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Low-cycle fatigue of P91 and P92 steels used in the power engineering industry

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ABSTRACT

Purpose: The aim of the study was to determine the life characteristics of low-cycle P91 and P92 steels used in the power unit components that work under the highest effort. The life of the steels was determined for constant ranges of total strain from the range of $\Delta\varepsilon_t$= 0.6-1.2% and with the application of gradual loading two-stage.

Design/methodology/approach: Low-cycle fatigue tests of the material in its initial state were performed at room temperature. The fatigue tests were conducted on an MTS-810 system, while controlling the strain. The tests at graded loads were performed for two strain ranges: $\Delta\varepsilon_t$ =0.6 and 1.2%. Fractographic analyses of fractures were conducted on a Hitachi 4200 scanning microscope.

Findings: It has been found that the fatigue life of steels exposed to graded loads is strictly correlated to the strain history. Higher fatigue life was a characteristic of steels in the case of which during the tests a smaller strain range, $\Delta\varepsilon_t$=0.6%, was applied.

Practical implications: Presented in this work fatigue properties characterization could used in the low-cycle fatigue durability evaluation of creep element. Especially in the case of work conditions characterized by gradual loading of elements made from P91, P92 of steels in power plant systems.

Originality/value: Low-cycle fatigue characteristics taking into account the influence of graded loads were developed for the P91 and P92 steels used in the power engineering industry.

Keywords: Fatigue; Low-cycle life; Fractography; Mechanical properties; Structure

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PROPERTIES

1. Introduction

Life forecast of industrial facilities after many years of service is a problem bothering both industrial plants and academic centres in the country and abroad. This problem is particularly important in the power engineering industry where replacement of a given item or the entire facility entails huge costs [1]. There are both domestic and foreign centres which specialise in forecasting the life and repairing such facilities. This field, however, requires further advancement and development of new approaches in assessing the life, including the fatigue life, of facilities subjected to mechanical and thermal impacts [2-8].

There have been numerous attempts to describe the phenomenon of destruction of industrial facilities after many years of operation in the conditions of variable mechanical and thermal loads. Yet, the question of fatigue life remains unresolved due to its complexity. Therefore, such a description of the fatigue phenomenon which on the basis of specific calculations shows the advisability of carrying out a repair or replacement of a given item [9-11], seems reasonable. In this case, it is necessary to develop fatigue characteristics of materials, with parameters simulating the operating conditions of the analysed facility.

The currently applicable world standards and procedures regarding the assessment of the life of industrial facilities capture this phenomenon in many different ways. The following standards should be mentioned here: German (TRD) and British (BS 7910). These procedures consider the problem of nucleation and incubation of cracks and the subsequent development of fissures. This paper presents the characteristics of the low-cycle life of steels P91 and P92 for a permanent strain range, $\Delta\varepsilon_c$, and graded loads. The obtained results may be used in the procedures of forecasting the life of power engineering facilities made of these materials.

2. Research material

Samples made of P91 and P92 steels, used for pipelines and power unit components being part of conventional boilers due to their high strength properties at elevated temperatures, were subjected to tests. The chemical composition, microstructure (Figs. 1, 2) and the principal mechanical properties of the steels are presented in Tables 1, 2.

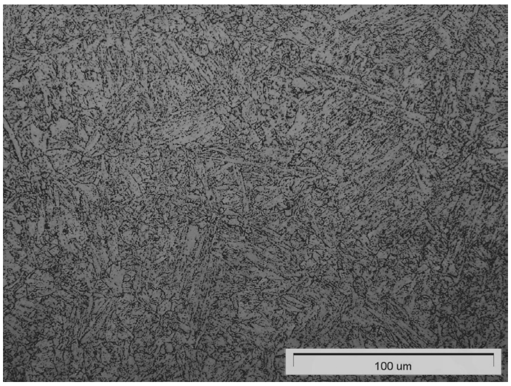

Fig. 1. Microstructure of P91 steel, LM

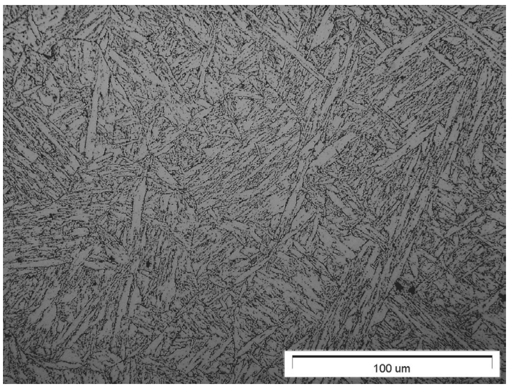

Fig. 2. Microstructure of P92 steel, LM

Table 1.
Chemical composition of P91 and P92 steel

Steel	Content of an element, wt.%								
	C	Si	Mn	P	S	Ni	Cr	Mo	W
P91	0,10	0,36	0,42	0,017	0,004	0,13	8,75	0,96	-
P92	0,11	0,30	0,60	0,017	0,004	0,20	9,50	0,50	1,90

Table 2.
Principal mechanical properties of P91 and P92 steel

Steel	R_m [MPa]	$R_{0,2}$ [MPa]	A_5 [%]	Z [%]	$R_{z100000/600C}$
P91	694,4	544,6	23,8	71,4	98
P92	705,7	529,7	25,4	67,5	132

3. Low-cycle fatigue tests

Low-cycle fatigue tests were performed under controlled strain, at room temperature, on samples prepared according to the PN-EN 10002-1+AC1 (Fig. 3) standard in MTS-810 system (Fig. 4).

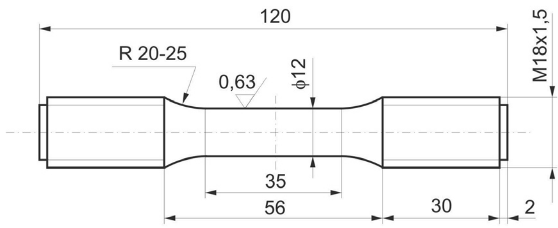

Fig. 3. Low-cycle fatigue test sample

Fig. 4. Servohydraulic test system MTS-810

The research focused on the deformation range of $\Delta\varepsilon_t$ = 0.6-1.2%, using a sinusoidal cycle with factor R = -1. Based on the obtained results, the fatigue life characteristics were developed, as shown in Figs. 5, 6 as well as cyclic strain graphs (Figs. 7 and 8). Table 3 contains mathematical models of cyclic strain of the investigated materials.

The fatigue tests show that the investigated materials are characterised by very similar fatigue durability, N_f, as well as similar values of saturation stress σ_{an}. Both grades of steel are characterised by cyclical weakening, however, in the case of steel P92, the cyclical weakening factor reaches a higher value (Table 3). The particularly intensive cyclical weakening of the P91 steel (Fig. 7) reduces its operational properties compared to P92. The ranges of plastic, $\Delta\varepsilon_p$, and elastic strain, $\Delta\varepsilon_e$, and their corresponding range of stress, $\Delta\sigma$, were determined in tests based on the recorded hysteresis loops (Figs. 9, 10). The obtained results were used to develop the fatigue life graphs of the investigated steels (Figs. 11, 12). The fatigue life is described by the Smith, Hirschberg and Manson's dependence [12-15]:

$$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e = M \cdot N_f^z + \frac{G}{E} \cdot N_f^\nu \qquad (1)$$

where:

M, G, E, z, ν - material constants.

An analysis of the fatigue life (Fig. 11, 12) has shown that in both cases, the intersection point N_t of the graphs $\Delta\varepsilon_e = f(N_f)$ and $\Delta\varepsilon_p = f(N_f)$ is located within the low-cycle range, i.e. ca. 1000 cycles. This testifies to the fact that for the adopted complete deformation ranges, $\Delta\varepsilon_t$, the cyclic strain process of the steels was proceeding with a dominant participation of the elastic strain component (Fig. 11, 12). Therefore, it can be assumed that the cyclic deformability depends mainly on the strength properties of the steel.

Table 3.
Cyclic deformation models of P91 and P92 steels

Steel	$\sigma_{an} = K' \cdot \varepsilon_p^{n'}$	
	K′- cyclic strength coefficient	n′- cyclic softening exponent
P91	750.3	0.07
P92	953.5	0.11

Table 4.
Fatigue models of P91 and P92 steels

Steel	$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e$			
	$\Delta\varepsilon_p = M \cdot N_f^z$		$\Delta\varepsilon_e = (G/E) \cdot N_f^\nu$	
	M	z	G/E	ν
P91	1.205	-0.78	0.009	-0.1
P92	1.671	-0.84	0.010	-0.1

In a subsequent stage of the research, fatigue tests were conducted at graded loads. Two variants of total strain were used in the low-cycle fatigue test.

For variant A (L-H) (Fig. 13), at first the tests were conducted for a strain range of $\Delta\varepsilon_t$ =0.6% with the adopted number of cycles, and next, the tests were continued until failure at $\Delta\varepsilon_t$ = 1.2%.

For variant B (H-L) (Fig. 14), a reverse order of the application of complete strain ranges, $\Delta\varepsilon_t$, was used.

The obtained results constituted a basis for developing graphs of low-cycle fatigue at graded loads (Figs. 15, 16), prepared against the graph consistent with the Palmgren-Miner hypothesis. Analysis of the obtained graphs indicates that in the case of both the P91 and P92 steel, the curve representing the low-cycle life specified according to procedure A lies above the straight line illustrating the Palmgren-Miner hypothesis, while the curve describing the characteristics of the life determined in accordance with procedure B, lies below the line. This corroborates the fact that the history of strain has a great influence on the fatigue life of steels tested at graded loads.

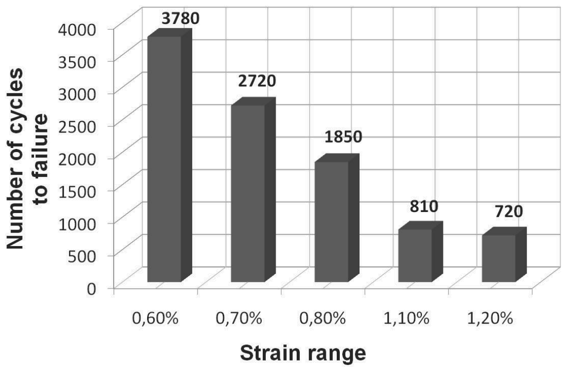

Fig. 5. Low-cycle fatigue of P91 steel

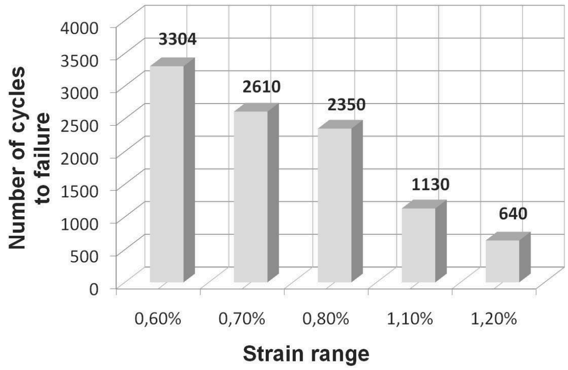

Fig. 6. Low-cycle fatigue of P92 steel

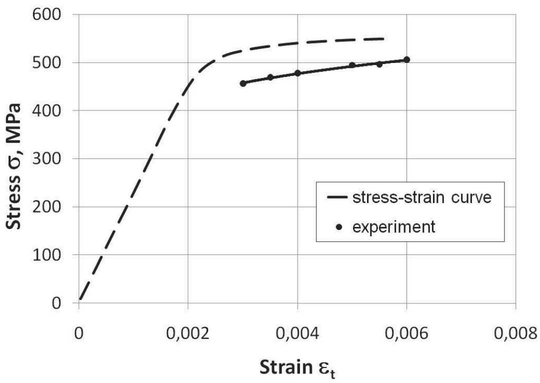

Fig. 7. Cyclic strain graph of steel P91

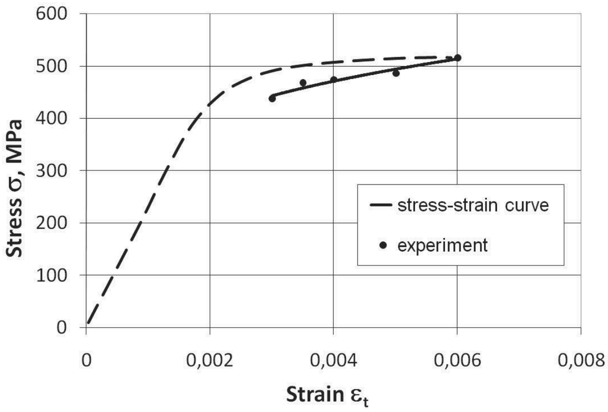

Fig. 8. Cyclic strain graph of P92 steel

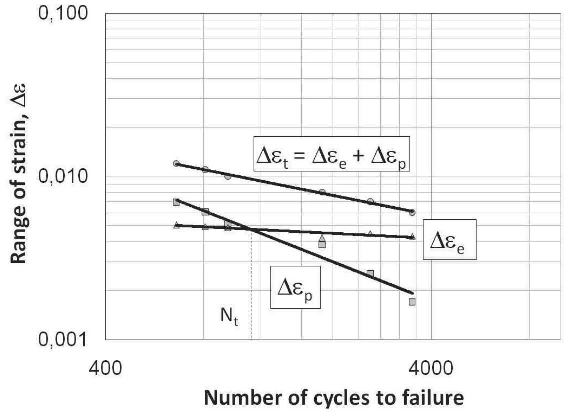

Fig. 11. Fatigue durability graphs of P91 steel

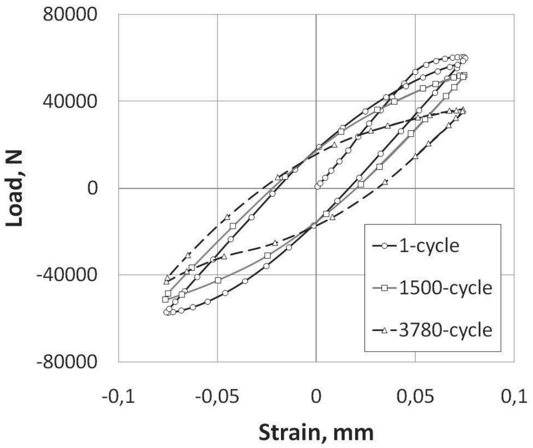

Fig. 9. Hysteresis loops recorded in $\Delta\varepsilon_t$ = 0,6% strain range test of P91 steel

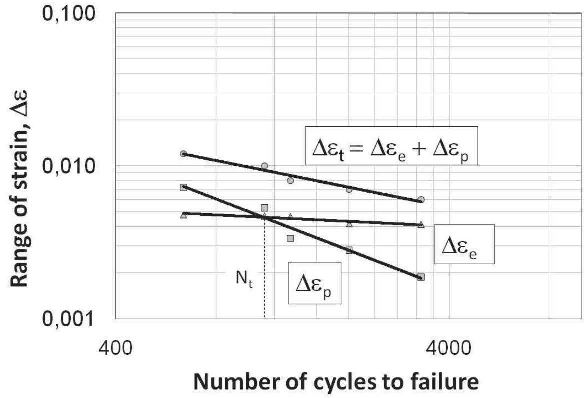

Fig. 12. Fatigue durability graphs of P92 steel

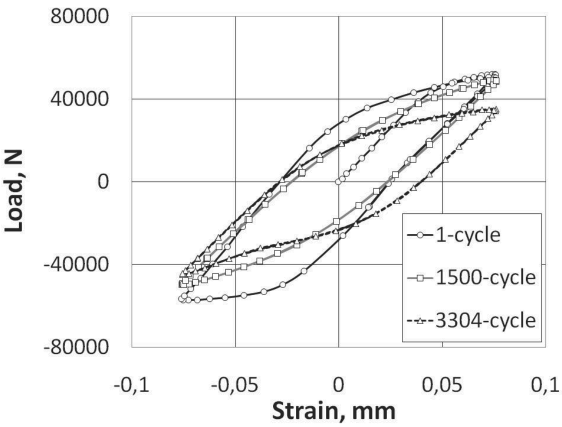

Fig. 10. Hysteresis loops recorded in $\Delta\varepsilon_t$ = 0,6% strain range test of P92 steel

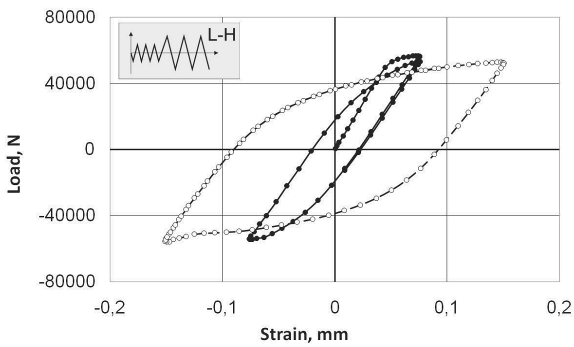

Fig. 13. Characteristic hysteresis loops recorded in test conditions of P92 steel - variant A (L-H)

Fractographic observations conducted on specimen fractures after the low-cycle tests at graded loads have shown the fracture morphology properties characteristic of fatigue cracking. For example, in steel P91 and P92, in a fracture with visible areas of fissile cracking, systems of resting lines have been detected (Fig. 17), as well as secondary cracks and fatigue striae (Figs. 18-20).

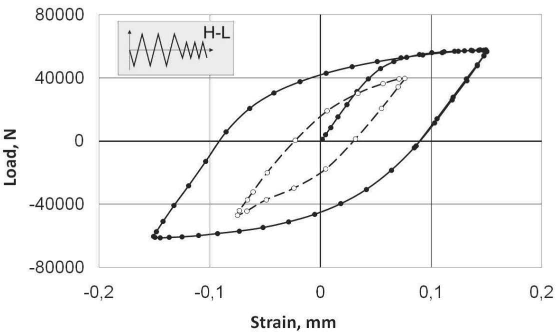

Fig. 14. Characteristic hysteresis loops recorded in test conditions of P92 steel - variant B (H-L)

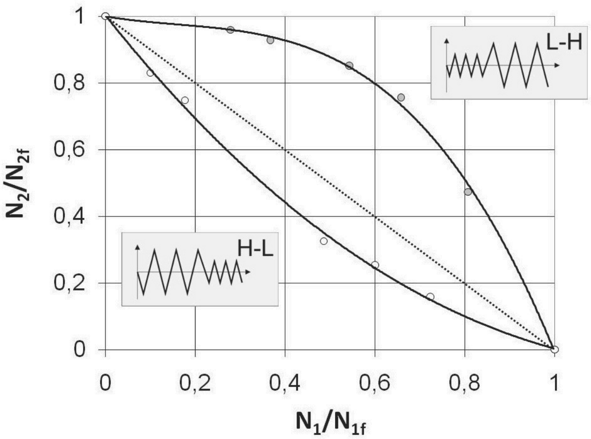

Fig. 15. Characteristics of the low-cycle fatigue durability of P91 steel under graded loads

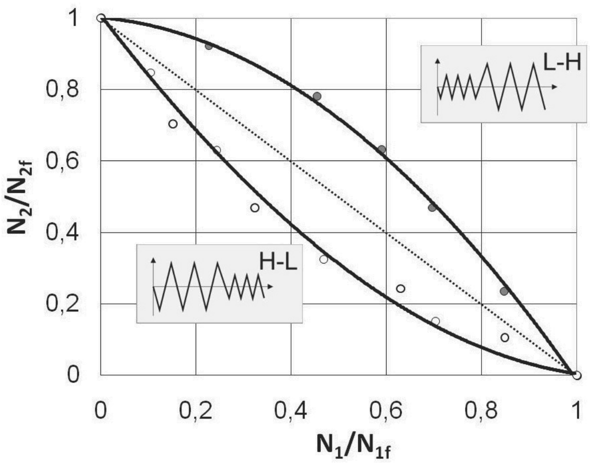

Fig. 16. Characteristics of the low-cycle fatigue durability of P92 steel under graded loads

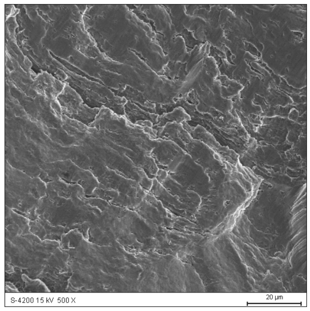

Fig. 17. Fatigue fracture of P91 steel. Distribution of resting lines in the area of transcrystalline fissile fracture

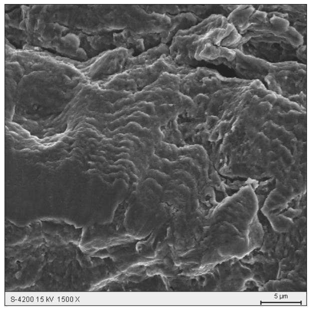

Fig. 18. Fatigue fracture of P91 steel. Distribution of fatigue striae; visible areas of fissile fracture and secondary cracks

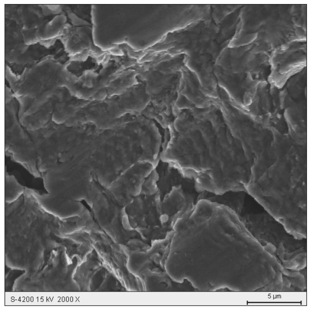

Fig. 19. Fatigue fracture of P92 steel. Distribution of fatigue striae; visible areas of fissile fracture and secondary cracks

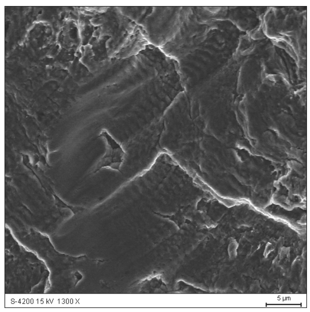

Fig. 20. Fatigue fracture of P92 steel. Distribution of fatigue striae; visible areas of fissile fracture and secondary cracks

4. Analysis of research results

Steels P91 and P92 have shown similar low-cycle fatigue characteristics (N_f, σ_{an}) at constant ranges of strain. In both cases, cyclical weakening of the material was observed.

An analysis of the life-cycle characteristics developed for sequential loads coupled with a graphic form of the Palmgren-Miner hypothesis shows a significant influence of the strain history on the service life of the investigated steels (Figs. 15 and 16). In such test conditions, the P91 steel has exhibited higher low-cycle life.

Modern power engineering technologies and power unit structures, especially those working at supercritical parameters, require the application of new materials, such as for example P91 and P92 steels, which exhibit high creep resistance. Steel P92 proves to have a better creep resistance than P91. It should be pointed out, however, that such a statement cannot be formulated for the fatigue properties, especially with regards to the low-cycle fatigue. At the same time, crack resistance of both the P92 steel and its welded joints is significant. Therefore, taking into account the possible interaction of loads, variable in time, the behaviour of both steels should be considered with regard to the interdependence of creep and fatigue, for it is impossible to affirm unequivocally which of them is more suitable for work as a material of components of power engineering devices. In any case, the decision whether to apply the P91 or P92 steel should be made with taking into consideration the operating conditions of a specific facility, for which the level of stationary loads present within long time intervals and the level of stresses variable in time in transient states should be defined.

References

[1] D. Renowicz, M. Cieśla, Crack initiation in steel parts working under thermo-mechanical fatigue conditions, International Journal of Computational Materials Science and Surface Engineering (IJCMSSE) 1/4 (2007) 424-437.

[2] J. Okrajni, K. Mutwil, M. Cieśla, Steam pipelines' effort and durability, Journal of Achievements in Materials and Manufacturing Engineering 22/2 (2007) 63-66.

[3] D. Renowicz, M. Cieśla, Crack initiation in steel parts working in boilers and steam pipelines, Journal of Achievements in Materials and Manufacturing Engineering 21/2 (2007) 49-52.

[4] J. Okrajni, A. Marek, G. Junak, Description of the deformation process under thermo-mechanical fatigue, Journal of Achievements in Materials and Manufacturing Engineering 21/2 (2007) 15-23.

[5] M. Cieśla, K.J. Ducki, Influence of increased nitrogen content on tool steel structure and selected properties, Journal of Achievements in Materials and Manufacturing Engineering 27/2 (2008) 123-126.

[6] M. Cieśla, K. Ducki, Effect of increased nitrogen content on the structure and properties of tool steels, Journal of Achievements in Materials and Manufacturing Engineering 29/2 (2008) 15-22.

[7] B. Tomkins, Fatigue failure and the integrity of structures, Course of Metal Fatigue, University of Sheffield, 1991.

[8] K.J. Miller, K.P. Zachariach, Cumulative damage laws for fatigue crack initiation and stage propagation, Journal of Strain Analysis 12/4 (1977) 263-277.

[9] D. Renowicz, A. Hernas, M. Ciesla, K. Mutwil, Degradation of the cast steel parts working in power plant pipelines, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 219-222.

[10] J. Dobrzański, The classification method and the technical condition evaluation of the critical elements' material of power boilers in creep service made from the 12Cr-1Mo-V, Journal of Materials Processing Technology 164-165 (2005) 785-794.

[11] J. Dobrzański, A. Zieliński, M. Sroka, Structure, properties and method of state evaluation of low-alloyed steel T23 (HCM2S) worked in creep conditions, Proceedings of the 11th International Scientific Conference on the "Contemporary Achievements in Mechanics, Manufacturing and Materials Science" CAMSS'2005, Gliwice-Zakopane, 2005, 171-180.

[12] S. Kocańda, A fatigue cracking of metals, WNT, Warsaw, 1985.

[13] J. Okrajni, A. Marek, G. Junak, Stress-strain characteristics under mechanical and thermal loading, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 271-274.

[14] K.J. Ducki, M. Cieśla, Effect of heat treatment on the structure and fatigue behaviour of austenitic Fe-Ni alloy, Journal of Achievements in Materials and Manufacturing Engineering 30/1 (2008) 19-26.

[15] K. Ducki, M. Cieśla, Influence of initial heat treatment on the fatigue life of austenitic Fe-Ni alloy, Archives of Materials Science and Engineering 29/2 (2008) 89-92.