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THE INFLUENCE OF LOAD HISTORY ON DURABILITY OF P92 STEEL USED FOR THE CONSTRUCTION OF ENERGY PIPELINES

WPŁYW HISTORII OBCIĄŻENIA NA TRWAŁOŚĆ STALI P92 STOSOWANEJ DO BUDOWY RUROCIĄGÓW ENERGETYCZNYCH.

The research material used in the study was the martensitic creep-resistant steel P92 used for the manufacture of pipes being part of power generation units subject to heavy load. The research problem focused on two issues. The first one was to analyze how the plastic deformation cumulated in the material in low-cycle fatigue conditions affects the characteristics of the material in creep conditions in a temperature of 600°C. The other one was concerned with analysis of a reverse situation, i.e. how the initial plastic deformation of the material in creep conditions changes the mechanical characteristics of the steel under low-cycle fatigue conditions in a temperature of 600°C.

Keywords: P92 steel, load history, creep, low-cycle fatigue

W pracy materiałem badawczym była żarowytrzymała stal martenzytyczna P92 wykorzystywana do wytwarzania rur wchodzących w skład wysokoobciążonych bloków energetycznych. Problem badawczy koncentrował się na dwóch zagadnieniach. W pierwszym analizowano jak odkształcenie plastyczne kumulowane w materiale w warunkach procesu zmęczenia niskocyklowego wpływa na charakterystyki materiału w warunkach pełzania w temperaturze 600°C. W drugim analizowano sytuację odwrotną, tzn. jak wstępna deformacja plastyczna materiału w warunkach pełzania zmienia charakterystyki mechaniczne stali w warunkach zmęczenia niskocyklowego w temperaturze 600°C.

1. Introduction

In the current decade, the principal direction of the power industry development is the construction of modern 1000 MW supercritical coal-fired boilers. The design process for devices of this kind requires the use of state-of-the-art materials, such as P91 and P92 steels, which are able to meet very high requirements in terms of the efficiency and availability expected by the user. This applies especially to steam pipelines, which operate at a temperature equal or higher than 600°C and under pressure exceeding 28 MPa. These objects are exposed mainly to the harmful effects of progressive changes in the material caused by creep processes and, in many cases, by low-cycle material fatigue [1, 2, 3, 4]. The latter is caused, to a high degree, by variable thermo-mechanical load which occurs in transient conditions (between the cold and hot states of an object) connected with the start-up and shutdown of power units [5, 6, 7, 8]. The above-mentioned overlapping loads, as well as the sequence of their occurrence, may locally induce plastic deformation in the components of power engineering objects. It may have a significant influence on changes in the mechanical properties of the materials used [9]. Therefore, there is a need to assess the influence of load history (taking into account the thermo-mechanical effects observed in the operating conditions) on the mechanical characteristics, including durability, of elements such as pipes used in power installations. Knowledge in this scope will enable forecasting the time period of safe operation of power objects at the stage of design calculations more accurately.

The research material used in the study was the martensitic creep-resistant steel P92 used for the manufacture of pipes being part of power generation units subject to heavy load, including those in nuclear power stations. The research problem focused on two issues. The first one was to analyze how the plastic deformation cumulated in the material in low-cycle fatigue conditions affects the characteristics of the material in creep conditions in a temperature of 600°C. A reverse situation were analyzed in the second case, i.e. how the initial plastic deformation of the material in creep conditions changes the mechanical characteristics of the steel under low-cycle fatigue conditions in a temperature of 600°C.

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2. Material, methodology and research results

Two variants of research experiments were used in the study to determine the influence of load history on durability of the material. In these variants, the material destruction processes observed in the operating conditions of high-pressure energy pipelines, i.e. creep and low-cycle fatigue (which may occur under unsteady operation conditions), were simulated. In the first variant, the influence of the low-cycle fatigue process on durability t_r in creep conditions was evaluated, and the second one was used to assess the influence of the creep process on durability N_f in low-cycle fatigue conditions. Cylindrical specimens (Table 3) made of a material cut from a P92 steel pipe (after normalization and drawing) intended for power engineering installations were used in mechanical tests. The steel microstructure is shown in Fig. 1 and its chemical composition and basic mechanical properties are listed in Table 1. The conditions of conducted experiments are shown in Table 2.

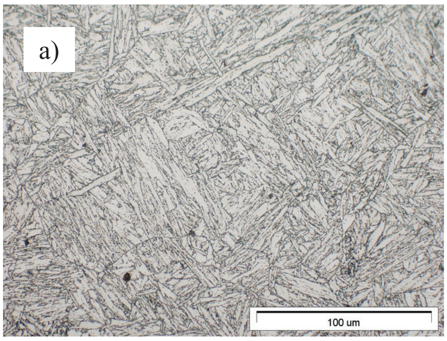


Fig. 1a. LM – P92 steel microstructure. Tempered martensite with visible non-metallic inclusions.

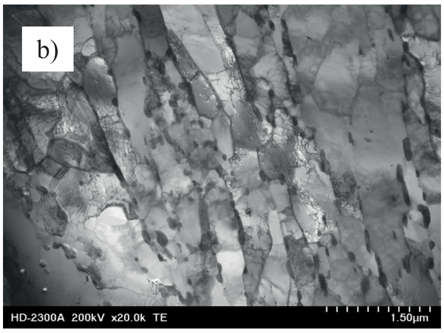


Fig. 1b. TEM – Substructure of tempered martensite in the P92 steel with diverse dislocation density and M23C6 carbide precipitates along martensite lamellae borders.

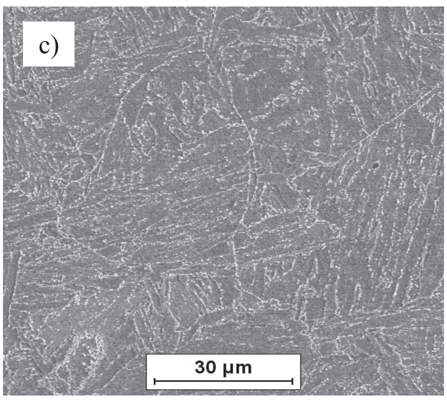


Fig. 1c. SEM – Tempered martensite with carbides precipitates along the borders of martensite lamellae and former austenite grains.

In order to determine the influence of the material fatigue on durability tr in creep conditions, a series of the low-cycle fatigue tests were carried out on an MTS servo-hydraulic machine at a temperature of 600°C under tension and compression conditions, with the cycle asymmetry ratio R=-1. The research was conducted by controlling strain in the ranges $\Delta\varepsilon_t$=0.6 and 1.2%. Fatigue tests in research experiments no. 2 and 3 were carried out until the specimen fractured, but at the first stage of experiments no. 4 and 5 the tests were performed only up to the number of cycles of approximately $0.4N_f$, as shown in Figs 2 and 3.

In order to conduct the second stage of experiments no. 4 and 5, specimens for creep tests were cut from those used in experiments no. 2 and 3, as shown in Table 2. The prepared specimens as well as specimens from the material in its initial condition (experiment no.1) were subjected to creep tests using the following parameters: σ =170 MPa, T=600°C. The results of the performed creep tests are shown in Figure 4 and listed in Table 3.

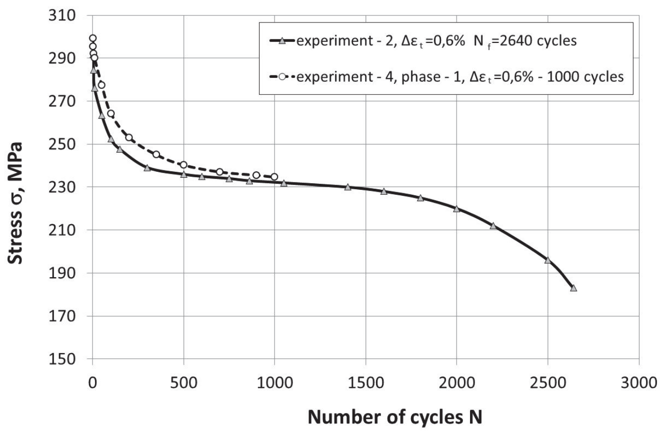


Fig. 2. Diagrams of cyclic deformation of the P92 steel in conditions of research experiments no. 2 and 4

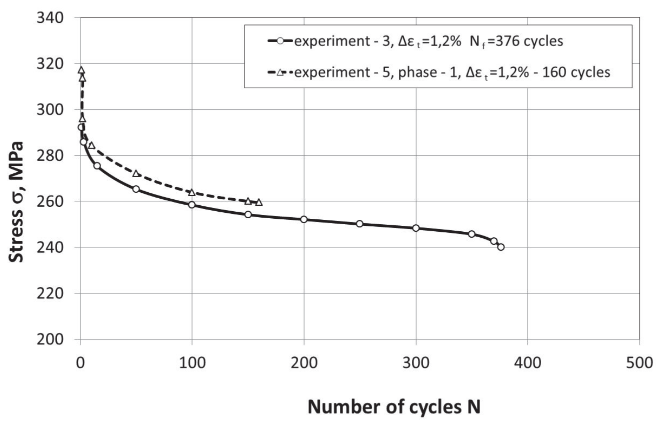


Fig. 3. Diagrams of cyclic deformation of the P92 steel in conditions of research experiments no. 3 and 5

TABLE 1

Chemical composition and basic mechanical properties of the P92 steel

Chemical element content, wt-%								
C	Si	Mn	P	S	Ni	Cr	Mo	W
0.11	0.30	0.60	0.017	0.004	0.20	9.50	0.50	1.90

Basic mechanical properties			
R_m, MPa	$R_{p0.2}$, MPa	A_5, %	Z, %
705.7	529.7	25.4	67.5

TABLE 2

The conditions of conducted experiments and the size and shapes of specimens

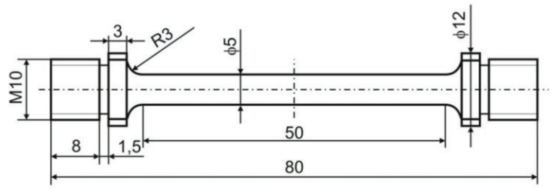
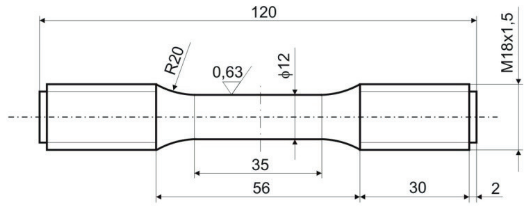
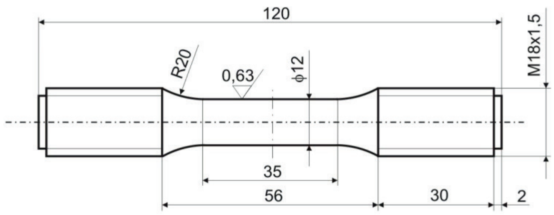
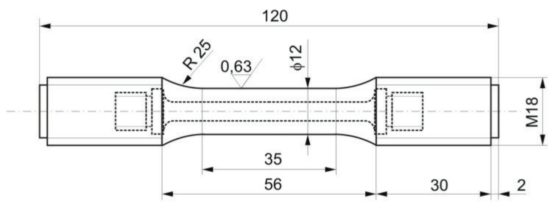
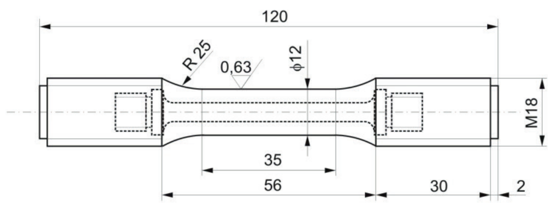
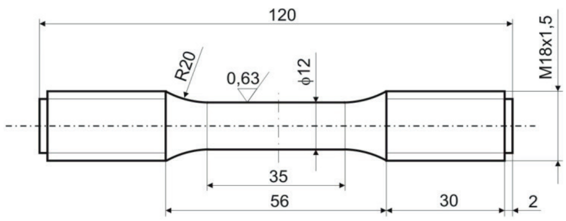
Experiment	Test parameters	Specimen dimensions
1	Material at initial state; Creep until failure: stress $\sigma = 170$ MPa temperature $T = 600^{o}$C.	
2	Material at initial state; Low-cycle fatigue until failure: total strain range $\Delta\varepsilon_t = 0.6\%$, temperature $T = 600^{o}$C.	
3	Material at initial state; Low-cycle fatigue until failure: total strain range $\Delta\varepsilon_t = 1.2\%$, temperature $T = 600^{o}$C.	
4	**First phase of the experiment:** Low-cycle fatigue until $0.4N_f$, $\Delta\varepsilon_t = 0.6\%$, $T = 600^{o}$C **Second phase of the experiment:** Creep until failure $\sigma = 170$ MPa, $T = 600^{o}$C	
5	**First phase of the experiment:** Low-cycle fatigue until $0.4N_f$, $\Delta\varepsilon_t = 1.2\%$, T = 600^{o}C **Second phase of the experiment:** Creep until failure $\sigma = 170$ MPa, $T = 600^{o}$C	
6	**First phase of the experiment:** Creep over 100 h $\sigma = 170$ MPa, $T = 600^{o}$C **Second phase of the experiment:** Low-cycle fatigue until failure $\Delta\varepsilon_t = 0.6\%$, $T = 600^{o}$C	

TABLE 3

Durability tests results for P92 steel in conditions of the first load history variant. Influence of the low-cycle fatigue process on durability tr in creep conditions

Durability t_r (time until specimen failure) in creep conditions: σ = 170 MPa, T = 600°C				
Experiment no.		First phase of the experiment Low-cycle fatigue	Second phase of the experiment Creep until failure σ=170 MPa, T=600oC	Comments
1	specimen 1	----	t_r=245h	t_{r_mean}= 227h
	specimen 2	----	t_r=209h	
4	specimen 3	0.4N_f≈1000 cycles ($\Delta\varepsilon_t$=0.6%, T=600°C)	t_r=72h	Durability reduction by 68%
5	specimen 4	0.4N_f≈160 cycles ($\Delta\varepsilon_t$=1.2%, T=600°C)	t_r=25h	Durability reduction by 88%

TABLE 4

Durability tests results for P92 steel in conditions of the second load history variant. Influence of the creep process on durability N_f in low-cycle fatigue conditions

Durability N_f (number of cycles until specimen failure) in low-cycle fatigue conditions: $\Delta\varepsilon_t$ = 0.6%, T = 600°C			
Experiment no.	First phase of the experiment Creep	Second phase of the experiment Low-cycle fatigue until failure De=0.6%, T=600°C	Comments
2	----	N_f= 2640 cycles	comparable durability values N_f (increase by 5% after a creep test)
6	Creep t = 100h σ=170 MPa, T=600°C	N_f = 2770 cycles	

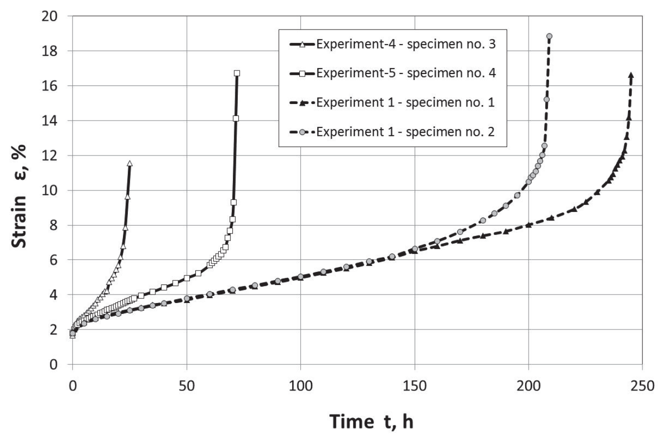


Fig. 4. Creep characteristics of P92 steel obtained in conditions of the first load history variant

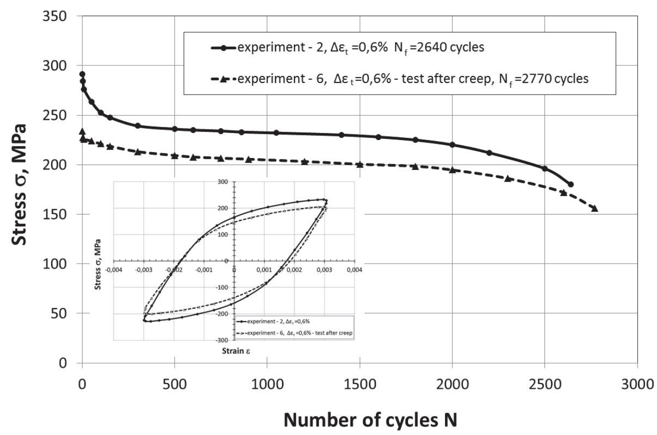


Fig. 5. Diagrams of cyclic deformation of the P92 steel in conditions of research experiments no. 2 and 6

The second load history variant analyzed a reverse situation, i.e. how the initial plastic deformation of the material in creep conditions changes the mechanical characteristics of the P92 steel under low-cycle fatigue conditions at a temperature of 600°C. For this purpose two phases of research experiment no. 6, which are characterized in Table 2, were carried out on the same specimen. The results of the performed mechanical tests (a creep test and then a low-cycle fatigue test) are shown in Figure 5 and listed in Table 4.

3. Summary of test results

An analysis of the obtained results indicates a significant influence of the load history, in the sequence: low-cycle fatigue and subsequent creep process (research experiments no. 4 and 5), on durability of the P92 steel. The bigger the total strain range $\Delta\varepsilon_t$ used in the fatigue test conditions, the greater the reduction of the material's durability in creep conditions. It has been found in the analyzed load history case that the creep life was reduced by 68% when the initial low-cycle fatigue process progressed with the strain range of $\Delta\varepsilon_t$ =0.6%, and by 88% when it occurred at $\Delta\varepsilon_t$=1.2%.

On the other hand, a reverse sequence of the load history (research experiment no. 6) did not cause any significant differences in the P92 steel fatigue durability N_f. After a creep test carried out over 100 h (experiment no. 6) it increased by only 5% compared to the durability of the material in its initial state (experiment no. 1). Furthermore, it was found in the analyzed case that the saturation stress of the material initially subjected to creep-fatigue loading decreased by approximately 30 MPa compared to its initial state.

REFERENCES

[1] G. Junak, M. Cieśla, Low-cycle fatigue of P91 and P92 steels used in the power engineering industry, "International Conference "Achievements in Mechanical and Materials Engineering", Archives of Materials Science and Engineering **48**, 19-24 (2011).

[2] A. Marek, J. Okrajni, Local stress-strain behavior of a high-temperature steam valve under transient mechanical and thermal loading. J. Mater. Eng. Perform. **23**, 1, 31-38 (2014).

[3] J. Zieliński, J. Dobrzański, T. Jóźwik, Assessment of loss in life time of the primary steam pipeline material after long-term service under creep conditions, Journal of Achievements in Materials and Manufacturing Engineering **54**, (1), 67-74 (2012).

[4] A. Hernas, J. Dobrzański, Durability and damage of boiler and steam turbine components, Publishing House of the Silesian University of Technology, (2003).

[5] K. Mutwil, M. Cieśla, Study on Cracking Process of Power Boiler Element, Production Editor, IOP Conference Series: Materials Science and Engineering **35** 012017, 1-11 (2012).

[6] J. Okrajni, Zmęczenie cieplno-mechaniczne i trwałość instalacji energetycznych. Wydawnictwo Politechniki Śląskiej. Gliwice (2011).

[7] H. Sehitoglu, Thermal and Thermo-mechanical Fatigue of Structural Alloys, Fatigue and Fracture, ASTM Handbook **19**, 527-556 (2008).

[8] A. Marek, J. Okrajni, "Local Stress-Strain Behavior of a High-Temperature Steam Valve Under Transient Mechanical and Thermal Loading", Journal of Materials Engineering and Performance, ISSN 1059-9495 **23,** 1, 1-8 (2013).

[9] Z. Kowalewski, Zjawisko pełzania metali – eksperyment I modelowanie, Polska Akademia Nauk, Instytut Podstawowych Problemów Techniki, Warszawa (2005).

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