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EFFICIENCY OF APPLICATION OF SUBSTRUCTURE STRENGTHENED TUBES ON HEATING SURFACES OF SUPERCRITICAL BOILER BLOCKS

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The results are presented on investigation of mechanical-thermal treatment of the tubes as an effective method to increase life and operation reliability of power equipment. General experience of commercial application of the tubes of mechanical-thermal strengthened steel 12Kh1MF on the heating surfaces of supercritical boilers is presented. Possibility and efficiency of application of this method is shown by the example of Trypolie HPP capacities. 11 Ref., 7 Tables, 7 Figures.

Keywords: *mechanical-thermal treatment, steel strengthening, equipment life, substructure, high-temperature strength, heat resistance*

Increase of operation reliability of the heating surfaces is one of the main conditions for reliable operation of the whole boiler unit.

Operation conditions of the heating surfaces in boilers of high capacity power generating units differ by corrosion activity of the medium at operating temperatures, effect of combustion products and other harmful factors on tube surface that results in rapid wear out. All this determines increased requirements to reliability and life of equipment operation.

One of the main reasons of emergency shutdown of power generating units of large unit capacity is damage of the tubes of boiler heating surfaces. Thus, breakdown of the tubes of superheaters, related with overheating of metal and accelerated development of creep or typical damage of waterwall system due to corrosion-thermal fatigue and gas corrosion, takes place already after 10–15 thou h of operation.

A relevant problem of reliable operation of the heating surfaces of boilers, supercritical pressure (SCP) blocks is studied in the work from point of view of application of tubes from 12Kh1MF steel, strengthened using mechanical-thermal treatment (MTT) method.

MTT method is one of the most effective modern methods of substructure strengthening of pearlite class steels. Idea of the method lies in deformation of metal after standard [1] heat treatment (normalizing (N) and tempering (T)) for small reduction above a yield plane and further polygonizational annealing in precrystallization temperature interval.

Metallurgical industry of Ukraine has produced MTT strengthened tubes of 32–42×4–6 mm diameter from steel 12Kh1MF on TU 14-3-1072 specification [2]. This work considers the results of investigation of MTT tubes as a method to increase life and operation reliability of power generating units. Possibility and efficiency of application of this method for increase of operation life of power generating units is shown by the example of Trypolie HPP capacities.

In accordance with accepted technology the tubes of preformed size on [1] in a condition after N and T are subjected to deformation by 10–15 % and further annealing at 700–720 °C temperature with 1.5 h holding.

Additional treatment does not make changes in the relationship of main structural constituents (bainite, ferrite, carbide phase), but results in change of fine dislocation structure of steel. Deformation provides introduction of additional amount of dislocations in a steel lattice and further annealing promotes their redistribution, partial annihilation and development of heat-resistant substructure. At the same time, there is grain fragmentation, ordering of submicrodefects with formation of dislocation walls and formation of polygonal substructure that generates strengthening effect [3, 4].

Data of metallographic investigations of 12Kh1MF steel tubes, carried out on micro- and substructural levels, verify these concepts [4].

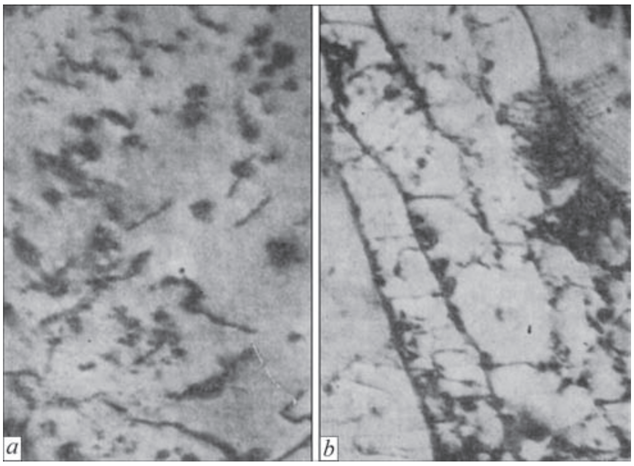

Figure 1. Fine structure (×30000) of metal of 12Kh1MF steel tubes: *a* — after normalizing with tempering; *b* — after MTT

A steel microstructure after MTT virtually does not change. At the same time, electron-microscopy analysis has detected significant changes in a material substructure. Thus, an unsystematic distribution of dislocations in the volume of inherent grains is typical for the initial state of steel after N and T. Clearly expressed polygonization of the structure with formation of subboundaries and dislocation walls (Figure 1) [4] is observed in steel after MTT.

Comparison of short-term mechanical characteristics of steel after standard heat treatment (N and T) and MTT, at normal and elevated temperatures in 300–570°C interval, showed stable strengthening of tube metal after MTT at sufficient level of ductility (Table 1) [3, 4]. Thus, strengthening by ultimate strength makes 19 % and that by yield strength at normal temperature is 27.5 %. At elevated temperatures strengthening by ultimate strength, on average, makes 8.4 % and that by yield strength is 25.5 %. A value of relative elongation in the researched temperature interval is 17–23 %.

It is important to note a higher level of strengthening of MTT steel by yield strength that is provided by stability of developed strengthened state in process of long-term operation of the tubes under the stresses below the yield plane, i.e. at normal working stresses.

Table 2. High-temperature strength properties of metal of 12Kh1MF steel tubes at 540 °C after standard heat treatment (N and T) and MTT [5]

Loading in testing, MPa	N and T		MTT		
	τ_{fail}, h	δ, %	τ_{fail}, h	Increase τ_{fail}, h (times)	δ, %
160	2003	12.0	8352	4.2	13.7
180	950	25.0	2727	2.9	9.0
200	425	38.0	1643	3.9	13.0
220	109	22.5	913	8.4	10.0
240	51	23.5	270	5.3	13.0

High-temperature strength properties of metal of tubes from strengthened steel 12Kh1MF were determined by the results of creep-rupture tests and long-term rupture resistance at 540 °C and stresses in 160–240 MPa range. Samples of standard [3] and after MTT [2] tubes (Table 2) [5] were tested under the same conditions. The results of tests were used to evaluate the increase of creep-rupture life of MTT samples in relation to standard ones.

Data given in Table 2 indicate the increase (on average 5 times) of long-term rupture resistance of MTT strengthened steel even at static stresses, which 2–3 times exceeds the nominal service operating stresses of power generating units.

Thus, complex examination of structure, substructure, short-term and long-term mechanical properties of the MTT strengthened heat-resistant tube steel 12Kh1MF showed a perspective of application of this method to increase the reliability of tubes of the heating surfaces of high- and superhigh-pressure boilers.

The work provides the results of long-term commercial operation of the substructure strengthened tubes of steel 12Kh1MF on low pressure convection

Table 1. Mechanical properties of metal of 12Kh1MF steel tubes after standard heat treatment (N and T) and MTT

T, °C	N and T			MTT				
	σ_t, MPa	σ_y, MPa	δ, %	σ_t, MPa	$\%_{str}$	σ_y, MPa	$\%_{str}$	δ, %
20	500	400	27.8	595	19.0	510	27.5	23.0
	Requirements of TU 14-3-460 [3], not less			Requirements of TU 14-3-1072 [4], not less				
	450–650	280	21	490–637		372		21
300	510	410	19.0	570	12.0	500	22.0	17.0
400	545	440	21.0	590	8.3	520	18.2	17.0
450	490	360	26.0	530	8.2	450	29.0	20.0
540	420	310	28.0	455	8.3	424	36.8	19.0
550	407	345	26.3	444	9.1	404	17.1	22.3
570	374	285	25.0	390	4.3	370	29.8	20.0

*Average values of received mechanical characteristics of metal are given in the Table.

superheater (l/p CSH) of TPP-210 A boiler and panels of lower radiant section (LRS) of TGMP-314A boilers of 300 MW blocks.

Long-term commercial operation of MTT tubes on l/p CSH of TPP-201A PC-fired boilers of 300 MW block. An experience of application of substructure strengthened tubes of steel 12Kh1MF on the heating surfaces of power boilers has own prehistory.

For the first time MTT strengthened tubes in form of the straight test inserts were installed in an exhaust stage of high-pressure superheater h/p CSH of BKZ 210-140 PT boiler with operating steam parameters, namely temperature 550 °C and pressure 14.0 MPa [3]. In accordance with the design the boiler's h/p CSH was manufactured of austenite steel 12Kh18N12T with tube dimension-type 32×5.0 mm.

The experiment conditions were knowingly toughened. The inserts with thinned tube wall of 32×4.0 mm dimension-type were installed in h/p CSH together with the test inserts of nominal dimension-type.

MTT strengthened inserts of steel 12Kh1MF run on the superheater for 51382 h without damages and were disassembled during repair and reconstruction of the equipment.

Systematic inspections of MTT tube state were carried out in course of test inserts operation. Periodic examinations, measurement control and results of investigation of the reference cutoffs showed metal in a good state.

Investigation of stability of created strengthened state in process of long-term operation of the test inserts showed that dislocation subboundaries, dislocation walls and fragmentation of structure are preserved (Figure 2). At that, some widening of metal subboundaries takes due to inflow of the dislocations and precipitations along the boundaries of carbide phase disperse particles. It should be noted that decrease of wall thickness up to 4 mm does not activate these processes that can be explained by lower temperature gradients on the thinned tube section.

At the same time, there is a natural process of differentiation of bainite and ferrite-pearlite microstructure of steel due to aging with formation of areas of ferrite-carbide mixture, precipitations of detached carbides and their coagulation. However, preservation of the fragmented substructure provides stability of properties and inhibition of steel creep rate.

The maximum registered residual deformation of MTT tube inserts after 51 thou h of operation did not exceed 0.63 %.

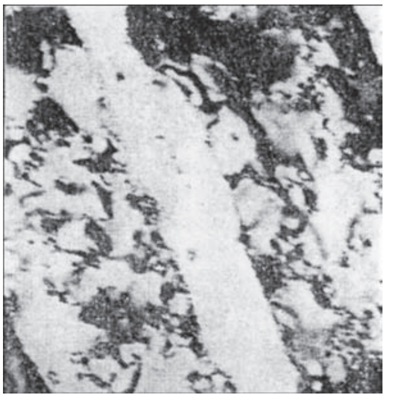

Figure 2. Fine structure (×30000) of MTT strengthened tube metal after 51382 h of operation on h/p CSH

To prove the stability of strength characteristics and ductility of MTT tubes of steel 12Kh1MF there are the results of short-term mechanical tests of the cutoffs from the 32×4.0 mm diameter test inserts of PK-41 boiler h/p CSH after different periods of operation (Table 3).

As can be seen from provided data, during the first operation period up to 5000 h there is a partial 5–4 % recovery of strengthened state of steel by yield strength and then decrease of strength is delayed and makes 3.6–2.7 %.

Steel softening by yield strength is insignificant and during the whole investigated operation time virtually does not exceed 1 %.

At that, steel ductility for all investigated time range remains at acceptance level.

The positive results of operation testing of MTT strengthened steel 12Kh1MF on the test inserts made the basis for commercial implementation of MTT tubes instead of standard materials on HP and SCP boilers' superheaters.

3840 loops (100 %) of four legs of secondary l/p CSH superheater were mounted on two TPP-201A boilers of 300 MW block from 12Kh1MF steel tubes of 42×4.0 mm diameter after MTT [4]. Operating parameters of the assembly were steam temperature 545 °C and pressure 3.7 MPa.

Table 3. Mechanical properties of metal of test inserts of MTT strengthened steel 12Kh1MF after different periods of operation on h/p CSH

Time of operation, h	Testing temperature 20 °C			Testing temperature 570 °C		
	σ_t, MPa	σ_y, MPa	δ, %	σ_t, MPa	σ_y, MPa	δ, %
Initial state	630	542	22.1	396	364	30.2
4000	600	476	29.5	379	347	31.0
7000	585	455	28.5	355	314	29.5
15000	582	451	29.5	344	303	29.0
23000	565	459	31.0	294	286	29.4

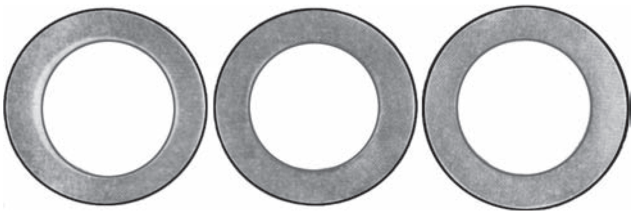

Figure 3. Cross-section of MTT strengthened LRS tubes after 21 thou h of operation

Earlier the boiler superheater, following the design, had the tubes of steel 12Kh2MFSR [1] that did not provide reliable operation of the assembly.

The total number of straight and bended elements of tubes after MTT, installed in the superheater, makes 3840.

There were no difficulties with bending and welding of the tubes in manufacture of the superheater loops at the plant.

Up to the moment the tubes after MTT have worked 65374 and 68095 h in secondary l/p CSH of the boiler (block B and A of the boiler, respectively).

Tubes operation is virtually troublefree. During operation of the secondary l/p CSH it was one case of damage due to a wormhole in the welded joint that makes 0.03 % of number of welded joints of tubes after MTT. Hydraulic pressure tests of the boiler after the scheduled repairs resulted in reject of 9 tubes on different loops of the superheater also because of the wormholes in welded joints that makes 2.8 % of total number of welded joints.

Data on damages of standard 12Kh2MFSR steel tubes of boiler secondary l/p CSH for the same operation period can be provided for comparison. In course of this time 38 tubes were rejected by emergency or based on the results of inspection that makes 10 %.

There is a systematic monitoring of state of the metal of the strengthened tubes in process of operation during standard shutdown for routine and major shutdowns of the boiler, including inspections, measurements of residual creep deformation, determination of wall thickness and corrosion wear of tube metal.

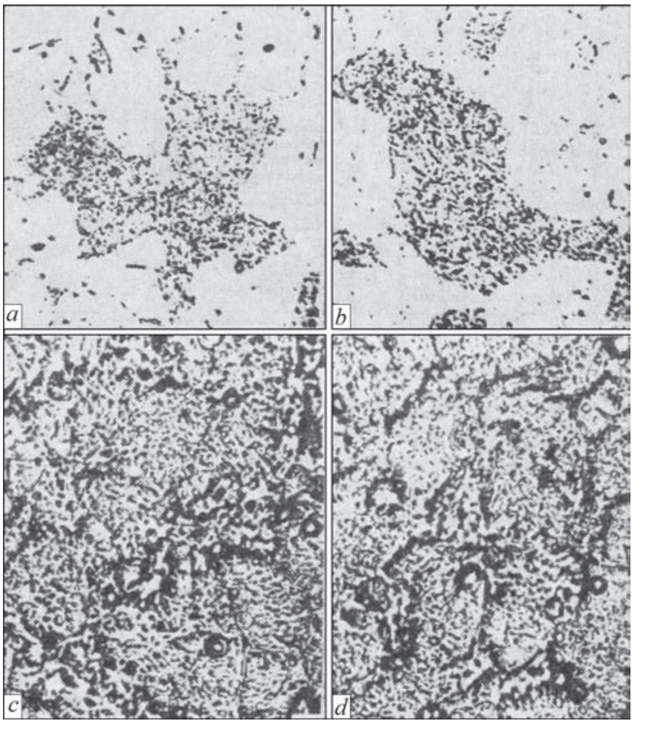

Figure 5. Microstructure (*a*, *b*) and dislocation structure (*c*, *d*) of strengthened LRS tube after 1 thou h of operation: *a*, *b* — fireside; *c*, *d* — backside of tube (×1000)

It is planned in the future to do the reference cutoffs for investigation of structural changes and level of mechanical properties, high-temperature strength and heat resistance of metal in process of long-term operation.

Long-term commercial operation of tubes after MTT in lower radiation section (LRS) of TGMP-314A gas-and-oil-fired boilers of 300 MW blocks. The positive results of testing and long-term commercial operation of MTT tubes in superheaters of HP and SCP boilers made a basis for expansion of the experiment on application of substructure strengthened tubes in power generating units.

Investigation of the possibility of application of the strengthened tubes in zones of the largest man-

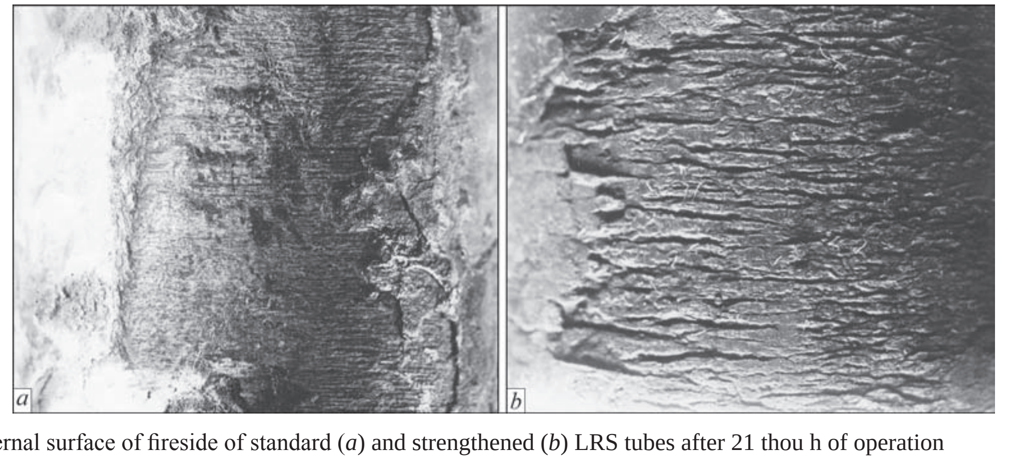

Figure 4. External surface of fireside of standard (*a*) and strengthened (*b*) LRS tubes after 21 thou h of operation

Table 4. Mechanical properties of metal of MTT strengthened test inserts of side waterwalls of TPP-210 A boiler LRS after 21 thou h of operation

Insert number	Place of sample cutoff (tube side)	Testing temperature 20 °C			Testing temperature 550 °C		
		σ_t, MPa	σ_y, MPa	δ, %	σ_t, MPa	σ_y, MPa	δ, %
1	Backside	632	488	24.6	401	379	22.4
	Fireside	633	506	22.5	401	368	22.3
2	Backside	645	507	22.5	419	400	20.0
	Fireside	645	508	22.5	409	378	21.0
3	Backside	608	460	24.4	404	374	21.6
	Fireside	606	450	24.2	390	360	21.4

caused risk on SCP boilers, which are the waterwalls of furnace lower radiation section, is of undoubted interest. The experience of application of standard [1] tubes of steel 12Kh1MF showed a mass damage of the waterwalls being observed already in the first operation period. There is virtually single-type damage nature for PC-fired and gas-and-oil-fired blocks. In the beginning there is thinning of wall of the tube front part due to thermal fatigue corrosion wear or external gas corrosion. Then thinned tubes failure due to development of accelerated creep under conditions of increased operating stresses.

During the first stage of the experiment the straight inserts of strengthened tubes were installed in the panels of side waterwalls of lower radiation section (LRS) of TPP-210A boiler and panels of backside and front LRS waterwalls of TGMP-314A boiler of 300 MW block using coal-dust mixture and oil-and-gas fuel. The straight sections of 12Kh1MF steel tubes after MTT of 38×6.0 and 32×6.0 mm diameters were used for operation testing. Assembly operating parameters are medium temperature 400–389 °C, pressure 30 MPa, tube wall temperature 460 °C.

It should be noted that TPP-210A boilers had the experimental strengthened inserts without studding and, thus, they were operated under more rough conditions than standard stud LRS tubes [3].

The results of investigations [6] of cutoff metal of three test inserts in side wall of TPP-201A boiler LRS after 21 thou h of operation showed that deformation and thinning of the tubes due to corrosion are not observed (Figure 3).

Initial stage of development of corrosion-thermal metal fatigue from tube external surface (Figure 4) was detected.

Tube operation did not influence the structure and fine dislocation structure of steel even in the most stresses area of the section, i.e. tube fireside. State of the microstructure of strengthened tube is homogeneous along the whole section with the light features of differentiation (Figure 5, *a*, *b*). Examination of the dislocation structures [7] indicates absence of fine structural changes on tube section (Figure 5, *c*, *d*). Dislocation density, which is uniformly distributed in ferrite grains, makes $(0.6–0.8)\cdot10^{-8}$ cm^{-2} that corresponds to the initial state.

Homogeneity of structural state on tube section after MTT agrees with the level of strength and ductile properties of steel, which are, virtually, the same on fireside and backside part of the tube. Determination of mechanical characteristics of metal under normal and high temperatures after 21 thou h of operation showed stability of the strengthened state and retention of steel ductility (Table 4).

The experience of troublefree operation of MTT inserts in boilers' LRS allowed proceeding from operation tests of the separate tubes to testing the block-panel at LRS back waterwall of TGMP-314A boiler. It was completely produced under plant conditions of 41 strengthened tubes (1/2 of LRS standard panel).

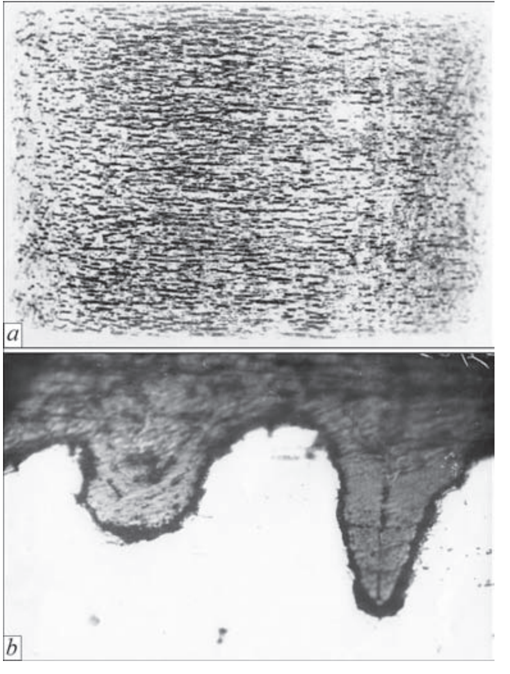

Figure 6. Corrosion-fatigue cracks on external surface (*a*) and in section (*b*) of MTT strengthened tube in LRS after 89 thou h of operation (×100)

Table 5. Heat resistance of MTT tubes in panels of front waterwall of TGMP-314A boiler LRS after long-term operation (operation time 89 thou h)

Sample	Corrosion depth, mm					
	Tube external surface		Tube internal surface		Corrosion depth (total wall thinning)	Sum corrosion depth
	Thinning	Suboxide layer	Thinning	Suboxide layer		
Tube after MTT	–	0.22	–	0.10	0.40	0.72
Tube after N and T (calculation data)	0.71	–	0.13	–	0.84	0.84

Performance of technological operations on bending of the strengthened tubes, resistance and manual electric arc welding of tubes after MTT as well as composite butt joints of tubes after MTT with standard tubes did not provoke any difficulties.

Operation of the test block-panel takes place troublefree. Periodic technical diagnostics of the panel in process of operation showed good state of metal. There are no traces of intensive external corrosion and tube thinning, unallowable residual tube deformation is absent. Bended parts of the tubes and butt joints are also in satisfactory state, that indicates inheritance of the strengthened state on tube bends and in welded joints.

Life of the test parts of LRS waterwalls of TPP-201A and TGMP-314A boilers made 28–31 thou h.

Analysis of the results of carried operation testing proved stability of strengthened state of the tubes after MTT and made a sufficient basis for their commercial implementation in the LRS of boilers of SCP blocks instead of standard materials.

46 % of panels from MTT strengthened tubes (13.5 panels) were installed on two TGMP-314A boilers of 300 MW blocks at front, back and bottom LRS waterwalls. Installed panels are of plant production in accordance with the requirements of [2]. Total number of installed in the panels bended and straight MTT strengthened tube elements made 3500 units.

A period of commercial operation of tubes after MTT in the panels of TGMP-314A boiler LRS up to the moment has made 96–104 thou. h including 137.6 thou h of test inserts being in operation.

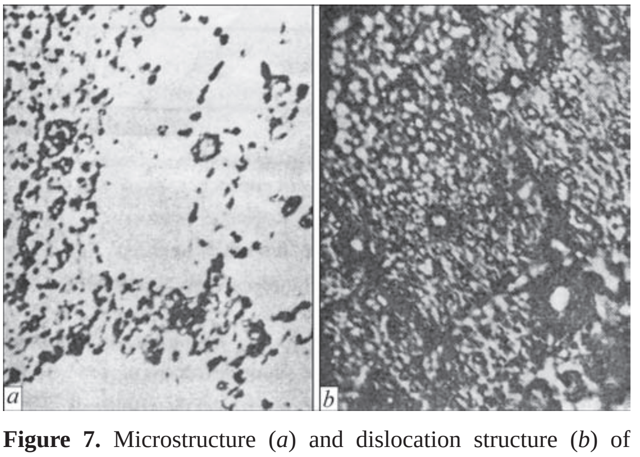

Figure 7. Microstructure (*a*) and dislocation structure (*b*) of strengthened LRS tubes after 89 thou h of operation (×1000)

Tube operation is virtually troublefree.

One of TGMP-314A boilers had a damage of MTT strengthened tube in burners' zone during the analyzed period of unit operation. It happened due to overheating (less that 0.03 % of quantity of tubes installed after MTT) that was related with unsatisfactory operation of burner assembly of the boiler and required replacement and assembly reconstruction. 54 tubes were rejected during scheduled inspections due to surface appearance (external corrosion, tube deformation etc.). It made 1.5 % of quantity of installed tubes.

The systematic periodic inspections of state of tube metal in situ and on reference cutoffs were carried out in process of operation.

The data given below refer to investigation of cutoff of one of MTT strengthened tubes of 32×6.0 mm diameter taken from the font panel of TGMP-314A boiler LRS after 89 thou. h of operation.

No tube deformation on diameter was found in cutoff investigation.

State of external and internal surfaces of the tube were investigated after cleaning from deposits and special heat etching.

The external surface of tube front part has a mesh of transverse (circumferential) corrosion-fatigue cracks (Figure 6, *a*). Single corrosion pits of up to 0.5 mm diameter were found on tube internal surface.

Metallographic examinations of a tube cross-section were carried out to determine a nature and level of corrosion damages. It is shown that the transcrystalline blunt cracks filled with oxides propagate to

Table 6. Mechanical properties of tube metal after MTT of front waterwall of TGMP-314A boiler LRS after operation (testing temperature 20 °C)

Operation time, thou h	σ_t, MPa	σ_y, MPa	δ, %
21 (test inserts)	606–645	450–508	22.5–24.6
89	$\frac{623–692}{490–637}$	$\frac{511–557}{\geq 372}$	$\frac{21.1–20.7}{\geq 21}$
In the denominator the values are in accordance with [4].			

Table 7. Calculation of residual life by microdamage in metal of MTT strengthened tube of front waterwall of TGMP-314A boiler LRS after 89 thou h of operation

Object being investigated	Operation time, thou h	Density, g/cm^3	Damage ω	Residual life, thou h
Tube after MTT of LRS front waterwall	89	7.831	< 0.1	≥ 100
Steel 12Kh1MF after N and T [11, 12]	Initial state	7.835	0	≥ 100

0.22 mm depth (Figure 6, *b*) in the section from the external surface. Corrosion damages of internal surface look like round-shape pits of up to 0.1 mm depth also filled with oxides.

Thus, sum depth of corrosion-damaged layer of tube section makes 0.32 mm.

Depth of tube corrosion after MTT was evaluated on total wear of external and internal surfaces, expressed by the maximum value of wall thinning, which made 6.7 % or 0.4 mm.

A calculation [8] of allowable corrosion depth for the same period of service of standard tube was carried out for comparison as a sum value of wear of internal surface in SCP medium and external surface in a medium of combustion products of sulfur black oil.

As can be seen from the data given in Table 5, development of corrosion of strengthened tubes is delayed and corrosion depth after 89 thou. h is two times lower than the maximum allowable one [8]. The total volume of corrosion losses of tube metal after MTT can be considered as a sum of corrosion depth and depth of corrosion-damaged layers. Even in this case, taking into account corrosion-damaged suboxide layers of the section the sum depth of corrosion of MTT tube is below the allowable one for standard tube of steel 12Kh1MF.

Provided data indicate increased heat resistance of steel 12Kh1MF after MTT under conditions of long-term commercial operation.

There were no significant changes in the microstructure of metal of MTT tube cutoff after 89 thou h of operation. The structure consists of sufficiently dense bainite areas, ferrite and isolated carbides located along the grain boundaries.

Single dispersed carbides (Figure 7, *a*) are found in a ferrite grain volume. Such a structure can be referred to «acceptance» on scale [1] for steel 12Kh1MF after N and T.

Comparison of state of investigated tube with microstructure of LRS tube test inserts shows their complete identity.

Investigation of dislocation structure of steel showed uniform distribution of the etch figures in a ferrite field with $(0.8–0.9)\cdot 10^{-8}$ cm^{-2} density (Figure 7, *b*), that is insignificantly higher than a density level after 21 thou. h of operation. The areas of regular construction of the etch figures with fragmented structure of separate grains (Figure 7, *b*) were detected that indicates stability of polygonal structure of MTT tubes in process of long-term operation.

Therefore, there are no fundamental changes in short-term mechanical properties of the tube metal (Table 6) in comparison with state of the strengthened tubes after 21 thou h of operation. It is only noted 3.9 % decrease of a value of relative elongation, however, mechanical characteristics of tube metal after 89 thou h of operation are at the level of requirements [2].

A residual life of MTT tube metal after 89 thou h of operation was evaluated by a level of accumulated microdamage of steel, which is related with the processes of nucleation and propagation of pores and microcracks [9, 10]. An integral estimation of changes being the result of these processes is a value of accumulated damage ω [11]. The samples for determination of volumetric density of material were taken from tube front part.

The value of integral damage ω was determined as a relationship of specific volume of pores in steel at the moment of 89 thou h investigation to volume of pores at the moment of failure. Calculation of residual life was carried out using empirical dependence of relative time before failure on damage. The latter was received in experimental way by measurement of material density (Table 7).

As can be seen from the Table, metal density of MTT strengthened tube after 89 thou h of operation turned out close to the reference density of standard steel in initial state.

Thus, process of damage accumulation in MTT strengthened steel during operation is delayed that indicates stability of fragmented substructure of strengthened state, in which polygonal boundaries prevent dislocation movement and formation of new microdefects in a crystalline lattice volume. Actual accumulated microdamage of tube metal after MTT is minimum and residual life after 89 thou. h of operation is at the level of calculation one, i.e. not less than 100 thou h.

Received results of commercial operation of MTT tubes of 12Kh1MF steel in SCP boiler LRS prove the stability of MTT strengthened state and retention of operation reliability of steel in course of long-term service.

Conclusions

1. Systematic periodic inspections of state of tube metal showed that dislocation polygonal steel substructure, providing strengthening effect, remains stable in process of operation. Therefore, no significant changes of mechanical, high-temperature strength and heat resistance properties of steel were found. Unallowable wall thinning of tube due to external corrosion was not determined. Welded joints of MTT tubes made by resistance and manual welding are in satisfactory state. Accumulation of microdamage of steel after MTT is delayed and residual life of tube metal after long-term operation is kept at the level of calculation, namely not less than 100 thou h.

2. The experience of commercial operation of tubes of MTT strengthened 12Kh1MF steel on the heating surfaces of SCP boilers was generalized. Stability of MTT strengthened state in process of operation of up to 104 thou h duration was shown. Damages of the tubes after MTT for the indicated operation period do not exceed 0.1 % of total determined amount.

3. Positive experience of long-term commercial operation of MTT strengthened tubes of 12Kh1MF steel on the heating surfaces of SCP boilers indicates technical and economical relevance of application of such tubes in power engineering that provides increase of life duration of critical assemblies in power generating units for more than 5–6 times and solves the relevant problem of rise of operation reliability of critical assemblies of the units.

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