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Fatigue life of creep resisting steels under conditions of cyclic mechanical and thermal interactions

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ABSTRACT

Purpose: This study sets out to determine the characteristics of high-temperature creep resisting steels under conditions of thermo-mechanical fatigue with the use of a method proposed in the Code-of-Practice under the EU TMF-Standard project.

Design/methodology/approach: The thermo-mechanical fatigue (TMF) tests were carried out in the conditions where the value of complete strain and the temperature were under control. Two methods of investigating samples in TMF tests were applied: OP (out-of-phase) and IP (in-phase).

Findings: Based on the tests, the characteristics of TMF life was determined and it was found that X20CrMoV12.1 steel shows lower life in comparison with new steels: X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92). The results of the OP tests made for X10CrMoVNb9-1 (T/P91) steel are an exception here. Tests of thermo-mechanical fatigue have shown that in a majority of cases in fatigue tests, the X20CrM0V12.1 steel has lower TMF life when compared to X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92) steels, despite its better strength properties, as a measure of which, the range of stress was adopted.

Research limitations/implications: At the present stage of the research, two types of tests (IP and PO) were performed. Due to a limited number of experiments connected with the application of selected types of tests and their number, the conclusions resulting from the research may, at the present stage, serve as guidelines for its continuation only.

Practical implications: The test results may also be used to compare the properties of creep resisting steels used in the power engineering industry and represent a contribution to widening the knowledge of the behaviour of materials under thermo-mechanical fatigue conditions.

Originality/value: This study is one of the first attempts to determine the TMF life characteristics of the steels used in the Polish power engineering industry.

Keywords: Thermo-mechanical fatigue; Creep resisting steels; Fatigue life

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PROPERTIES

1. Introduction

Thermo-mechanical fatigue (TMF) belongs to the phenomena which determine the life of components of power engineering devices. “Thick-walled elements”, in which under conditions of rapid temperature changes, variable in time thermal stresses occur, may serve as an example here. Such interactions are usually of a cyclic nature.

Despite common awareness of power engineers, concerning the significant role of thermo-mechanical fatigue in the damage processes of components of power engineering devices, this phenomenon is not given sufficient prominence in the procedures of design and life evaluation of high-temperature creep resisting materials. Still, the basic properties taken into account when evaluating the life of power engineering devices, due to the missing characteristics of high-temperature creep resisting steels subject to thermo-mechanical fatigue, are the properties determined in creep tests and the characteristics obtained under conditions of isothermal fatigue [1-5].

The thermo-mechanical fatigue test is one of the most complex and time-consuming mechanical tests, based on which the life of materials is determined. During tests, the parameters of the temperature cycle, strain and stress may be variable. In the conditions of uniaxial state of stress, the controlled values are the temperature and strain. Tests may be conducted for various angles of phase displacement between the temperature cycle and the mechanical strain cycle [6-7]. The tests performed most often are in-phase (IP) tests (phase displacement angle $\varphi=0^o$) and out-of-phase (OP) tests (phase displacement angle $\varphi=180^o$). As results of a review of the subject literature, TMF life of materials understood as the number of cycles until failure of a specimen, with other test parameters being similar, may vary, depending on the test type (IP or OP). For example, the TMF life of superalloys and some ferritic steels under conditions of IP tests is higher than the life determined in OP tests. The specimens had failed by transgranular initiation and propagation during these both tests [8-9]. In the case of austenitic steels and oxide dispersion strengthened alloy MA754, the situation is reverse, where IP testing produces intergranular cracking, that IP lives are shorter than OP lives [10-11].

2. Methodology and research material

Thermo-mechanical fatigue tests consisted of in-phase and out-of-phase tests [12-15].

The test stand used for the thermo-mechanical fatigue tests was built on the basis of a strength testing machine, MTS-810. The stand was equipped with a digital control system TestSTAR II and an induction heating system by Hűttinger Company (Fig. 1).

The tests were conducted under temperature and strain control. The scope of temperature changes amounted to 450°C, with the minimum temperature of 200°C and the maximum temperature of 650°C. Pipe specimens of internal diameter of 12 mm and wall thickness of 2 mm were used in the tests.

Induction heating was applied in the tests. Cooling was forced using compressed air blown through an axial hole in the sample.

Tests were performed for three creep resisting steel grades used in power engineering: X20CrMoV12.1, X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92). The steels were tested in state after normalizing and tempering. The material for the tests was sampled from thick-walled pipe elements.

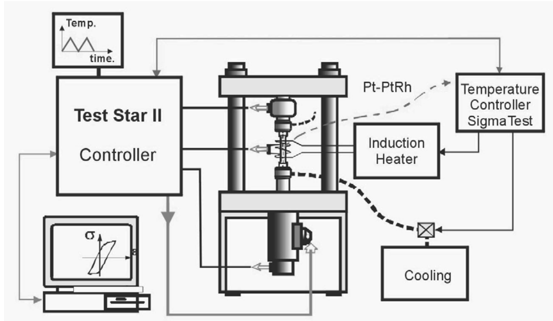

Fig. 1. Thermal-mechanical fatigue test stand

3. Research results

During the tests, the following values were recorded: temperature, number of cycle, force and elongation (contraction) of the sample, on the basis of which, fatigue characteristics of the materials were developed. Some of them were used to evaluate life and strength properties of the materials. Some examples of the test results are shown in Fig. 2 and Fig. 3, which depicts the course of changes of the range of stress as a function of the number of cycles for various types of tests and various materials.

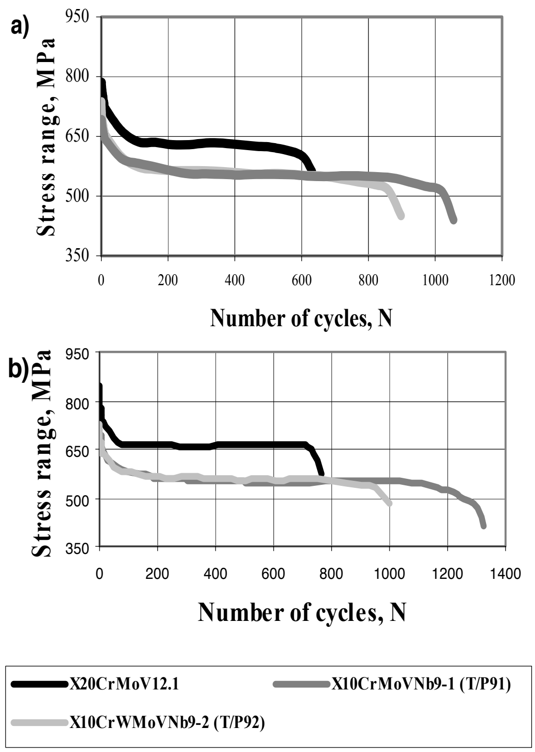

Fig. 2. Course of relations between stress range and number cycles for the X20CrMoV12.1, X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92) steels for the chosen cycle type: a) displacement angle in the mechanical strain cycles in relation to the thermal strain cycles $\varphi=180^o$ b) displacement angle in the mechanical strain cycles in relation to the thermal strain cycles $\varphi= 0^o$

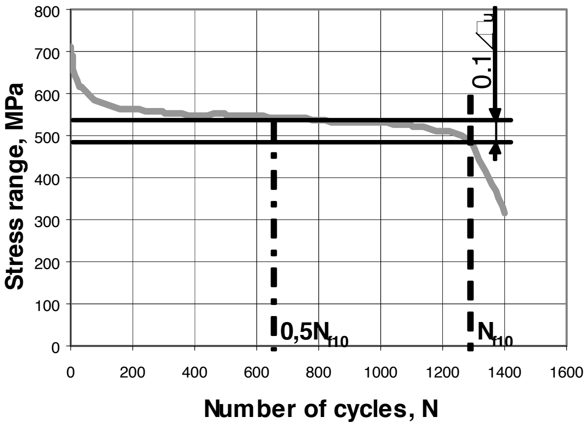

Fig. 3. Course of relations between stress range and number of cycles to failure for the chosen cycle type – displacement angle in the mechanical strain cycle in relation to the thermal strain cycle φ= 0° for the X10CrMoVNb9-1 (T/P91) steel, N_{f10} – number of cycles corresponding to a 10% decrease stress range

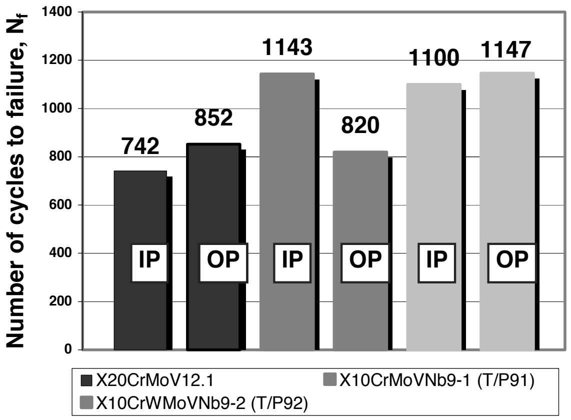

Fig. 4. TMF life for the X20CrMoV12.1, X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92) steels for the cycle type IP and OP

Using this criterion, life of the individual samples was determined. The results of the tests are compiled in Table 1 and illustrated in Fig. 4.

4. Discussion

The papers published previously by the team of authors concerned mainly the problems of material deformation under thermal and mechanical fatigue conditions [13-15]. Mathematical models have been worked up, enabling the description of the behaviour of materials in the conditions of variable temperature and mechanical loading. Characteristics have been thus obtained, which may provide a basis for determining the criterial quantities associated with fatigue life of the material. Such quantities comprise the total strain range, the range of stress, maximum and minimum temperatures, as well as the energy of plastic strain. In technical literature, various approaches can be found, which use some of the above-mentioned quantities determining the fatigue life of materials.

Table 1.
TMF life for the X20CrMoV12.1, X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92) steels for the cycle type IP and OP

Steel code	Cycle type	Spec. No.	TMF life	Average of TMF life
X20CrMoV12.1	IP	1	750	742
		2	745	
		3	730	
	OP	1	925	852
		2	620	
		3	1010	
X10CrMoVNb9-1 (T/P91)	IP	1	1275	1143
		2	960	
		3	1195	
	OP	1	640	820
		2	860	
		3	915	
X10CrWMoVNb9-2 (T/P92)	IP	1	970	1100
		2	1350	
		3	980	
	OP	1	1135	1147
		2	1275	
		3	1030	

This paper is focused on determining the fatigue life of the selected material under thermal and mechanical fatigue. At the same time, the study constitutes a preliminary stage of studies to be aimed at elaborating and verifying the criterion of fatigue life of creep resisting steels subject to such fatigue process and used in the power engineering industry. However, the elaboration of such criterion requires conducting studies in various conditions, i.e. in tests of different types. At the current stage, two types of tests were selected, IP and OP.

It was found that the behaviour of materials varies, depending on the test type. Further, fatigue properties were analysed in connection with the strength properties of the materials.

Although this study presents the results of preliminary tests only, it is possible, on the basis of the results obtained, to find differences in the fatigue behaviour of the particular steel grades already at the present stage. The tests of thermo-mechanical fatigue have shown that despite better strength properties, the measure of which may include the range of stress as well as the maximum and minimum stress of the cycle, X20CrM0V12.1 steel is characterised, in a majority of cases, by lower life compared to X10CrMoVNb9-1 (T/P91) and X10CrWMoVNb9-2 (T/P92). steels. The results of the OP tests made for X10CrMoVNb9-1 (T/P91) steel are an exception here.

In spite of diverse opinions quoted in the literature, regarding the influence of the type of cycle on fatigue life, in case of the materials investigated in the range of temperature adopted in the study, it should be expected that the specimens examined in the IP test would be characterized by lower fatigue life. The results presented in the study may serve as a contribution to the substantiation of this statement. This is because in two cases (steels X20CrMoV12.1 and X10CrWMoVNb9-2 (T/P92).), the IP tests revealed lower fatigue life. The IP test is characterized by a higher temperature while tensioning the samples, which may be conducive to the formation and development of cracks due to the impact of temperature on decreasing strength properties and on the direction of load causing crack growth. The deviation observed for steel X10CrMoVNb9-1 (T/P91) may result from too small number of specimens examined at this stage of research. The complexity of the test causes a large dispersion of results of the study. Apart from that, the influence of structural factors related to such effects as creep and increasing and decreasing strength properties of materials, which will be taken into account in subsequent tests, cannot be neglected. The life determined now would have to be examined as a part of an entire set of phenomena which decide about the crack formation processes and degradation of mechanical properties of materials. They comprise creep phenomena, precipitation processes and processes of fissure formation and development. In this context, the authors' intention were tests, the results of which could contribute to widening the knowledge on the fatigue behaviour of materials used in the power engineering industry.

A detailed analysis of the phenomena investigated requires widening the scope of the research. For a precise quantitative comparison of the properties of steels determined in thermo-mechanical fatigue tests, it would be recommended to use a larger number of samples, to enable objective determination of the average value, confidence interval and probability, which will be the subject of our on-going research.

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