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EMPIRICAL PREDICTED RESIDUAL LIFE OF THE BASE METAL OF MCP OF WWER-1000 REACTORS IN OPERATION

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The comprehensive analysis of the results of research by direct methods of BM of MCP of the South-Ukraine NPP after 100,000 and 200,000 h of operation was carried out. In BM with a fine-grained initial structure, the first stage of the aging process, accompanied by metal strengthening, is completed during the first 100,000 h of MCP operation; then the second stage begins, accompanied by decreasing of metal strength. In BM with a coarse-grained initial structure, the first stage of the aging process lasts more than 200,000 h of operation. The predicted residual resource of MCP is determined by the resource of BM with a fine-grained initial structure. The critical regulatory property at the first stage of the aging process of BM is relative elongation, at the second stage – the strength limit.

INTRODUCTION

The main circulation pipelines (MCP) of WWER-1000 reactors are among the most responsible elements that ensure the safe operation of the nuclear power plant. At a temperature above 250 °C, steel 10ГН2МФА, from which the MCP of power units of WWER-1000 reactors is made, is prone to temperature aging. The replacement of MCP during the operation of Ukrainian NPPs is not foreseen, the reliability of their operation is ensured by periodic control of the real properties of the base metal (BM) of the MCP during operation.

During the long-term operation of pipelines, in most cases, the processes occurring in the metal have not been sufficiently studied. At the same time, quantitative forecasting has insufficient reliability. The step-by-step control of the actual properties of BM during the operation of pipelines allows you to automatically consider the influence of all processes that take place during the aging of the metal on the mechanical properties. The control ensures the further trouble-free operation of the pipelines.

The task of periodic control is to establish compliance of the mechanical properties and metal structure of pipelines with regulatory requirements, in particular, ПНАЕ Г-7-002- 86 [1].

A comparison of the initial properties of BM with similar characteristics after 100,000 and 200,000 h of MCP operation [2] showed that in most cases the changes are insignificant, and the properties are not lower than the level stipulated by regulatory requirements. However, most studies do not reveal the aging of BM in the process of MCP operation, they only register the properties of individual fragments of MCP elements. In connection with this, the difference in the rate of aging of individual elements of the MCP is not considered during the selection of the areas of the MCP survey, and it is impossible to develop justified forecasted residual resources.

The main problem of studying the aging of BM of MCP according to periodic control data is the absence of significant changes in the standard properties of the metal during operation. The "natural" spread of mechanical properties of metal even in its initial state is so significant that it is difficult to detect their changes during operation. The influence of metal aging processes on the mechanical properties of BM can be detected only by systematic examination of the same areas of MCP fragments during long-term exploitation of MCP by direct methods. At present, these conditions are satisfied only by direct control of BM of MCP power units 1, 2, and 3 of the South-Ukraine NPP after 100,000 and 200,000 h of operation [3–5].

The article is devoted to the comparison of the results of this control, to the detection of the dependence of the aging rates of BM on the properties of the starting metal during the operation of the MCP. The work examines the methodology for determining the control areas of the BM of MCP, which require key attention during periodic control.

RESEARCH METHODOLOGY

To reduce the influence of "natural" dispersion of metal properties on research results:

1. BM was monitored from the same pipe element of the MCP, from the closest neighboring areas of the surface, in the initial state and after 100,000 and 200,000 h of operation.
2. Control of BM properties was carried out by direct methods in laboratory conditions.
3. Sampling of BM was carried out by the electroerosion method from the thickening of pipe elements, without reducing the operational characteristics of the MCP.
4. Samples for research were made of metal located at a distance (depth) of ~ 2 mm from the surface of thickenings on the compressed side of the bends.

The methodology for cutting BM samples and research by direct methods is sufficiently fully described in work [5], which gives the results of BM control of the MCP of power unit 3 of the South-Ukraine NPP after 200,000 h of operation.

The initial characteristics of BM bends and their operating conditions are presented in Table.

Initial characteristics of BM bends of MCP examined by direct methods

Bend	Power unit	Operating tempera-ture, °C	Average grain diameter, μm	Limits of strength R^t_m, kgf/mm^2		Flow limit $R^t_{p\,0.2}$, kgf/mm^2		Relative elongation A, %		Relative narrowing Z, %	
				20□	350□	20□	350□	20□	350□	20□	350□
1	1	288	55	58.5	53.3	42.7	32.5	29.4	25.3	75.6	71.8
2	2	320	22	58.1	53.1	44.8	39.1	26.7	21.8	75.6	68.7
3	3	288	18	58.9	52.5	44.3	41.6	22.5	21.5	71.1	68.9

EMPIRICAL PREDICTED RESIDUAL LIFE OF THE BM OF MCP

The study of structural changes in BM during long-term operation of MCP by direct methods [3–5] indicated that these changes are due to temperature aging processes. This process is caused by the thermodynamic non-uniformity of the initial state of BM and the gradual approach during operation of the structure to the equilibrium state under conditions of sufficient diffusion mobility of carbon atoms. Structurally, this is reflected in the migration of carbon from the grain body to the boundaries with the formation and growth of carbide particles along the boundaries (Fig. 1).

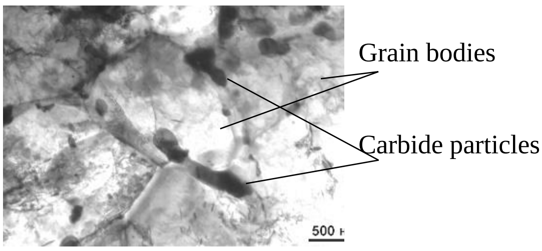

Fig. 1. Structure of BM after 200,000 h of MCP in operation [3]

Preliminary measurements of the hardness distribution and Young's modulus of BM grains by volume using the nanoindentation method showed that BM is homogeneous in its initial state; and during long-term operation of the MCP, the strength of the body of the BM grain decreases, and in the region of the boundaries it increases.

Structural changes lead to changes in the properties of BM, on which the operational reliability and, ultimately, the service life of the MCP depends. The list of mechanical properties, the value of which is strictly regulated, is determined by regulatory documents. For BM of MCP of power units of WWER-1000 reactors, this is the strength limit R_m, yield strength $R_{p0.2}$, relative elongation A, relative narrowing Z. The term during which, because of operation, one of the named properties of the BM will exceed the regulatory limits, is the resource of the MCP. During periodic control, the real properties of the BM are determined and the change in properties is predicted until the next control stage, the short-term predicted residual resource (PRR) is calculated, as a rule, for one period until the next inspection of the pipeline. The calculation of the empirical PRR of BM of MCP is based on experimental data.

The change of BM properties in the process of MCP operation is shown in Fig. 2–5.

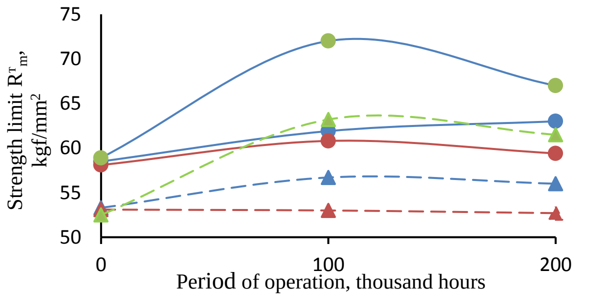

Fig. 2. Change in the strength limit of BM of MCP in operation

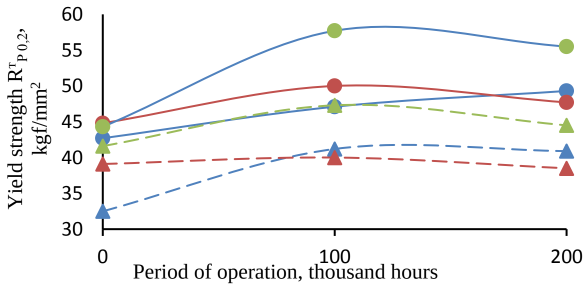

Fig. 3. Change in yield strength of BM of MCP in operation

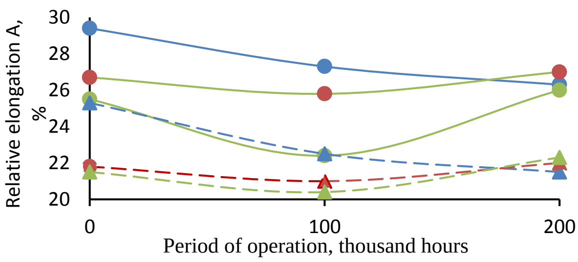

Fig. 4. Change in the relative elongation of the BM of MCP in operation

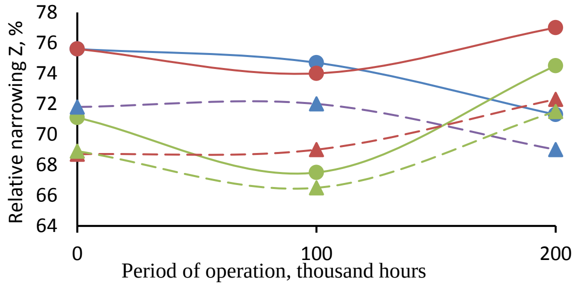

Fig. 5. Change in the relative narrowing of BM of MCP in operation

In the figures, the results of control of bend 1, bend 2, and bend 3 of BM are displayed in blue, red and green colors, respectively. Marker ● indicates control data at a temperature of 20 °C, marker ▲ – at a temperature of 350 °C.

It should be noted that the BM properties of all examined bends meet the requirements of normative documents, but the rates of their changes vary.

The change in the mechanical properties of BM during the operation of the MCP has a non-monotonic character. Control of BM properties after 100,000 h of MCP operation (due to the specifics of control by direct methods of MCP in use) does not allow to determine their bending points, but allows, assuming that the rate of changes in properties does not change after every 100,000 h of operation, to calculate the PRR for each normative property.

During the first 100,000 h of operation, there is a strengthening of the BM of MCP (compared to the data of archival metal studies), a decrease in plasticity, regardless of the properties of the original metal and the operating temperature. At the same time, the rate of change varies significantly due to the “natural” dispersion of the properties of the original metal.

PRR calculations based on data for the first 100,000 h of operation showed that the relative elongation of the BM of bend 3 is a critical property. Fig. 6 shows the linear trend of the relative elongation of the BM in the initial state and after 100,000 h of MCP operation.

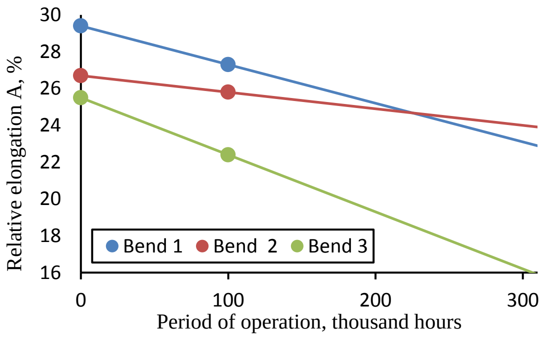

Fig. 6. Linear trend of changes in the relative elongation of BM based on data for the first 100,000 h of MCP operation

Empirical PRR of BM, based on examination of three bends during the first 100,000 h of MCP operation, was ~ 305,000 h.

The figure shows that with the initial properties of BM, close to the normative ones, the relative elongation of individual elements of the pipeline can reach a critical level even before the next inspection of the MCP.

Over the next 100,000 h of operation, a slight weakening of the BM of bends 2 and 3 is observed. The BM of bend 1 continues to strengthen, while the rate of strengthening has significantly decreased. This is observed both at 20 and at 350 °C tests. PRR calculations show that at this stage of MCP operation, the critical property is the strength limits of bend 3. Fig. 7 presents a linear trend of the data obtained during MCP control after 100,000 and 200,000 h of operation to their critical level.

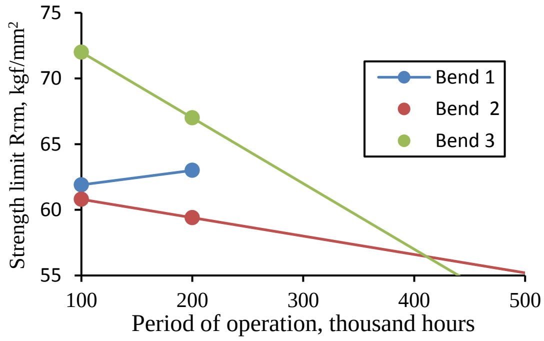

Fig. 7. Linear trend of changes in the BM strength limit based on data for the second 100,000 h of MCP operation

Empirical PRR of BM, based on examination of three bends during the second 100,000 h of MCP operation, amounted to ~ 440,000 h.

Figs. 6 and 7 show that the PRR of BM of MCP with bend 3 after 100,000 and 200,000 h of operation is the smallest. A characteristic feature of this bend is that in its original state, the metal from which it is made has the smallest grain size. It should be noted that the 10ГН2МФА steel, from which the MCP is made, consists of a mixture of grains of different shapes and sizes. In the passports of the pipe elements used in the production of MCP, the average grain sizes are given, which only indirectly characterize their real sizes. The dependence of changes in normative mechanical properties (at a temperature of 20 °C) during the second 100,000 h of MCP operation on the average grain size of the original BM is shown in Figs. 8–11.

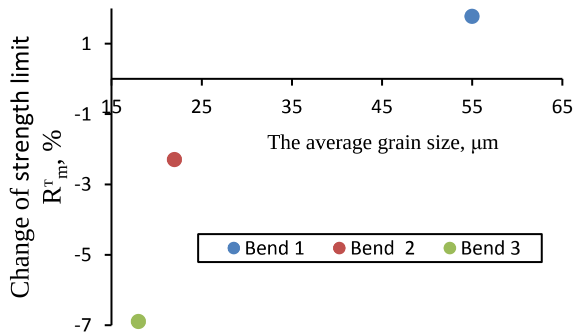

Fig. 8. Dependence of BM strengthening on grain size during MCP operation

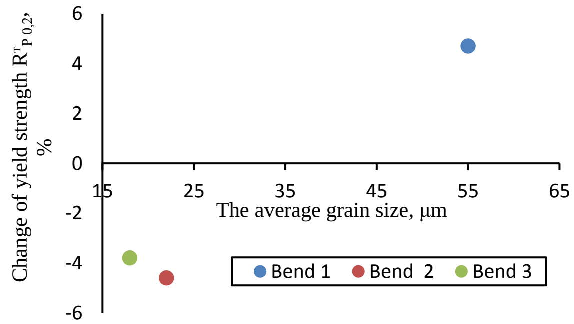

Fig. 9. Dependence of yield strength $R_{p0.2}$ on grain size during MCP operation

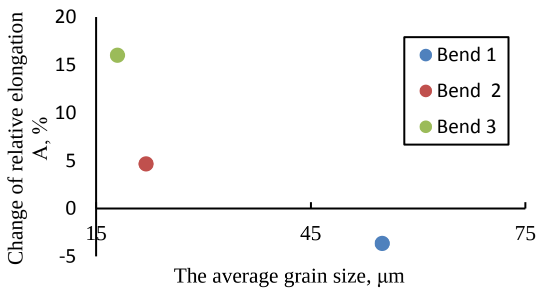

Fig. 10. Dependence of the relative elongation of the BM on the grain size during operation of the MCP

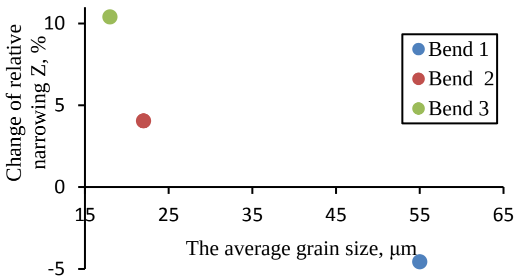

Fig. 11. Dependence of the relative narrowing of the BM on the grain size during operation of the MCP

The figures show that the grain size is one of the parameters on which the rate of “aging” of BM depends. This is because the time of migration of carbon atoms to the grain boundaries depends on the grain size.

As a result of the limited amount of experimental data, different temperature conditions for the operation of bends, and the indirect display of real grain sizes, it is impossible to quantitatively display the dependence of aging rates on grain size. However, such a dependence is decisive when the MCP is operated for 200,000 h. The average grain size can be a reference parameter when determining the BM control areas. The dependence on the operating temperature of the BM of MCP is also observed. This is noticeable from the comparison of the obtained dependences for the BM of “hot” (bend 2) and “cold” (bends 1 and 3) of MCP threads.

CONCLUSIONS

1. A comprehensive analysis of the results of research by direct methods of the BM of MCP of the South-Ukraine NPP after 100,000 and 200,000 h of operation was carried out.

2. The first stage of the aging process of BM with a fine-grained initial structure, accompanied by strengthening of the metal, ends during the first 100,000 h of MCP operation, then the second stage begins with a decrease in the strength of the metal. In BM with a coarse-grained initial structure, the first stage of the aging process lasts 200,000 h of operation.

3. The predicted residual resource of MCP is determined by the resource of BM with a fine-grained initial structure. During the first 100,000 h of MCP operation, the critical normative property is the relative elongation, during the second 100,000 h – the strength limit.

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ЕМПІРИЧНИЙ ПРОГНОЗОВАНИЙ ЗАЛИШКОВИЙ РЕСУРС ОСНОВНОГО МЕТАЛУ ГЦТ РЕАКТОРІВ ВВЕР-1000, ЩО ЗНАХОДЯТЬСЯ В ЕКСПЛУАТАЦІЇ

С.В. Гоженко

Проведено комплексний аналіз результатів досліджень прямими методами основного металу (ОМ) ГЦТ Південно-української АЕС після 100 та 200 тис. год експлуатації. В ОМ з дрібнозернистою вихідною структурою перший етап процесу старіння, що супроводжується зміцненням металу, завершується впродовж перших 100 тис. год експлуатації ГЦТ, а потім починається другий, що супроводжується зниженням міцності металу. В ОМ з крупнозернистою вихідною структурою перший етап процесу старіння триває 200 тис. год експлуатації. Розрахунки прогнозованого залишкового ресурсу показали, що ресурс ГЦТ визначається ресурсом ОМ з дрібнозернистою вихідною структурою. Впродовж перших 100 тис. год експлуатації ГЦТ критичною нормованою властивістю є відносне подовження, впродовж других – межа міцності.