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CONNECTION BETWEEN INTERNAL STRUCTURAL STRESSES OF THE IST AND THE IIND KIND AND OPERATIONAL RELIABILITY OF THE BOILER HEATING SURFACE

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Abstract. This paper presents new approaches to solving problems of forecasting the life of heating surface of boilers, based on an analysis of internal structural stresses of the first and second kind that could affect the intragranular and intergranular strength and reliability of the pipeline in continuous operation by making it work without damage by preventing the disclosure of zone cracks.

1 Introduction

Power equipment elements specifications influencing the parameters of reliability and resource depend on the presence of complex operational conditions – stress from the operating pressure, high temperature, temperature gradients, residual stresses, bending stresses from self-compensation, volumetric stress, and transient operational modes. Also cyclic temperature fluctuations are typical specifics.

The highest value for the reliability and efficiency of the power plant is in the steam pipelines through which steam and water with high parameters flows.

During manufacture a tubular billet goes through a long and a complex technological path of thermomechanical operations, resulting in the pipe walls metal structure acquiring individual characteristics, such as appearance of heterogeneity, discontinuities, work hardenings, stratification and internal residual stresses, the role of which is not considered in the theory of questions on the processes of intergranular (stress corrosion, IEC – Intergranular corrosion) and intragranular (IAC – intragranular corrosion) destruction. The complexity of studying residual stresses is associated with the need to take into account mechanical, thermal, physical and chemical factors affecting the technological process.

In accordance with the Standards of pipes durability the Ist kind macroscopic properties – elasticity modulus, yield strength, tensile strength, ultimate strain, hardness, which were taken for the calculation do not contain microstructure parameters which determine the properties of the IInd kind (microscopic parameters) with respect to the microstructure components – grains or the components of multicomponent alloys – grain elasticity moduli, microhardness, etc., as well as the properties of

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^{III}d kind (submicroscopic) relating to the mosaic blocks in the metals grains (SCR – coherent-scattering region), boundary sections – grains or inclusions, etc. Consequently the expressions used for the strength calculation, do not suggest how the properties II and III, for example, residual (internal) and Thermostructural voltage (^{II}nd kind) when metal is working in the creep conditions in the presence of mechanical and thermal alternating loads affect the macroscopic properties of the heating surface steel and their resource characteristics .

This is particularly important in view of the reported numerous cases of mechanical equipment elements long-term strength loss including steam pipelines long before the end of their design life, which manifests in the steels corrosion instability, expressed in the formation of main cracks due to stress corrosion cracking (SCC), intergranular (intragranular corrosion) and transgranular corrosion (Intergranular corrosion), creep, graphitization.

Analysing the problems of residual life prediction and life extension of the heating surface, it may be noted that in the listing of hazardous operational factors within the boiler and reactor engineering processes to improve the quality of designed models, to provide recommendations on the choice of materials, safe operating temperatures, in diagnosis and prevention of cracking and brittle fractures the role of internal structural stresses kinds I and II is not evaluated, clearly manifesting themselves in the process of structural and physical degradation of structural materials and determining in this respect individual physical capabilities of the metal [1].

In an effort to ensure a trouble-free operation and boilers long life, one must consider the magnitude of the internal stresses in the design, assess conditions of their redistribution and relaxation, summing it up with the stresses caused by external loads. This will allow to avoid exceeding the given limits, avoid microstructural porosity and structural cracking.

In this paper we present new approaches to solve problems of forecasting, based on an analysis of internal structural stresses of the first and second kinds.

2 Methods of investigation

As an object of research we used a low-alloy heat-resistant structural pipe steel 12H1MF (Russian designation is 12X1MΦ; chemical composition according to GOST 20072-74,% by weight: 0.08-0.15 C; 0,9-1,2 Cr; 0,25-0,35 Mo; 0,15-0,30 V; 0,4-0,7 Mn; 0,17-0 37 Si; <0,25 Ni; <0,20 Cu; <0,025 S; <0,030 P; rest – iron), which is used in boiler construction process for the production of pipes of high, ultrahigh-pressures and superheater pipes, flanges, diaphragms for long-time operation at temperatures not exceeding 585 °C [2], and which according to the design should provide continuous operation at high temperatures, in constructions under high pressure.

Originally heatproof and heat resisting pipe pearlitic steel for steam lines of high and ultrahigh-pressures and superheaters with brands 12HM (12XM), 15HM (15XM), 12H1MF (12X1MΦ), 15H1MF (15X1MΦ) were designed for use at operating temperatures of 565-600 °C.

A characteristic feature of the steel 12H1MF is a not very high stability of the austenite [2], low hardenability, large heterogeneity of the structure and properties across the section and the length of the steam lines, sewers, and other elements of the thermal and mechanical equipment , development of cracks, porosity, reducing long-term plasticity [3] and, as a result, stress corrosion cracking and intragranular corrosion. These circumstances have led to the fact that the estimated temperature of the steam was first lowered to 545 °C and then to 510 °C, and the pipes fleet life was reduced from 300 000 hours to 100 000 hours [4].

Found deficiencies in the superheater pipes identified through long operating experience and related to the structural heterogeneity, makes vital the question of the heating surfaces forecast performance on the basis of the analysed properties of II and III kind.

The studies were conducted by the method of thermal cycling by X-ray diffraction using the anti-cathode molybdenum with an average wavelength λ_{av} = 0,71069 Å and zirconium β-filter.

Establishing the nature of own internal (residual) stresses redistribution in the sample 12H1MF during thermal cycling was carried out in the "heating–cooling–heating" mode increasing temperature in each successive test cycle. After reaching steady-state thermal mode during heating and cooling, marked on the thermogram we performed radiographing of the diffraction lines experimental profiles and measured the lines intensity distribution depending on the diffraction angle [5]. To establish the influence of dispersion factors and microstressing we singled out from the resulting overall physical line broadening of the section *m* – the broadening associated with the dispersion and of the section *n* – the broadening associated with microstresses.

3 Results and discussion

Experimental results are presented in Figures 1-3 [6, 7].

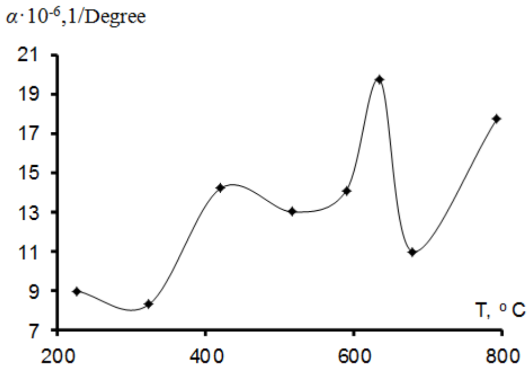

Figure 1. Thermal linear expansion of the α crystal lattices (steel 12H1MF).

a) b)

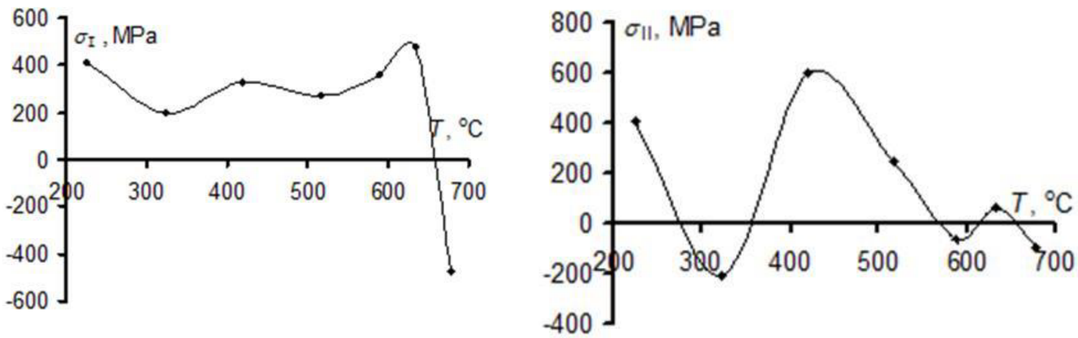

Figure 2. Microstresses depending on the temperature (steel 12H1MF): a – microstresses of the Ist kind, b – microstresses of the IInd kind.

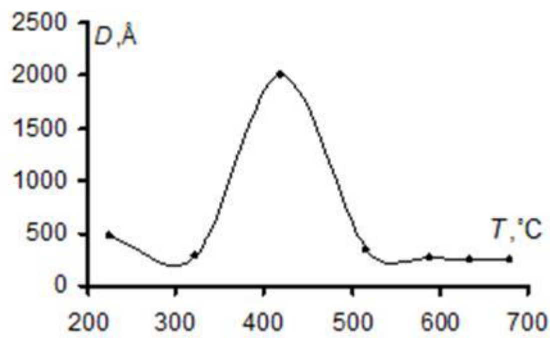

Figure 3. The crystallite size versus temperature (steel 12H1MF).

The experiment shows (Fig. 2) that the average levels of internal stresses in the sample 12H1MF according to the order of magnitude correspond to the basic mechanical characteristics of the given steel $\sigma_{в}$= 520-200 MPa, $\sigma_{0.2}$ = 330-160 MPa within temperatures range from 20 to 650 °C [2], but have alternating character.

Experiments on thermal structural transformations of the boiler steel 12H1MF [6, 7] led us to the production of the dependence of thermal expansion coefficients of the crystal lattices (Fig. 1) on the temperature, distinguished by the nonlinear nature and the presence of the temperature curve $\alpha = f(T)$ of the anomalous effects λ-anomalies.

Such anomalous expansion of the crystal lattices of certain materials at certain temperatures was observed in [6-8], etc. For the steel 12H1MF anomalous thermal deformations are observed at temperatures of about 420 °C and in the vicinity of 635 °C (Fig. 1).

The presence of extreme points on the curve of thermal deformation shows that it is associated with changes in the properties and condition of pipe steel.

In particular, during structural materials research for the fuel assembly and fast reactor control and safety system stainless steels of ferritic-martensitic class and alloys [8] it was found that there is a certain point of temperature or temperature ranges in which there are significant changes in the properties of the material. For example, at T = 380-400 °C – there is a low-temperature embrittlement with a marked decrease in ductility. At T = 340-700 °C – a dangerous reduction of mechanical properties, especially in the range of 500-600 °C. Also there was a marked decrease in ductility in the range 400-600 °C. So, for the alloy 0H20N45M4BRTS (0Х20Н45М4БРЦ) the ductility decrease practically to zero corresponds to the two temperature intervals, coinciding with the two areas of maximum fuel assembly shell ballooning: 400-420 ° C. and 550 ° C. Received by V.V. Chuev and co-authors. The temperature intervals of anomalous changes in the properties [8] approximately coincide with anomalies of the crystal lattices linear thermal expansion established for the steel 12H1MF, and in [6, 7].

The crystal lattices anomalous behaviour is obviously linked to indicators of strength and ductility and changes them not in the right direction: strength index falls, and ductility index increases. Specifically, for example, in [9] it is noted that the low alloyed steel begins to lose strength at 427 °C and at 538 °C its strength becomes half of what it is at the room temperature. Carbon steels begin to lose strength rapidly at temperatures 371-454 °C. Approximately at 418 °C they are subjected to graphitization. Strength of austenitic stainless steels is somewhat reduces at 538 °C and decreases sharply at 649 °C.

In studies of promising domestic heat-proof and heat-resistant Chrome Manganese steel Di-59 (10H13G12BS2N2TS2; Russian designation is 10Х13Г12БС2Н2Ц2) there is a decrease in the strength of steel due to creep and lack of the necessary operational reliability level in the same temperature ranges, namely at 427-445 °C and 600-650 °C.

All these temperature points of anomalous crystal lattices expansion, abnormal fuel assembly shell ballooning, abnormal steam boilers materials strength characteristics lowering, steam pipes graphitization are very close to each other, suggesting a unified pattern of the phenomena occurring in the structure of the material at these temperatures.

Constructional steel and alloys in the solid state is a complex multi-phase system of solid solutions, chemical or intermetallic compounds, interstitial phases, electronic connections, separated by interfacial boundary. The phases have different chemical composition, grain size are different, different grain orientation in relation to the other phases, different from of the crystal structure and physical properties. The phase alloy state depends on the concentration and temperature of the alloy.

When using superalloys at high temperatures under the influence of thermomechanical stresses there are solid-state reactions in the alloys structure with constant change of the phase composition when alloying elements fall under redistribution.

Phase transition in the broadest sense means the transition from one phase to another under the influence of changing external factors – temperature, pressure, magnetic or electric fields, etc. In the narrow sense, phase transition is an abrupt change in physical properties under continuous change of the external parameters. Phase transition is accompanied by phase boundaries change.

Abnormal manifestations of properties stated during the analysis of the structural polymorphism as a kind of phase transition should thus be valid for any phase transition. Since the grain boundary is also considered as a separate phase in the material structure as well as any other solid phase, it may also undergo a phase transformation [10].

Solid-phase boundary reactions include discontinuous precipitation, discontinuous coarsening and discontinuous dissolution. Thus, "... grain boundaries may exist in more than one phase condition, and they may undergo the same phase transitions. Such phase transitions can occur in an abrupt change in structure, strength, chemical and kinetic properties of boundaries" [11].

However, one still can't say that today we understand how the structure is related to its boundary properties. On the one hand, modern theory of grain boundaries is almost entirely limited to the description of low-temperature structures; on the other hand, for the thermodynamic description of phase transitions within the boundaries just the boundaries between the chemically identical grains are considered [11].

In [10] it is noted that there are no direct experimental evidence for the existence of grain boundary phase transformations in the solid state. However thermodynamic theory predicts that, if at a temperature not exceeding the melting point at the grain boundary occurs a phase transition, then in the transition point the high-temperature phase h and the low temperature phase l must be in thermodynamic equilibrium. This requires equality of the pressure P and the temperature T and the surface tension σ of the two phases, and the entropy S and volume v must change abruptly at the transition from one phase to another [10, 11].

Thus, evidence of grain boundary phase transformations need to be looked in the predicted by the theory of jump equilibrium characteristic changes – entropy, volume, number of adsorbed impurities, as well as non-equilibrium or kinetic characteristics – boundary migration speed, grain boundary diffusion, grain boundary sliding speed, grain boundary internal friction and so on [10, 11].

The large-scale phase transition such as "disorder" in the border can be caused by the following defects: vacancies in the nodes belonging to the boundary, or atoms displaced from these nodes to other not occupied nodes, as well as the interaction of defects, since to each of these elementary defects or "disruptive element" corresponds its own forming energy.

In [11] it is shown that at temperatures approximately equal to half of the melting point on the large-transformation boundaries there can be a disorder transformation. Moreover, since the bond energy, and coordination number of the atoms in the boundary is smaller than in the matrix, the critical temperature at the boundary should also be lower. But whatever the grain boundary transformation is, its characteristic feature will serve as an abrupt change in characteristics. It is important that in polycrystals containing a very large number of boundaries, the transition temperature can't be the same for all possible orientations of the boundaries and abrupt change in characteristics can be observed at different temperatures. Nevertheless, even in this case the transition temperature for many boundaries lies probably in a fairly narrow range, so there should be observed, if not abrupt, then at least abnormally rapid change of the measured characteristics.

Changing the properties due to grain-boundary phase transition must be reversible (Fig. 1).

These facts show that the choice of structural material for Boiler and Reactor are evaluated not taking into account all factors that can affect the strength and reliability of the pipeline for the long term use. In particular, the experimental results similar to Figure 1, can prevent a non-grounded choice of materials and operating temperatures, thus providing a long-term strength.

Figure 2 (b) shows the experimental dependence of its own internal stresses of type II (intragranular). The main feature of the obtained dependence is in following:

• In the oscillatory character of the internal structural stresses varying during cyclic heating.

• In the redistribution of internal stresses from straining (+) to compressive (–), which occurs through the stress relaxation.

• In the implementation process of the cyclic hardening and softening under thermal cyclic loading:

- on the curve (Fig. 2, b) there are several points of elevated temperature creep – 270, 350, 575, 620, 635 °C, when the lowest amount of resistance change of the material or shape can be expected;

- maximum resistance to deformation occurs at a temperature of about 220 °C (420 MPa) in the range of 400-425 °C (600 MPa), which initiates destruction due to structural fracture when local yield-point value is risen by the tensile stress.

Figure 3 shows the crystallite size change dynamics in the structural grain depending on the temperature, showing growth of crystallites at the temperature of 420 °C, which, according to the known concepts, will reduce the grain brittle strength. Temperature 420 °C can be defined as the most dangerous in terms of intragranular (intergranular) fracture.

Figure 2 (a) shows the dependence of internal macrostresses of the Ist kind (zonal) depending on the temperature. Zone stress relaxation associated with the process of cracking is observed in the temperature range of 600-635 °C.

Consequently, according to X-ray micro-dilatometry we can conclude that the temperature range 550-600-635 °C can't be recommended as an operational. Temperature 420 °C provokes intergranular corrosion. Most favorable temperature for the operation of the steel 12H1MF is in the vicinity of 520 °C (Fig. 2).

Moreover, the temperature gradients of ± (15-20) °C from the given level will lead to a sharp deterioration of steel.

Apparently, these circumstances have led to a decrease in operating temperature of the 12H1MF steel, first to 545 °C and then to 510 °C [4].

4 Summary

X-ray diffraction method, differentiating intragranular and intergranular strength, can reasonably choose operating temperatures, achieving such relation between them that it would ensure long-term operation without damage by preventing zonal cracks disclosure.

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