https://doi.org/10.46813/2025-159-064

UDC 621.039:620.17:620.186:620.187

THE CHANGE OF THE SUBSTRUCTURE AND PHYSICAL-MECHANICAL PROPERTIES OF THE MCP BASE METAL OF WWER-1000 OVER 30 YEARS OF OPERATION

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The article presents the results of studying the changes in the substructure and physical and mechanical properties of the base metal (BM) of the main circulation pipelines (MCP) of the WWER reactor units over 200,000 h of operation. It was found that the change in the mechanical properties of the BM has a non-monotonic extreme character. At the same time, metallographic analysis using optical methods did not show any significance changes in the BM structures. The nanoindentation method revealed an increase in the heterogeneity of the mechanical properties of the BM by the volume of grains during aging of the MCP. Electron microscopic studies revealed changes in the BM structure at the subgrain level. At the initial stage of operation of the MCP BM (100,000 h), the density of precipitates along the boundaries of grains and subgrains increases, which leads to a decrease in ductility. At the subsequent stage (≈ 100,000…200,000 h), coalescence of subgrains and precipitates is observed. Basically, depending on the initial state of the BM, this leads to a decrease in strength characteristics, and, accordingly, some increase in plasticity and impact toughness characteristics.

INTRODUCTION

Since the early 2000s, a number of works have been carried out at PNPP (units 1–3), ZNPP (unit 1), and RNPP (unit 3) to determine the actual state of the base metal (BM) of the main circulation pipeline (MCP) of WWER reactor units using direct methods [1]. These works did not lead to a decrease in the operational performance characteristics of the MCP and were based on taking BM samples from the thickenings of the bend walls and studying the BM properties using the microsampling method [2]. To minimize damage the BM MCP samples for studies were cut using the electrical discharge method [3].

Continuing the operation of the MCP after determining the actual state of the BM using direct methods without significant influence (for example, during repair and restoration work when cutting out «coils») on the properties of the BM fundamentally made it possible to study the aging processes, leveling the limitations associated with the natural spread of the properties of the BM in the initial state. In particular, during the sequential study of the BM using direct methods after 100 and 200 thousand hours of operation with the registration of changes in the properties of the BM from control links close to each other at the 1st, 2nd, and 3rd power units of the PNPP [4]. This approach made it possible to track the kinetics of the configurations of the mechanical parameters of the BM during operation [5].

The aim of this work is to study the general mechanisms of evolution of the dislocation and phase structure of 10GN2MFA steel in combination with the analysis of changes in its mechanical characteristics during the planned service life of the MCP under the conditions of the primary circuit of the NPP. Understanding the nature of these processes is the basis for predicting the operational reliability of the MCP. The relevance of the work is due to the increase in the service life of modern NPPs with WWER reactors to 60 years with the possibility of extending the service life for another 20 years.

MATERIALS AND OPERATING CONDITIONS

The main circulation tube of WWER-1000 reactors is made of bimetallic pipes DN 850 mm. The BM of the pipe is low-alloy pearlitic steel 10GN2MFA, the internal cladding is made of austenitic steel 08Kh19N10G2B. The thickness of the BM pipe is 70 mm, the thickness of the cladding is 5 mm. The internal diameter of the pipe is 850 mm. The bend radius of the main circulation tube is 1340 mm.

The main requirement for the BM MCP is to meet the requirements of TU 975EOO4511 (ed. 5) during operation. In the initial state, the BM is heat-treated according to TU 108.766 – 86 (Table 1). The studied chemical composition of the BM is given in Table 2. The structure of the BM is the tempered bainite with a quantitative ratio of pearlite to ferrite ~ 85/15%.

Table 1

Heat treatment conditions according to TU 108.766 – 86

Heat treatment	Heating for stamping	High steel tempering	Quenching	Tempering	Tempering
Temperature, °C	1070	650…670	910…920	655…665	640…650
Holding time, h	0.5	6.00	2.66	8.08	9.00
Heating medium	In the air	In the air	water	In the air	In the air

Table 2

BM MCP chemical composition of the PNPP (1 and 2 power units)

Source of information	Element, %									
	C	Si	Mn	Ni	Mo	V	S	P	Cr	Cu
TU 975EOO4511 (ed. 5)	0.08…0.12	0.17…0.37	0.70…0.90	1.70…2.00	0.40…0.60	>0.04	>0.02	>0.02	>0.3	>0.3
1 unit certificate	0.09	0.31	0.79	1.89	0.52	0.03	0.013	0.011	0.17	0.04
2 unit certificate	0.11	0.26	0.77	1.85	0.58	–	0.07	0.01	0.14	0.03

Samples of BM for research were taken from bends of the main circulation pipeline, which were operated at 288 °C (1st and 3rd power units) and 320 °C (2nd power unit).

CHANGES IN THE MECHANICAL PROPERTIES OF THE BM DURING OPERATION

Analysis of the results of periodic monitoring of the mechanical properties of the metal of the pipelines of the NPP power units by direct methods showed a non-monotonic (extreme) change in the normalized mechanical properties of the BM MCP. These changes are presented in Fig. 1. The results confirm the general behavior of the mechanical properties of materials at test temperatures below 0.3 T_m: strength and ductility generally change in opposite directions.

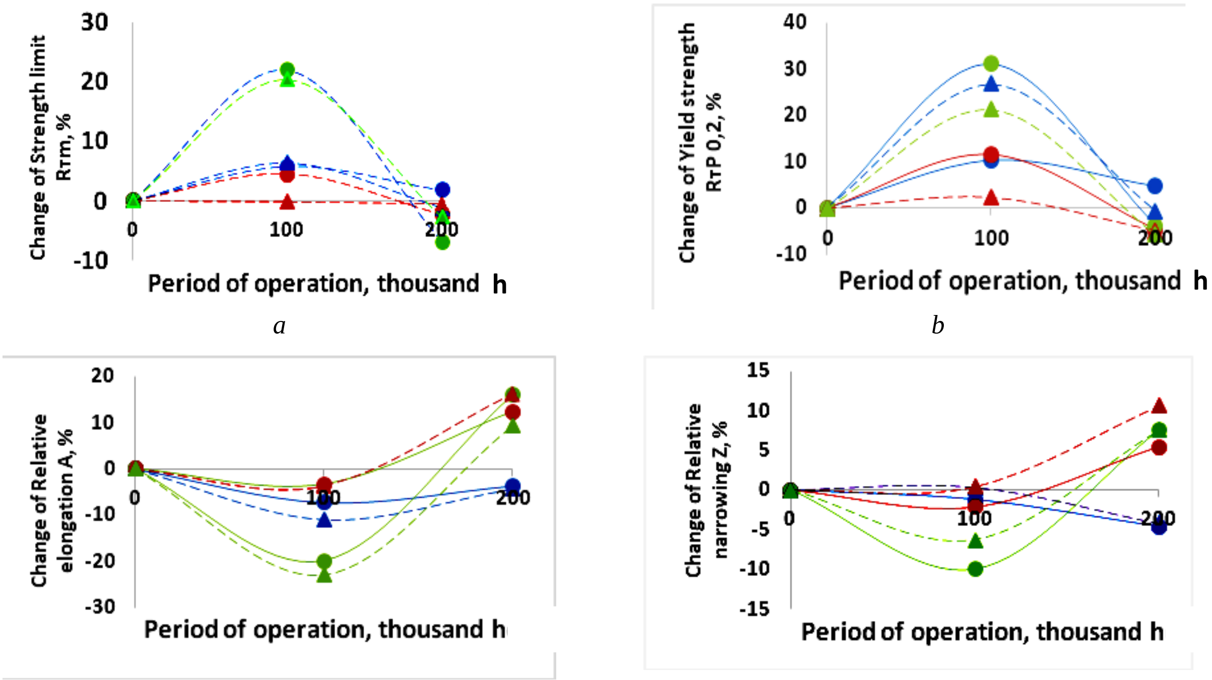


Fig. 1. Change of the Strength limit (a); Yield strength (b); Relative elongation (c); Relative narrowing (d) BM MCP PNPP at 20 (●) and 350 °C (▲) after of operation: --- – 1st power unit; –·–·– 2nd power unit; —·—·– 3rd power units

NANOINDENTATION

Considering that the normative metallographic analysis by optical research methods did not show significant changes in the structures, studies of mechanical properties at the substructure level were conducted using the nanoindentation method (Berkovich triangular indenter, nanohardness tester "Nano Indenter G200", (USA)) were found using the Oliver and Farr method [6]. The results are presented in Fig. 2.

The average values of the Young's moduli (E) of these three regions became equal: grain boundary – 326.8 GPa, subgrain boundary – 267.2 GPa, grain body – 204.7 GPa. As a result of nanoindentation, it was found that the hardest (strongest) are the grain boundaries, then the subgrain boundaries, and then the grain body. This does not contradict the classical concepts regarding the relative strenght of the body and grain boundaries at deformation temperatures less than 0.4 of the melting temperature [7]. However, it is important to note the difference between the deformation strengthening (albeit small) of the grain body and the deformation softening of the grain boundaries (see Fig. 2,b), which is observed during the entire immersion of the indenter.

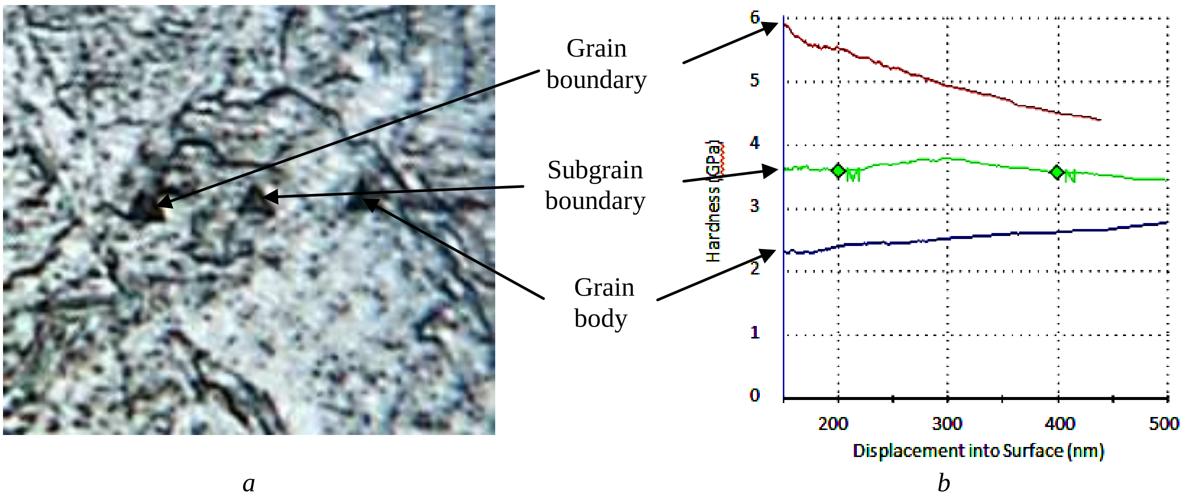


Fig. 2. Nanohardness of the BM of the 3rd power unit of the MCP after 200,000 h of operation:
a – imprints on the BM surface from the immersion of the indenter (at a distance of 20 μm from each other);
b – dependence of nanohardness on the depth of the material for three elements of the substructure:
grain body, subgrain boundary, grain boundary

IMPACT PROPERTIES

The change in impact toughness (20 °C) of BM during operation is given in Table 3.

Table 3

Impact toughness BM MCP PNPP

NPP Unit	Thousand hours of operation		
	Before operation	100	200
	Impact toughness, (kg·m)/cm^2		
No 1	21.0	21.6	13.8
No 2	28.8	24.2	23.1
No 3	21.0	22.4	22.1

Impact toughness was recorded in accordance with RD.00.EK.HF.MO.M.09-09; the data from the passports of the corresponding bends of the MCP were used as the initial state of the impact toughness. Thus, the impact toughness of steel during the first 100,000 h remains almost unchanged. The deviation of the control results can be caused by the natural spread of the properties of the BM by the volume of the samples.

CHANGES IN THE BM SUBSTRUCTURE DURING THE OPERATION OF THE MCP

This section presents the results of electron microscopic studies of the microstructure of 10GN2MFA steel in three states: initial, after 100,000 and 200,000 h of operation in the first circuit of the reactor.

This material is made of very thin grains (lath structure) and therefore a significal effect of the inernal interfaces on the dislocation arragments and properties.

It should be noted that the same lath structure occurs in other steels that are classified as pressure vessel steels – 15X2MFA, 15X2NMFA, A508, and 16MND5, after approximately the same heat treatment parameters [8, 9].

In the initial state (Figs. 3 (a); 4,a) the inclusions have several types of varieties: intra-substructural, with a size of 40…80 nm, and inclusions located at the boundaries of grains and subgrains, with a much larger size. Their shape differs significantly. Grain boundary inclusions and inclusions at subgrain boundaries have crystallographic faceting, and the internal substructures have the form of globules.

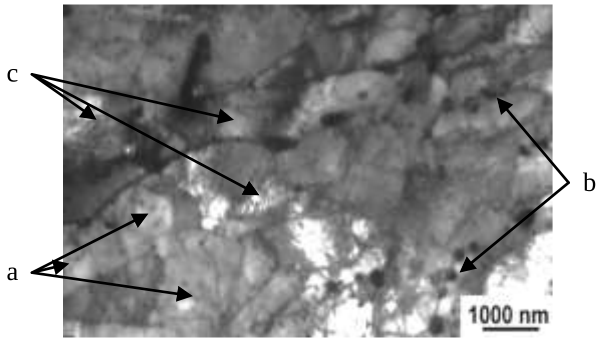


Fig. 3. The "lath" structure of the BM MCP in the initial state: a – internal subgrain small precipitates;
b – formation of carbides on the interfaces;
c – polygonized structures in the body of subgrains

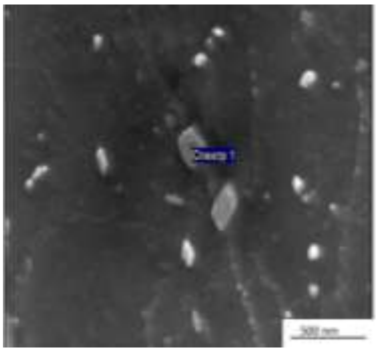
Fig. 4,b shows the energy-dispersive (EDX) spectrum from one of the grain boundary precipitates, and Table 4, respectively, shows its elemental composition.

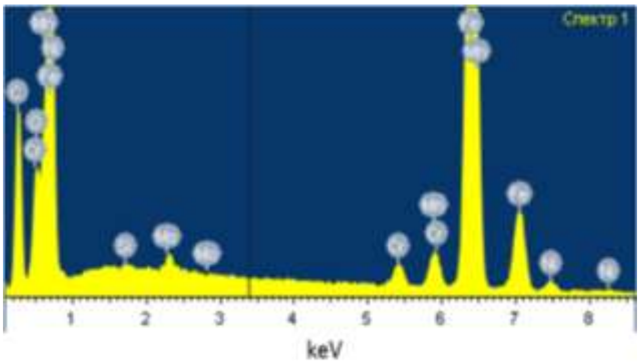
Thus, they are, first of all, complex iron carbides, with impurities of oxides and silicates.

The grains have an internal structure with weakly misoriented subgrains of the order of 500 nm in size, and the formation of polygonal dislocation structures in their interior.

This feature of structure formation may be associated with two processes occurring simultaneously – dynamic recrystallization "in situ" and dynamic polygonization.

The presence of a polygonized substructure indicates the transition of the metal during hot processing during bending, from the stage of deformation strengthening to the stage of dynamic recovery.





a *b*

Fig. 4. Grain boundary precipitates in the original BM: a – location; b – EDX spectrum from the precipitation

Table 4

Element	C	O	Si	Cr	Mn	Fe	Ni	Mo
Composition, wt.%	28.97	9.42	0.17	1.15	2.48	55.29	1.38	1.13

It is the level of accumulated deformation energy during stamping (bending) in the austenitic region will determine the rate of metal softenning during post-deformation thermal holding. At the same time, many researchers have pointed to the possibility of static softenning processes occurring in the period between the end of high-temperature deformation and the beginning of cooling [10]. These processes can be considered as static recrystallization processes due to migration of the original boundaries under the influence of deformation-the so-called "strain induced migration".

In smaller subgrains, there is almost complete "overgrowth" of dislocations formed under conditions of so-called metho-dynamic recrystallization (see Fig. 3). Such a highly developed internal surface should strongly influence the distribution of dislocations and the strength of steel.

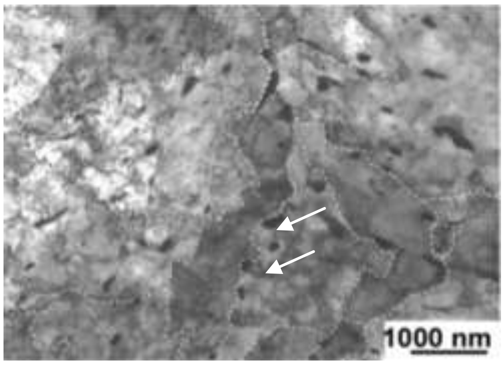


Fig. 5. The structure of the metal of the 3rd unit of the PNPP after 100,000 h of operation. The contours indicate the center of coalescence of steel. The arrows indicate "overgrown" small subgrains that do not take part in this process

STRUCTURE AFTER OPERATION

Analysis of the structures shown in Fig. 5 indicates that several types of microstructure evolution processes of opposite directions occur simultaneously in steel during operation. At the level of the smallest subgrains (< 500 nm), dislocation processes of "overgrowing of the body of subgrains with dislocations" similar to dynamic polygonization can occur, which leads to a decrease in their effective size.

In contrast to this, in the BM structure, during operation, collective processes of subgrain enlargement also occur, which are in fact the beginning of primary recrystallization. Enlargement of cells can occur not only by migration of their boundaries, but also by coalescence of neighboring subgrains, as shown in Fig. 5.

In the figure, the contours indicate the centers of steel coalescence. The arrows indicate the "overgrowing" small subgrains that do not participate in this process.

As a result, the scale level of the process increases from the size of subgrains (cells) equal to 350…400 nm, to the size of the new structure that is just being formed, that is, almost an order of magnitude larger.

This collective unification process begins with the disappearance of unstable subboundaries (cell walls) (see Fig. 5 – marked by arrows). They "scatter" into dislocations, which move to a new position, forming a new subboundary that unites the coalesced subgrains. The process is energetically favorable because it leads to the redistribution and annihilation of dislocations with the participation of the processes of slip and climb, and the formation of more stable configurations.

Considering the relationship between strength and subgrain size, these processes can lead to softening of steel in accordance with the formula [11]:

$$\sigma_{суб} = k\, D^{-1},$$

k – interdislocation interaction parameter (0.13…0.15)·106 MPa·nm, D – sizes of cells, blocks, fragments. Based on this, the process of coalescence of subgrains should contribute to the observed process of softening during long-term operation of steel. Nanohardness studies (see Fig. 2) strongly confirm this fact.

After 200,000 h of operation, a significant increase in the size of precipitates at the boundaries of substructural elements and primary austenite boundaries is observed, with a simultaneous (in the middle of subgrains) process of redistribution, recovery, and poligonization of the dislocations (Fig. 6).

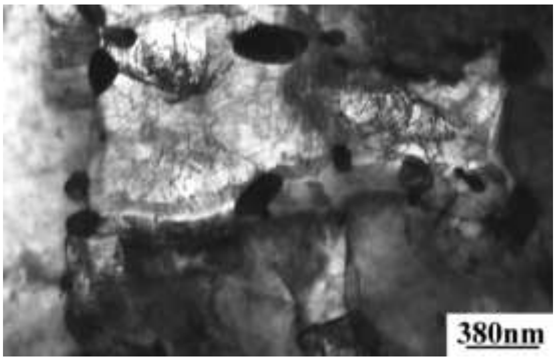


Fig. 6. Substructure BM after 200,000 h of operation

FRACTOGRAPHIC STUDIES OF THE BM MCP AFTER 200,000 h

Fractographic studies of the fracture surfaces of the BM MCP samples were carried out using a JSM 7001F electron microscope. EDS microanalysis was performed using an INCA Energy 350 spectrometer at a voltage of 20 kV.

The fracture surface of the original BM MCP sample after tensile testing is shown in Fig. 7.

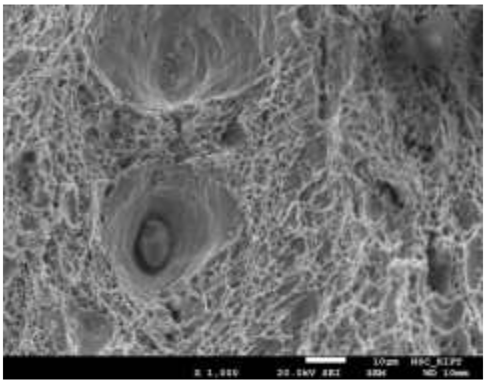
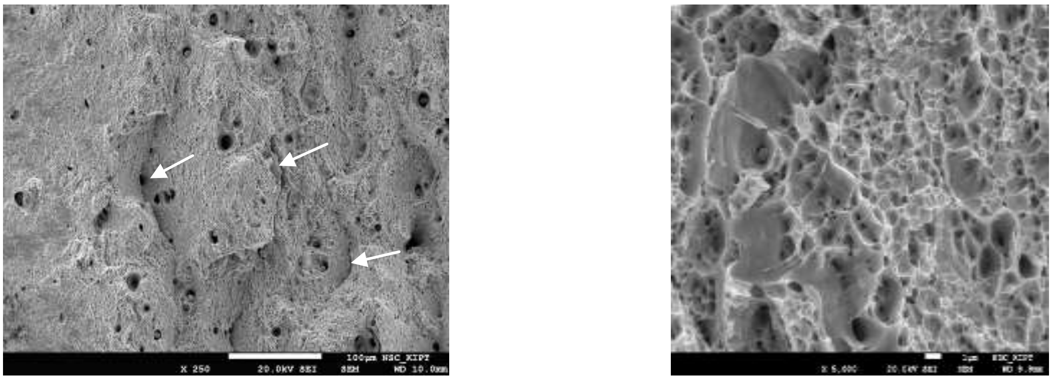


Fig. 7. Fracture surface initial sample of BM MCP after testing at 20 °C

There is a relatively viscous type of destruction with dimples of about 1 μm in size, not associated with the precipitates inside them. At the same time, a small (compared to them) number of very deep dimples were established, at the bottom of which there are spherical precipitates up to 3…4 μm in size. EDS microanalysis showed that they are, first of all, MnS precipitates.

The fracture surface of the BM MCP sample (after 200,000 h of operation) under tension at 20 °C is shown in Fig. 8. Thus, at the meso level (see Fig. 8,a), so-called quasi-brittle fracture occurs, the signs of which are cleavage facets along the boundaries of grains and subgrains.



a *b*

Fig. 8. The fracture surface of the BM (200,000 h of operation), after tensile testing at 20 °C. Meso-level – cleavage facets along the boundaries of grains and subgrains (a) and microstructural level – coalescence of ductile dimples (b)

At the micro level (see Fig. 8,b), two types of dimples are observed: low-energy, almost flat dimples with low elongation ridges between them (which indicates low energy costs for their merging), and, in comparison with them, a small number of deep dimples of ductile fracture with precipitates. EDS microanalysis showed that they are MnS precipitates.

The fracture surface of the BM MCP sample (after 200,000 h of operation) under tension at 350 °C, shown in Fig. 9. The flattening of the dimples due to reducing of the energy intensity of steel fracture after operation.

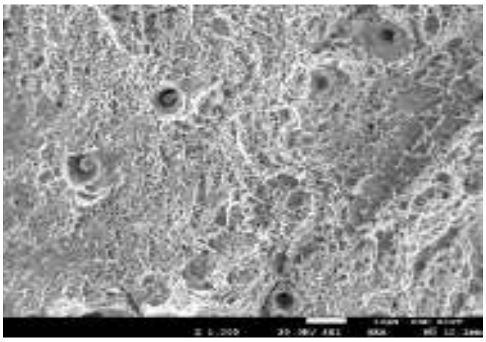


Fig. 9. The fracture surface of the BM MCP sample after tensile testing at 350 °C (200,000 h)

SEGREGATION ON THE GRAIN AND SUBGRAIN BOUNDARIES

In the work [12], after heat treatment (quenching from 890…910 °C in water, tempering at 650 °C for 18 h) and holding at temperatures from 300 to 400 °C for 10,000 h, steel 10GN2MFA showed high stability and resistance to stability. The activation energy of this process was determined for vessels steels – 15Kh2MFA and 10GN2MFA. It was shown that the aging mechanism is controlled by carbon diffusion and is associated with a change in the state of the carbide phase. However, microstructural studies confirming this conclusion were not provided. Therefore, these studies were carried out using electron microscopy.

Specific surface etching, together with the use of scanning electron microscopy made it possible to study the segregation of precipitates along the grain boundaries of the BM. Fig. 10 show the surfaces of the samples of the BM MPC of the 3rd unit of the PNPP after 100,000 and 200,000 h of operation, respectively.

The images were obtained using a JEOL JSM-7001F scanning electron microscope with a Schottky cathode. The technique is based on the registration of backscattered electrons (COMPO mode), which is sensitive to the composition of the sample surface.

It is clear that not only the degree of coverage of grain boundaries (subgrains) with carbides has changed fundamentally (which has increased significantly), but also their shape and size have changed dramatically after 200,000 h (large globules up to 3…5 μm in size). The precipitates are located both along the grain boundaries and in their body. At the same time, the size of the precipitates along the grain boundaries increases during the operation of the MCP.

Image processing shows that over the last 100,000 h of operation in the BM, the number of precipitates (larger than 80 nm in size) has decreased by ≈ 33%, while their average size has increased by ≈ 39%. It is natural to assume that the existing precipitates are merging and their sizes are increasing due to the migration of individual elements from the body of the BM grains (carbon).

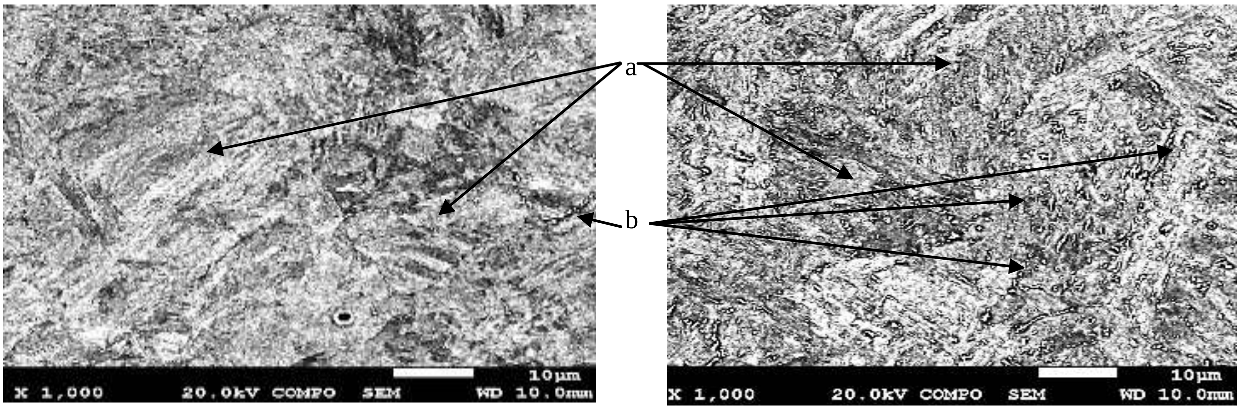


Fig. 10. The surfaces *of the BM MCP of the 3rd block of the YuU AES after 100,000 h (a) ta 200,000 h (b) of operation: a – BM grains; b – visibility along the grain boundaries and BM subgrains*

DISCUSSION

Thus, there are the following features of the evolution of the steel structure for 200 thousand h.

1. Increase in the content of lamellar-dislocation pearlite.

2. Change in the size and redistribution of carbides within the structural components of steel.

3. The effect of coalescence of the subgrain structure.

4. Softenning of steel with a high level of residual mechanical properties and impact toughness.

As can be seen from the presented figures, BM does not have “classical” lamellar pearlite.

From our point of view, the formation of the main component of pearlite (in our case, flat cementite nuclei) can be of a dislocation nature (Fig. 11) [13].

The presence of dislocation pearlite leads to an increase in the strength of the material.

This morphology of cementite is due to the following features of the transformation mechanism [14]: thermoplastic deformation of supercooled austenite and the formation of a polygonal structure in the form of flat dislocation walls, elastic interaction of dislocations in the walls with carbon atoms and the resulting formation of flat nuclei.

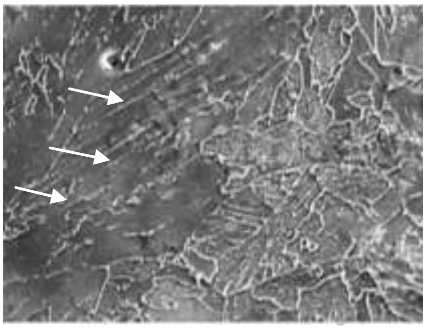


Fig. 11. Surface structure of a steel after 100,000 h of operation. The arrows indicate flat cementite nuclei, wich may have a dislocation origin

A similar mechanism of pearlite nucleation in carbon steels [15, 16] is when in austenite, at a temperature below the A1 point (stable austenite temperature), polygonal dislocation walls become centers of cementite platelet nucleation.

Thus, the evolution of precipitates involves processes of redistribution of both dislocations (stress relaxation) and carbon. Naturally, the amount of carbon associated with defects (dislocations) is determined by the density of the latter and increases with plastic deformation and high-temperature holding. It is well known that carbon migration into defects begins already at temperatures of minus 40°C [17]. Therefore, during operation, already at temperatures of about 300 °C, the aging of hardened and heat-treated steel will also be determined by the processes of carbon migration into dislocations (defects) and transfer along the defects themselves. The very relationship between the density of defects, dislocations and the concentration of carbon affects the intensity of steel aging.

The competition of the processes of the deformation strengthening and softenning (static, dynamic and *methododynamic* recrystallization) during hot deformation of the material of pipes made of 10GN2MFA steel are the main mechanisms determining the processes of structure formation, and, as a consequence, the change in its mechanical properties.

The reason for softenning hot deformed metal is the occurrence of processes of *methododynamic* recrystallization. When deformation is interrupted at the stage of dynamic recrystallization (heating for stamping and hot deformation), there are many fresh, not yet slandered, nuclei of recrystallized grains capable of growth in static conditions immediately after the cessation of hot deformation. This is due to the most important feature of methododynamic recrystallization for practice – the absence of an incubation period, recrystallization growth of grains in a short time of cooling of the metal with the deformation temperature [18].

As noted in [19], in forgings of 10GN2MFA steel there is an extraordinary liquefaction heterogeneity, which can lead to a local decrease in the critical point A_1 in links enriched with alloying elements – austenite formers. When tempering in the range of 660…670 °C of steel with a reduced critical point A_1 in steels of the 10GN2MFA type, a partial polymorphic transformation of ferrite into austenite occurs on these links. During the transition to the intercritical range, austenite islands are formed, which undergo a martensitic transformation upon subsequent cooling. The so-called martensitic-austenitic component (MAC) is formed, the presence of which increases strength and reduces impact toughness [18].

When hot forming products made of 10GN2MFA steel, for example, stamping of bottoms, bending of pipeline elbows of main circulation pipelines, liquefaction heterogeneity can lead to recrystallization processes that change their mechanical properties. When heated for stamping, partial dissolution of microalloying particles of vanadium carbides (VC) occurs, resulting in uncontrolled growth of austenite grains on links depleted in alloying elements [19].

In the study of the kinetics of thermal aging of 15Kh2NMFA steel at 350 °C for 10,000 h, it was established [20] that the change in strength, plastic and fracture toughness is extreme. The kinetic curves "property - aging time" are characterized by two stages. At the first stage (~1…2 thousand hours), slight embrittlement of the steel occurs, accompanied by an increase in strength and a drop in ductility. At the second stage, the recovery of these properties begins. At the first stage, the number of carbide particles increases, at the second, their growth and coagulation are observed, without changes in the phase composition. Statistical analysis of the sizes of carbide precipitates shows that the areas of maximum embrittlement correspond to the minimum average particle size. This may be due to an increase in the number of small particles and a decrease in the number of large ones in a given aging time region, which is consistent with the data on monitoring the value of the coercive force. The author of this work suggested that the first stage of aging is associated with the formation of carbide precipitates at dislocations as cities facilitated by carbon diffusion, and the second – with their subsequent coagulation and growth.

As shown in Fig. 1, the initial structure had a large number of finely dispersed carbides inside the subgrains. During operation (as can be seen from Fig. 5), a significant redistribution of carbon to the internal interfaces occurred. As a result, the boundary areas were depleted of carbide-forming elements.

In turn, this could create conditions for the diffusion of phosphorus to the separation boundaries, the development of brittleness of steel during further operation[21]. But, given that the concentration of phosphorus in steel (see Table 1) does not exceed 0.011%, the effect of phosphorus staining can be achieved over significantly longer periods of operation.

To test this hypothesis, the internal friction (IF) method was used [22]. The temperature dependence of IF indicate the carbon (120 °C), and phosphorus peaks (320 °C). The phosphorus peak of internal friction indicates changes in the state of grain boundaries and their enrichment with phosphorus.

The formation of a developed dislocation microstructure of the BM under the conditions of tube manufacturing and its evolution under the conditions of 30-year operation led to the fact that the mechanical characteristics and impact toughness of the pipes remained almost unchanged. Comparison of these results with the conclusions of a recent work on the behavior of aluminum alloy SAV under neutron irradiation conditions over the same 30 years at temperatures of 40…50 °C [23], allows us to conclude: the presence of preliminary thermo-mechanical treatment of the material and moderate operating temperature makes it possible to undergo recovery processes within 200 thousand h.

In [24], the evolution of the microstructure of vessel steel 2.25Cr-1Mo (analog 15Kh2MFA) after operation in the technological process of oil hydrocracking in the initial state and after operation for 60,000 h at a temperature of 450 °C was also investigated. A significant increase in the density of carbides at the boundaries of substructural elements was established, which is indisputable evidence of depletion of the solid solution both in alloying elements and in carbon, which led to some softenning of the matrix.

Thus, we have the same dependencies after different operating conditions of vessel steels.

CONCLUSIONS

A comprehensive study of the BM CMP PNPP was conducted, covering mechanical properties, impact toughness, nanohardness, scanning and transmission electron microscopy, metallography, etc.

1. A comparative analysis of the behavior of steel under different operating conditions was carried out:

• under cracking conditions in the oil and gas industry, 60,000 h, 450 °C,

• when studying the kinetics of thermal aging of vessels steel 15Kh2NMFA at 350 °C for 10,000 h,

• under operating conditions of the first circuit of a nuclear reactor (PNPP), 100,000 and 200,000 h.

The extreme nature of the evolution of the structure and properties of these steels, associated with the simultaneous action of changes in the dislocation substructure, and the redistribution of carbon (primarily) and phosphorus from the grain matrix to its boundaries.

2. It is shown that:

• at the initial stage of operation of the BM of the MPC (100,000 h), the density of precipitates along the boundaries of grains and subgrains increases, which leads to a decrease in plasticity regardless of the properties of the original metal and the operating temperature;

• at the subsequent stage of operation of the MCT (≈100…200 thousand h), depletion of the body of the grains of the BM in carbon, as well as coalescence of subgrains and precipitates are observed. Basically, depending on the initial state of the BM, this leads to a decrease in strength characteristics, and accordingly, some increase in the characteristics of plasticity and impact toughness.

3. Fractographic studies of fracture surfaces of BM samples after 200,000 h of operation indicate the so-called quasi-brittle fracture of BM steel at the mesostructural level (after tensile tests at 20 and 350 °C), with a simultaneous viscous (dimple) mechanism at microstructural level.

4. The contribution of thin-dislocation pearlite to the BM structure increases in the aging processes. This is facilitated by thermoplastic deformation of supercooled austenite and the formation of a polygonal structure in the form of flat dislocation walls, elastic interaction of dislocations near the walls with carbon atoms and the resulting formation of flat cementite nuclei.

5. The revealed changes in the BM structure at the subgrain level during the aging of the MCP, especially taking into account the increase in the service life of NPPs, it is necessary to expand the range of research methods at the subgrain level, which is most sensitive to changes during the aging of materials under operating conditions. Now it is necessary to carefully monitor the physical processes accompanying fractographic and relaxation (internal friction) studies, which may indicate the first signs of possible future brittleness.

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Article received 12.09.2025

ЗМІНА СУБСТРУКТУРИ ТА ФІЗИКО-МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ МЕТАЛУ ГЦТ РЕАКТОРА ВВЕР-1000 ВПРОДОВЖ 30 РОКІВ ЕКСПЛУАТАЦІЇ

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Наведено результати досліджень змін субструктури та фізико-механічних властивостей основного металу (ОМ) головних циркуляційних трубопроводів (ГЦТ) ПАЕС впродовж 200 тис. год експлуатації. Встановлено, зміна механічних властивостей ОМ має немонотонний характер. При цьому металографічний аналіз оптичними методами не показав значних змін структур ОМ. Методом наноіндентування виявлено зростання ступеня неоднорідності механічних властивостей ОМ по об'єму зерен при старінні ГЦТ. Електронно-мікроскопічні дослідження виявили зміни структури ОМ на субзеренном рівні. На початковому етапи експлуатації ОМ ГЦТ (~ 100 тис. год) зростає густина виділень по межах зерен і субзерен, що призводить до зміцнення, та зниження пластичності сталі. На наступному етапі (≈ 100…200 тис. год) спостерігається коалесценція субзерен та виділень. Це, переважно, призводить до зниження характеристик міцності і відповідно деякого збільшення характеристик пластичності та ударної в'язкості.