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DEVELOPMENT OF NEW STRUCTURAL ELEMENTS OF GAS COOLERS IN ATOMIC AND THERMAL POWER PLANTS WITH IMPROVED CORROSION-MECHANIC RESISTANCE

Introduction. *In power engineering, there is a need to improve the performance of gas coolers in contact with explosive atmospheres to ensure reliable operation of turbogenerators.*

Problem Statement. *Important problems that require constant improvement of equipment are local corrosion, hydrogenation, etc., in particular, of pipe joints with pipe boards, which is characterized by the emergence and development of cracks under the influence of simultaneous mechanical stress and corrosive environment. The cracks promote depressurization that leads to emergency stop of turbogenerator.*

Purpose. *To develop a new design of sealing joints of heat exchange tubes and tube sheet with increased corrosion and corrosion-mechanical resistance.*

Materials and methods. *The samples made of steel 09G2S, M2 copper, steel 09G2S with a clad layer of copper M2, cupronickel MNZhMC 30-1-1, brass L68 have been tested. The vacuum extraction of hydrogen under elevated temperature, corrosion-fatigue, metallographic, and X-ray spectral test methods have been used.*

Results. *A new structural element of gas coolers with improved characteristics has been designed. It is based on a welded-rolled joint of a copper tube with a copper-clad tube sheet, which does not cause deformation of the structure and crack formation. The studies of the effect of different modes of flaring of such joints on their resis-*

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tance to failure under the simultaneous action of cyclic loads and the environment have shown that as the degree of flaring of copper tubes 19 1.5 and 19 1 mm increases, the crack generation period and durability combined with connections grows ~1.5 times.

Conclusions. *The new structural element reduces the probability of corrosion and mechanical destruction of parts of heat exchange equipment and helps to extend the period of its trouble-free operation.*

Keywords: gas cooler, pipe board, copper tubes, crevice corrosion, hydrogenation, and turbogenerator.

To improve safety of power engineering systems, in particular, cooling systems of turbogenerators, power plants are reconstructed and upgraded with the extension of power units, continuous improvement of existing structural elements or creation of new ones with improved technical and economic parameters. High reliability of the equipment shall be ensured at the stage of its design and installation and kept throughout a long period by proper operation, timely and thorough repair. However, even if these requirements are met, the probability of turbogenerator failures and accidents is not excluded [1—7].

To date, gas coolers for turbogenerators of nuclear and thermal power plants in Ukraine have mainly spent their estimated service life. Gas coolers of turbogenerators are in contact with flammable and explosive environments, in particular hydrogen [1—3, 6, 7]. To ensure the Impermeability in the intertube space of the heat exchangers, the heat exchange tubes are connected to the tube sheets by electric arc welding [4] and flared [5]. The pipe boards of gas coolers are made mainly of 09Mn2Si steel, while heat exchange tubes are made of cupronickel in which corrosion-fatigue damage may develop in the vicinity of pipe boards on the gas phase side. The process of crack formation is stochastic and unpredictable, so it may cause depressurization of heat transfer tubes in the tube sheets, the overflow of media, which is inadmissible for the operation of turbogenerators. In addition, it is problematic to obtain high-quality welded joints of a pipe board with cupronickel tubes by electric arc welding. In this regard, it is especially important to identify the main factors influencing the corrosion and mechanical destruction of sealing joints and to develop recommendations for ensuring the reliability and durability of heat exchange equipment.

Therefore, the purpose of this research is to develop a new welded-rolled connection of the heat exchange tube and the tube sheet of gas coolers, which has an increased resistance to corrosion and mechanical destruction, by choosing a more durable (to hydrogenation) material of heat transfer tubes and cladding tube sheets.

STUDYING THE CORROSION RESISTANCE OF MATERIALS AND THEIR HYDROGENATION

Hydrogen is used as a refrigerant with a high heat capacity, heat transfer, and a low density to create an acceptable thermal regime in the turbogenerator. Hydrogen circulates through the intertube cavities of the gas cooler, transfers heat to the cupronickel tubes, and is discharged with water. Heat exchange tubes in the tube sheets of the gas cooler are under-rolled by about 1.5 mm on the side of the intertube cavity, so in these places gaps of 0.01 mm are formed [5, 6]. During the operation of turbogenerators, hydrogen may be humidified, which has a detrimental effect on the insulation of the windings and the mechanical strength of the rotor shells and cause condensation of moisture on the structural elements inside the turbogenerator housing. Moisture causes corrosion of steel in gas coolers. Galvanic couple is formed between the cupronickel tubes and the 09Mn2Si steel tube sheet, so bi-metallic and crevice corrosion may develop. In these couples, the tube surface acts as a cathode on which, as a result of the electrochemical reaction, atomic hydrogen is released. It may diffuse into the material of the tubes and the tube sheet and thereby spoiling them.

Hydrogen absorption by cupronickel МНЖМц 30-1-1, steel 09Mn2Si and other metals of heat

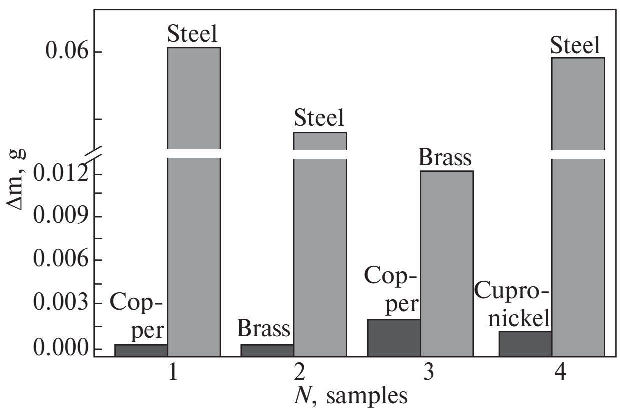


Fig. 1. Mass losses in the case of bi-metallic corrosion of different materials

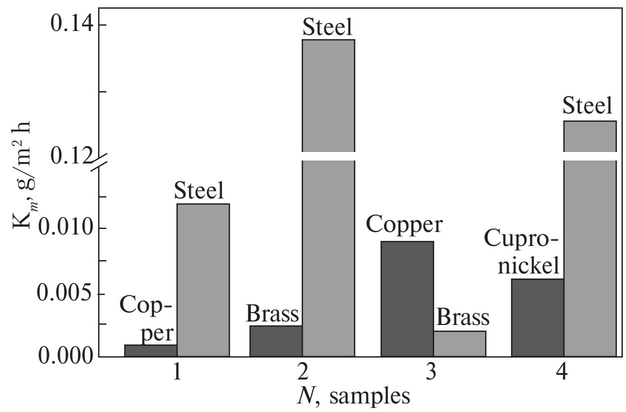


Fig. 2. Contact pair gap corrosion rate

exchange tubes (copper M2 and brass L68) have been studied (Table 1). The hydrogen content in them is determined on polished cylindrical samples (Ø = 9 mm, H = 30 mm) by vacuum extraction at a temperature of 200 °C [2, 7] after their electrolytic hydrogenation in a solution of 0.5 M H_2SO_4 with an admixture of 10 g/l $(NH_2)_2CS$, at a current density of 10 A/dm². It has been found that the concentration of hydrogen in the samples of cupronickel, of which the heat transfer tubes are made, is 17 times higher than in the copper samples and 4.25 times higher than in the brass ones. This may be a precondition for cracking of such heat transfer tubes.

The rates of bi-metallic and crevice corrosion in 3% NaCl solution in the case of 14-day exposure of the following contact pairs: copper-steel, brass-steel, cupronickel-steel, copper-brass have been studied and compared. The bi-metallic corrosion rate is determined by the gravimetric method; the galvanic currents of the contact pairs are set according to [7]. The rate of crevice corrosion of the contact pairs is calculated by the formula

Table 1. **Hydrogen Concentration in Metals**

Material	Hydrogen concentration, ppm
Copper	0.5
Brass	2.0
Cupronickel	8.5
Steel 09G2S	17.5

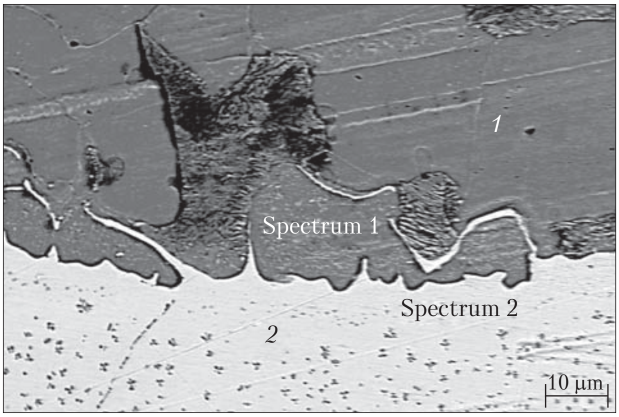
$K_m = m_0 - m/S \cdot \tau$, where m_0 and m are the sample masses before and after the experiment, respectively, g; S is the sample cross section, m²; τ is time of sample exposure in corrosive environment, h.

The studies of corrosion resistance of steel 09Mn2Si in 3% NaCl solution have shown that its corrosion losses are $3.58 \cdot 10^{-2}$ g; those in the contact pairs are 1.6—1.7 times higher. The largest losses have been reported for the steel-copper couple and are equal to $6.02 \cdot 10^{-2}$ g, while for the steel-brass and steel cupronickel couples, they amount to $5.0 \cdot 10^{-2}$ and $5.97 \cdot 10^{-2}$ g, respectively (Fig. 1).

It has been found that after testing for 338 h and replacement of solutions the galvanic currents of the contact pairs do not differ significantly. Thus, copper may be considered an alternative to cupronickel material for the manufacture of heat transfer tubes of gas coolers. However, final recommendations can be made after studies of the resistance of contact pairs to oxygen concentration corrosion.

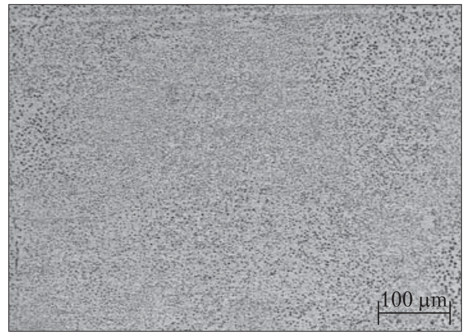
It has been established that in 3% NaCl solution, the crevice corrosion rate of 09G2C steel is the highest in a pair with brass and the lowest in a pair with copper. At the same time, the corrosion rate is the highest in cupronickel samples (about 0.0006 g), and the lowest in brass and copper (about 0.0002 g) (Fig. 2).

The analysis of malfunctions of gas coolers after their long operation has shown that cracks are formed in the vicinity of the gap between the cupronickel heat transfer tubes and the surface of the

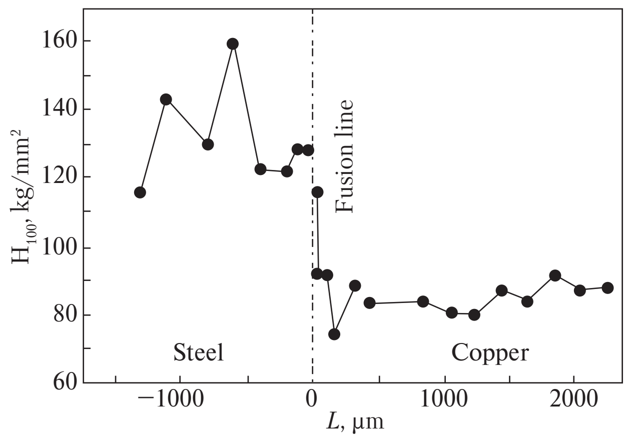


Material		Element	wt., %	ат., %
Steel	Spectrum 1	Si	0.29	0.57
		Mn	0.65	0.66
		Fe	98.75	98.50
		Cu	0.32	0.28
		Total	100	100
Copper	Spectrum 2	Fe	5.01	5.66
		Cu	94.99	94.34
		Total	100	100

Fig. 3. Relief of the transition zone between the steel surface (*1*) and the clad copper layer (*2*) and the results of their local X-ray spectral analysis



a



b

Fig. 4. Microstructure of clad copper layer (*a*) and microhardness of the transition zone between the steel surface and the clad layer (*b*)

holes of the tube sheets. However, neither a decrease in the thickness of the tubes nor losses in their weight has been observed, so we can assume that the cracks on the surface of the cupronickel heat transfer tubes of the gas cooler are caused by their hydrogenation in the cracks and by vibrations.

Therefore, to improve the performance of the structural elements of gas coolers, copper may be recommended as material for heat exchange tubes. In addition, it has been proposed to clad copper tubes of heat exchangers on the liquid phase side, which allows additional fastening of copper tubes to them by welding. This enables the formation of galvanic couple and the prevention of local corrosion.

The main requirement for the clad copper layer is high adhesion to the base metal. Sufficient adhesion of the copper layer to the steel board is ensured by the surfacing technology of *Ukrspetsmash* LLC, which includes pre-machining to form a high relief of the steel surface (Fig. 3, *a*) and the required cooling mode of the board weighing 90 kg with a furnace from 1250 to 350 °C for 24 years [6]. The metallographic analysis of the clad layer has shown that it has no internal defects, in particular pores, cavities or shrink holes, and the metal structure itself is dense and uniform (Fig. 4, *a*). At the interface between the two metals, molten copper evenly filled the microrelief of the steel surface thereby forming a toothed shape of the fusion line. The determined concentration of copper (~ 0.3% wt.) near the fusion line in steel corresponds to its content in α-solid solution (Fig. 4, *b*).

The measurements of the microhardness of the base metal and the deposited layer have shown that at a distance of more than 260 µm from the joint line, the microhardness of copper varies from 82 to

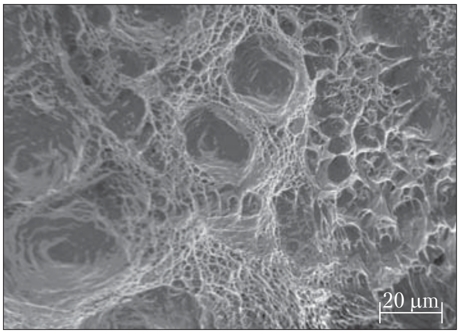


Fig. 5. Microfractogram of a sample of M2 copper layer on 09G2S steel after tensile tests

93 kg/mm^2, and the microhardness of 09Mn2Si steel is 115—160 kg/mm^2 (Fig. 4, *b*). The minimum difference between the microhardness of steel and that of copper is observed near the line of fusion of two metals, which is explained by the morphology of the transition zone. According to the data of micro-X-ray spectral analysis, in the clad layer, at a distance of 150—200 μm from the fusion line, there has been recorded an increased (5% wt.) content of iron, which indicates the presence of α-solid solution grains formed by melt crystallization. These grains increase the microhardness of this zone to 90—110 kg/mm^2 (Fig. 4, *b*).

The strength of the transition zone between the base metal (09Mn2Si steel) and the M2 copper clad layer has been determined with the use of an EU-20 device by means of tensile test with cylindrical specimens that reproduce a contact of the base metal with the clad layer on the side of the end face of the tube sheets and in the place of the flaring of heat transfer tubes. It has been found that the fracture occurs along the copper layer at a distance of ~ 250 μm from the line of fusion with the base metal, at a stress of 310 MPa, in the area with the lowest microhardness (73 kg/mm^2). The macrofracture in the neck of the stretched specimen has a "bawl" structure, which is a sign of the viscous nature of the fracture (Fig. 5). Numerous hollows with a size of 5—40 μm are present at the central area of the fracture, which are the result of the formation, growth, and fusion of micropores as a result of significant plastic deformation of the macro-separation zone in the viscous material. The elongated holes of smaller sizes are observed in the peripheral areas of the fracture formed as a result of metal failure under the action of tangential stresses along the surface of localized plastic deformation by sliding.

The high strength of the connection of the clad copper layer with the base metal of 09Mn2Si steel has been confirmed by the bending test results of the samples with the use of a prism R = 3 mm, at an angle of 150° (GOST 14080). The visual analysis of the most strained areas of the sample has shown that there are neither cracks nor delaminations on their surface, both along and across the clad copper layer.

CORROSION-FATIGUE DESTRUCTION OF THE COMBINED JOINT OF THE HEAT TRANSFER TUBE WITH THE TUBE SHEET OF GAS COOLER

A new structural element based on a M2 copper heat transfer tube that is fixed in a M2 copper-clad tube sheet made of 09Mn2Si steel by welding followed by flaring has been designed (Fig. 6). To improve the quality of the welded joint, at least, 6 mm wide annular groove is made around each hole of the clad tube sheet, since high thermal conductivity and high coefficient of linear expansion of copper cause deformation of the structure.

Corrosion-fatigue tests of samples under conditions of rigid loading at cantilevered bending have been carried out on the upgraded device developed and made at the Institute of Physics and Mechanics for studying fatigue destruction of materials [9] (Fig. 6).

The schematic diagram of the configuration of the facility is shown in Fig. 7. The sample *15* that is fixed through mounting plate *16* to base plate *19* is bent cyclically by moving faceplate *9* located on the axis of fork *8* of connecting rod *6*. The deflection of the sample is set by eccentric mechanism *2* that sets a defined value of displacement of the connecting rod. The deflection is measured by indicator 14 of the clock type with an accuracy of 0.01 mm, which is fixed in a vertical rack at the level of the middle line of grip *10*. Adjusting the speed

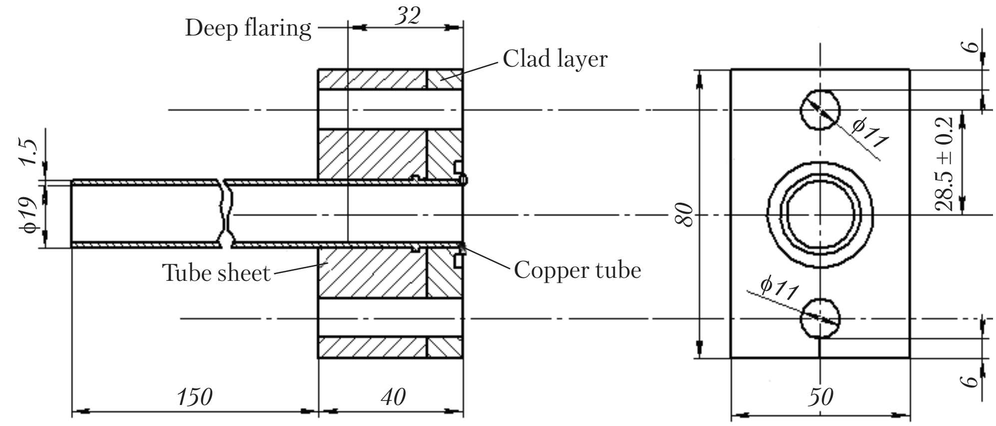


Fig. 6. Welded-rolled connection of a tube sheet with a clad layer and a heat-transfer copper tube

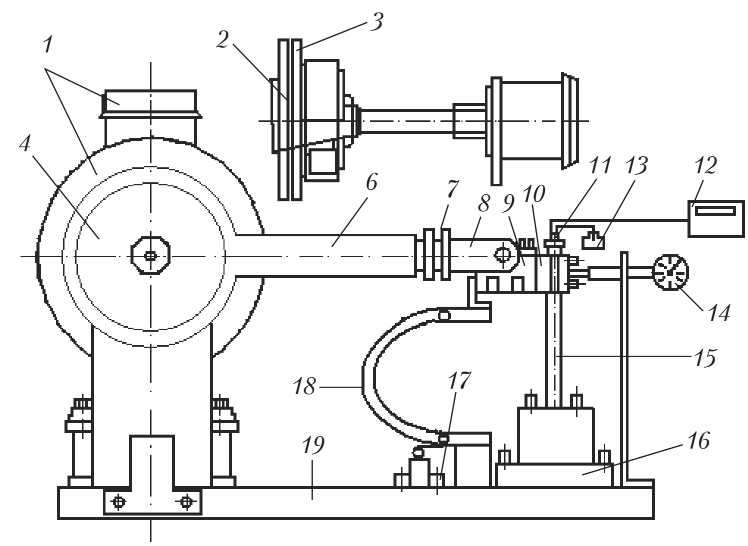


Fig. 7. The facility for corrosion and fatigue tests: *1* — electric motor; *2* — eccentric mechanism; *3* — fixing nut; *4* — disk; *5* — cycle counter; *6* — connecting rod; *7* — length adjuster; *8* — fork; *9* — faceplate; *10* — grip; *11* — electrode; *12* — millivoltmeter МТМ-РЭ-160 mini (potentiometer), *13* — reference electrode; *14* — indicator; *15* — sample; *16* — mounting plate; *17* — end switch; *18* — elastic plate; *19* — plate

of electric motor *1* enables changing the frequency of the cyclic load on the sample from 0 to 50 Hz.

Under conditions of complete destruction of the sample copper tube in the area of its connection with the fragment of the tube sheet, under the action of elastic plate *18,* grip *10* with tube *15* moves up (respectively with the faceplate, the fork, and the connecting rod), with end switch *17* that shuts the motor triggered.

The cavity of the sample tube serves as an electrochemical cell for corrosive medium $2 \cdot 10^{-5}$M KOH solution (pH = 9) (this solution circulates in the tubular cavities of gas coolers to remove heat from hydrogen) (Fig. 6). The cell is tightened by a rubber gasket placed between sample base *15* and mounting plate *16*. In the upper part of the sample there is placed the capillary of silver chloride reference electrode that measures the electrode potential. The data are recorded with by a two-channel electronic recorder MTM-RE-160-mini with the use of potential — time of cyclic deformation dependence.

The maximum stresses in the tubular part of the sample during its bending is determined by the formula

$$\sigma = M/W, \quad (1)$$

where M is bending moment, W is sample resistance moment.

The axial moment of resistance of a tubular section having an inner diameter d and an outer diameter D is determined from the formula:

$$W = \varpi(D^4 - d^4)/32D. \quad (2)$$

Bending moment M is calculated by the formula:

$$M = f \cdot 2E \cdot I/L^2, \quad (3)$$

where f is deflection of the sample, E is the Young modulus for cold drawn copper, I is the moment of inertia of the sample cross section, L is the length of the working part of the sample.

The axial moment of inertia for a tubular section having an inner diameter d and an outer diameter D is determined by the formula:

$$I = \varpi(D^4 - d^4)/64. \quad (4)$$

Hence, the bending moment is:

$$M = f \cdot 2E \cdot \varpi(D^4 - d^4)/L^2\, 64. \quad (5)$$

The final formula for calculating the maximum bending stresses is:

$$\sigma = f \cdot E \cdot D/L^2. \quad (6)$$

Having substituted the deflection of the sample f, which is set by adjusting the eccentric mechanism, the length of the working part of the sample L = 140 mm, the modulus of elasticity for copper $E = 1.25 \cdot 10^5$ MPa, given the geometric cross-sectional characteristics of the tube I and W and bending moment M, we find the maximum bending stresses for the three groups of samples: Ø19 × 1.5 mm, Ø19 × 1.0 mm, and Ø16 × 2.0 mm. The results of the calculations are summarized in Table 2.

The influence of different flaring modes of combined joints of heat transfer tubes of different diameter and wall thickness with clad copper tube sheet on their resistance to corrosion and fatigue failure has been studied: Group I Ø19 × 1.5 mm, flaring to inner diameters (d_{inn}) 16.3 and 16.4 mm; Group II Ø19 × 1.0 mm, flaring to d_{inn}17.3 and 17.35 mm; Group III: Ø 162.0 × 2 mm, flaring to d_{inn}12.4 and 12.45 mm.

The design of the facility combines testing of the sample for corrosion-fatigue durability with constant measurement of its electrode potential in a corrosive environment. This possibility is important when testing the samples designed in such a way as it is impossible to visually observe the destruction zone. This enables recording the stages of origin and development of the fatigue crack and the moment of formation of through corrosion of the tube wall. Impregnation of the electrolyte through a through crack leads to contact of the medium with the steel surface of the tube sheet, which is reflected by a change in the potential.

It has been established that in a certain range of cyclic stresses (Table 2), increasing degree of flaring of the tubes Ø19 × 1.5 mm and Ø19 × 1 mm positively affects (leads to about 1.5 times increase in) the resistance to corrosion and fatigue failure of the combined joints with tubular sheet (Fig. 8 *a*, *b*). For the combined connection with a copper tube Ø16 × 2 mm, no significant effect of the degree of flaring on corrosion resistance has been found, although there is a slight decrease in the cyclic durability of samples with a larger inner diameter (Fig. 8 *c*).

The appearance of the surface of fatigue fractures of the samples Ø 19 × 1.5 mm flared to d_{inn} = = 16.40 mm (Fig. 9, *a*) indicates that with a durability of $3.8 \cdot 10^6$ cycles (at σ_{-1} = 119 MPa) it has a developed relief with numerous protrusions and depressions, i.e. contains signs of viscous nature of the destruction. The fracture microstructure has a classical grooved structure that differs for

Table 2. **Calculated Values of M and σ_{max} Depending on Cycle Amplitude**

Eccentric displacement, points	Deflection, mm	I group (Ø19 × 1.5 mm)		II group (Ø19 × 1.0 mm)		III group (Ø16 × 2.0 mm)	
		M, kg · cm	σ_{max}, MPa	M, kg · cm	σ_{max}, MPa	M, kg · cm	σ_{max}, MPa
8	1.13	506.8	151.2	365.9	151.2	350.0	127.3
7	1.02	456.7	136.3	330.3	136.5	315.9	114.9
6	0.89	398.5	119.0	288.2	119.1	275.7	100.2
5	0.75	335.8	112.5	242.9	100.4	232.3	84.5
4	0.62	x	x	x	x	192.0	69.8

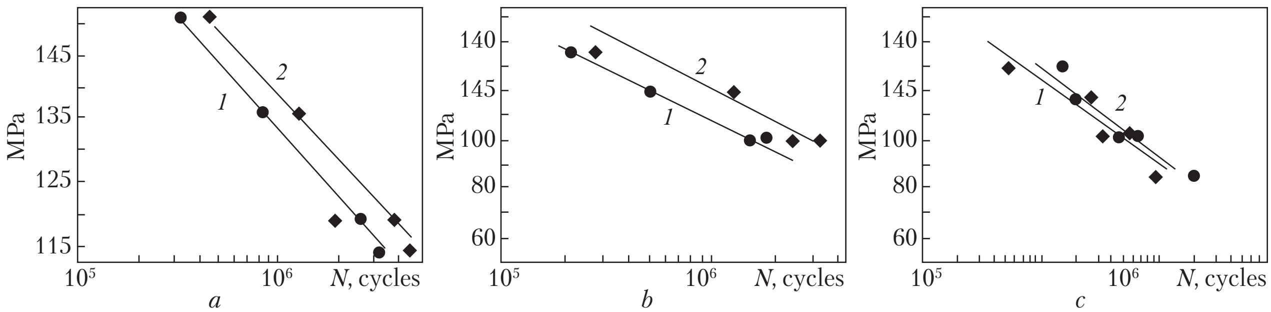


Fig. 8. Welded-rolled joint fatigue curves: *a* — tube Ø19 × 1.5 mm (*1* — d_{inn}=16.30 mm; *2* — d_{inn}=16.40 mm); *b* — tube Ø19 × × 1.0 mm (*1* — d_{inn}= 17.30 mm; 2 — d_{inn}= 17.35 mm); *c* — tube Ø16 × 2.0 mm (*1* — d_{inn}= 12.40 mm; *2* — d_{inn}=12.45 mm)

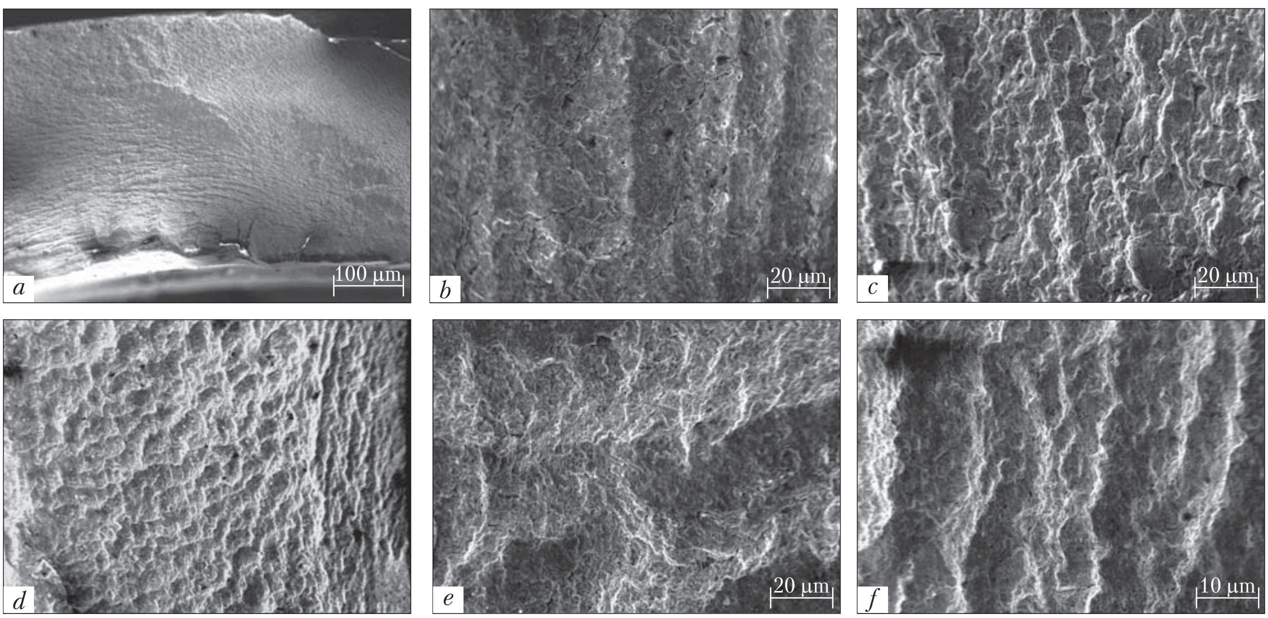


Fig. 9. Fracture (*a*) and microfractograms of the fatigue failure of samples Ø19 × 1.5 mm flared to d_{int}= 16.40 mm (*b*, *c*) and samples Ø19 × 1.5 mm flared to d_{inn}= 16.30 mm (*d*, *e*, *f*)

the inner and the outer cross-sectional areas in the area of flaring of the copper tube.

The fracture microstructure of the inner part of the tube (Fig. 9, *b*), due to a higher degree of deformation of this volume during the rolling, is characterized by a flat relief with low wrinkles and smooth areas of stratification, which indicates the presence of brittle fracture conditions in this area. At the same time, the topography of the fracture in the central and outer parts of the tube (Fig. 9, *c*) has a clear and well-developed microrelief typical for high-energy-intensive destruction.

While analyzing the topography of fractures of the samples of this series, we have noted that there may be secondary changes in their appearance because of the influence of prolonged fretting that leads to wearing out the conjugate surfaces of the formed cracks. As a result of abrasion of protrusions, the surface is smoothed and the expressiveness of a grooved structure of the fracture decreases (Fig. 9, *b*).

The presence of cracks in the area of the inner surface of the tube and the specific appearance of the macrofracture (Fig. 9, *a*) indicates that the main crack actually spreads from here. Intense plastic

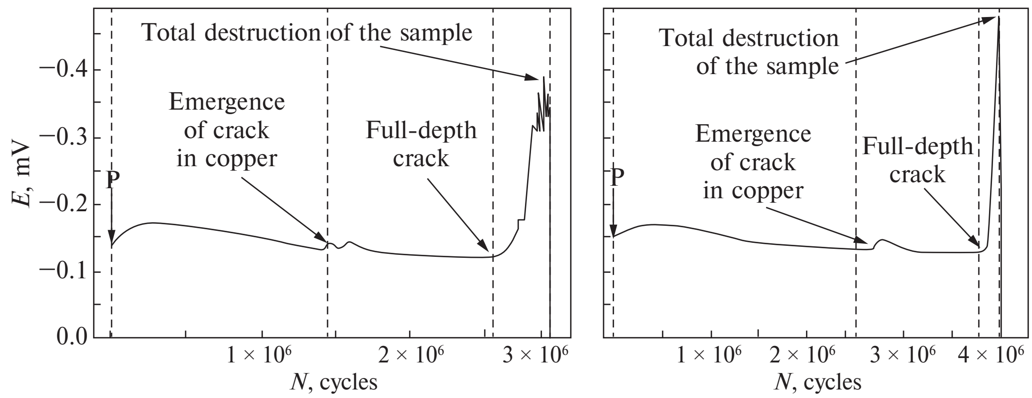


Fig. 10. The nature of the change in the electrode potential of the combined welded-rolled joint of pipes Ø19 × 1.5 mm with an inner diameter of 16.3 mm (*a*) and 16.4 mm (*b*) during corrosion-fatigue tests

strain of this zone during flaring to d_{inn} = 16.40 mm leads to the accumulation of strain defects in the structure and the appearance of stress concentrators, which crumbles the riveted material. Obviously, this mode of flaring the tubes of such sizes is close to optimal. Its excess (increasing the degree of flaring) causes re-riveting and negatively affects their durability [10].

The grooved structure of the fatigue fracture is typical for the samples Ø19 × 1.5 mm flared to d_{inn} = 16.30 mm, under the same test conditions (Fig. 9, *d*). Their durability is slightly less ($2.4 \cdot 10^6$ cycles at σ_{-1} = 119 MPa) than the samples of the previous flaring mode. The microfractogram clearly distinguishes the inner zone of strongly deformed metal, as well as the lesser deformed central and outer ones (Fig. 9, *d*). Accordingly, it affects the width of the fatigue grooves. Increasing the density of grain boundaries that are strongly deformed by the rolling of the inner zone of the tube reduces the rate of crack spread, which accordingly reduces the pitch of the formed grooves (Fig. 9, *e*).

Measuring the electrode potential of the samples in $2 \cdot 10^{-5}$ M KOH medium during the corrosion-fatigue tests enables establishing certain patterns of its change depending on the stages of development of fatigue damage. For the samples with a tube Ø19 × 1.5 mm, flared to an inner diameter of 16.3 mm, at the initial stage of the cyclic tests, the electrode potential is about 150 mV (Fig. 10, *a*).

When the sample undergoes $1.4 \cdot 10^6$ cycles of deformation, a potential shift towards more negative values, as a result of surface deformation, destruction of passive films, and the beginning of crack formation, has been observed. The crack spread over the body of the sample lasts up to $2.6 \cdot 10^6$ cycles, after which there is a sharp deterioration of the potential, which indicates a full-depth crack and depressurization of the tube. The fracture of the sample lasts up to $2.9 \cdot 10^6$ cycles.

A similar nature of the potential change has been observed for the samples with a higher degree of flaring (up to d_{inn} = 16.40 mm). Only the duration of the first stage before the crack is noticeably longer, while the duration of the second one is shorter, which increases the durability of combined compounds about 1.5 times (Fig. 10, *b*).

Therefore, a new structural element of gas coolers with increased resistance to corrosion and mechanical failure has been proposed to improve the reliability and durability of gas coolers by reducing the risk of depressurization of the welded-rolled joint of copper-clad tube sheet with copper heat transfer tube. Provisional specifications for the new design of combined connections of copper tubes with tube sheets of the gas cooler (*Structural Element with a High Resistance to Corrosion and Mechanical Failure for Gas Cooler of Turbogenerator*) have been developed and used in the manufacture of gas coolers for the turbogenerator. Improved gas coolers GO-1800/

5453-U3 with a new structural element of turbogenerator TVV-1000-4UZ have passed experimental tests at the power unit No.4 of Zaporizhia NPP.

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РОЗРОБЛЕННЯ НОВИХ КОНСТРУКТИВНИХ ЕЛЕМЕНТІВ ГАЗООХОЛОДЖУВАЧІВ АТОМНИХ І ТЕПЛОВИХ ЕЛЕКТРОСТАНЦІЙ З ПІДВИЩЕНОЮ ОПІРНІСТЮ КОРОЗІЙНО-МЕХАНІЧНОМУ РУЙНУВАННЮ

Вступ. Необхідність підвищення експлуатаційних характеристик газоохолоджувачів, які контактують з вибухонебезпечним середовищем, виникає в енергетичній промисловості для забезпечення надійної роботи турбогенераторів.

Проблематика. Під час експлуатації теплообмінного обладнання важливими проблемами, що вимагають постійного вдосконалення устаткування, є локальна корозія, наводнювання та ін., зокрема, стикових з'єднань трубок з трубними дошками, яке характеризується зародженням і розвитком тріщин під впливом одночасної дії механічних напружень та корозивного середовища. Виникнення тріщин сприяє розгерметизації цих з'єднань, що призводить до аварійної зупинки турбогенератора.

Мета. Розробка нової конструкції ущільнювальних з'єднань теплообмінних трубок та трубної дошки газоохолоджувачів для атомних та теплових електростанцій з підвищеною корозійною тривкістю, опірністю корозійно-механічному та водневому руйнуванню.

Матеріали й методи. Випробовували зразки із сталі 09Г2С, міді М2, сталі 09Г2С з плакованим шаром міді М2, мельхіору МНЖМЦ 30-1-1, латуні Л68 методом вакуумної екстракції водню за підвищених температур, корозійно-втомним, металографічним, рентгеноспектральним та ін.

Результати. Розроблено новий конструктивний елемент газоохолоджувачів із підвищеними характеристиками, основою якого є зварно-вальцьоване з'єднання мідної трубки із плакованою міддю трубною дошкою, що не викликає деформації конструкції та щілиноутворення. Дослідження впливу різних режимів розвальцювання таких з'єднань на їх опірність руйнуванню за одночасного впливу циклічних навантажень і середовища показали, що із збільшенням ступеня розвальцювання мідних трубок Ø19 × 1,5 і Ø19 × 1 мм зростає період зародження тріщин і довговічність комбінованих з'єднань підвищується приблизно у ~1,5 рази.

Висновки. Розроблений новий конструктивний елемент забезпечує зниження ймовірності корозійно-механічного руйнування деталей теплообмінного обладнання та сприяє подовженню терміну його безаварійної експлуатації.

Ключові слова: газоохолоджувач, трубна дошка, мідні трубки, щілинна корозія, наводнювання, турбогенератор.