PHYSICAL-MECHANICAL ASPECTS OF DEGRADATION OF HEAT-ECHANGE TUBES METAL FOR STEAM-GENERATORS OF THE TYPE PGW-1000

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By metallography and scanning electron microscopy the effect of titanium carbonitride and silicon carbide on degradation of steel 08X18H10T was revealed on heat exchanging tubes (HET) of steam generators of power-generating units of WWER-1000. The role of structural features of steam generators on nucleation and growth of operational defects of HET is shown.

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INTRODUCTION

Power generating units of South-Ukraine NPP (SU NPP) with reactors WWER-1000 operate more than 30 years (first and second). The operation of third units approaches this term.

During the operational period the problematic parts of the project were revealed. The shut-downs of reactor plants and unscheduled maintenances were carried out for the removal of leakages of steam generators HET. For the stable operation of steam generators on all NPP with reactors WWER the regular inspection of HET is carried out by the systems of non – destructive control with the use of the method of eddy-current control (ECC). This method allows to obtain the large information about the HET metal state and the decision about shut-downs are based on the obtained results. The extremely topical problem is the setting of substantiated criteria of shut-downs [1, 2] and, as consequence, of HET the expediency of changes in technology of HET production is considered.

METHODS

Specimens for investigation were produced from fragments of HET cut out from steam generator SG-1 after its removal from service on second power unit of SU NPP [3]. Metallographic studies were carried out on microsection metallographic specimens prepared in longitudinal and cross section of HET segments with the use of optical microscopes MMO-1600. Structure of metal, morphology of defects and non-metallic impurities were investigated on scanning microscope JOEL-7100 F. Materials obtained early on development of catalog “Atlas of operational defects in heat-exchange tubes of steam generators PGW-1000 on power units with reactors WWER-1000“ were also analyzed [4].

To analyze the data and statistical estimates results of zone-periodical controls on SU NPP were used; these results were obtained during the use of ECC on three power units of reactor WWER-1000 (from 2006 to 2017 years). Control of HET was performed by the “System of eddy-current control “TEDDY-4” with the use of inner axial eddy-current transducer (ECT). Methods of calculations and analysis of results of control steam optimization of the volumes and regularity of the control. It is well-known that the solution of this problem must be based on the results of fundamental material-science investigation.

Institute of solid state physics, material science and technologies (ISSPMST NSC KIPT) was involved in investigation of operational damage of heat-exchange tubes (HET) of steam generators PGW-1000. In the result of these investigations a cycle of papers describing character and mechanism of defects production in HET was published, atlas of corrosion defects was made.

The goal of presented paper is the definition of the reasons of degradation of HET with operational damages on the base of published papers and also obtained new data on positions of indication along HET. On development of prospective projects on the base of experience in technology of production generator of the type PGW-1000 (M) are published early [5].

RESULTS AND DISCUSSION

At Ukrainian NPPs, in order to assess the TOT health status, the established criteria are used, which are based on the phase ("shortage of metal", %) and amplitude characteristics of the eddy current signal (amplitude, V). In the process of control, these characteristics are displayed on the operator's display in the form of indications. Indication - any ECC signal showing deviations from the normal state of the HET wall.

Results of statistical investigation data of ECT have shown that HET of steam generators of SU NPP during all years of their operation the considerable quantity of defects are near site of mounting in spacer grids [5]. Moreover on the base of monitoring results about 80% of defects are concentrated in the area of 3-4 inter grid distances from hot collector (Fig.1). Much higher quantity of defects is observed in the area near “cold” collector (CC). And comparatively low percent of defects is detected in the areas of tube bundle a long way of collectors.

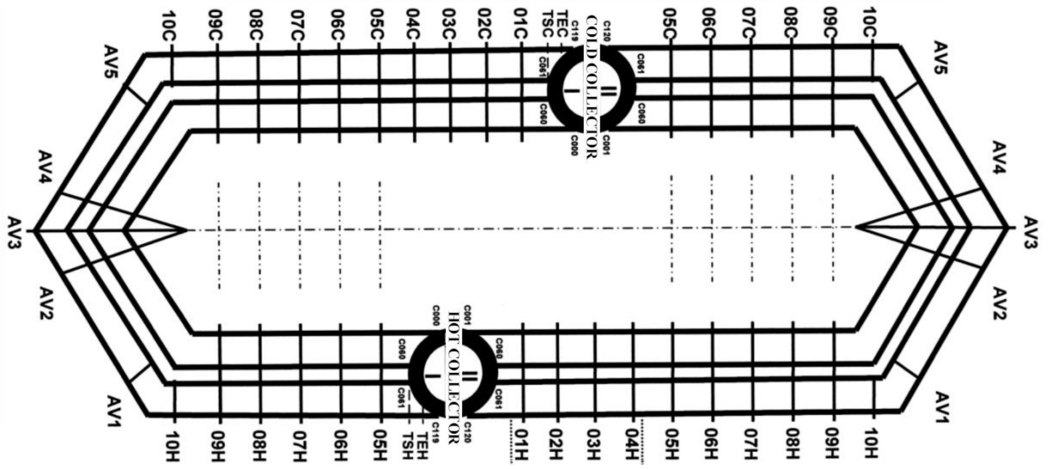


Fig. 1. Scheme of heat exchangers of steam generators of SU NPP: TEN (TEC) –inner surface of “hot” (“cold”) collector; TSH (TSC) – outer surface of “hot” (“cold”) collector; 01H(C) –number od spacer grid from “hot” (“cold”) collector

The same distribution of defects in tube bundles is observed on power units of reactors WWER-1000 and on other NPPs. On steam generators of power units of WWER-440 the analogous picture is observed [7]. The nature of indications shows that their majority represents cracks with low opening. According the results of statistical data analysis the assumption was made that nucleation and growth of cracks proceeds due to the metal fatigue, namely, corrosion fatigue. Besides, experimental facts of the effect of non-metallic impurities in steel on processes of corrosion-fatigue nucleation of cracks were obtained [5, 6]. Due to the significance of these conclusions for determining of causes of degradation metal science aspects of their damage were studied in more details.

On eddy-current control of HET the majority of obtained indications have comparatively low amplitude of signal on “shortage of the metal” in limits to 70%. Such indications occur from cracks with low opening which are the fatigue cracks [7].

Fig. 2 shows the typical crack the depth of which makes about 500 μm (“shortage of metal” 33%).

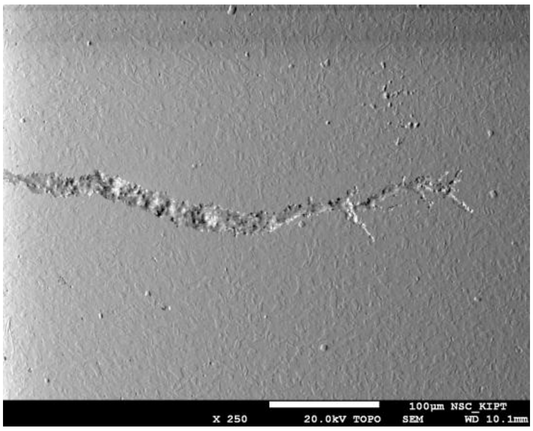
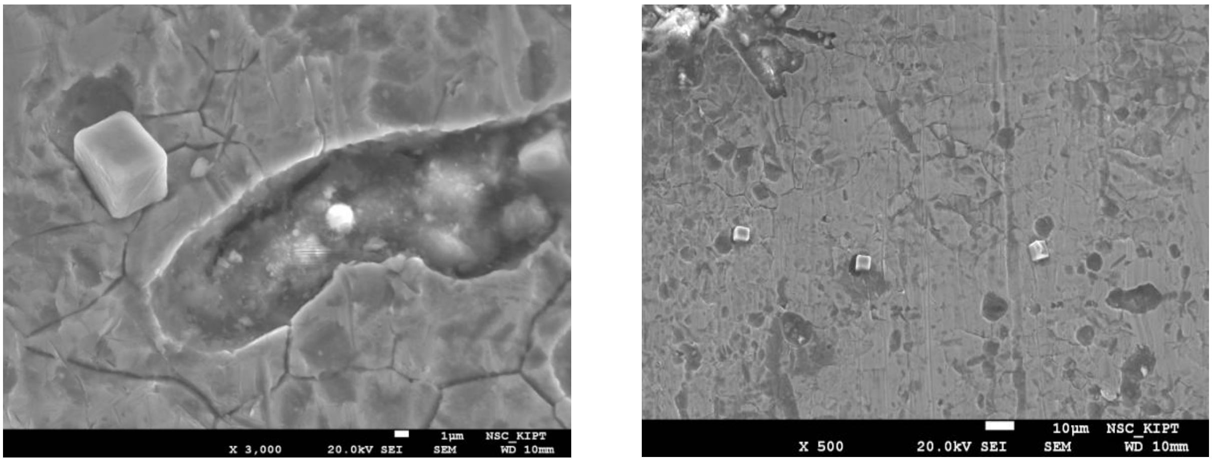


Fig. 2. Characteristic cracks (indication of ECC with characteristics: “shortage of metal”, amplitude – 1.74 V)

Crack spreads by surface of HET along its generating on the distance near 1 mm. Mouth of crack is filled by products of corrosion of steel 08X18H10T.

What factors in operating conditions influence on nucleation and growth of cracks? First of all, on our opinion, this is vibration of HET and effect of thermal cyclic loads. Existence of vibration was noted by the results of metallographic study in paper [5].

One more important factor which influences of cracks nucleation is inhomogeneity of surface of the metal. As it is shown in paper [8] such inhomogeneities on surface of HET may be non-metallic impurities. According to normal in steel 08X18H10T impurities of nitrides, carbonitrides, sulphides and others on level of fourth marks over the scale [9]. According to the results of investigations the quantity of non-metallic impurities in the material of HET doesn`t exceed normal. Metallographic studies of steel showed group and isolated non-metallic impurities with cubic cut of gold paint with the size 10 μm. X-ray structure microanalysis demonstrated the composition of impurities – these are titanium carbonitirides. Inclusions are of metallurgical origin. Titanium mixture is charged into ladle with melt in air. Titanium which has high affinity for nitrogen forms chemical composition of titanium with nitrogen with high area of homogeneity from $Ti_{10}N_6$ to TiN [10]. Titanium nitride has face-centered cubic lattice, temperature of melt 2930°C and approaches diamond by hardness. Due to the high temperature of melting nitrides precipitate into melt. On crystallizing they are dissipated in ingots as cubic crystals of gold paint. According to the mechanism of formation these crystals may be regarded as “precipitation of secondary phase”. During tube refining process crystals on appear on treated surface; due to their high hardness they are pressed into matrix or crack on fragments. In [8] are shown the cases of inclusion arrangement in metal near surface of HET on micro section metallographic specimens. In present investigations the same inclusions are revealed directly on the surface of HET. Fig. 3,a shows the inclusion with cubic cut on HET surface near the top of the crack. Surface was chemically treated for removal of deposits. The banks and fronts of crack are pickled, mouth is filled by products of corrosion. Fig. 3,b shows the group of characteristic inclusions on the surface of HET.



a *b*

Fig. 3. Titanium nitride on surface of HET: a – inclusions with cubic cut and the top of crack on surface of HET; b – group of inclusions of cubic shape.

It is interesting that these inclusions have the similar cubic shape, their dimensions are also nearly the same (5…7 μm). Element composition of inclusions determined by x-ray microanalysis is shown in Tabl. 1.

Table 1

Element composition of inclusions of cubic shape

Chemical composition	C	N	Ti	Cr	Fe	Ni
Atomic %	11…25	1…35	60…90	0,6…1,7	1…5	0…0,5

Composition of inclusions shows that these are the same carbonitrides that were detected early in the base metal 08X18H10T [8]. Cubic cut and similar dimensions testify that crystal were formed into the melt under conditions near to equilibrium one. They have occurred on the HET surface during tube refinement. Square of inclusion cross-section and surrounding them discontinuities into the metal is comparable with cross-section of grains in steel 08X18H10T. This allows consume that in operational conditions local ruptures of protective oxide film occur on HET surface under inclusions. Just these ruptures give the origin of nuclei of local corrosion. This circumstances and also stressed state of adjoining volumes of the metal induce the nucleation of cracks (Fig. 4). Tabl. 2 represents the element composition of inclusion.

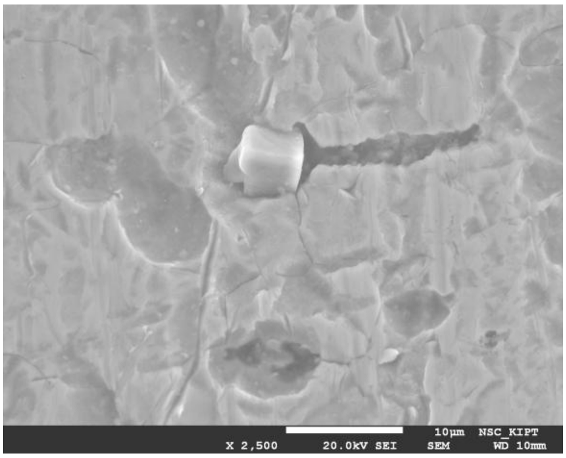


Fig. 4. Formation of crack from inclusion of titanium nitride on surface of HET

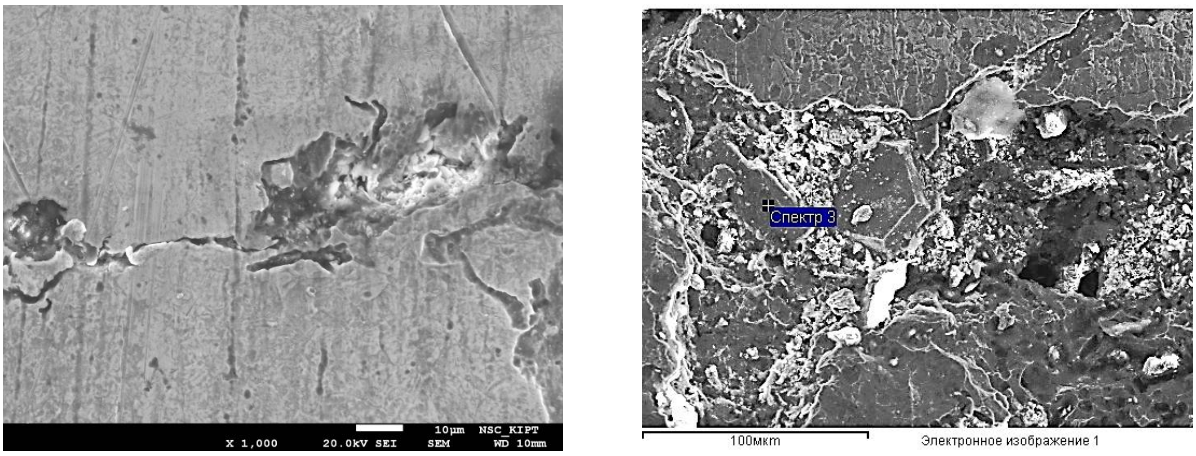
Table 2

Element composition of inclusion

Chemical element	Weight %	Atomic %
N	4.18	13.10
Ti	87.74	80.46
Cr	2.02	1.70
Fe	5.42	4.26
Ni	0.64	0.48
Total	100.00	100.00

In the future operational conditions, aggressive environment and difference in coefficients of thermal expansion of metal and oxides induce preconditions for crack growth in the result of wedging out action of corrosion products. It is known that disturbing the continuity of the metal inclusions serve as the concentrators of stresses, deteriorate the fatigue strength and induce the failure at stresses in the base material. Besides, inclusions influence on evolution of electrochemical corrosion at operation in corrosion media and on formation of fatigue cracks. It follows that in the cases with HET inclusions of titanium nitrides on surface are together with alternate stresses under vibration are the obvious reason of formation of local corrosion nuclei. Cycles tension-compression induce the formation and growth of cracks on boundaries with inclusions. The crack growth proceeds by mechanisms of corrosion fatigue because in this process are simultaneously involved alternate cyclic stresses and corrosion medium. Mechanism of nucleation and development of cracks of corrosion fatigue is the same as that under corrosion cracking but occurs only during the action of tensile stresses [11]. Such mechanism is described by electrochemical theory of corrosion fatigue [12, 13]. During the fabrication of heat exchanger tubes of steel 08X18H10T are treated: from inside they are sand treated and electro polished. The outer surfaces are grinded.

Fig. 5,a shows parallel lines (micro marks) formed during grinding of outer surface of the tube and crack perpendicular to these lines along the guide of HET. In is seen from this figure that the traces of grinding are not the causes of crack nucleation. But the examples of the presence of silicon carbide crystals in crack beds were observed (Fig. 5,b).



a *b*

Fig. 5. Outer surface of HET with defects: a – longitudinal crack and traces of grinding on HET surface; b – crystals of silicon carbide in the bed of crack

These crystals were implanted into the tube surface during mechanical grinding and may become the first reason of metal cracking.

Preferential formation of defects near collectors. According to numerous data of ECC the majority of defects were detected in the area of tube bundle near the "hot" collector (HC), considerably lower portion in the area of "cold" collector (CC) and only single defects – a long way from collectors. Up to now such distribution of defects was explained by variation of acidity (pH) by the volume of steam generator [14, 15]. As to our opinion it can be explained from physical point of view. Steam generators PGW-1000(M) belong to apparatus in which the heat source (heat-transfer agent) is situated inside the horizontal arranged tubes and heated feeding water boils on their outer surface. In such conditions the circulation of feeding water has the nature of free convection near the surface of heating [16, 17]. Heat transfer and vapor production realize at the expense of upward convection flows of vapor-water mixture throughout tube bundle of steam generator. HET shows the tendency not only vibrate due to the inhomogenity of boiling but also flex in upward flows of steam-water mixture. The last conclusion was confirmed during investigation of HET on formation of atlas of operational defects [4]. The clear tendency of defect production on one side of HET surface was established. We may affirm that this is the lengthy side formed on tube flexure in upward flows of vapor-water mixture.

Definition of configuration of convection flow in steam generators represents the problem of special thermal-physical investigations. Distribution of temperature by the size of steam generator is not known. But it may be supposed that in the processes of heat exchange the convective heat transfer of collector walls plays an important role; spikes of defect production in these areas points on this. Near collectors the intensive boiling and maximum upward heat flow of vapor-water mixture are observed. Therefore in these areas the higher vibration of HET and the more intense formation of corrosion-fatigue cracks is observed. With the removal from collector wall and decrease of the temperature of tube bundle the quantity of upward flows decreases and this induce the decrease of vibration intensity and flexure of the tube. According to this concept the highest intensity of defect production in the area of "hot" collector became explicable.

DECREASE OF INTENSITY OF DEFECT PRODUCTION IN HET

On the base of realized study one can conclude that for prevention of defect production in HET the main possibility is in the improvement of the purity of steel 08X18H10T. It is well-known that especially pure steel is necessary for equipment with long service life at high temperatures. On fabrication of HET the more dangerous inclusions in steel are nitrides and titanium carbonitrides. Plastic sulphides and oxide withdraw into fine fibres during rolling; such fibres are not dangerous for local corrosion and crack formation. Technology of steel 08X18H10T melting includes the introduction of titanium into the ladle with the melt. It was established that nitrides are absent during all melting until the titanium addition. Just after addition of titanium the considerable quantity of titanium nitrides form and on recrystallizing the net of carbides and titanium carbonitride form. It is obvious that problems of HET cracking may be solved by the improvement of technology of steel 08X18H10T melting on the stage of titanium introduction .It is also necessary to improve the technology of surface tube treatment for eliminate the presence of inclusions of silicon carbides.

Unfortunately, it may be realized only in the future on fabrication of HET for new steam generators. As to the operating HET we consider that the fact of existence of crack nuclei must be took into account on ECC and also on selection of service conditions for steam generators.

The second possibility for decrease of HET damaging is the decrease of hydraulic pressure of upward flows of vapor-water mixture in the area of collectors. But excluding the variant of power decrease this will need the complicated thermal-physical calculations, new organization of tube bundle; this will be possible only on producing the new steam generator.

ACCOUNT OF REAL STRUCTURE OF STEEL 08X18H10T ON PERFORMING ECC

Knowledge of real structure of the metal may be took into account on analysis of the results of ECC. As example we have examined the modern state of tube bundle of steam generator SG-4 on the first power unit of SU NPP. This steam generator (type PGW-1000M) is operating from 1991 year and three steam generators of same series were replaced in 2007 due to the exceeding of number of turned off HET.

Distribution of defects in tube bundle of steam generator SG-4 on first power unit of SU NPP. Fig. 6 shows the histogram of distribution of different indications on half-loop (half-tube) of hot collector HC-II. Columns on histogram show the number of indications on areas between collector and spacing grids from thirst to the sixth.

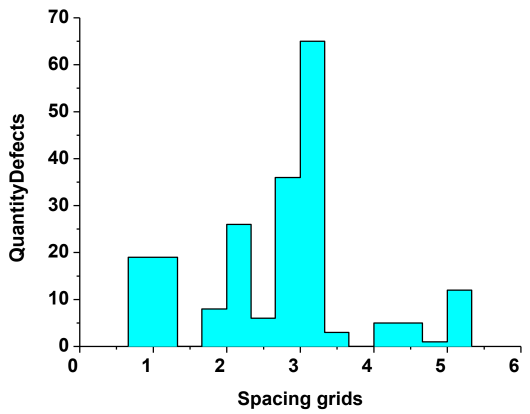


Fig. 6. Diagram of distribution of indications on HET between collector and six spacing grids

It must be firstly noted that all indications are arranged on distance not more than five inter grid gaps from hot collector (all length of half-loop (half-tube) has 10 inter grid gaps with length 350…585 mm). Such arrangement of indications is characteristic not only of 1-unit SG-4, but also and another steam generators of power units of WWER-1000. For steam generators of power units WWER-1000 the same situation is observed: majority of indications are revealed near the “hot” collector. The second important observation made on Fig. 6 – indications are situated near the spacer grids. The highest number of indications is observed near the third grid (distance from hot collector – 1150 mm). Fig. 7 shows indication of ECC on HET in the area of spacer grids from 01H to 06H.

It is seen from figure that sharp increase of indication number is observed for the third grid. This is true for “signal amplitude” and also for “metal loss”. (From ECC theory these terms are associated with the volume and depth of indications). After the third grid the abrupt decrease of indications number is observed. Analogous pattern was observed on three replaced steam generators of fist unit. Literature data also indicate the zone arrangement of indications in tubes near the hot collector; this was observed for power units of WWER-1000 and for power units with WWER-440 [17].

According to the existing representations the development of corrosion cracking of heat exchange tubes under spacing grids is promoted by active impurities in the layer of deposits and increased level of stresses. Concept based on the zone change of water-chemical regime pH is also use. But all these concept doesn`t explain the observed facts.

The examined laws are explained by physical representations based on the concept of HET vibration and presence into the metal of non-metallic inclusions. Asymmetrical arrangement of collectors induces the inhomogeneous heating of water by the volume of SG. Feeding water in the areas HC-I, HC-II (see Fig. 1) of tube bundle is heated at the expense of heat transfer from surface of “hot” and also the “cold” collectors. In the areas CC-I, CC-II “the hot” collector take less part in water heating. Due to this fact the vapor production in the area HC-I, HC-II and up to fourth grid is more intense. This induces the increase vibration of HET and, respectively, the formation of corrosion fatigue cracks from inclusions in metal just in HC-I and HC-II, up to the fourth grid. On the base of presented data and also on the base of ECC on other power units it is possible to consume that zone nature of defect production in HET is systematic one for steam generators of power units WWER-1000 and WWER-440.That is, such situation is the consequence of steam generator structure.

The presented example of steam generator of SG-4 state shows that the higher number of indications on HET is formed in the areas of tube bundle on distance 1750 mm from hot collector towards the cold end.

Analysis of results of eddy-current control of HET on the base of material science gives the scientific substantiation of control norms [1, 2]. On this, the demands to criteria of turn out must remains high for indications with large amplitude of signals (corrosion pits).

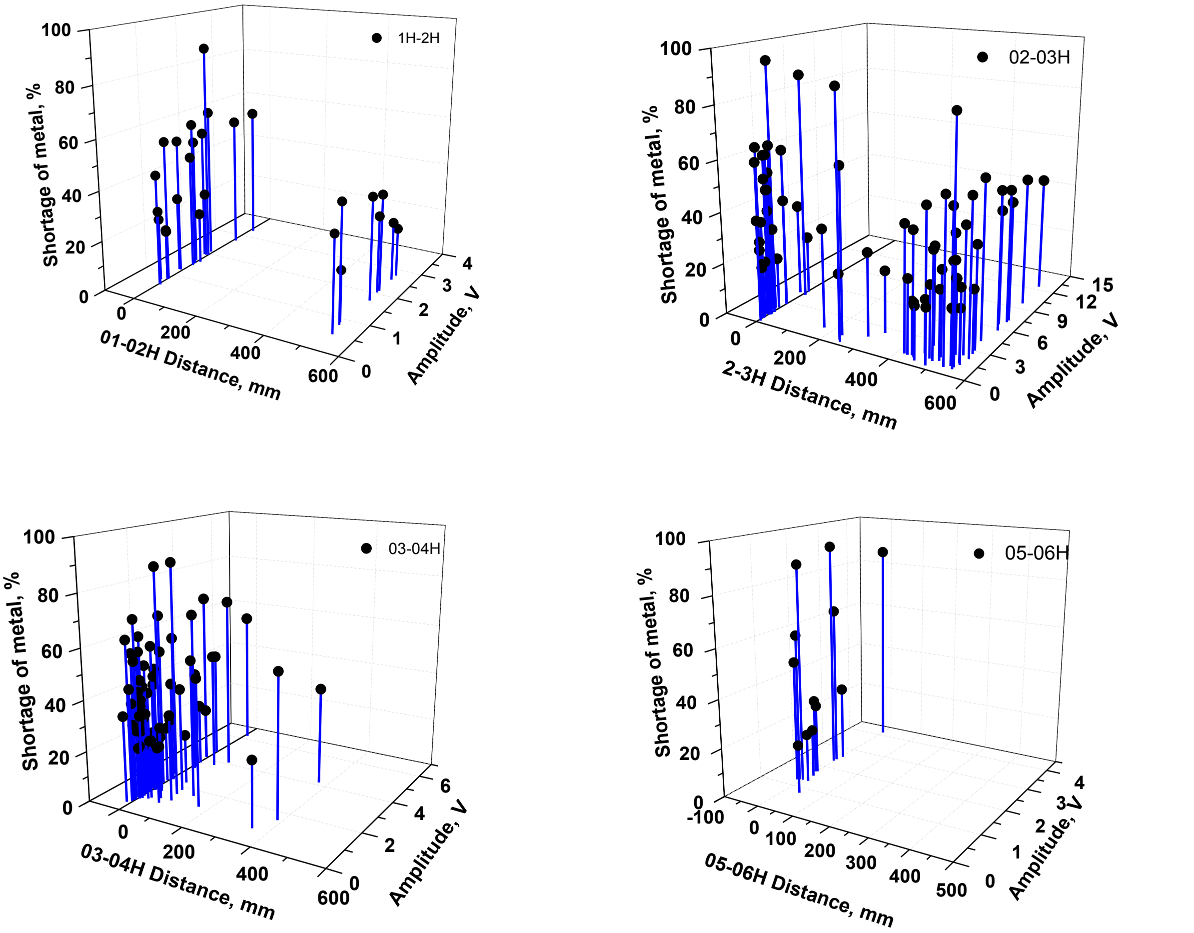


Fig. 7. Indications on HET, arranged between grids 01H and 06H (steam generator 1SG-4, 2017 year)

CONCLUSION

1. Mechanism of crack formation in steel 08X18H10T of heat-exchange tubes of steam generators of power units WWER-1000 is revealed by metal-science methods with the use of scanning electron microscopy and micro probe analysis.

2. The role of non-metallic inclusions in formation and growth of cracks in operational conditions of HET in steam generators PGW-1000 is determined.

3. The effect of structure of steam generators PGW-1000 on defect production in HET is examined.

4. The determined laws of nucleation and growth and arrangement of indications must be took into account on analysis of data of eddy-current control of HET.

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ФИЗИКО-МЕХАНИЧЕСКИЕ АСПЕКТЫ ДЕГРАДАЦИИ МЕТАЛЛА ТЕПЛООБМЕННЫХ ТРУБ ПАРОГЕНЕРАТОРОВ ТИПА ПГВ-1000

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С помощью металлографии и растровой электронной микроскопии установлено воздействие включений карбонитридов титана и карбида кремния на деградацию стали 08Х18Н10Т в теплообменных трубах (ТОТ) парогенераторов энергоблоков ВВЭР-1000. Показана также роль конструкционных особенностей парогенераторов в зарождении и росте эксплуатационных дефектов ТОТ.

ФІЗИКО-МЕХАНІЧНІ АСПЕКТИ ДЕГРАДАЦІЇ МЕТАЛУ ТЕПЛООБМІННИХ ТРУБ ПАРОГЕНЕРАТОРІВ ТИПУ ПГВ-1000

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За допомогою металографії та растрової електронної мікроскопії встановлено вплив включень карбонитридів титану і карбіду кремнію на деградацію сталі 08Х18Н10Т у теплообмінних трубах (ТОТ) парогенераторів енергоблоків ВВЕР-1000. Показана також роль конструкційних особливостей парогенераторів у зародженні і зростанні експлуатаційних дефектів ТОТ.