Available online at www.sciencedirect.com

SciVerse ScienceDirect

AASRI Procedia 2 (2012) 249 – 255

AASRI Procedia

www.elsevier.com/locate/procedia

2012 AASRI Conference on Power and Energy Systems

Fatigue Life at 550 ^{o}C Temperature of Aged Martensitic Cast Steel

Grzegorz Golański[a]*, Stanisław Mroziński[b]

[a]*Institute of Materials Engineering, Czestochowa University of Technology, Armii Krajowej 19, 42 – 200 Częstochowa, Poland*
[b]*Faculty of Mechanical Engineering, University of Technology and Life Sciences in Bygdoszcz, Kaliskiego 7, 85-796 Bydgoszcz, Poland*

Abstract

The paper presents the results of research on low cycle fatigue life of GX12CrMoVNbN9 – 1 (GP91) cast steel at the temperature of 550 ^{o}C. The cast steel under investigation was in the as-received condition (after heat treatment) and after 8000 hours of ageing at the temperature of 600 ^{o}C. Cyclic loads were realized at five levels of total strain amplitude ε_{ac} amounting to: 0.25; 0.30; 0.35; 0.50 and 0.60%, respectively. Performed research has shown that GP91 cast steel is subject to strong cyclic softening within the entire experiment scope, and does not reveal any clear period of stabilization. Greater extent of softening was observed for the cast steel after the process of ageing. It has also been proved that the ageing process influences the basic parameters of hysteresis loop and fatigue life. Ageing in the case of the examined cast steel causes an evident decrease in its fatigue life which depends on the level of total strain.

Keywords: *cast steel, low – cycle fatigue, elevated temperature;*

* Corresponding author..:Tel. +48-34-3250-721; fax: +48-34-3250-721 .
E-mail address: grisza@wip.pcz.pl

 doi:10.1016/j.aasri.2012.09.042

1. Introduction

Steel casts used in the power industry are at a risk of exposure to changeable heat loads, as well as mechanical loads (often exceeding the yield point) during start-ups and shut-downs of power units. The changes of temperature and loads after a certain number of cycles can often lead to the occurrence of cracks, which in consequence can result in the material damage. This type of damage in massive multi-ton steel casts, resulting from low cycle fatigue, constitute ca. 65% of all steam turbine failures [1]. The basic requirement put for high-temperature creep resisting steels/cast steels applied in the power industry is retaining stable microstructure for a long period of service, and thereby, maintaining certain mechanical properties. The effect of temperature and time, and also stress in the creeping conditions, is a cause of changes occurring in the microstructure of serviced steels/cast steels, which also results in the changes of their properties, including the cyclic ones [2]. Nowadays, the tendency, both: home and abroad, is to aim for creating comprehensive characteristics which determine the usefulness and potential risks for the newly implemented high-temperature creep resisting steels and cast steels. For this purpose, proper characteristics are necessary, such as fatigue characteristics of new grades of steels and cast steels, determining the gradual reduction of properties during service. The paper presents the results of research on fatigue life of GX12CrMoVNbN9 – 1 cast steel at the temperature of 550 ^{o}C. Low cycle test were carried out on the cast steel in the as-received condition and after 8000 hours of ageing at the temperature of 600 ^{o}C.

2. Material and methodology of research

The material under research was GX12CrMoVNbN9-1 (GP91) cast steel of the following chemical composition (%mass): 0.12C, 0.49Mn, 0.31Si, 0.014P, 0.004S, 8.22Cr, 0.90Mo, 0.12V, 0.07Nb, 0.04N. The tests of fatigue life of GP91 cast steel in the conditions of loads for constant - amplitude strain were performed at the temperature of 550 ^{o}C. The tests of life were realized for the material in the as-received condition (after heat treatment) and after 8000 hours of ageing at the temperature of 600 ^{o}C. Cyclic loads were realized at five levels of total strain amplitude ε_{ac} amounting to: 0.25; 0.30; 0.35; 0.50 and 0.60%, respectively. Wide description of methodology of tests performed is presented inter alia in the work [3].

3. Results of research and their analysis

In the as-received condition, GP91 cast steel was characterized by a microstructure of high-temperature tempered martensite with numerous precipitations of $M_{23}C_6$ and MX carbides. The process of ageing of the examined cast steel contributed most of all to the following changes in microstructure: privileged precipitation of $M_{23}C_6$ carbides on grain boundaries and the process of their coagulation, a decrease in the dislocation density, a growth of the subgrains width and precipitation of Laves phase. Detailed description of the microstructure and properties of GP91 cast steel in the as-received condition and after the ageing process is provided inter alia in the work [4]. The fatigue tests were preceded by the static test of tension performed at room temperature and at 550 ^{o}C. Obtained results of the tests are shown in Table 1.

Table 1. Mechanical properties of GX12CrMoVNbN9 – 1 cast steel determined in the test of static tension

Parameter	Temperature of testing, ^{o}C		
	20	***550***	
	as-received condition	*as-received condition*	*after ageing*
$R_{p0.2}$, MPa	468	339	332
TS, MPa	632	395	386
El., %	26	47.3	48.8

E, MPa	206870	161460	163013
Requirements		***$R_{p0.2}{}^{550}{}_{min.}$ =270MPa*** ***$TS^{550}{}_{min.}$ = 330MPa***	

In the tests of static tension it has been proved that the ageing process (at the hold time up to 8000 hours) practically did not influence the changes in mechanical properties of GP91 cast steel which were higher than the minimum required.

On the basis of the instantaneous values of forces loading the test piece recorded during the test and the following calculations of stress amplitudes σ_a in the successive loading cycles, the graphs of cyclic strain were plotted for the examined cast steel (Fig. 1). Fatigue tests have proved that GP91 cats steel in the as-received condition, as well as after the process of ageing, is characterized by a strong cyclic softening (a growth of width of hysteresis loop $\Delta\varepsilon_{ap}$ and an intense decrease in the stress amplitude σ_a) without a clear period of stabilization and parameters of hysteresis loop.

Cyclic softening of the investigated cast steel proceeded until the end of the test. For this reason, in accordance with [5], the occurrence of deformation of hysteresis loop in the compression half cycle was assumed to be the criterion for the end of the test at each of five strain levels. Cyclic softening observed within the entire fatigue test proves the fatigue life exhaustion in the examined cast steel. Analysis of literature data [6, 7] allows to state that similar strong cyclic softening was also observed in the case of high-chromium martensitic steels used in the power industry. In those cases, however, the occurrence of stabilization period of hysteresis loop parameters was noticed.

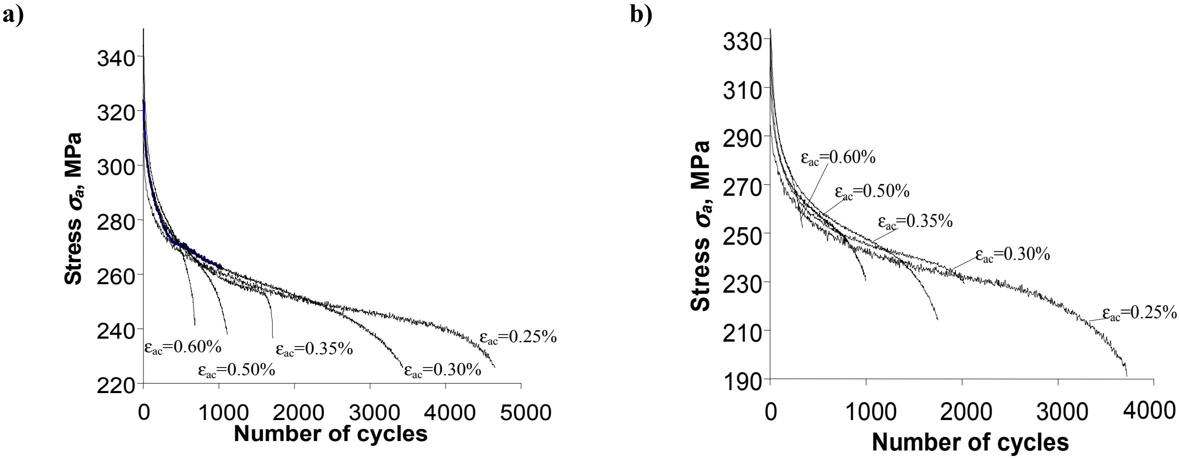

Fig. 1. Characteristics of cyclic strain of GP91 cast steel; a) in the as-received condition; b) after ageing process

Table 2 includes the values of parameters of hysteresis loop assumed for determining the basic characteristics, i.e. fatigue graph ($2N_f$ - ε) and the graph of cyclic strain (ε_{ap} - σ_a). These parameters were determined from the period corresponding to half the fatigue life n/N =0.5.

Table 2. Fatigue characteristics of GP91 cast steel in the as-received condition and after ageing process

Amplitude of strain ε_{ac}, %	***Temperature 550 °C***					
	As-received condition			***After ageing***		
	N	σ_a, *MPa*	ε_{ap}	*N*	σ_a, *MPa*	ε_{ap}
0.25	4533	249	0.00102	3916	232	0.00107
0.30	3040	257	0.00146	2206	245	0.00156
0.35	1819	261	0.00197	1753	250	0.00205
0.50	889	273	0.00338	997	257	0.00346
0.60	723	278	0.00437	657	277	0.00440

Stress σ_a determined for the investigated cast steel at half the fatigue life ($n/N = 0.5$-Table 2), reaches lower values in comparison with the yield strength $R_{p0.2}$ determined in the static test of tension (Table 1). This proves that the strength properties of GP91 cast steel during the low cycle fatigue process are getting exhausted. At the same time, it has been noted that after ageing the process of low cycle strain of the examined cast steel runs with the values of stress σ_a and plastic strain ε_{ap} being lower by several percent.

The measure of an extent of material softening within the entire fatigue test was the softening coefficient δ proposed in the works [8]. The extent of cast steel softening during fatigue tests was assessed by comparing the values of this parameter for the cast steel before and after ageing. The obtained results of calculations of coefficients for the stress description δ_σ and strain description δ_ε for particular levels of strain amplitude ε_{ac} at the temperature of testing are presented in Fig. 2.

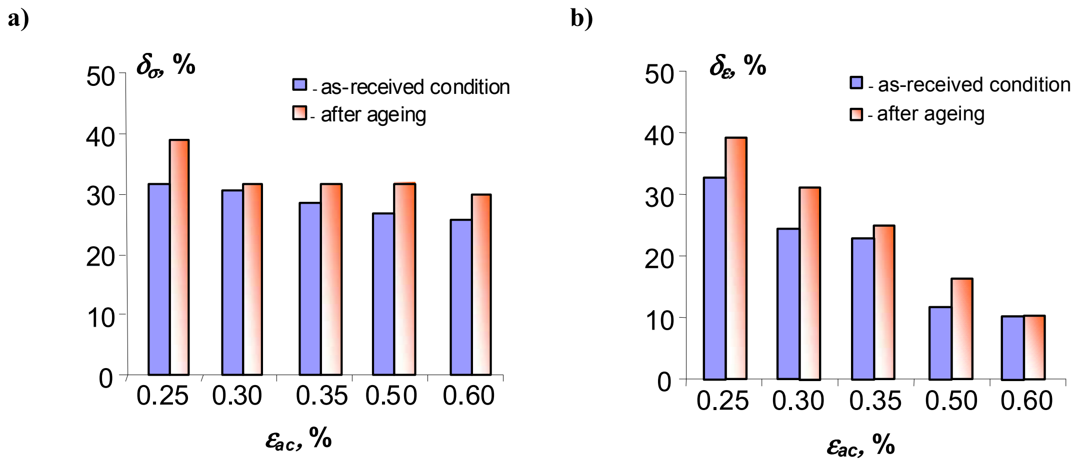

Fig. 2. Coefficients of softening of cast steel at the temperature of 550 °C in the as-received condition and after ageing: a) δ_σ , b) δ_ε

On the basis of the plotted graphs, it can be concluded that the values of softening coefficients δ_σ and δ_ε depend on the strain level ε_{ac}, and they are higher for the material after ageing process. Whilst on the basis of analysis of the values of coefficients δ_σ and δ_ε, it can be stated that the sensitivity of both parameters of hysteresis loop (σ_a and ε_{ap}) to changes in cyclic properties of the cast steel is similar. The values of coefficient δ_σ for the examined cast steel in the as-received condition amounted to about 32% for the strain level $\varepsilon_{ac} = 0.25\%$, to about 26% at the level $\varepsilon_{ac} = 0{,}60\%$, and for the aged material they amounted respectively to 42 and 30%. Whilst the values of coefficient δ_ε for the cast steel in the as-received condition ranged from about 10% for the highest strain level (ε_{ac}=0,60%) to about 34% for the strain level ε_{ac}=0,25%. In the case of the cast steel after ageing, the values of coefficient δ_ε amounted to 39 and 10%, respectively. This leads to the conclusion that the changes in microstructure running during the ageing the process of GP91 cast steel contribute to its higher softening.

Cyclic strains of the investigated cast steel, described with the Morrow's equation, are shown graphically in Fig. 3, whilst Table 3 includes the values of parameters for this equation. Mutual location of the strain graphs for the cast steel in the as-received condition and after ageing is a consequence of diversity of the values of hysteresis loop parameters for the examined cast steel (Table 2). At the same time, the decrease in the stress amplitude σ_a and plastic strain amplitude ε_{ap} (at the same levels of strain ε_{ac}) is the reason why the graphs obtained for the aged cast steel lie above the graphs obtained for the cast steel in the as-received condition (Fig. 3). What is more, the consequence of this are also higher values of coefficient K', as well as coefficient n' in Morrow's equation for the aged cast steel (Table 3). On the basis of the research performed, the influence of ageing on fatigue life was also analyzed. The values of hysteresis loop parameters, essential for the approximation of test results with the fatigue graph described with the Manson – Coffin equation, were determined for the cycles from the period corresponding to half the fatigue life n/N =0.5.

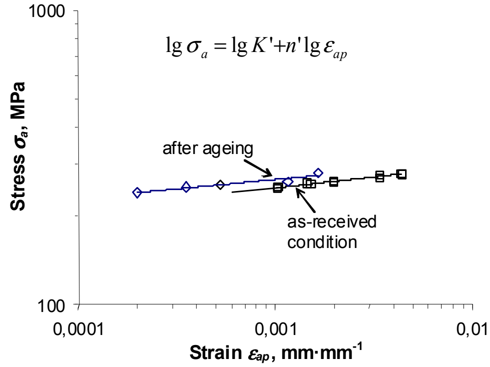

Fig. 3. Influence of ageing process on the graphs of strain of GP91 cast steel

Table 3. Functions describing the course of cyclic strain of GP91 cast steel in the as-received condition (sw) and after ageing (ps) expressed with Morrow's equation

Temperature of testing, °C	Function of regression and correlation coefficient **$\lg\sigma_a = \lg K' + n' \lg\varepsilon_{ap}$;** *K' – cyclic strength coefficient; n' – cyclic strengthening coefficient.*
550 (sw)	**$\lg\sigma_a = \lg 416 + 0.0743 g\varepsilon_{ap}$; R^2= 0.96**
550 (ps)	**$\lg\sigma_a = \lg 490 + 0.1086 g\varepsilon_{ap}$; R^2= 0.92**

Obtained graphs of fatigue are shown in Fig. 4, and the values of coefficients and exponents of Manson – Coffin equation are provided in Table 4.

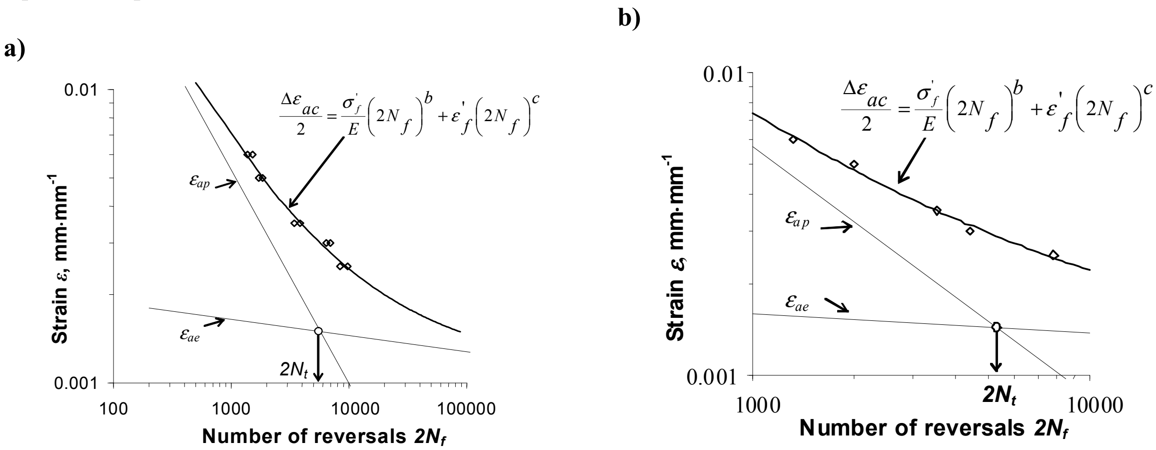

Fig. 4. Graphs of fatigue life of cast steel in the low cycle range at the temperature of 550 °C: a) as-received condition; b) after ageing

Analysis of the obtained graphs of fatigue (Fig. 4) shows that the abscissa N_t, i.e. the point of intersection of curves of elastic component ε_{ae} and plastic component ε_{ap}, lies in the so-called area of low cycle fatigue. This proves that for the levels of total strain amplitude ε_{ac} applied during the research, the process of cyclic strain of the examined cast steel ran at the dominant role of plastic strain component ε_{ap}. Therefore, it can be concluded that for the strain levels ε_{ac} assumed in the research, the resistance to cyclic strain of the investigated cast steel mostly depends on its strength properties – yield strength (apparent yield strength).

Table 4. Mathematic models of fatigue life of GP91 cast steel in the as-received condition *(sw)* and after ageing *(ps)*

Material	σ'_f	ε'_f	*b*	*c*	$2N_t$
	MPa	-	-	-	-
sw	526	0.8136	-0.0553	-0.7279	5717
ps	405	1.7556	-0.0643	-0.8289	5280

Similar dependence was also observed for high-temperature creep resisting martensitic steels of the P91 and P92 type (for the as-received condition), however, the abscissa N_t amounted to ca. 1000 cycles in this case [6]. In addition, it can be stated that shifting of the transition point N_t to a smaller number of cycles for the cast steel after ageing, compared to the as-received condition, proves deterioration in the plastic properties of GP91 cast steel.

Comparison of fatigue life of GP91 cast steel in the as-received condition and after ageing is presented in Fig. 5. It is evident that the process of ageing contributes to a decrease in fatigue life of the examined cast steel, and its degree depends on the level of strain amplitude ε_{ac}.

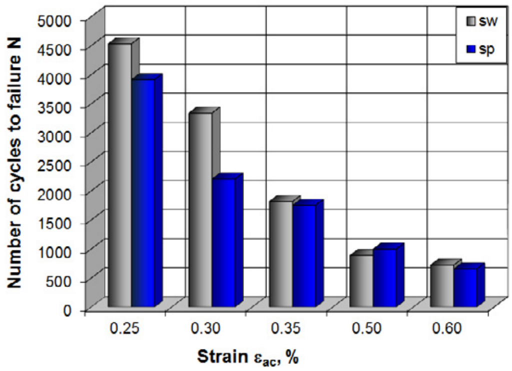

Fig. 5. Fatigue life of GP91 cast steel at the temperature of 550 °C: sw – the as-received condition; ps – after ageing

4. Summary

The paper presents fatigue characteristics of GX12CrMoVNbN9 – 1 cast steel at the temperature of 550 °C within a small number of loading cycles to failure, in the as-received condition and after 8000 hours of ageing at the temperature of 600 °C. Performed research has proved that GP91 cast steel, within the entire scope of the experiment carried out, is subject to strong cyclic softening and does not reveal a clear period of stabilization. Greater degree of softening was observed for the cast steel exposed to ageing process, which is strictly connected with the changes in microstructure of the aged cast steel.

Ageing of the cast steel influences the basis parameters of hysteresis loop and the fatigue life, causing an evident reduction of life. The extent of the life decrease is influenced by the level of total strain.

Comparative analysis of the parameters of the hysteresis loop in the half of fatigue life (n/N=0.5) of the aged cast steel and the cast steel in the as-received state, has shown smaller values of both: stress amplitude σ_a and plastic strain amplitude ε_{ap} for the cast steel subject to ageing.

Acknowledgements

Scientific work funded by the Ministry of Education and Science in the years 2010 - 2012 as a research project No. N N507 510 838.

References

[1] Viswanathan R. Damage mechanisms and life assessment of high temperature components, ASM International, Metals Park Ohio, USA, 1989.
[2] Kim S., Weertman J. R. Investigation of Microstructural changes in a ferritic steel caused by high temperature fatigue. Metall. Trans. 1988, 19A, 999.
[3] Golański G., Werner K., Mroziński S. Low cycle fatigue of GX12CrMoVNbN9-1 cast steel at 600 ºC temperature. Advanced Materials Research 2012, 396-398, 326.
[4] Golański G., Kępa J. The Effect of Ageing Temperatures on Microstructure and Mechanical Properties of GX12CrMoVNbN9 -1 (GP91) Cast Steel. Archives of Metallurgy and Materials, 2012 (in print).
[5] Polish Standard PN-84/H-04334
[6] Junak G., Cieśla M. Low-cycle fatigue of P91 and P92 steels used in the power engineering industry. Archives of Materials Science and Engineering 2011, 48/1, 19.
[7] Fournier B., Sauzay M., Renault A., Barcelo F., Pineau A., Microstructural evolutions and cyclic softening of 9%Cr martensitic steels, J. Nucl. Mater. 2009, 386 – 388, 71.
[8] Mathis K., Trojanova Z., Lukac P. Hardening and softening in deformed magnesium alloys. Materials Science and Engineering 2002, A324, 141.