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The effect of thermo-mechanical loading on fracture-related parameters of austenitic steel

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ABSTRACT

Failure analysis shows that 80–85% of emergency boiler shutdowns at power plants result from heating surface damage. When in service, the tubes are exposed to alternating thermo-mechanical loads, which trigger phase change affecting the individual service life. The service life sometimes differs significantly from its estimated value. This research is based on the hypothesis about the role and influence of internal structural stresses on the actual strength and long-term performance of tube products made of steels and alloys. The purpose of this work is to determine the limit state region of internal stresses of the first kind, in which microdamage will not lead to fracture. For that, we did a set of experiment studies to model the accelerated aging processes by thermal cycling and cold cyclic deformation. We chose a tube made of austenitic steel 10Cr13Mn12Si2Ni2Cu2Nb (Di59) as the object of research. The methods used were XRD analysis, microhardness testing, X-ray spectroscopy, and microstructure analysis. Due to redistributing properties, steel has no stable states: all its states are short-term and dependent on external disturbances. In accordance with the suggested hypothesis, the research findings make it possible to forecast the trends and direction of changes in the material properties. This allows us to evaluate the achievement of the limit state by the object and to use relaxations of internal stresses as a sign determining the conditions of crack initiation and propagation. The results are confirmed by the data obtained from the microstructure analysis of fractured tubes of a superheater from a functioning boiler.

1. Introduction

Heating surfaces of energy equipment are susceptible to a wide range of factors that affect their service life. Some failures, for example, are caused by poor design quality of some pieces of equipment, while others result from poor service conditions. Yet another condition of reliability assurance is the technological factor based on the quality of tubes and technology of their production. According to [1–4], failure analyses show that 80–85% of emergency boiler shutdowns at heat and power plants result from heating surface damage.

As-received tubes for producing heating surfaces have different structure and properties [5] due to their complex manufacturing process, which involves drawing, rolling, annealing, etc. This provides a significant spread in values of their mechanical performance [6–10].

The technological factor will manifest itself in operation in the form of inhomogeneous residual stresses, which may exceed local

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yield strength two or more times [11]. This will create temperature- and load-sensitive zones of heating surfaces and units of equipment that will affect the performance of the whole structure.

The current level of industrial engineering cannot provide a repeatable composition of the resulting steel or the same temperature and strain conditions of tube production [12]. In order to improve the performance and durability of tubes, the technology of their production must provide a homogeneous composition, no significant phase or structural nonuniformity, no zones with high-level internal structural stresses and low breakage resistance, and no zones with stresses relaxing to zero. Previous research has shown [13–17] that relaxation is a special case of creep, and accelerated creep is associated with destruction and is one of its signs [18]. Statistical deviations in a complex set of technological factors may lead to a wide range of damage to the tube surface. The structure should be monitored on both the inside and the outside of a tube.

This much diagnostics, however, is not required (especially in terms of internal stresses) nor is it covered by any rules, regulations or codes of enterprises.

Moreover, life-expired tubes undergo restoration thermal treatment (RTT) to relieve internal stresses or swaging to suppress the intergranular corrosion (e.g. of welds). However, there is no strong indication of efficiency in the case of RTT, since a decrease in residual stresses does not always improve the properties and sometimes even leads to softening [19,20]. When it comes to swaging, there is little information in the scientific literature on changes in the stressed state and no research-backed concept of appropriate swaging pressure, which leads to inconsistent results [21].

The above listed measures aim at restoring the properties to their initial state and providing structural stability of tubes for further service.

However, under mechanical and thermal operation loads, structural and mechanical characteristics of steel do not remain the same but change throughout its service life. The current system of standard calculations and theoretical evaluations does not consider phase-change induced degradation in the material structure, which changes the stressed state, actual stress pattern, microhardness, etc. The structure of the material as well as its properties are constantly changing, too [22,23]. Thus, RTT and swaging only provide a short-term restoration of mechanical properties.

Therefore, with all the variety of influences on structural stability, it is important to select a parametric criterion, define the allowable range of its change, and understand when this criterion reaches such extreme values within this range that will lead to microfracture.

In this paper, we choose internal structural stresses of the first kind as such a parametric criterion, because they react very delicately to all the structural states caused by any external factors. A set of our experimental studies simulated aging by thermal cycling and mechanical cyclic deformation in order to define the range of extreme states of the parametric criterion as a sign of structural stabilization.

2. Materials and methods

Austenitic steel 12Cr18Ni12Ti and pearlitic steel 12Cr1MoV are used in different countries as the main structural materials to produce boiler superheaters [24–27]. With the design lifetime of about 300,000 h, they, however, collapse prematurely for various reasons [1,27–29]. Mass strain-free brittle fractures are typical of the tubes of ultra-pressure boilers made of not only steel 12Cr18Ni12Ti but also pearlitic steels. Cracks always appear at the places where the protective oxide film loses its integrity. Therefore, many investigations tackling this problem focus on studying the plastic properties of the oxide film as well as its fracture resistance depending on its structure and texture. At the same time, too little attention is paid to transformations in the metal itself, which do not only reduce the adhesion of oxide films but also long-term durability of metal.

One of the fundamental reasons for premature failure is the accelerated structural degradation of metal due to temperature fluctuations.

Insufficient information on some aspects of structural transformations brought about by cyclic thermal and mechanical gradients is what makes it relevant to study certain materials that seem promising for boiler superheaters. Among these materials is chrome-manganese steel 10Cr13Mn12Si2Ni2Cu2Nb (Di59), which was developed to replace steel 12Cr18Ni12Ti.

According to GOST 5632-72, Di59 steel has the following chemical composition (by weight): 0.07% C; 1.99% Ni; 12.45% Cr; 13.0% Mn; 0.21% Si; 0.006% S; 0.015% P; 0.03% Al; 2.15% Cu; 0.79% Nb; 0.015% B; the rest is iron.

The methodological set of approaches used in this work involved physical simulation by thermal cycling and mechanical cyclic deformation with a wide range of external forces. A combination of these operations provides accelerated aging through structural degradation.

For this study, we used XRD analysis, microhardness testing, X-ray spectroscopy, and microstructure analysis.

Cyclic deformation implies cyclic loading of the sample under study by hydraulic pressing with an increasing load with each consecutive cycle. Each strain cycle was followed by quantitative X-ray spectroscopy determining the residual stresses σ_I of the first kind.

Residual stresses of the first kind σ_I were determined by X-radiography from lattice a dilations: $\sigma_I = (\Delta a / a)E$, where E is the modulus of elasticity. The XRD analysis was performed on a DRON-3 X-ray diffractometer (Russia).

X-ray fluorescence analysis showed the effect of cyclic deformation on the redistribution of alloying elements, whose concentration in the crystal lattice defines the magnitude of the parameter a. The X-ray fluorescence analysis was performed using EDX-2800 (SKYRAY, USA) for measuring the spectra of the characteristic radiation of the chemical elements in the test sample.

Microhardness was measured by means of a PMT-3 microhardness tester (Russia).

The microstructure was analyzed by a Metam LV-32 microscope (Russia) with a 500 × magnification.