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DETERMINATION OF CHANGES IN MECHANICAL PROPERTIES OF METAL OF FEEDWATER PIPELINES BENDS AND "HOT" STEAM OF THE SECOND POWER UNIT OF PIVDENNOUKRAINSK NPP FOR THE SECOND 100,000 h OF OPERATION

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An analysis of the results of periodic testing of hardness of metal of pipelines bends of power unit No. 2 of Pivdennoukrainsk Nuclear Power Plant (PNPP) after ~100,000 and ~200,000 h of operation was carried out. It is shown that during the operation of feedwater and "hot" steam pipelines during the second 100,000 h of operation, the aging of the metal is observed, which is manifested in a partial, at least in their surface layers, uneven decrease in the strength of the metal. An increased rate of aging of the metal of pipeline bends is observed in areas where the metal was subjected to the greatest plastic deformation during the pipe manufacturing process (compressed and stretched sides of the bends). The critical parameter among the normalized mechanical properties of bending metal is the tensile strength, which is the first to reach a critical level when extrapolating the obtained data. While maintaining the rate of change in the mechanical properties of the metal at the level of the second 100,000 h of operation for post-project operation, the projected residual resource of metal bends of feedwater pipelines and "hot" steam is ~590,000 and ~380,000 h, respectively.

INTRODUCTION

During the design and construction of nuclear power plants, it is envisaged to use materials that, considering aging and potential degradation mechanisms, ensure the operability of equipment and pipelines in all modes of project operation [1]. During NPP operation, safety is ensured by maintenance, which includes a set of operations to monitor and maintain the operability of structures, systems (elements) [2]. A set of control operations is carried out to determine the current state of the equipment and pipeline metal, to confirm the compliance of its properties with the project standardized values, to record changes in physical and mechanical properties (structure) during operation [3]. Monitoring of the current state of the metal, detection and fixation of metal defects is usually carried out during shutdowns of power units for scheduled preventive repairs according to the standard programs for operational monitoring of the condition of the base metal, welded joints and surfacing of equipment and pipelines of nuclear power plants from the WWER-1000 reactor "ПМ-Т.0.03.061-21" [4].

At present, the majority of Ukrainian NPPs have switched from project operation (PO) to long-term post-project operation (PPO), which is due to economic feasibility. During the transition from PE to DSE, the unconditional priority of safety over production and economic activities was considered, which led to changes in the methodology of operational control. Monitoring of the current state of the metal is carried out in accordance with the standard program for periodic monitoring of mechanical properties of pipelines metal of NPPs with WWER-1000 reactors "ТРКМ-10-01" [5]. The purpose of control according to the standard program is detection and recording of changes in the mechanical properties and structure of pipeline metal at intervals of at least every 200,000 h of operation, in particular, on completion of PO [3]. This current testing is carried out by destructive (laboratory) and non-destructive methods. The results of this control are compared with the results of the previous control, the rate of change in properties (aging rates) is calculated, and the residual life forecasts are determined. The main problem in the study of pipeline metal aging according to periodic control data is the absence of significant changes in the standard properties of the metal during operation. The "natural" variation of the mechanical properties of the metal, even in its original state, is so significant that it is difficult to catch their changes during operation. To determine these changes, it is necessary to study the dynamics of changes in the mechanical properties of the metal during the operation of pipelines. When using destructive methods, this is ensured by sequential sampling of metal microsamples for research in laboratory conditions from the controlled section of the pipeline [6]. Microsampling does not affect the operation of the pipeline. The use of this technique made it possible to identify the non-monotonic course of changes in the properties of the base metal of the main circulation pipelines of the PNPP [7] power units during the PO. Feedwater and "hot" steam pipelines of WWER-1000 reactor units usually do not have such residual metal. As a result, the method of non-destructive determination of the mechanical properties of a metal based on hardness measurement data has become the most widespread one [8]. Planned cuttings of metal from these pipelines do not allow to determine the dynamics of changes in mechanical properties during operation, since it is impossible to link the data of individual cuttings with each other. The article is devoted to the determination of changes in the physical and mechanical properties of the metal bends of feedwater pipelines and the “hot” steam of power unit No. 2 of PNPP for the second 100,000 h of operation according to hardness control data.

MATERIALS AND METHODS

The feedwater pipelines of the WWER-1000 reactor units are made of steel 20 in accordance with “ТУ 14-3-460-89” and are designed to supply chemically purified, heated and deaerated water to the second circuit of steam generators. The diameter of the feedwater pipelines is 426 mm, the wall thickness is 24 mm. The pipelines are operated at 230 °C, working pressure – 120 kgf/cm^2.

The “hot” steam pipelines of the WWER-1000 reactor units are made of 15ГС (15GS) steel in accordance with “ТУ 108-11-194-77” and 16ГС (16GS) steel in accordance with “ТУ 3-923-75”, designed for the transport of saturated steam from steam generators to the turbine. The diameter of the “hot” steam pipelines is 630 mm, the wall thickness is 24 mm. The pipelines are operated at 294 °C and a working pressure of 80 kgf/cm^2.The design service life of the pipelines is 30 years (~200,000 h).

The hardness of the pipeline metal is controlled at room temperature, the normative values of the mechanical properties of the metal of the pipelines at 20°C are given in Table 1 [9].

Table 1

Standard values of mechanical properties of the base metal of pipelines at 20 °C [9]

Pipeline	Steel	Limits of strength Rtm, kgf/mm^2	Flow limit RtP$_{0.2}$, kgf/mm^2	Relative elongation A, %	Relative elongation A, %
		no less			
Feedwater	20	41	22	21	40
“Hot” steam	15ГС	50	28	16	40
	16ГС	46	25	21	42

Hardness is not a normalized property of a metal, normalized mechanical properties are calculated according to the corresponding correlation between mechanical properties and hardness [9]:

for steel 20 – $\boldsymbol{R_m = 16.47 + 0.2266\ HB + 0.00021\ HB^2;}$

$$\boldsymbol{R_{p0.2} = -4.28 + 0.238\ HB + 0.00022\ HB^2;}$$

$$\boldsymbol{A = 49.0 - 0.131\ HB,}$$

$$\boldsymbol{Z = 137.0 - 0.525\ HB;}$$

for steels 15ГС and 16ГС – $\boldsymbol{R_m = 0{,}35HB;}$

$$\boldsymbol{R_{p0.2} = 0{,}545\ HB - 47{,}1;}$$

$$\boldsymbol{A = 49 - 0.131\ HB;}$$

$$\boldsymbol{Z = 137.0 - 0.525\ HB.}$$

The paper uses the results of periodic monitoring of the mechanical properties of the metal properties of the pipelines of power unit No. 2 of the PNPP after ~100,000 and ~200,000 operating hours in 2004 and 2017, respectively. Non-destructive testing was carried out in accordance with “РД ЭО 0027-94” [10]. The hardness (HB) of the metal was checked in 4 diametrically opposite places of the pipelines by the resonance-impedance method (UCI-method).

In non-destructive testing, the focus is on bend inspection because bends are the most dangerous elements in the piping system [11–13].

RESULTS AND DISCUSSION

The hardness of the metal of the inspected feedwater pipeline (steel 20) of the power unit varies in the range from 133 to 208 HB, and the hardness of the metal of the “hot” steam pipeline (steels 15ГС and 16ГС) – in the range from 143 to 220 HB. Calculations according to the corresponding correlation ratios [11] show that the mechanical properties of the metal meet the normalized requirements. In particular, the tensile strength (Rm) of the feedwater pipeline metal after 200.000 operating hours varies in the range from 48.9 to 62.7 kgf/mm^2, yield strength (Rp$_{0.2}$) – from 29.5 to 50.5 kgf/mm^2, elongation (A) – from 26.3 to 33.1 %, relative narrowing (Z) – from 47.2 to 66.8 %. Non-destructive testing has shown that the comparison of the average values of the mechanical properties of metals does not allow to single out the contribution due to the aging processes during the operation of pipelines. The variation in the initial state of the mechanical properties of the metal of the above pipelines outweighs the contributions to changes in the properties caused by aging processes. As a result, in the future, when analyzing the results of non-destructive testing, the properties of the metal of only the same pipeline inspection zones after ~100,000 and ~200,000 operating hours were compared, considering the area (compressed, neutral or tensioned) of the bend.

Hardness of metal (steel 20) of the corresponding sections of the feedwater pipeline after ~100,000 and ~200,000 operating hours are shown in Figs. 1–3.

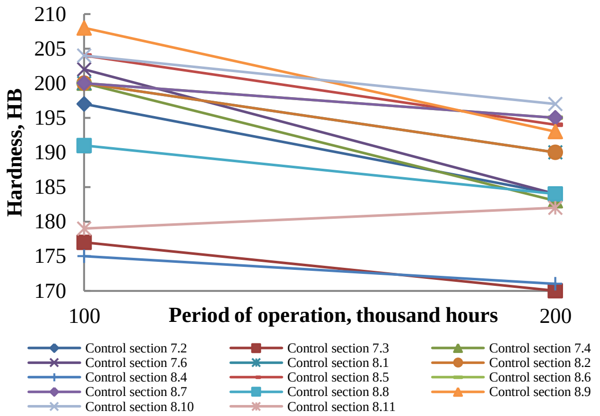

Fig. 1. Metal hardness of compressed bend zones of PNPP Unit 2 feedwater pipeline

Hardness of metal (steel 15ГС and 16ГС) of individual bends of the pipeline of “hot” steam after ~100,000 and ~200,000 operating hours are shown in Figs. 4–6.

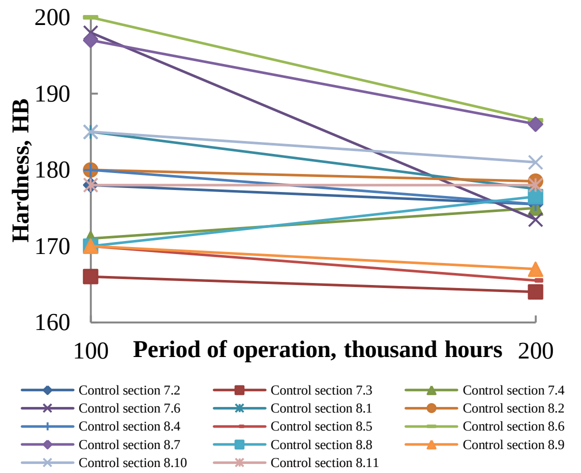

Fig. 2. Metal hardness of neutral zones of bends of the feedwater pipeline of PNPP Unit 2

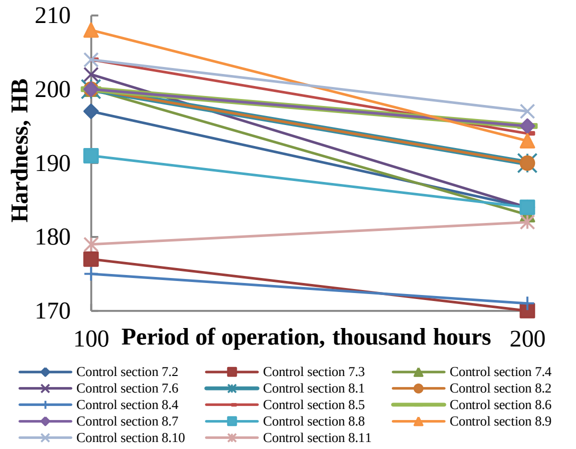

Fig. 3. Metal hardness of the tensile bend zones of the feed water pipeline of PNPP Unit 2

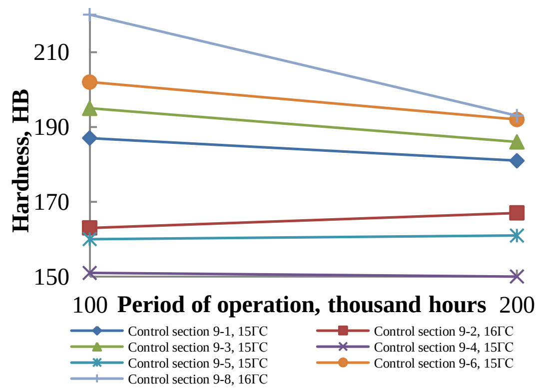

Fig. 4. Metal hardness of compressed zones of bends of the "hot" steam pipeline of PNPP Unit 2

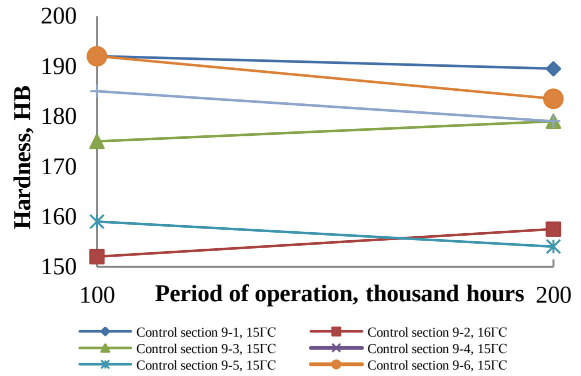

Fig. 5. Metal hardness of the neutral zones of the bends of the "sharp" steam pipeline of PNPP Unit 2

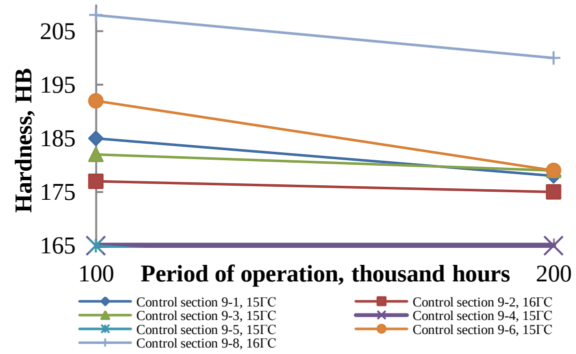

Fig. 6. Metal hardness in tensile bending zones of the "hot" steam pipeline of PNPP Unit 2

Table 2

The average change in the mechanical properties of the metal bends of feedwater pipelines and the "hot" steam of PNPP Unit 2 for the second 100,000 h of operation

Pipeline	Control area	Change in tensile strength, %	Change in yield boundary, %	Change in elongation, %	Change in relative narrowing, %
Feedwater	Compressed	-3.2	-4.6	3.8	9.8
	Neutral	-1.6	-2.4	1.7	4.1
	Tensioned	-3.7	-5.3	4.6	12.5
"Hot" steam	Compressed	-3.7	-7.1	3.6	8.7
	Neutral	-0.8	-1.5	0.6	1.4
	Tensioned	-3.1	-5.8	2.9	7.1

Figs. 1–6 show that the changes in the mechanical properties of the bending metal during the next 100,000 h of operation of these pipelines have multidirectional dynamics. This is mostly due to the dependence of the rate of aging processes on the initial characteristics of the metal (in particular, for example, the grain size) from which the pipeline elements are made [7].

The general direction of changes in the mechanical properties of metal bending during the operation of pipelines is given in Table 2.

The general trend of changes in the mechanical properties of the metal bends of the above pipelines is a decrease in strength during operation in the second 100,000 h of operation. Moreover, the highest rate of changes in mechanical properties is observed in the metal of compressed and tensioned bending areas (in areas where the metal was subjected to the greatest plastic deformation in the process of bending manufacturing).

Even though during the inspection, the mechanical properties of the bending metal meet the standardized requirements, the revealed effect of reducing the strength of the metal during the operation of pipelines requires the determination of the predicted residual life. It should be noted that in the development of the projected residual resource of metal, not the average results of metal control are considered, but those that, when forecasting, ensure the achievement of one of the normalized properties of a critical level in the shortest possible service life. The forecast made by extrapolating the values of the mechanical properties of bending metal after 100,000 and 200,000 h of pipeline operation is presented in Figs. 7 and 8.

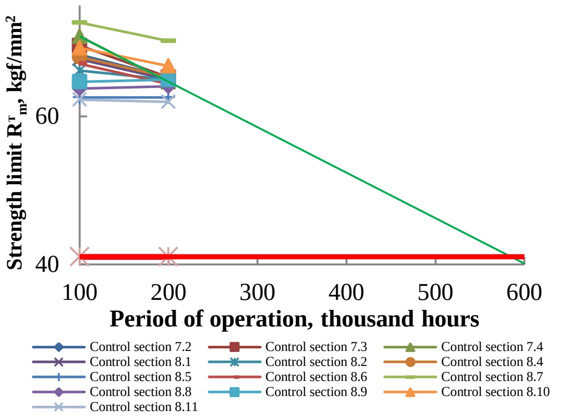

Fig. 7. Boundary of the metal strength in compressed bending zones of the feedwater pipeline of PNPP Unit 2

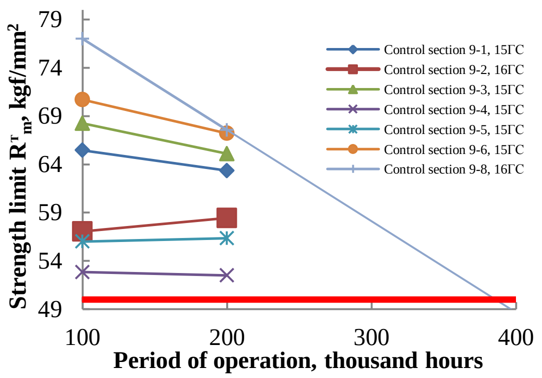

Fig. 8. Tensile strength of the metal of the compressed bending zones of the "hot" steam pipeline of PNPP Unit

Considering the non-monotonic change in the mechanical properties of the metal during the operation of pipelines [7], this forecast is short-term, valid for the period until the next regular inspection of pipelines. For the given pipelines, the critical normalized property of the metal is the tensile strength, the critical zone of bends is compressed. The projected residual life of pipelines significantly exceeds the time before the next inspection.

CONCLUSIONS

1. An analysis of the results of periodic testing of metal hardness of bends in the pipelines of PNPP Unit 2 after ~100,000 and ~200,000 h of operation was carried out.

2. It is shown that during the operation of feed water and "hot" steam pipelines during the second 100,000 h of operation, metal aging is observed, which is manifested in a partial, at least in their surface layers, uneven decrease in metal strength. Presumably, this is due to the migration of part of the carbon to the grain boundaries, which requires the study of pipeline metal samples after long-term operation by direct methods.

3. It is shown that the increased rate of aging of the metal of pipeline bends is observed in areas where the metal in the process of pipe manufacturing was subjected to the greatest plastic deformation (compressed and tensioned sides of the bends).

4. The critical parameter among the normalized mechanical properties of bending metal is the tensile strength, which is the first to reach a critical level when extrapolating the obtained data. If the rate of changes in the mechanical properties of the metal is maintained at the level of the next 100.000 hours of operation for non-design operation, the predicted residual life of the metal bends of feed water pipelines and "hot" steam is ~590,000 and ~380,000 h, respectively 2.

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ВИЗНАЧЕННЯ ЗМІН МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ МЕТАЛУ ЗГИНІВ ТРУБОПРОВОДІВ ЖИВИЛЬНОЇ ВОДИ ТА «ГОСТРОЇ» ПАРИ ДРУГОГО ЕНЕРГОБЛОКУ ПАЕС ЗА ДРУГІ 100 тис. годин ЕКСПЛУАТАЦІЇ

С.В. Гоженко

Проведено аналіз результатів періодичного контролю твердості металу згинів трубопроводів енергоблоку №2 ВП ПАЭС після ~100 та ~200 тис. год експлуатації. Показано, що при експлуатації трубопроводів живильної води та «гострої» пари впродовж других 100 тис. год експлуатації спостерігається старіння металу, яке проявляється у частковому, принаймні їх поверхневих шарів, нерівномірному зниженні міцності металу. Підвищена швидкість старіння металу згинів трубопроводів спостерігається на ділянках, де метал у процесі виготовлення труб піддавався найбільшій пластичній деформації (стиснені та розтягнуті сторони згинів). Критичним параметром серед нормованих механічних властивостей металу згинів є межа міцності, яка першою при екстраполяції здобутих даних досягає критичного рівня. При збереженні темпів змін механічних властивостей металу на рівні других 100 тис. год експлуатації на позапроєктну експлуатацію прогнозований залишковий ресурс металу згинів трубопроводів живильної води та «гострої» пари складає ~590 та ~380 тис. год відповідно.