SECTION 2
THERMAL AND FAST REACTOR MATERIALS

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INFLUENCE OF TiN-INCLUSIONS AND VIBRATION LOADS FOR DAMAGE TO HEAT EXCHANGE PIPES OF STEAM GENERATORS PGV-1000

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Operational damage to heat exchange tubes (HET) in the steam generators of power units WWER-1000 was studied using metallography and electron microscopy. The mechanism of crack initiation and growth has been established. It includes the combined action of non-metallic TiN inclusions in 08Cr18N10T steel, their drawing during pipe rolling, as well as vibration loads in HET. An interpretation is given for differences in HET damage rates in steam generators PGV-1000 and PGV-440. Activities to reduce the level of HET damage and increase the resource capabilities of steam generators is proposed.

INTRODUCTION

During the period of intensive construction of NPP power units, the issue of materials with the required properties has acquired particular relevance. Moreover, this issue applied not only to the materials of the reactor core itself, but also to the heat exchange equipment. For WWER-1000 projects, the choice of material of heat exchange tubes of steam generators has become a top priority. In the previous prototypes, WWER-440 projects, austenitic stainless steel 08Cr18N10T pipes were used in the heat exchangers of steam generators. The same steel was chosen as the material for heat exchange tubes in VVER-1000 reactors.

However, under the operating conditions of VVER-1000 power units, it was found that local damages appear in the HET metal over time: corrosion pits and cracks. Both types of damage pose a threat to the safe operation of power units. As it was established [1, 2], the metal ulceration is caused by the deposition of products of corrosion and erosion wear of the secondary circuit equipment, leading to contact corrosion. This reason was eliminated in the process of fine-tuning the operating modes of steam generators and making structural changes of the system of their cleaning.

To date, there is no consensus regarding the cause of the appearance of cracks in the walls of the HET, although it is generally recognized that this is due to the properties of steel 08Cr18N10T. In Refs. [3, 4] it was shown that non-metallic TiN inclusions in steel can be the cause of crack initiation, and crack growth is due to alternating stresses stimulated by HET vibration. However, the evidence bases of the positions put forward, according to the authors themselves, was not convincing enough.

Taking into account the importance of the proposed concept, additional studies of cracks in the walls of the HET were carried out in order to specify the mechanism of cracking. This paper presents the results of these researches.

EXPERIMENTAL PROCEDURE

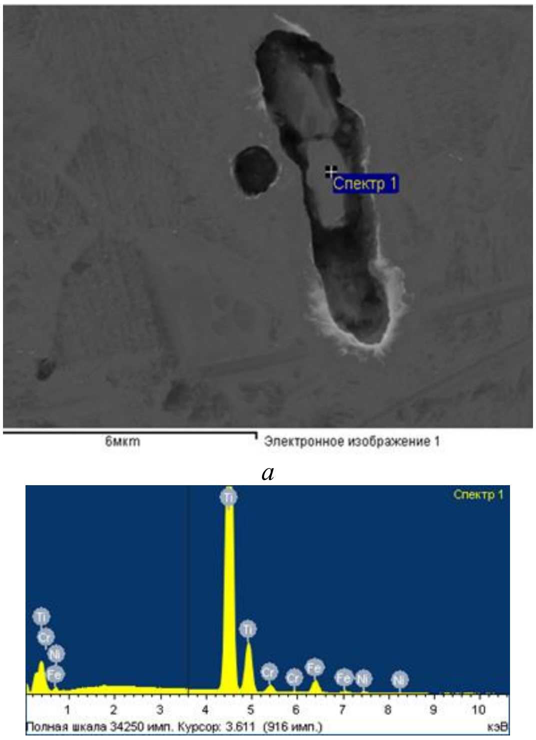
The objects of research were HET fragments cut from the steam generator PG-1 at the second power unit of the South Ukraine NPP after its decommissioning [2]. The state of the outer surface of the HET, located in the medium of the second circuit of the reactor, and cracks in the walls of the HET were investigated. Metallographic thin sections for research were made in the longitudinal and transverse sections of the HET segments. To reveal the microstructure and defects of 08Cr18N10T steel, electroetching was used, as well as chemical etchants based on solutions of ethyl alcohol and nitric acid.

For comparison, samples of the initial material from a pipe of the same range and size that was used for the manufacture of HET were also examined. The revealed inclusions and defects were analyzed using the methods of metallography and electron microscopy. Optical microscopes MMO-1600AT and MBS-7 with attachments for digital photography and scanning electron microscope JEOL JSM-7001 Energy350 with an energy dispersive microanalysis (EDS) system were used in the studies.

RESULTS

In high-quality steel 08Cr18N10T, which is used for the manufacture of HET, non-metallic inclusions of nitrides, sulfides and carbonitrides are allowed at the level of the fourth point according to the standards [5]. The presence of titanium nitride inclusions in steels alloyed with titanium was also found in [6], where the non-metallic phase in austenitic stainless steels 08Cr18N10T and 03Cr18N10T was studied by scanning electron microscopy. When studying the HET material, in addition inclusions of titanium nitrides, inclusions of metallic titanium (Fig. 1) and globular titanium sulfides (Fig. 2) were found in it.

The number of inclusions in the HET material did not exceed the established norms. The presence in the compositions of inclusions of elements included in steel 08Cr18N10T can be explained by the small size of the inclusions, which are comparable to the diameter of the analyzer probe (3 µm). The focus of the work was on TIN inclusions because the titanium nitride inclusions are much more common than others. Moreover, globular inclusions have a lesser effect on crack formation than acute-angled inclusions.



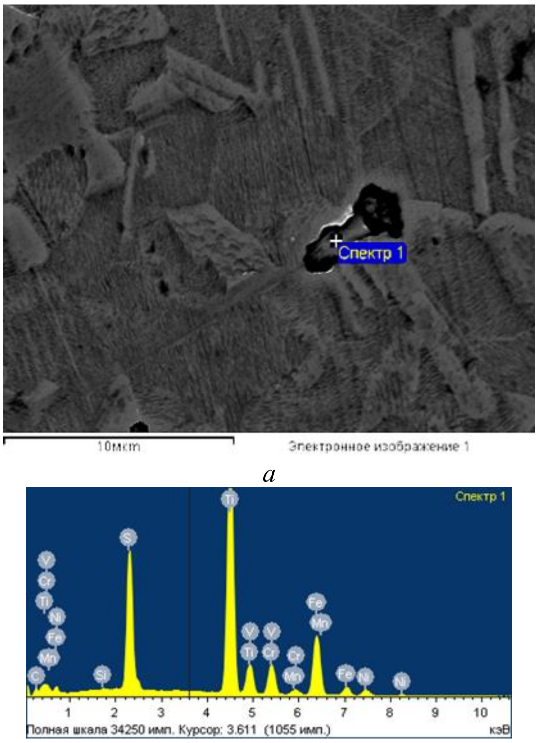
a

b

Element	Weight %	Atomic %
Si	0.16	0.28
Ti	77.31	79.52
Cr	5.94	5.63
Mn	0.28	0.25
Fe	14.52	12.81
Ni	1.79	1.50
Results	100.00	–

c

Fig. 1. Microsection in the cross section of HET with the inclusion of titanium in steel 08Cr18N10T (a), EMF spectrum (b) and elemental composition of the inclusion (c)



a

b

Element	Weight %	Atomic %
Si	0.24	0.39
S	16.04	23.20
Ti	46.78	45.30
V	0.24	0.21
Cr	8.68	7.75
Mn	0.49	0.41
Fe	24.26	20.15
Ni	3.27	2.59
Results	100.00	–

c

Fig. 2. Thin section in cross section HET. Inclusions of titanium in steel 08Cr18N10T (a), EMF spectrum (b) and elemental composition of the inclusion

Figs. 3 and 4 show TIN inclusions found on the HET surface. The inclusion in Fig. 3 was pressed by a rolling roller into the metal surface without dragging.

In the manufacture of pipes using the cold rolling method, TIN inclusions leave grooves on the metal surface. Fig. 4 shows the surface of the metal with a trace from the dragging of the inclusion before it was pressed into the metal and partially collapsed. It can be assumed that inclusions and grooves from them are the centers of crack initiation during the operation of HET.

Fig. 5 shows the surface of the HET with the ends of the cracks. The surface is cleaned of oxide deposits and etched electrolytically. The ends of the cracks are located in the depths of the “troughs” formed as a result of the washing out of the oxidized metal in the vicinity of the crack. The cubic Ti crystal is located directly above the crack channel (Fig. 5,a).

The matrix material (steel 08Cr18N10T) has an austenitic structure with a grain size of 5…10 µm. The crack propagated through the grains in a transcrystalline manner (see Fig. 5,b).

The ends of other cracks are shown at higher magnification (Fig. 6). As can see, cracks break off rectangular fragments from austenite grains, and these fragments are TIN inclusions.

Cracks in the middle part are shown in Fig. 7. Smooth bends and branchings characteristic of transcrystalline cracks are observed (see Fig. 7,a,b). Cracks opening in their middle part it can be quite large (see Fig. 7,c), while the outlines of the coasts do not correspond to one another. TiN inclusions partially embedded in the metal are observed on the banks of cracks (highlighted by contours). This confirms the participation of inclusions in cracking.

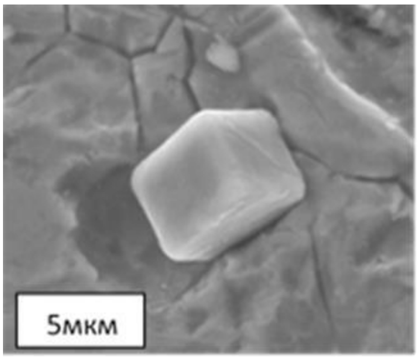


Fig. 3. Inclusion of TiN on the HET surface

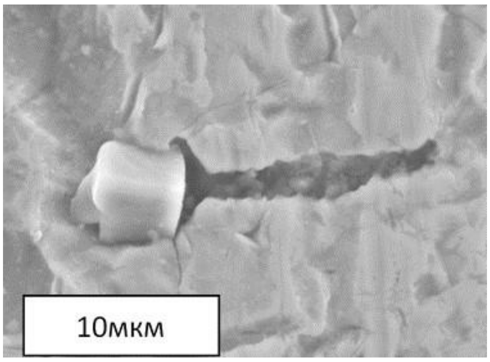
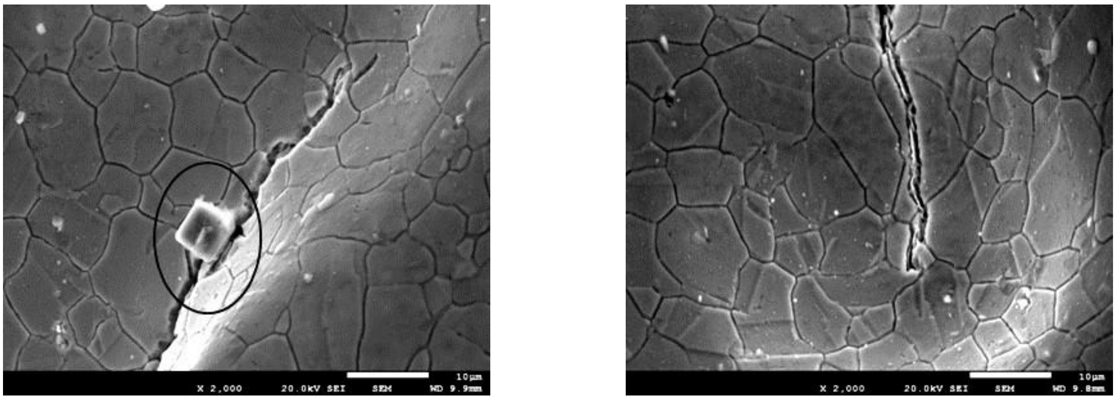
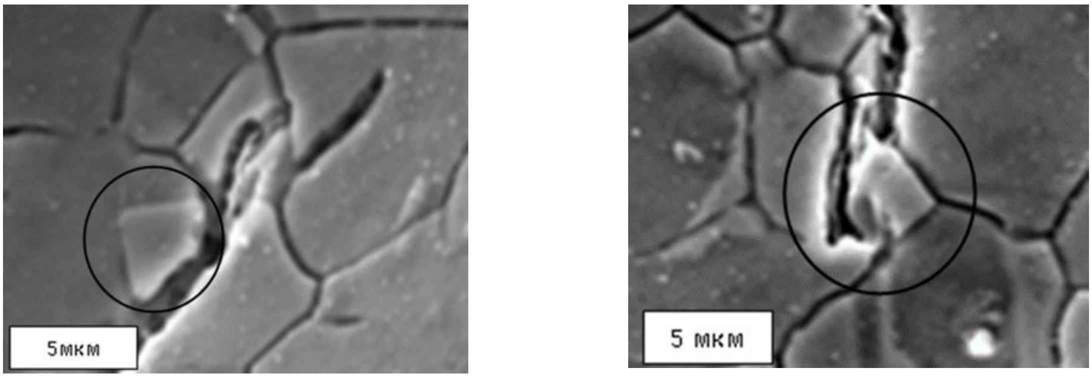


Fig. 4. Inclusion and trace from its dragging



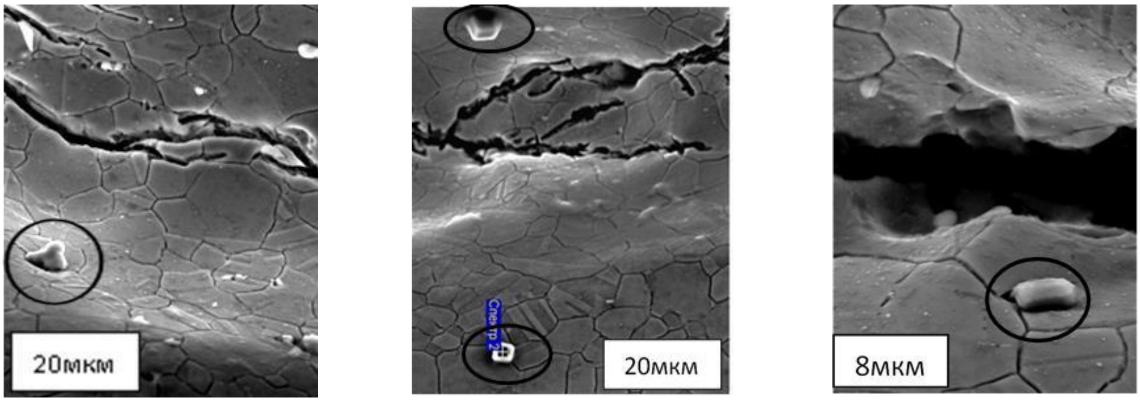
a *b*

Fig. 5. Crack endings on the HET surface: TiN above the crack channel (a), transcrystalline nature of crack growth (b)



a b

Fig.6. Crack ends (a) and inclusion on the HET surface (b)



a *b* *c*

Fig. 7. Middle part of cracks and inclusions of titanium nitrides on the HET surface (a,b,c)

Fig. 8 shows a fracture in the middle of a crack on the tube surface. It can be seen that the crack bed is filled with corrosion products.

Under the layer of oxides, the outlines of a cubic inclusion are guessed, similar to the inclusions of titanium nitrides shown earlier.

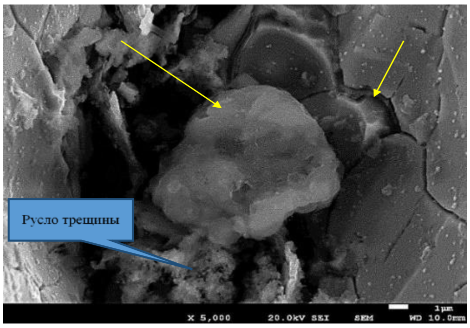


Fig. 8. Fracture on the surface of the tube. The arrows indicate the oxidized grain of the matrix metal and the cubic inclusion

The shapeless fragment in the center (shown by the arrow) is an oxidized grain of the matrix metal that has broken off from the crack wall, which most likely contains an inclusion of titanium nitride. It can also be seen that around the inclusion, along the grain boundaries, the edges of the crack collapsed, obviously, when it collapsed under the action of vibrations.

Cracks in the walls of the HET. Cracks in the walls of the HET were studied on thin sections in the cross section of the tubes. Cracks propagate into the metal perpendicular to the outer surfaces of the tubes. Secondary cracks branch off from the main crack. In this case, the general direction of cracking is preserved (Figs. 9, 10). The channels of cracks are widened due to deposits of corrosion products in them. One can to see TiN inclusions near the crack tip (Fig. 10,b).

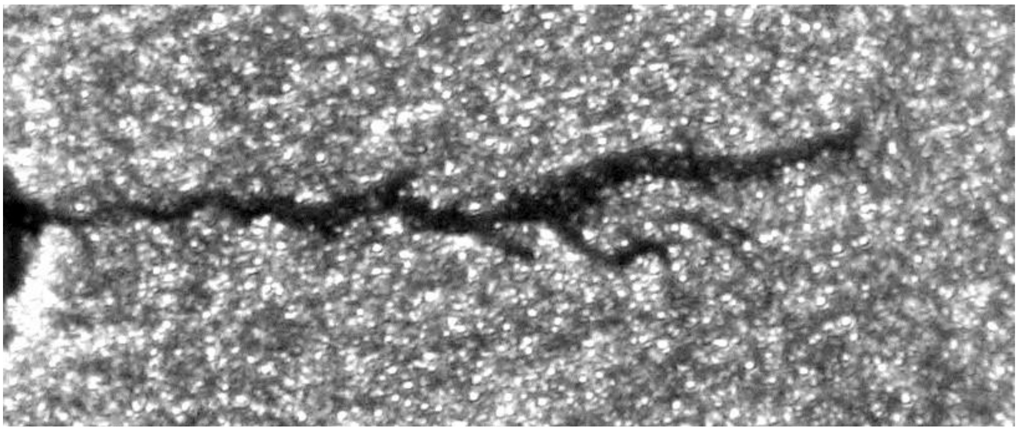
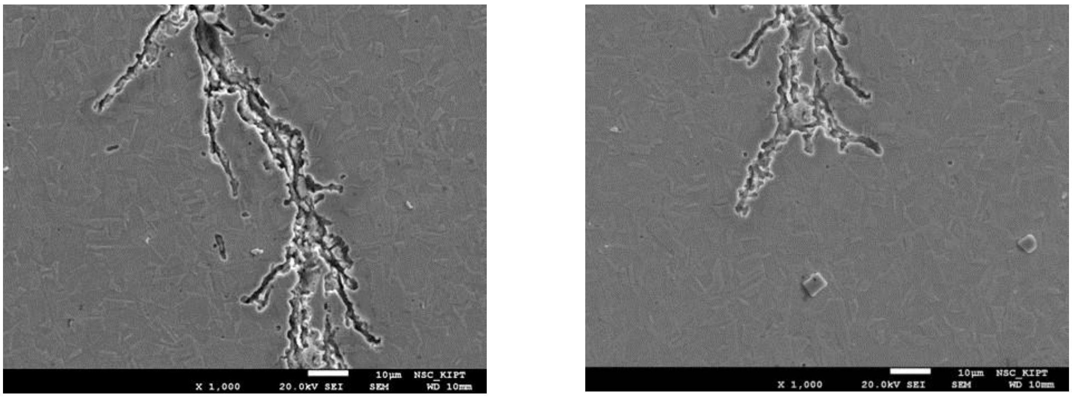


Fig. 9. Typical crack in the HET wall



a *b*

Fig. 10. Cracks in HET walls: middle part (a), crack tip and inclusions (b)

DISCUSSION

It can be seen from the above data that, in most cases, *HET* cracking is accompanied by TiN inclusions. The nature of the cracks is typically fatigue, and the presence of oxides inside the cracks makes it possible to concretize them as a manifestation of corrosion fatigue. Cracks in the pipe walls begin on the outer surface of the HET, the direction of the cracks is longitudinal, their length is limited to approximately 15 mm.

All the above figures testify in favor of the fact that the cracks were formed on the scratches left on the surface of the HET by inclusions and their fragments. The performed studies, in our opinion, give an idea of the mechanism of the influence of titanium nitride inclusions on the cracking of HET. It is well known that non-metallic inclusions often play a decisive role in the initiation of destruction of metal structures. In the monograph [7], modern ideas about the effect of inclusions on fracture processes in steels are quite fully presented. The initiation and development of cracks near non-metallic inclusions and the formation of various kinds of defects can be facilitated by mechanical loads, an aggressive (or non-aggressive) environment, deformation conditions (temperature, speed, degree, method of exposure).

The anti-corrosion property of stainless steels is based on the creation of a protective film of chromium oxide on their surface.

The thickness of this film is about 0.1 μm [8]. It was pointed out in [3] that the presence of TiN inclusions on the steel surface leads to discontinuity of the oxide film and, accordingly, to local corrosion. Such inclusions do not significantly affect the mechanical properties of the metal.

In our case, the effect of inclusions is manifested in the processes of local corrosion of stainless steel 08Cr18N10T. When the HET is bent, the inclusion-matrix bond is broken. The cavities formed near the inclusions on the HET surface open the access of the liquid medium to the inclusion–matrix interface. The juvenile surfaces of the matrix that border with the inclusion interact with the active liquid medium to form oxides that are deposited inside the cavity. Such a process intensively takes place in HET with their bending vibrations at the moments of tensile stresses. Over time, the cavity is filled with oxides. At the moments of action of compressive stresses in the inclusion-matrix system, the interface grows and the initial microcrack is formed deep into the metal. The microcrack volume, as well as the boundary cavity, is also filled with a liquid medium at the moment of the next stretching cycle, with the subsequent formation of oxides. Then, when the crack collapses in a cyclic mode, the acts of its growth take place.

Subsequently, the wedging effect is exerted by oxide deposits on the juvenile surfaces in the cavity of the formed initial crack. Periodic openings of the cavity between the inclusion and the matrix during pipe vibration cause steel corrosion processes near the inclusions and crack growth. The growth of a crack is associated with the accumulation of oxides in the crack, their loose structure, the nature of the vibration and the activity of the medium.

Over time, the inclusion on the HET surface loses its connection with the matrix and is pushed out of it by oxide deposits and compression cycles during vibration. Apparently, therefore, it is often impossible to see the inclusion in the oxide layer directly in the crack channel. Under the influence of the wedging action of oxides, the initial crack is transformed into a macroscopic one, which continues to grow deep into the metal until its channel is completely filled with oxides and the liquid active medium stops flowing to its tip.

The chains of fragments of TiN inclusions shown in the figures above and the scratches formed by them are stress concentrators that stimulate the growth of a crack along the HET surface.

Based on the above concepts, it is possible to explain the features and causes of defect formation in the HET of horizontal steam generators of the PGV types. In these steam generators, the headers are arranged asymmetrically, and a tube bundle zone with the most intense steam release is formed between them. The increased vibration of the HET in this zone causes the greatest alternating stresses in them. This, in our opinion, explains the fact that, according to statistics, this zone has the largest number of HET defects in both PGV-1000 and PGV-440 [9]. The methods of eddy current testing also note a common feature for these steam generators: defects are formed in HET mainly near the tube bundle supports (near the spacer grids). The reason for this is the greatest alternating stresses in these zones during the vibration of the HET. This also indicates a significant role of vibrations and inclusions in the formation of damage. Long-term operation of PGV steam generators shows that the HET damage rate in PGV1000 is higher than in PGV-440. The vibration level of HET depends on their thermal load. The specific heat load of the heating surface in PGV-440 (90 kW/m^2) is less than in PGV-1000 (123 kW/m^2) [10]. With the complete similarity of the designs of these steam generators, the HOT vibration level in PGV-1000 is obviously higher, which explains their more frequent damage.

The considered facts confirm the assumptions made earlier that it is the inclusions in steel 08Kh18N10T, as well as vibrations together with them, that are the causes of operational damage in the HET of steam generators.

The topical question is what measures should be taken to reduce the level of HET damage, taking into account the fact that the operation of power units is extended by 30 and 60 years in excess of the design life. In the initial period of operation of steam generators at WWER-1000 power units, a large percentage of HET damage was observed, and at different NPPs, the damage rates were different. A large number of HETs failed due to the formation of corrosion pits in the areas of steam generators filled with sludge deposits. In particular, for this reason, four steam generators that had not worked out their design life at the power units of the South Ukraine NPP were replaced.

Measures were taken to remove sludge and chemically wash the heat exchanger, as well as to optimize the aquatic environment (secondary circuit water chemistry). It became obvious that the operation of steam generators in the presence of sludge deposits is not permissible. At present, as a result of the organizational and technical measures taken, the formation of corrosion pits in the HET metal has been reduced to an acceptable minimum. Therefore, this type of damage is not considered in this work. However, it should be noted that the mechanism of formation of corrosion pits on steel 08Cr18N10T remains insufficiently studied. As for the causes of HET cracking, much has become clear with the disclosure of the role of non-metallic inclusions.

Steel 08X18H10T for the production of TOT. Regarding the prospects for the applicability of steel 08Cr18N10T for the production of HET, two interrelated issues are of practical interest:

1) what are the possibilities of eliminating non-metallic TiN inclusions during the smelting of blanks from steel 08Cr18N10T and the manufacture of HET;

2) how it is possible to improve the performance and durability of structures in the presence of titanium nitride inclusions in steel. From the foregoing, it follows that the precipitation of inclusions in castings of steel 08Cr18N10T, their concentration and size are determined by many technological factors: the method of introducing the charge, the grain size of the material, the method of mixing during melting, and so on. On different steam generators operating in the same modes, there are different rates of damping due to a different number of defects in the metal. This can be explained by the different content of inclusions in the HET metal, which is a matter of metallurgical technologies. The process of smelting steel 08Cr18N10T is constantly being improved. Apparently, with the development of melting

modes, it will be possible, if not completely avoided, then significantly reduce the concentration and size of inclusions.

The mechanism of formation of cracks in the walls of HET on the traces of drawing of inclusions left during cold rolling, considered in the work, gives grounds for recommendations to produce pipes up to the size of HET by hot rolling. Solid TiN inclusions during hot rolling are pressed into the matrix without drawing along the surface. Inclusions do not leave scratches and do not act as stress concentrators. The degree of cleanliness of the pipe surface during hot rolling decreases, however, in our opinion, this will not have a significant effect on the performance of the HET. Concerning the issue of the influence of inclusions on the resource characteristics of HET, it should be noted that the HTC methods show a large number of cracks in them that have stopped growing at the level of permissible defects. There are also through cracks that do not leak. This is quite understandable, based on the features of the crack formation mechanism discussed above, and suggests that the current kill criteria are do not quite correspond to the actual performance of the HET.

Thus, the decision to kill HET according to the HTC data should, apparently, be made taking into account the kinetics of crack growth, which should reduce the rate of killing.

CONCLUSION

The paper considers new experimental data obtained as a result of in-depth studies of cracks in HET using metallography, scanning electron microscopy and energy dispersive microanalysis.

Based on experimental studies, it has been shown that the formation of cracks in HET is caused by the presence of non-metallic inclusions and scratches in the near-surface layer of 08Cr18N10T steel, which are left by inclusions on the surface of pipes during their rolling, as well as by HET vibrations. The first two factors depend on the technology of steel smelting and pipe metalworking. Pipe vibration is determined by the design features of steam generators.

It is recommended to take into account the kinetics of their growth when making a decision on killing HET with defects such as cracks.

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ВПЛИВ TiN-ВКЛЮЧЕНЬ І ВІБРАЦІЙНИХ НАВАНТАЖЕНЬ НА ПОШКОДЖУВАНІСТЬ ТЕПЛООБМІННИХ ТРУБ ПАРОГЕНЕРАТОРІВ ПГВ-1000

А.С. Митрофанов

За допомогою металографії та скануючої електронної мікроскопії досліджено експлуатаційні пошкодження теплообмінних труб (ТОТ) у парогенераторах енергоблоків ВВЕР-1000. Встановлено механізм зародження і зростання тріщин, який включає спільну дію неметалічних включень TiN у сталі 08Х18Т10Т, їх волочіння при прокаті труб, а також вібраційні навантаження в ТОТ. Отримано пояснення відмінностей у темпах пошкодження ТОТ на енергоблоках ВВЕР-1000 та ВВЕР-440. Розглянуто питання, яких заходів слід вжити для зниження рівня пошкодження ТОТ та підвищення ресурсних можливостей парогенераторів.

ВЛИЯНИЕ TiN-ВКЛЮЧЕНИЙ И ВИБРАЦИОННЫХ НАГРУЗОК НА ПОВРЕЖДАЕМОСТЬ ТЕПЛООБМЕННЫХ ТРУБ ПАРОГЕНЕРАТОРОВ ПГВ-1000

А.С. Митрофанов

С помощью металлографии и сканирующей электронной микроскопии исследованы эксплуатационные повреждения теплообменных труб (ТОТ) в парогенераторах энергоблоков ВВЭР-1000. Установлен механизм зарождения и роста трещин, который включает в себя совместное действие неметаллических включений TiN в стали 08Х18Т10Т, их волочение при прокате труб, а также вибрационные нагрузки в ТОТ. Получено объяснение различий в темпах повреждаемости ТОТ в парогенераторах ПГВ-1000 и ПГВ-440. Рассмотрен вопрос, какие меры следует предпринять для снижения уровня повреждаемости ТОТ и повышения ресурсных возможностей парогенераторов.