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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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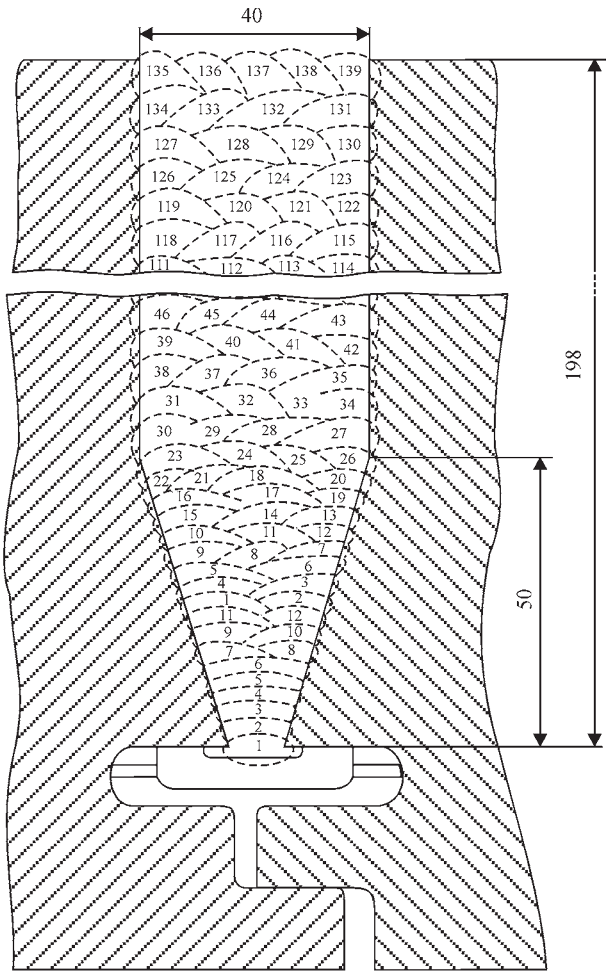

Figure 1. Scheme of automatic welding of a rotor model

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

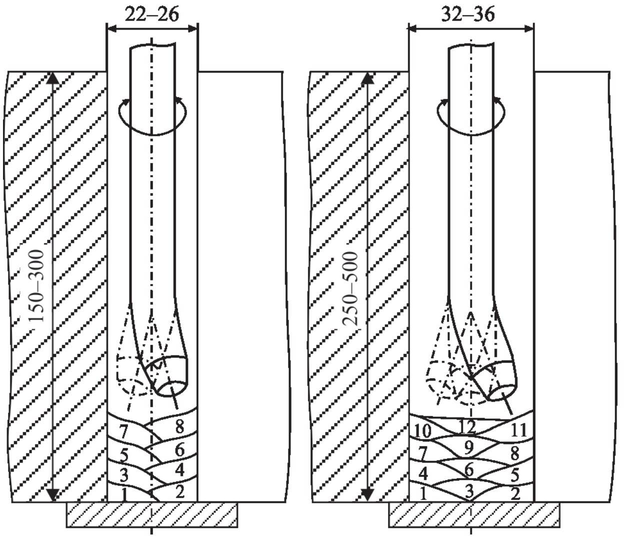

Figure 2. Examples of bead arrangement by the optimized technology of narrow-gap welding

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 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).

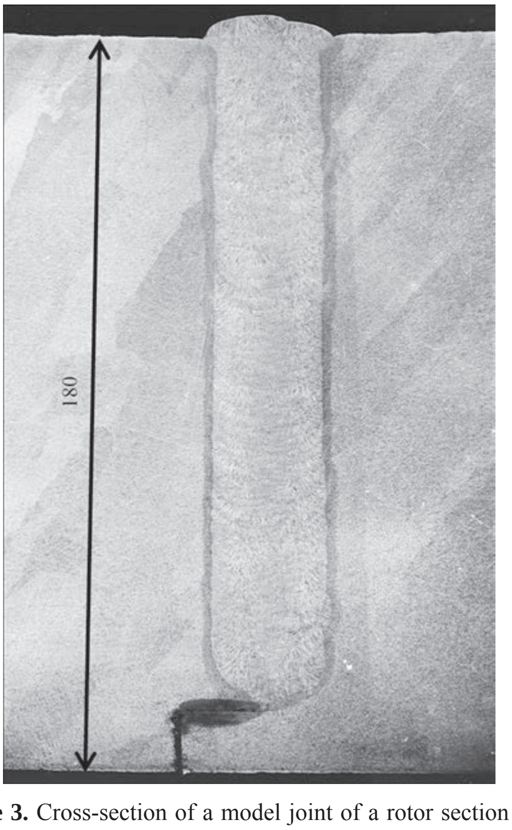

Figure 3. Cross-section of a model joint of a rotor section from 25Kh2NMFA steel of K-1000 steam turbine of 1000 MW power

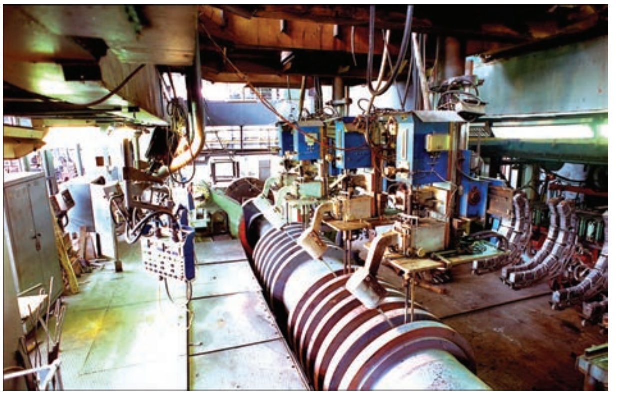

Figure 4. Welding of a rotor in a specialized stand at JSC «Turboatom»

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.

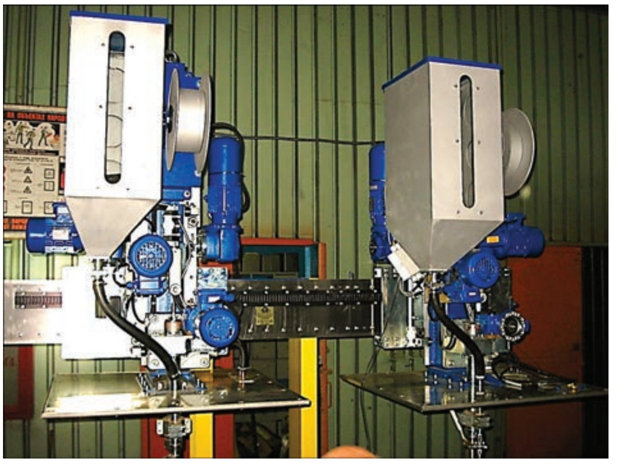

Figure 5. General view of dual automatic welding machines A1569M for narrow-gap submerged-arc welding of cylindrical products

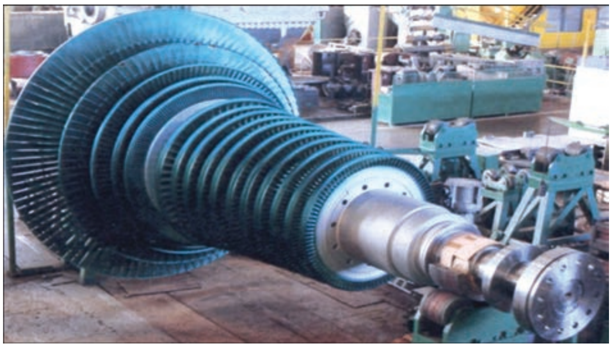

Figure 6. Composite rotor with mounted blades of medium-pressure cylinder of a new generation steam turbine of 325 MW power (JSC «Turboatom»)

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).

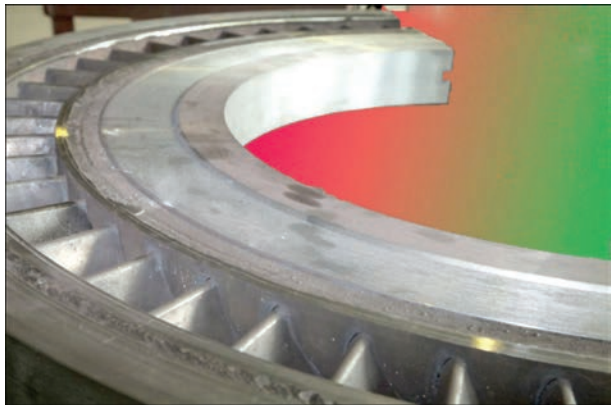

Figure 7. Element of welded high-temperature diaphragm of a steam turbine (JSC «Turboatom»)

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

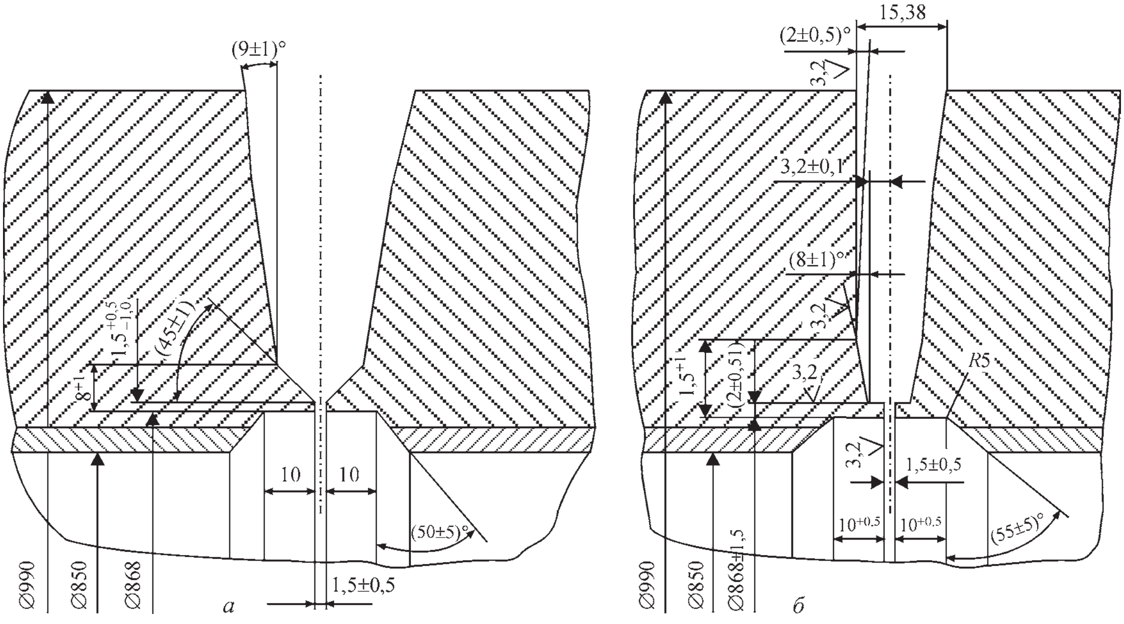

Figure 8. Edge preparation: *a* — standard; *b* — proposed

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

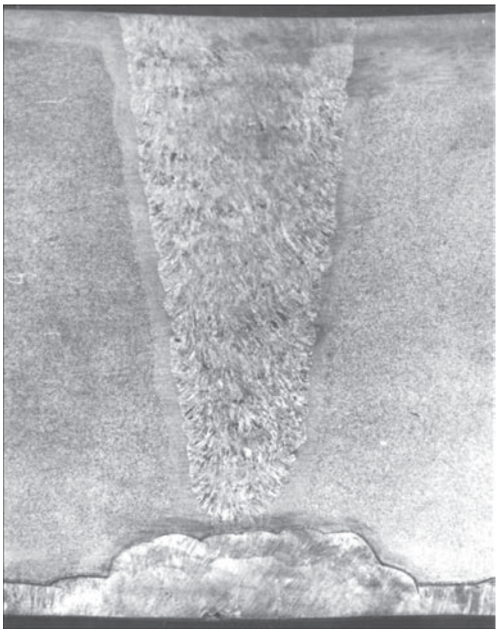

Figure 9. Cross-section of a certification joint from 10GN2MFA steel

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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