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Crack initiation in steel parts working in boilers and steam pipelines

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Properties

ABSTRACT

Purpose: The purpose of this paper is to identify the influence of loading history and the processes of material degradation on the crack initiation and on durability under thermo-mechanical fatigue conditions.
Design/methodology/approach: Based on the operation data, the conditions of laboratory examinations of specimens were determined. A specialist apparatus unit was used for the examination, enabling the simulation of any spectrum of mechanical load and temperature changes.
Findings: The material durability criterion has been defined based on an energy related approach to the problem of crack initiation in steels which work under thermal fatigue conditions.
Research limitations/implications: In the case discussed, i.e. a pipeline part, the present criteria should be expanded with critical values describing the total length of cracks initiated on the internal surface of a specimen.
Practical implications: The paper refers to the research on steel 10H2M (10CrMo.910) used in the conventional boilers, superheaters and pipelines in power plants.
Originality/value: Originality of the paper is the methodology of the lifetime prediction of steam pipeline parts working in thermo-mechanical fatigue conditions.
Keywords: Fatigue; Residual life analysis; Fracture mechanics; Properties of materials and products

1. Introduction

One of the most frequent types of load imposed on power engineering equipment are variable in time fields of forces and temperature fields which induce material degradation being the result of thermo-mechanical fatigue and creep [1-2]. The interactions of a distortive nature which occur under such conditions, resulting – in this case - in thermal stresses, have a significant influence on material durability. The distortion induced by temperature gradient and a difference in thermal expansion of microstructure components in a material are the cause of stress concentration in microregions and often exceed the strength of a material [3]. For this reason, for an assessment of the life of constructional components, the knowledge of material properties of the structural material, determined in conditions similar to the instalation's operating conditions, is necessary [4, 5]. The properties can be only determined based on laboratory investigations, using specialist instrumentation which enables meeting appropriate criteria to ensure the maintaining of physical and mechanical similarity conditions [6, 7].

During their operation, live steam pipelines undergo damage as a result of: mechanical load and elevated temperature, often of a variable nature and, in some cases, the interaction of hydrogen embrittlement [8].

In the conditions of cyclic temperature changes, as a result of start-ups and shut-downs of a power generation unit, this may lead to material crack initiation, in particular in the region of welded joints, edges of openings in steam blowdown and inlet connections, as well as in parts of pipeline installations, such as elbows, T-connections, valve chests and cut-off valves [5, 9]. In this connection, fatigue properties of materials used for the above-mentioned group of plants are one of the factors which determine the operational safety and durability of the elements of a power generation unit. The condition of the live steam pipelines' material changes throughout the operation period. Its microstructure changes and in consequence, its fatigue properties, fracture toughness and high-temperature creep resistance change as well [10, 11]. The residual life of facilities of this type cannot be considered separately from their real material features. This refers in particular to the changes that take place in the metal structure and to their relation with fatigue strength. Changes of the properties, which determines the durability, are mostly caused by structural processes, such as precipitations and carbide transitions as well as changes in their morphologies. The nature of microstructure changes and the rate at which they take place may differ, depending on the chemical composition of the steel, the initial condition of the material, the manufacturing technology and operational parameters [5]. The study focused on investigating the mechanical properties of the 10CrMo.910 steel in the presence of variable thermo-mechanical loads. The processes of fatigue cracks formation and development were analysed for selected variants of loads simulating the real conditions of a start-up pipeline and superheater chamber's operating conditions.

2. Test stand

To carry out thermo-mechanical fatigue tests, a test stand was built based on a strength testing machine, MTS-810. The shape and dimensions of the specimens shown in fig. 1 were elaborated. The test stand was equipped with a digital control system, TestSTAR II, and an induction heating system of HÜTTINGER Co. The TestSTAR II system enables independent and simultaneous control of two signals, which makes it possible to carry out thermal fatigue tests with independent control of temperature and mechanical load changes.

The apparatus used in the tests for induction heating facilitated maintaining the temperature at a constant level or controlling the thermal cycle by means of a SIGMATEST controller. It was also possible to interface the HÜTTINGER induction heating system with the TestSTAR II digital control system, thus enabling direct control of the thermal cycle through a program declared in the TestSTAR II interface. An advantage of such control is the ability to protect the specimen during the tests against excessive deviations of control signals (force, deformation, displacement or temperature). The system guaranteed a constant readout of test parameters and visual observation of the cycle on a monitor. In addition, the HÜTTINGER induction heating system was provided with a closed cooling system. The in-built cooling unit allowed cooling of the heating coil with water of the same temperature, independent from ambient temperature [3].

3. Development of test conditions and carrying out of the tests

The objective of this part of the research was to obtain information on the effect of thermal deformation, being the cause of variable in time thermal stresses, on material durability. Another objective was to determine the boundary conditions of operation of an installation under variable in time thermo-mechanical loads on the 10CrMo 910 steel used, e.g. for the manufacture of superheaters and live steam pipelines in the power plants. For this reason, an analysis was made of the operating conditions of boiler parts and the real operation time was determined until failure which qualified the superheater to replacement with a new one. The data collected at power plants made it possible to determine the parameters of the thermal cycle to be simulated on specimens at the test stand. The test parameters were determined based on the number of hours after which cracks were detected on the internal surface of the chamber, followed by its replacement. In that time interval, N_f of emergency or scheduled shutdowns of the power generation unit took place. A power unit shutdown was treated as a nonstationary state of boiler operation, during which the greatest thermo-mechanical loads are present. The total number of power unit shutdowns was assumed in the laboratory tests to be the basis for a fatigue test. That number equalled the number of temperature changes and axial stress changes in the specimen. Thermal fatigue tests were conducted on a material in its initial condition after normalizing. The mean value of the thermal expansion coefficient measured in the specimen was $\alpha_T = 1.401*10^{-5}$ K^{-1}. The specimens were heated with high frequency current, using an appropriately shaped heating coil, which ensured a uniform temperature distribution throughout the specimen length. Compressed air directed inside the specimen was used for cooling. Measurement of the temperature was made by means of thin thermocouples, Pt-PtRh, welded together with the specimen's outer surface. The parameters set in the program were:

- the minimum and maximum cycle temperature: T_{min}=160 °C, T_{max}=540 °C,
- heating rate $\dot{T}_h = 4{,}15$ K/s,
- cooling rate $\dot{T}_C = 4{,}15$ K/s,
- soaking time at maximum temperature τ_{max}= 8 s,
- soaking time at minimum temperaturze τ_{min}= 8 s,
- load rigidity coefficient $K = \varepsilon_m / \varepsilon_{th}$ [1]

During the fatigue tests, the course of the axial force, temperature and total strain ε_t, was recorded using a measuring system consisting of a Hottinger's digital SPIDER 8 converter interfaced with a PC. The course of those parameters was simultaneously recorded on a computer which controlled the operation of the TestSTAR II interface.

Two variants of fatigue tests were conducted on groups of pipe specimens. The specimens in the first testing variant were subjected only to a thermal cycle of a ramp course in a temperature range of 160°÷540°C during fixed grips of testing machine. Using an extensometer (base l_e=25mm), hard control of the MTS system testing was applied, as a result of which, during the fatigue tests, the load rigidity coefficient amounted to $K=\varepsilon_m/\varepsilon_{th}=1$ and the total strain was $\varepsilon_t=0$. This meant that thermal deformation of the specimen, ε_{th}, in the conditions of cyclic temperature changes, completely transformed to mechanical deformation ε_m, whereas the phase displacement angle amounted $\phi=180^0$. In the other variant, the specimens were additionally subjected to variable mechanical loads (out of phase thermo-mechanical cycle) with the range of the total strain amplitude $\Delta\varepsilon_t$=0,2% and $\Delta\varepsilon_t$=0,3%, as a result of which the thermo-mechanical fatigue tests were conducted with a rigidity coefficient K>1. The parameters of the fatigue tests are shown in Table 1.

In the first variant, the application of only a thermal cycle simulated the behaviour of inner areas of superheater chambers in nonstationary states caused by the power unit shutdowns or start-ups.

In the other variant, the subjecting of the specimens to an additional cycle of mechanical loads was supposed to simulate the operating conditions of the superheater chamber areas subject to the greatest effort e.g. flanges. This results from additional mechanical loads caused by the presence of a notch and limitation of free displacement in points of support of the chamber or by incorrectly worked or selected hangers. The recorded courses enabled the preparation of fatigue diagrams for the material investigated, as a function of the number of cycles of thermo-mechanical load changes [12, 14]. Some examples of diagrams of cyclic curves of strengthening and weakening, $\sigma_{max}(N)$ and $\sigma_{min}(N)$, are shown in fig. 2, whereas fig. 3 shows a curve, corresponding to this group of specimens, of the deformation energy dissipation W (N).

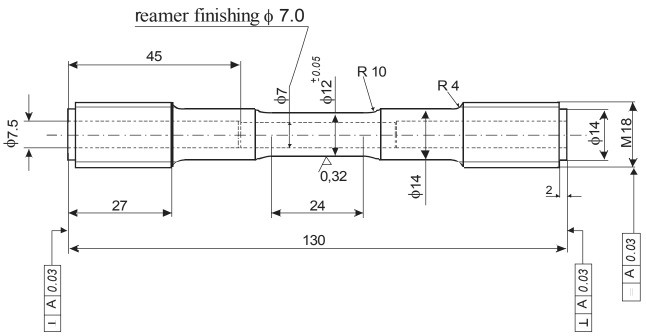

Fig. 1. Dimensions of specimens for thermal fatigue tests

The deformation energy dissipation test results shown in Fig. 3 are described with power trend functions. This enabled the determination of the specific deformation energy cumulated during the tests in the specimen material until the test was stopped and metallographic investigations were carried out [2÷5]. The value of the cumulated energy was determined from dependence:

$$W_K = \sum_{1}^{N_f} W(N) \quad (1)$$

where W(N) is a dependence describing the change of the density of strain energy as a function of the number of thermo-mechanical loading cycles, whilst N_f is the number of cycles after which the test was stopped and measurement of the depth of microcracks throughout the specimen length was made [7].

By substituting equation (1) with the experimentally determined power trend functions, the following equation was obtained:

$$W_K = \int_{1}^{N_f} W(N) \cdot dN = \int_{1}^{N_f} C \cdot (N)^m \cdot dN \quad (2)$$

where C and m are constant, experimentally determined quantities.

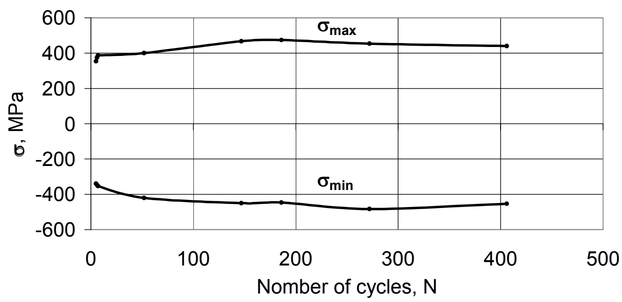

Fig. 2. Curves of cyclic strengthening for specimens from variant I, group 1 (Table 1)

Table 1.
Variants and parameters of fatigue tests

Testing variant	Specimen group	Fatigue tests' parameters: Thermal cycle (ramp)	Mechanical load (ramp)	$K=\|\varepsilon_m/\varepsilon_{th}\|$
I	1	160°C÷540°C	$\Delta\varepsilon_t = 0$	K=1
	2			
II	1		$\Delta\varepsilon_t = 0.2\%$	K=1.37
	2		$\Delta\varepsilon_t = 0.3\%$	K=1.55

Integration of expression (2) yields:

$$W_K = C \cdot \frac{N_f^{m+1} - 1}{m+1} \quad (3)$$

By substituting formula (3) with number values of the experimentally determined constant quantities, the values were calculated of the cumulated deformation energy W_K, dissipated after N_f cycles of changes in the thermo-mechanical load of a specimen.

4. Discussion of results

The investigations have shown that it is possible to simulate, in laboratory conditions [3, 13, 15], the thermo-mechanical loads present during the operation of boiler superheaters. One of the principal criteria of their life is the crack initiation moment [5, 10]. This criterion was also assumed in relation to the tests on specimens, performed in laboratory conditions. To determine the influence of the number of loading cycles on crack growth in variants I-1 and I-2, different bases were assumed for the fatigue test. In test variants II-1 and II-2, the influence of the value of strain intensity on the crack depth was determined. A measure of the intensity was in that case the load rigidity coefficient, K.

As a result of the tests, an energy-related criterion was formulated. It characterizes the material degradation state during the time of the growing number of loading cycles. It is the so-called cumulated value of the density of strain energy, which initiates cracking in the tested material.

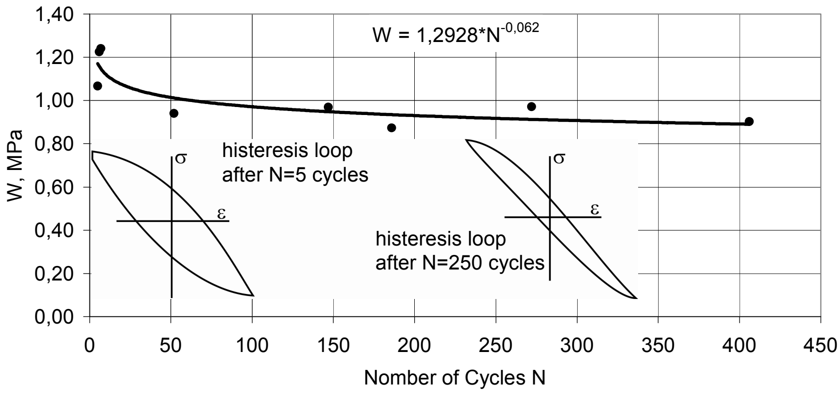

Fig. 3. Strain energy dissipation for specimens from variant I, group 1 (Table 1)

On these grounds, it is possible to determine the durability (number of cycles until the crack process initiation) of any constructional elements operating under the conditions of variable thermo-mechanical loads.

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