-Paton.

At the start of its activity, Ukrainian-USA Joint Venture Pratt & Whitney-Paton entered into production and intellectual cooperation with Pratt & Whitney Company, which together with British Rolls-Royce Company and USA General Electric belong to the «big three» of aircraft manufacturers.

Just one year after the Company was established, manufacture of high-tech electron beam equipment for the USA partners began in Kiev, which was stage-by-stage placed and upgraded in the USA and Singapore.

In 1998, EB-PVD ceramic coating was first deposited on blades of the first stage of PW 4000 aircraft engine, some series of which were designed for Airbus A300-600, Airbus A310-300, Boeing 747-400, at RC Pratt & Whitney-Paton in Kiev. Now the Company achievements include formation of coatings on the components of CF-6 aircraft engines, produced by GE Aviation for Airbus A300/310/330, Boeing747, Boeing 767; CFM-56 produced by CFM International (joint

Figure 1. General view of the Company production facilities: *a* — coating shop, *b* — shop for repair of gas turbine engine components

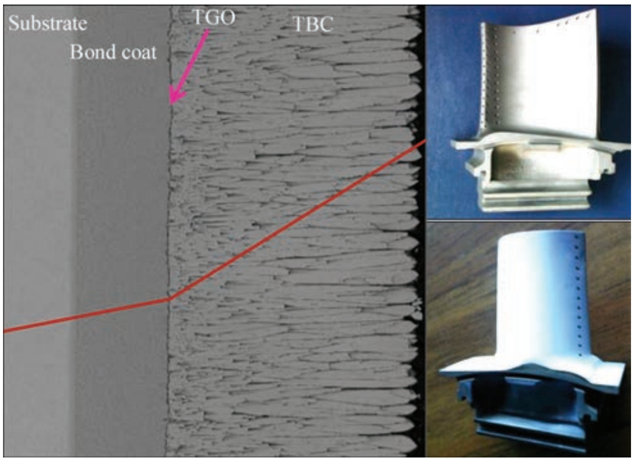


Figure 2. Thermal barrier coating and appearance of blades with metal and ceramic coatings

venture of Safran Company and USA General Electric) for Airbus A319/320/321 and Boeing 737. Over the last thirteen years the coatings were successfully deposited on more than 280 thou blades and 18 thou rings of additional power units APU 131-9 Honeywell.

Another important page in the history of PTT development is long-term cooperation with Siemens Industrial Turbomachinery AB Division (Swedish Branch) on deposition of thermal barrier coatings on blades of SGT 800 turbine (nominal power of 47/53 MW). By the level of pollutant emissions into the atmosphere at 50 to 100 % load it was noted by experts as the best among the medium-power generating turbines. The active cooperation phase started in the first quarter of 2006, and during this time EB-PVD metal and ceramic coatings were deposited on more than 60 thou blades of SGT 800 turbines of four different generations. Here, the production efficiency was higher than 99.8 %. And now Paton Turbine Technologies, as a leader in thermal barrier coating sector, is developing and testing original coatings for a new generation of single-crystal blades of 1-st stage of the modified SGT 800 turbine, which will be marketed this year.

At present thermal barrier coatings on various types of base alloys and metal layers are produced at PTT by EB-PVD method. Today TBC are deposited on a wide range of blades and vanes, made from high-temperature nickel alloys of equiaxial, directional crystallization and single-crystal alloys of different generations, for instance, MAR M-247, CMSX-4, PWA-1484, Rene-5, CM-186LC, IN-939, ZhS-32, ZhS-36, etc. Used as bond coats are metal layers of MeCrAlY (+Hf, Si) systems, formed by the methods of EB-PVD, high-velocity flame spraying in an oxygen-containing atmosphere (HVOF), plasma spraying in low vacuum (LPPS); aluminide NiAl and platinum-aluminide (Pt, Ni)Al coatings (Figure 3).

In addition, the majority of them are now produced in Kiev. Development strategy of Paton Turbine Technologies reflects targeted diversification for creation of a production complex, which helps producing various types of coatings or their systems. These coatings are used for the components of hot section of turbines in gas turbine engines. The composition and method to produce metal coatings are selected, depending on their functional features, and base alloy type of the component to be coated. It is important to note that testing coated samples for thermal cyclic fatigue showed that some systems of thermal barrier coatings provide the fatigue life of more than 3700 thermal cycles at maximum temperature of 1100 °C.

Our Company experienced periods of ups and downs, and 2014 was a quite serious challenge, when USA partners withdrew from RC «Pratt & Whitney-Paton» and its assignee — Paton Turbine Technologies Company was organized on its base. Owing to the support of PWI and Institute directorship personally, as well as maximum interest of the new PTT partner in the development of Paton Turbine Technologies, the Company received an impetus for further growth, and reaching new horizons, both in commercial production and in mastering advanced technologies.

At present, owing to the knowledge, creative approach and proper organization of production, the EB-PVD units manufactured at Paton Turbine Technologies/Pratt & Whitney-Paton, continue operating successfully to fulfill the aviation industry orders in the USA and Singapore. International cooperation with Siemens Industrial Turbomachinery AB, Honeywell, Meyer Tool, Inc., and Kawasaki Heavy Industries, Ltd. Companies continues to develop. For international positioning of the Company, it is important to note that PTT is included into the data base of Siemens Industrial Turbomachinery AB as a qualified and approved supplier (SIT Approval Supplier Data Base (ASD) SQ).

The high level of the Company was confirmed by ISO 9001, AS 9100, ISO 14001, FAA, and NADCAP certificates, which are revalidated on a regular basis.

The Company purposefully maintains a high level of production organization, which was established by USA partners. In 2009 Pratt & Whitney-Paton reached the Silver Level in ACE system (Achievement of Competitive Excellence) within the United Technologies Corporation, and Paton Turbine Technologies continues maintaining the operation of all the key elements of the system up to now.

Stable and confident development of Paton Turbine Technologies is also reflected in the Company personnel policy. Over the last three years, 67 workplaces

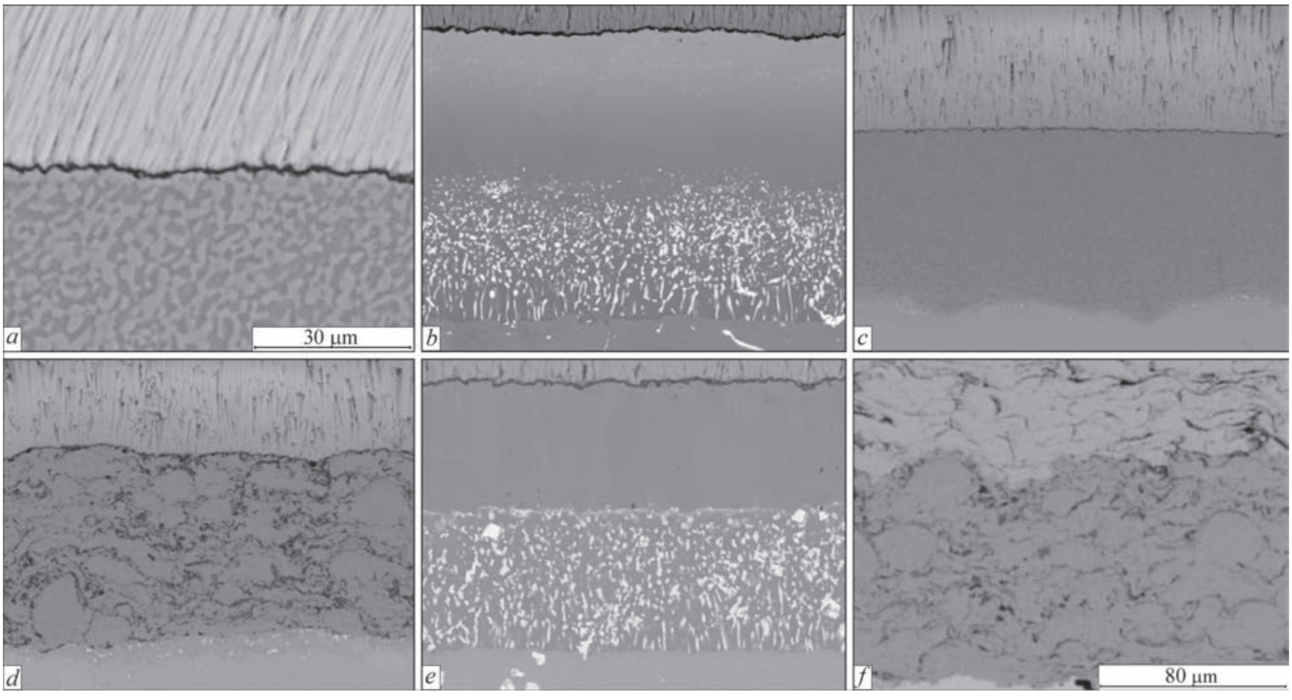


Figure 3. Different types of bond coats in thermal barrier systems of coatings produced by EB-PVD: (*a*–*e*) and APS: *a* — EB-PVD; *b* — PtAl; *c* — LPPS; *e*, *f* — HVOF; *e* — NiAl

were additionally created (more than 50 % Company growth, compared to 2014). Here, the number of employees with higher education is more than 2/3 of the Company total staff. A significant rejuvenation of the workforce took place.

During development of EB-PVD coating technologies more than 25 different patents were granted over the twenty-five year history. Here, the patented technologies have been and are currently used in actual production. Paton Turbine Technologies/Pratt & Whitney-Paton developed and registered Company Specification both for metal PWP-400 (18 coating types) and for ceramic coatings — PWP-100.

Together with development of «traditional» areas, the scientific and technical units of Paton Turbine Technologies continue investigations in the field of creating fundamentally new types of protective coatings. To the Company's credit are the new types of advanced MeCrAlY coatings, produced by EB-PVD of the coating alloy with addition of alloying elements. Development of ceramic coatings was continued in the application of new materials, based on a mixture of REM oxides. Such materials have the heat conductivity below that of standard ZrO_2-Y_2O_3 ceramics. Application of EB-PVD of such materials allows producing new generation ceramic coatings, which is exactly realized in PTT.

Focusing on the realities of the market of protective coatings for aircraft engines and industrial gas turbines, alongside EB-PVD of MeCrAlY type coatings, the Company began actively developing and using other methods of protective coating deposition. Platinum-aluminide coatings are widely used as a metal bond coat for GTE first stage blades. These coatings are a separate group of platinum-modified aluminide coatings.

Our Company achievements already include thermal barrier coatings deposited on platinum-aluminide coatings of the Customer for the aircraft engine blades, the fatigue life of which exceeded 1000 thermal cycles. Starting from 2018, a platinum electroplating section was set up and has been operating in the Company. It is fitted with competitive Ukrainian equipment. This year we will finish setting up the laboratory and will commission the production section for gas-phase aluminizing, based on available equipment, upgraded in the Netherlands. This will widen PTT production line as to producing aluminide and platinum-aluminide coatings for foreign and Ukrainian partners. It is important that the result of long-term study of the properties and features of forming platinum-aluminides was the developed at Paton Turbine Technologies optimum composition of the coating, which, as the bond coat, ensures formation of reliable thermal barrier systems with sufficient service life, both on equiaxial crystallization alloys, and on single-crystal alloys of different generations (Figure 4).

As alternative and less expensive methods of coating deposition, Paton Turbine Technologies production complex developed and introduced coatings produced by the methods of HVOF and APS (air plasma spray). Processes of thermal spraying are widely

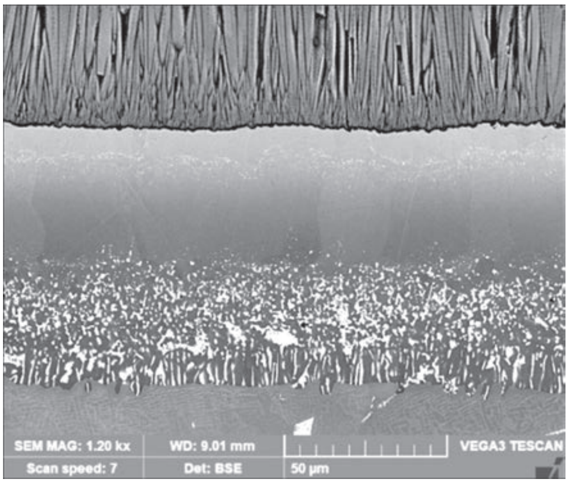


Figure 4. Structure of platinum-aluminide coatings formed as a bond coat in the system of thermal barrier coating deposited by EB-PVD

applied for deposition of thermal barrier coatings and bond coats for components of engines and land gas turbines. These deposition technologies are popular from the viewpoint of cost, as well as due to the simplicity and repeatability of the process. HVOF process allows forming rather dense coatings of NiCoCrAlY (+HF, Si) system (with less than 2 vol.% porosity), which due to the features of the lamellar structure and alloying complex demonstrate good resistance to high-temperature oxidation and thermal stability, that allows applying them both as independent protective coatings, and as bond coats for thermal barrier coatings, deposited by APS method (Figure 5). In terms of cost, APS-coatings, which are produced in air or shielding atmosphere, are more profitable in commercial use for components of industrial and power turbines, and provide a fatigue life of more than 1000 thermal cycles. TBCs deposited by this method have low heat conductivity.

APS unit was also used for development of a method of producing abradable ceramic coatings of ReSZ system: they are used in the turbine flow section to minimize the radial gap above the blades, in order to reduce the gas losses and increase the turbine effectiveness. These coatings have sufficient erosion and corrosion resistance, heat resistance, proper porosity (>20 %), etc. In the case of the blade interaction with the casing, the coating protects the blade and the casing from serious damage, improves the turbine efficiency and reduces fuel consumption.

It should be noted that Paton Turbine Technologies performs new developments, aimed at further progress of modern technologies, their adaptation in production not only for the aerospace industry, but also for other sectors, in particular, transport engineering, metallurgy, and chemical industry.

At present, producing wear-resistant coatings is in great demand with different customers in the market. Using the HVOF unit, PTT started really applying the method of high-velocity thermal spraying of wear-resistant, corrosion-resistant and antifriction coatings of the type of WC, Cr, C_2, Mo, PG-10N-01, etc., for rotation products and on flat abradable surfaces (Figure 6).

In 2006 Pratt & Whitney-Paton began developing a new direction, namely repair of gas turbine engine components. Now, a separate shop is functioning in the production complex, which performs comprehensive repair of both serial batches of aviation products, and of individual components. Advanced methods of blade repair include welding and brazing to extend the operating life of blades of turbines and gas-turbine units as a whole. At reconditioning products after service most attention is given to high-temperature brazing in vacuum. Diffusion brazing of high-temperature nickel alloys as to its technological capabilities is equivalent to argon-arc welding and provides the required physico-mechanical properties of the joints.

The entire repair cycle includes the operations on product cleaning, removal of used coatings, machining and heat treatment, operations of cladding,

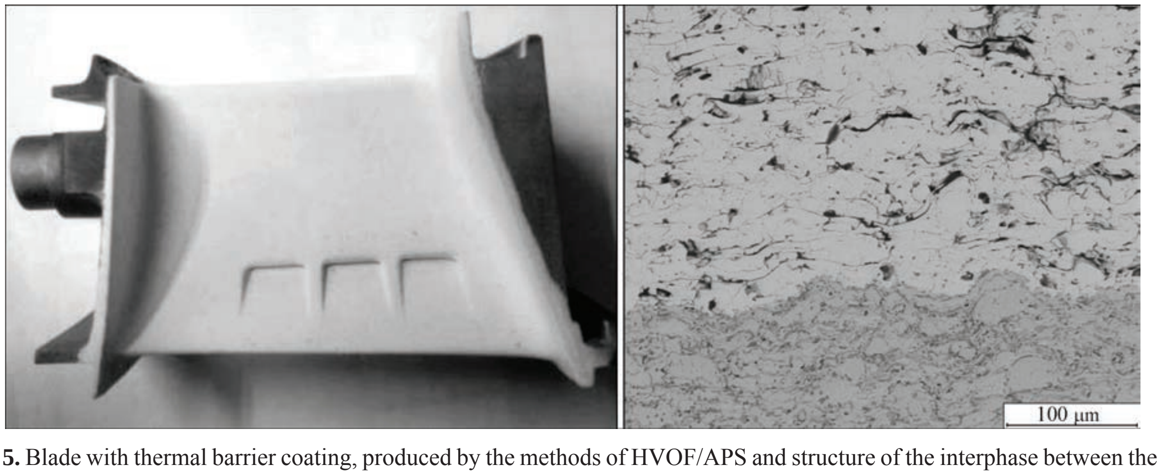


Figure 5. Blade with thermal barrier coating, produced by the methods of HVOF/APS and structure of the interphase between the metal (HVOF) and ceramic (APS) layers of TBC system

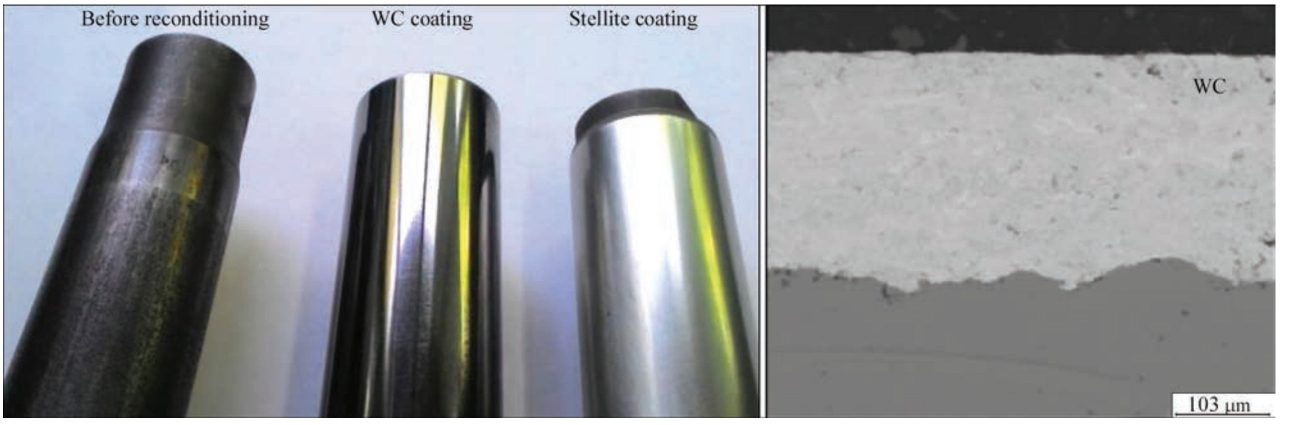


Figure 6. General view of the shaft after operation and reconditioning with deposition of wear-resistant coatings of WC and Stellite type, and microstructure of WC coating

Figure 7. General view of the nozzle blade after operation with burn-out on the leading edge (*a*) and after reconditioning for further operation (*b*)

brazing, restoration of the dimensions and profile, coating deposition, hardening, etc. The main attention is given to combining higher strength and low-temperature ductility of the repaired areas, and ensuring heat resistance of base alloys of the reconditioned products. Paton Turbine Technologies

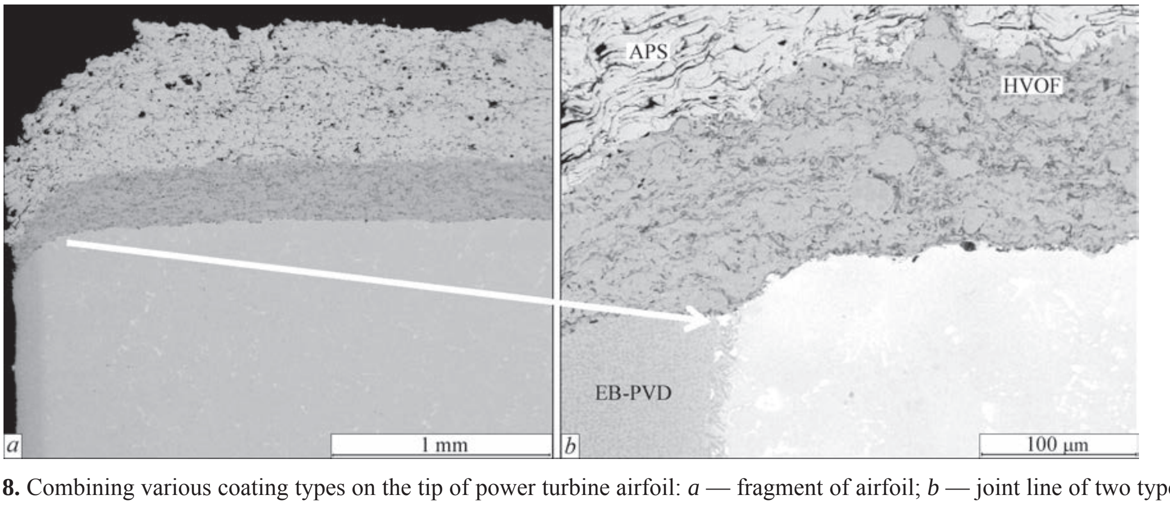


Figure 8. Combining various coating types on the tip of power turbine airfoil: *a* — fragment of airfoil; *b* — joint line of two types of protective and thermal barrier coatings

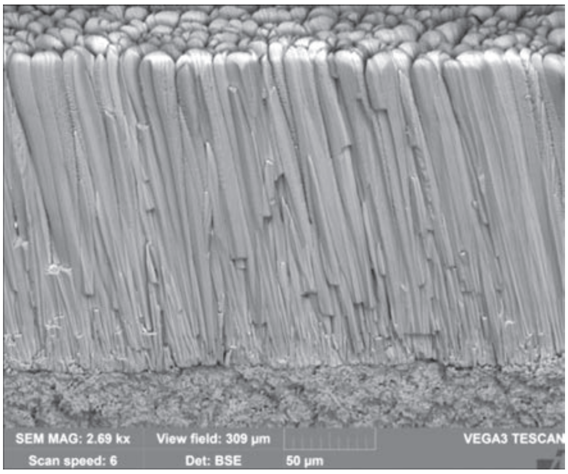


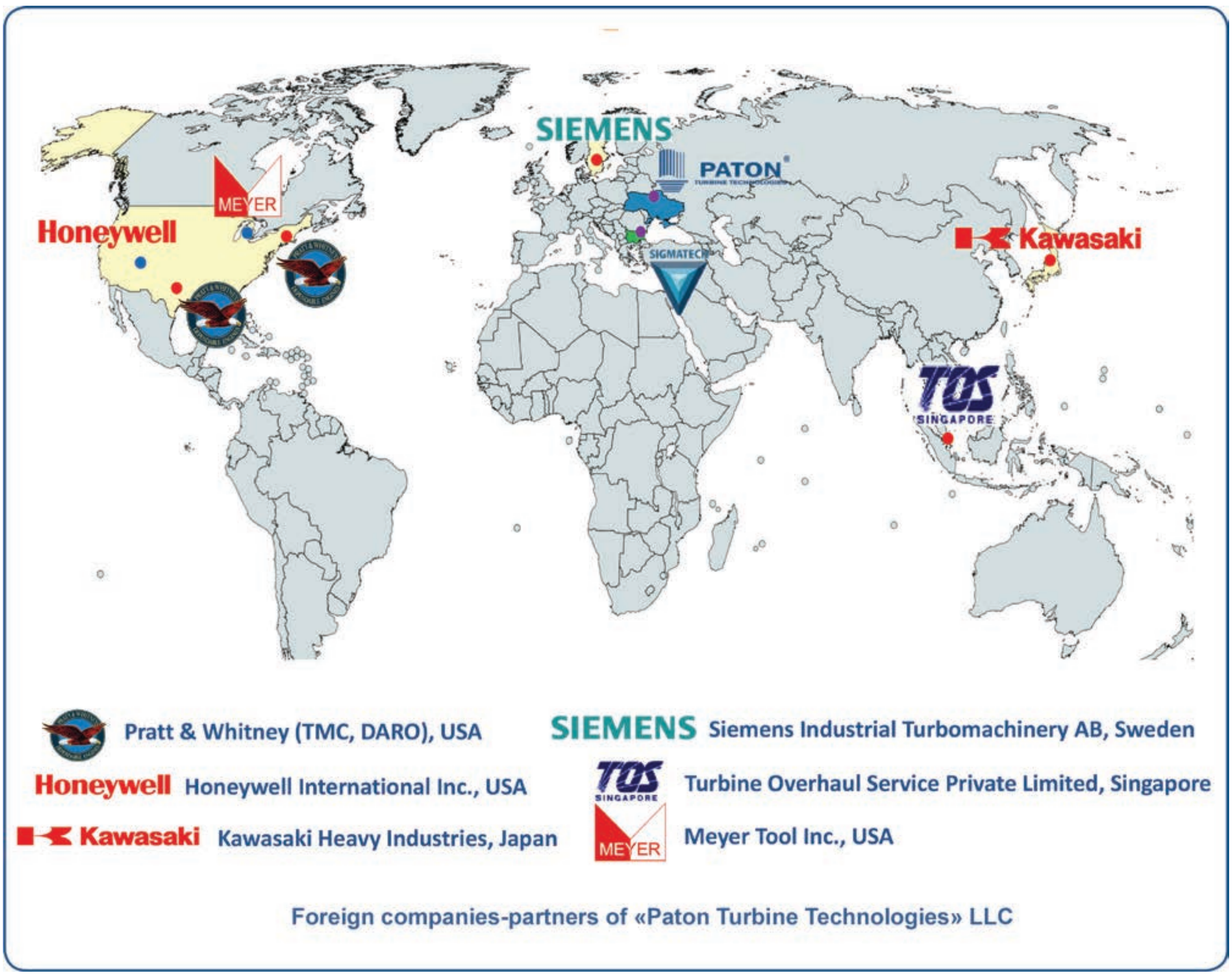
Figure 9. Classical columnar structure of thermal barrier coating produced by EB-PVD

performs reconditioning of components of RD-33, AL-31, D 30KP, D 36, TVZ-117, DSU GTDE-117 aircraft engines and industrial gas-turbine units, GTK 10-4, GTK 10I, MS 3002, DR-59, etc.

In order to repair burns-through, mechanical and corrosion-erosion damage, crack «healing» and restoration of the dimensions of blades, segments and other gas turbine components, multilayer preforms or composite filler metals are now used, which ensure optimization of the processes of formation of sound strong welds with sufficiently high physico-mechanical characteristics. The new mastered cladding and brazing technologies allow repairing the casting and service extended developed defects (cracks, burns-through, fusion, degradation, etc.) of the components of GTE hot section (Figure 7).

Having the knowledge, skills, experience and production capacity, PTT now conducts the entire complex of reconditioning of gas turbine engine components after service, and performs the full cycle of repair and deposition of various types of coatings, required for this product type (Figures 8, 9). This method includes expert assessment, fault detection, a set of thermomechanical operations, and testing. Thus, customer requirements are satisfied in «all inclusive» format, i.e. the entire reconditioning process is in one place.

Paton Turbine Technologies LLC is an example of successful adaptation and introduction of the achievements of fundamental science into production, development of modern technologies, and moving forward, while taking into account the urgent needs of the society.



Continuous way to improvement lasting more than 60 years

PILOT PLANT OF WELDING EQUIPMENT OF E.O. PATON ELECTRIC WELDING INSTITUTE

On January 1, 1959, the Pilot Plant of Welding Equipment of E.O. Paton Electric Welding Institute was founded, whose main task was mastering the technology of production and manufacture of experimental models of the advanced welding equipment, which was developed at the EDTB and other structural units of PWI. From that moment, the continuous movement of the Plant towards recognized leadership in the field of production of modern welding equipment and materials began.

For more than 60 years of its history, the team of the Pilot Plant has made hundreds of thousands of units of welding equipment, in which the advanced developments of domestic scientists in the field of welding, surfacing and metal cutting technologies were embodied. The equipment produced by the Plant has been often used in as wide as possible range of conditions in different parts of the world: from deepwater welding for the facilities of oil and gas exploration to the first ever open space welding operations; from repair of ships in hot equatorial or humid tropical climates to welding pipelines in the Extreme North. All this helped to gain valuable experience, which provided a solid foundation for the Plant to take the leading positions at this market — today PPWE is the only plant in Ukraine capable of producing welding equipment with welding currents from 150 A for domestic consumers to 10000 A for giants of Ukrainian and world industry.

Today the products range of the Plant has more than 60 items, of which more than 30 models are inverter welding equipment, more than 15 models are conventional equipment and more than 10 grades of welding electrodes.

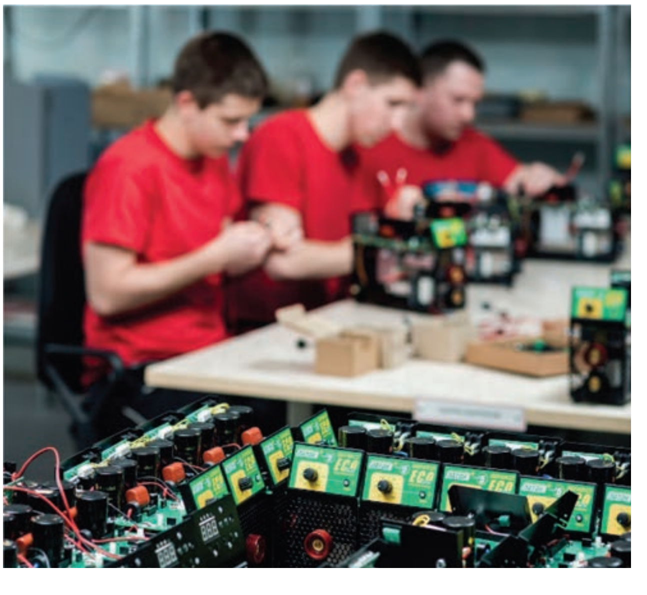
The inverter welding machines PATON™ occupy the largest part in the total volume of production of the PPWE equipment. They are commercially produced in the following categories:

- inverter rectifiers (welding currents from 150 to 500 A, operating from the power supply networks of 220 V/380 V);
- units for semi-automatic welding (welding currents from 160 to 500 A, operating from the power supply networks of 220 V/380 V);
- units for argon-arc welding (welding currents from 5 to 315 A, operating from the power supply networks of 220 V/380 V);
- multifunctional digital inverters (welding currents from 250 to 350 A, operating from the power supply networks of 220 V/380 V);
- units for air-plasma cutting.

For the most complete compliance with the market requirements, most units from the range of inverter equipment are produced in several series: units of general-purpose and professional series, which allow welding under particularly rigid working conditions.

Also, at the demand of ever-increasing customer requests, the Plant is actively working on expanding its range and modifying its existing models. Over the last year, the designing of the inverter rectifiers and semiautomatic units with a rated welding current of up to 500 A and the argon-arc inverter for welding with both direct and alternating current up to 315 A was completed and all were put into production. Already in 2020, it was already decided to replace the models of units with the currents of 315 and 250 A powered by a three-phase network with more powerful models of 350 and 270 A, respectively. The development of a new perspective model of unit for plasma-cutting with a rated current of up to 100 A is at the final stage.

In the production of units the most updated and high-quality components from the world's leading



manufacturers like INFINEON, VISHAY, KENDEIL and NXP are used and the units of professional series are equipped with accessories from a well-known German manufacturer Abicor Binzel. All this allows the Plant to produce «extra-class» products, the highest quality of which is reflected in the extended warranty period of up to 5 years.

The welding electrodes PATON™ also occupy a large part in the overall structure of the products manufactured by the Plant. Today, 12 grades of welding electrodes with both classic and improved composition are manufactured. And taking into account the variety of diameters and packaging variants, the number of assortment items in this category of products exceeds 50. The production uses modern technologies and rigid input quality control of raw materials, and a professional team of specialists constantly monitors the development of production of welding materials in order to timely introduce innovations.

The welding electrodes PATON™ meet all necessary requirements to products of this type and are regularly certified by relevant Ukrainian and international certification centers. In 2018, these products were certified to meet the EU standards requirements and regular deliveries of electrodes to the markets of European countries began and in 2019 a certificate was received that the manufacturing process was in compliance with the high standards of ISO 9001:2015.

This area of work of the PPWE is actively developing — today the process of organizing a new area for the production of welding electrodes PATON™ in Kyiv is at the final stage. After completion of commissioning works, several production lines of a new area will be able to provide the production of up to 600 t of welding electrodes per month. In addition to the production departments, the new complex of manufacturing welding electrodes in Kyiv includes an analytical laboratory, a mechanical testing laboratory and a department for welding and technological testing. The set of laboratory equipment allows carrying out the complex input control of all raw materials, controlling the technological process of electrode production and performing acceptance tests of each batch of finished products. In the near future, it is planned to launch a line of experimental molds for the development of new grades of electrodes with improved welding and technological properties.

It is important to note that a considerable part of PATON™ products is already exported and namely this vector has been identified as one of the main ones in the Plant's development strategy. Over the last year, a number of countries at which markets the deliveries of the products were organized, has increased to 30. In particular, in 2019, deliveries of welding units and electrodes were organized to India, Sri Lanka, Egypt, Turkey and Burkina Faso. Negotiations about the start of deliveries in 14 more countries, including such European countries as Spain, Croatia, Macedonia and Bulgaria; Middle Eastern countries — Saudi Arabia, Pakistan, Israel, as well as Asian countries — Philippines and Singapore are underway at different stages. In view of such high interest to the products of the Plant, it can be stated that a high reliability, wide functionality and many unique technical characteristics allow the PATON™ welding equipment to compete successfully with the products of the leading world manufacturers at the markets around the world.

Namely the choice of the PATON™ products by both domestic and foreign welders makes the staff of PWI to be proud of its work and inspires them for new achievements!

ENGINEERING CENTER OF PRESSURE WELDING OF E.O. PATON ELECTRIC WELDING INSTITUTE

The Department of Butt Welding of E.O. Paton Electric Welding Institute of the NAS of Ukraine and the State Enterprise «Engineering Center of Pressure Welding NTC «E.O. Paton Electric Welding Institute of the NAS of Ukraine» for many decades have specialized in the development of technologies and equipment for flash butt welding (FBW) of rails of various grades as well as pipes of different diameters and assortments.

The State Enterprise «Engineering Center of Pressure Welding» was found in 1987 for industrial implementation and extensive mastering of the Institute developments.

The main activity of the Center is the production of basic models of machines, repair and modernization of the equipment for FBW of rails in the field conditions, as well as training personnel to work in the mentioned areas.

The technologies and equipment developed at the PWI and manufactured at the Engineering Center, have quickly found a widespread applicaiton on the railways of Ukraine and in the world. In the conditions of high global competition, this technology and equipment became interesting to the leading world railway companies from Austria, France, Japan, USA, China and other countries.

In the last decade, in many countries an intense reconstruction of railways and rail track is observed. In these works high-strength rails with the hardness of up to *HB* 400 are used. According to the technological conditions, it is required to obtain the strength of welded joints practically equal to base metal of the rail steel and high ductile properties. Such indices could not be obtained using traditional technologies. The PWI conducts systematic studies of weldability of new high-strength rails of different world manufacturers (Austria, China, USA, Ukraine, Japan) in order to develop welding technologies which provide the required mechanical properties. This raises the need for a significant change in the control systems of welding machines and designs of their individual units. In particular, it was found that for high-quality welding of high-strength rails it is necessary to significantly change the technology of contact heating and the design of a mechanical part of the machines, that provide an increase in the clamping forces by 1.5–2.0 times.

It is known that during the operation of a continuous welded rail, the fixed rails are subjected to stresses related to changes in temperature, i.e. under the influence of the environment. Their impact leads to defor-

Geography of deliveries of machines for welding rails

Machine K900

Machine K960

Machine K1045

mation of the track, violations of the set dimensions of the track and in critical situations to accidents.

As a result of the carried out developments, in leading foreign countries a new generation of welding machines and the technology, known as «pulsating flashing», were created and patented. The first machines of a type K900 and K920 were designed at the PWI and tested on the US railways together with «Norfolk Southern Corporation» and other US customers.

Over the past five years, a new generation of machines of a type K1045 and K960 for FBW have been developed at the PWI with the tension of rails of up to 1000 m length.

For today, the Center has a successful experience in welding rail sections with the use of the developed equipment and technology for metro in the USA, China, Singapore and other countries of the world. Moreover, joining is performed directly in the tunnels.

CHINA-UKRAINE E.O. PATON INSTITUTE OF WELDING

The China-Ukraine E.O. Paton Institute of Welding (CUPIW), found in 2011, is a platform for international scientific and technical cooperation in the PRC for implementation of the achievements and experience of the E.O. Paton Electric Welding Institute, other institutes of the NAS of Ukraine and enterprises in China and Ukraine, as well as for cooperation with Chinese partners on joint developments and organization of high-tech industries in the fields of shipbuilding, marine engineering, aviation, railway transport, production and transportation of oil and gas, power engineering, energy saving. This form of cooperation has no analogues in terms of the scale of already realised projects.

Currently, the China-Ukraine E.O. Paton Institute of Welding is a legal entity, acting under the Chinese law, which is a part of the Guangdong Academy of Sciences. All international cooperation activities within the framework of the CUPIW are funded by the Chinese side. The sources of funding from the Chinese side are applied projects of the central government of the PRC, the government of Guangdong province, the city of Guangzhou or state-owned industrial corporations, as well as joint-stock and private companies in the PRC. The financial support of the projects is carried out on a competitive basis, that is, in order to receive funding in China for each project, in the competition state institutions and enterprises of the PRC, as well as leading foreign companies in the field of welding and related processes, participate.

Within the framework of CUPIW, in the fulfillment of international projects a number of institutes of the NAS of Ukraine, leading technical universities of Ukraine, as well as large industrial enterprises and research and production innovation companies are involved. In particular, except of the E.O. Paton Electric Welding Institute of the NAS of Ukraine, the following academic institutes are involved in such cooperation: Frantsevich Institute for Problems of Materials Science, PTIMA. In the international projects within the framework of CUPIW, the following universities take the most active part: NTUU «Igor Sikorsky Kyiv Polytechnic Institute», Admiral Makarov National University of Shipbuilding. Also, for realization of production tasks, in particular for the production of critical units of high-tech equipment, CUPIW involves a number of industrial and scientific-production enterprises from different regions of Ukraine, in particular, from Kyiv, Dnipro, Kharkiv, Zhytomyr, Mykolaiv, Sumy and other cities.

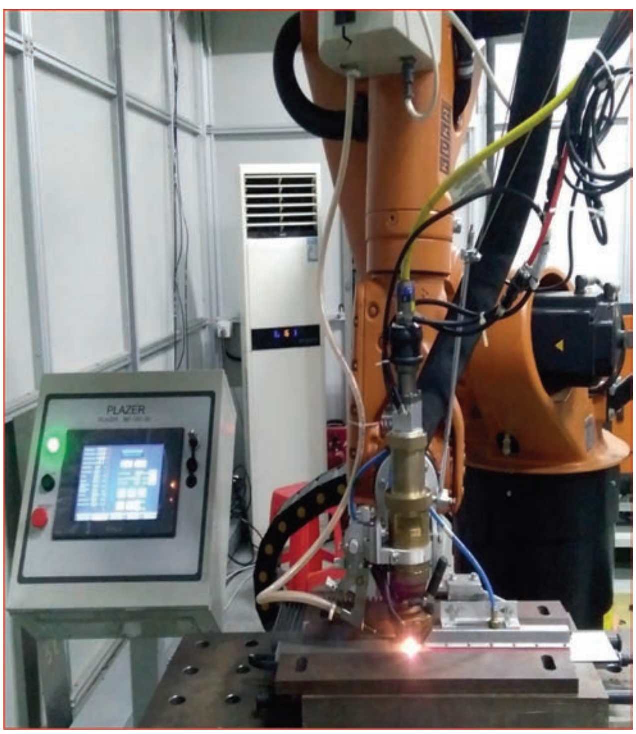
Throughout the period of its activity, CUPIW in cooperation with the E.O. Paton Electric Welding Institute of the NAS of Ukraine (PWI) has realized several dozen major projects on modifying and implementation of the advanced developments of the PWI into industry. Among them the following could be mentioned:

- development of universal equipment and technology for flash butt welding of structural steels, aluminum and titanium alloys and their industrial application;
- creation of new generation of equipment for flash butt welding of pipes (114−320 mm);
- development of technology and equipment for orbital welding of power equipment pipelines over the active flux layer (A-TIG);

Signing of official documents on establishment and organisation of activity of the China-Ukraine E.O. Paton Institute of Welding (2012–2013). From left — to right: Mr. Zhu Xiaodan, governor of Guangdong province; Academician B.E. Paton, President of the National Academy of Sciences of Ukraine, honoured Chairman of the CUPIW Board; Mr. Cao Jianlin, Vice-Minister of Science and Technology of PRC, honoured Chairman of the CUPIW Board; Academician I.V.Krivtsun, Deputy Director of the PWI, Chairman of the CUPIW Board

Equipment for narrow gap welding of long-length structures of titanium alloys of 20–120 mm thickness and up to 4 m length and welded product of titanium Ti4–Al–2V alloy of 120 mm thickness under the controlling magnetic field

● creation of technology and universal equipment for high-speed plasma as well as hybrid and combined (tandem) plasma-arc (Plasma-MIG) welding, its integration into a robotic complex;

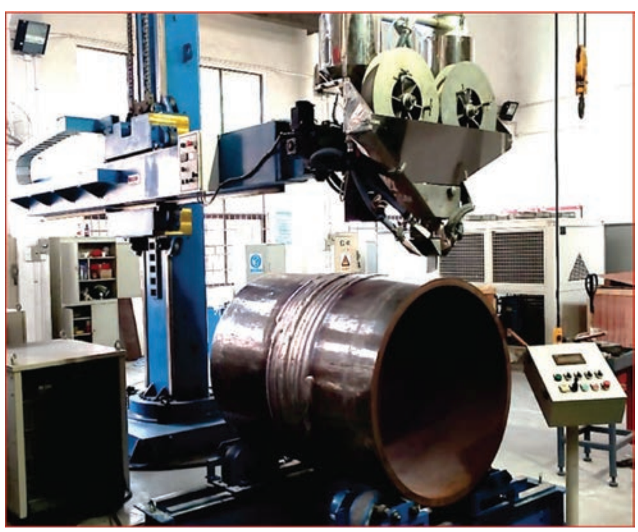


Robotic technological complex for high-speed hybrid laser-plasma welding

● creation of technology and new generation of equipment for microplasma and hybrid laser-microplasma pulsed current welding in different polar modes;

● creation of technology and equipment for automated arc welding of long-length structures (up to 4 m) of high-strength titanium alloys of large thickness (up to 120 mm) into a narrow gap in a controlled magnetic field;

● development of equipment and technology of electrodynamic treatment of welds of aluminum alloys for shipbuilding in order to effectively reduce and regulate welding deformations;



Electroslag surfacing of large-sized structures of the power equipment with the use of two strips

● development of technology and equipment for producing spherical shape powders from high-strength complexly alloyed titanium alloys using plasma processes;

● application of advanced electron beam technologies in turbine construction during producing billets of gas turbine blades by the method of hot isostatic pressing of powders (filling, degassing, compaction, sealing (welding) of containers with metal powder for further hot isostatic pressing);

● development of technology of diffusion welding of heat-resistant alloys based on Ni_3Al with controlled stress-strain state;

● improvement of equipment for high-frequency welding of living tissues, its adaptation to working conditions in the Chinese medical institutions;

● development of new titanium-steel plasma welding technologies and their testing in the production of bimetallic pipes for oil and gas transportation;

● creation of specialized equipment and technology of high-performance (up to 45 kg/h) electroslag surfacing with two strips of large-sized products of power equipment;

● creation of technology and equipment for high-performance plasma cutting of metals of increased thicknesses (up to 120−150 mm) on reverse polarity, its integration with systems of numerical program control in relation to the production of large-sized structures;

● development of new generation equipment for supersonic plasma spraying of heat-resistant, thermal-barrier, wear-resistant, corrosion-resistant and special coatings.

The China-Ukraine Welding Institute has a high authority in the PRC. The Government of the PRC highly appreciates the results of CUPIW's activities and the contribution of PWI to these activities. In particular, Ukrainian colleagues of PWI, who participated in the implementation of joint projects, were awarded more than ten governmental awards by the PRC, including the highest awards by the central government of the PRC.

Installation for electron beam welding for application in granular metallurgy

Awarding I.V. Krivtsun, Deputy Director of the PWI, 2019 (left) and V.M. Korzhyk, Chief of the PWI Department, Director of the CUPIW on the Ukrainian side (2014) the highest awards of the PRC Government — medals «For outstanding achievements in the international scientific and technical and economic cooperation»

SUBSCRIPTION

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