Available online at [www.sciencedirect.com](http://www.sciencedirect.com/)



AASRI Procedia 2 (2012) 249 – 255

AASRI

Procedia

[www.elsevier.com/locate/procedia](http://www.elsevier.com/locate/procedia)

2012 AASRI Conference on Power and Energy Systems

# Fatigue Life at 550 oC Temperature of Aged Martensitic Cast Steel

Grzegorz Golańskia\*, Stanisław Mrozińskib

*aInstitute of Materials Engineering, Czestochowa University of Technology, Armii Krajowej 19, 42 – 200 Częstochowa, Poland*

*bFaculty 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 oC. 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 oC. Cyclic loads were realized at five levels of total strain amplitude *εac* 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.

© 2012 Published by Elsevier B.V. Selection and/or peer review under responsibility of American Applied Science Research Institute

© 2012 Published by Elsevier B.V. Selection and/or peer review under responsibility of American Applied Science Research Institute

© 2012 The Authors. Published by Elsevier B.V.

Selection and/or peer review under responsibility of American Applied Science Research Institute

Open access under [CC BY-NC-ND license.](http://creativecommons.org/licenses/by-nc-nd/3.0/)

*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](mailto:grisza@wip.pcz.pl)

2212-6716 © 2012 Published by Elsevier B.V. Selection and/or peer review under responsibility of American Applied Science Research Institute

Open access under [CC BY-NC-ND license.](http://creativecommons.org/licenses/by-nc-nd/3.0/) 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 oC. 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 oC.

1. 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 oC. 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 oC. Cyclic loads were realized at five levels of total strain amplitude *εαc* 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].

1. 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 M23C6 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 M23C6 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 oC. 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

Temperature of testing, oC

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | *20 550* | | |
|  | *αs-received condition* | *αs-received condition* | *αfter αgeing* |
| Rp0.2, MPa | 468 | 339 | 332 |
| TS, MPa | 632 | 395 | 386 |
| El., % | 26 | 47.3 | 48.8 |

E, MPa 206870 161460 163013

Requirements *Rp0.2550min. =270MPa*

*TS550min. = 330MPa*

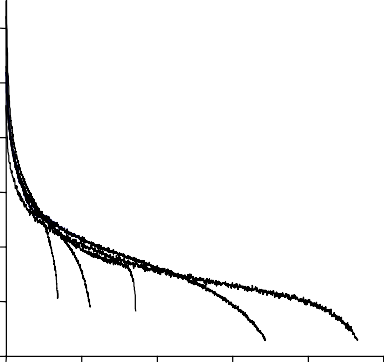
In the tests of static tension it has been proved that the ageing process (at the hold time up to 8000 hours) practically did not influence the changes in mechanical properties of GP91 cast steel which were higher than the minimum required.

On the basis of the instantaneous values of forces loading the test piece recorded during the test and the following calculations of stress amplitudes *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

*ap* and an intense decrease in the stress amplitude *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.

a) b)



340

320

300

280

260

240  =0.60%

ac

 =0.35%

ac

220

ac=0.50%

ac=0.25%

ac=0.30%

Stress *******a*, MPa

0 1000 2000 3000 4000 5000

Number of cycles

330

310

290

Stress *******a*, MPa

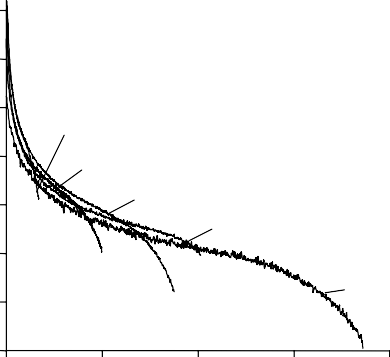
270

250

230

210

190



ac=0.60%

ac=0.50%

ac=0.35%

ac=0.30%

ac=0.25%

0 1000 2000 3000 4000

Number of cycles

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 (*2Nƒ* - *ε*) and the graph of cyclic strain (*εap - σa* ). 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

*Temperature 550 oC*

*Amplitude oƒ strain As-received condition After ageing*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *εac, %* | *N σa,*  *MPa* | | *εap N σa, εap MPa* | | | |
| 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 *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 *Rp0.2* 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 *a* and plastic strain *εap* being lower by several percent.

The measure of an extent of material softening within the entire fatigue test was the softening coefficient **

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 *σ* and strain description *ε* for particular levels of strain amplitude *εac* at the temperature of testing are presented in Fig. 2.

a) b)

0 0.25 0.30 0.35 0.50 0.60 0



50

****** %

* as-received condition
* after ageing

40

30

20

10



50

****** %

* as-received condition
* after ageing

40

30

20

10

*******ac******* %

0.25 0.30 0.35 0.50 0.60

*******ac******* %

Fig. 2. Coefficients of softening of cast steel at the temperature of 550 oC in the as-received condition and after ageing: a) *σ*  b) *ε*

On the basis of the plotted graphs, it can be concluded that the values of softening coefficients *σ* and *ε* depend on the strain level *εac*, and they are higher for the material after ageing process. Whilst on the basis of analysis of the values of coefficients *σ* and *ε* it can be stated that the sensitivity of both parameters of hysteresis loop (*σa* and *εap*) to changes in cyclic properties of the cast steel is similar. The values of coefficient *σ* for the examined cast steel in the as-received condition amounted to about 32% for the strain level *εac* = 0.25%, to about 26% at the level εac = 0,60%, and for the aged material they amounted respectively to 42 and 30%. Whilst the values of coefficient *ε* for the cast steel in the as-received condition ranged from about 10% for the highest strain level (*εac*=0,60%  to about 34% for the strain level *εac*=0,25%. In the case of the cast steel after ageing, the values of coefficient *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 *σa* and plastic strain amplitude *εap* (at the same levels of strain *εac*) 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.

1000



lg ** *a*  lg *K* '*n*' lg *ap*

after ageing

as-received condition

Stress *******a*, MPa

100

0,0001 0,001 0,01

Strain *******ap* , mm·mm-1

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,

oC

Function of regression and correlation coefficient lg*******a* = lg*K’* + n’ lg*εap*;

*K’ – cyclic strength coefficient; n’ – cyclic strengthening coefficient.*

550 (sw) lg*******a* = lg416 + 0.0743g*εap*; *R2*= 0.96

550 (ps) lg*******a* = lg490 + 0.1086g*εap*; *R2*= 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.

a)

0.01

** ** ' *b*

b)

0.01



** *ac*

** ' 

*b*

2 *E* 

 *f*  2*N*   **  2*N*

*f*  *f*  *f* 

'  

*ap*

*ae*

*c*

*c*

*ac*  *f*  2 *N*

  ** '  2 *N* 

2 *E*  *f* 

*f*  *f* 

*ap*

Strain *ε*, mm****mm-1

Strain ******, mm****mm-1

0.001

*ae*

*2Nt*

0.001

100 1000 10000 100000

1000

*2Nt*

10000

Number of reversaIs *2Nf*

Number of reversaIs *2Nf*

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

Analysis of the obtained graphs of fatigue (Fig. 4) shows that the abscissa *Nt*, i.e. the point of intersection of curves of elastic component *εae* and plastic component *εap*, lies in the so-called area of low cycle fatigue. This proves that for the levels of total strain amplitude *εac* applied during the research, the process of cyclic strain of the examined cast steel ran at the dominant role of plastic strain component *εap*. Therefore, it can be concluded that for the strain

levels *εαc* 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)*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | MPa | - | - | - | - |
| sw | 526 | 0.8136 | -0.0553 | -0.7279 | 5717 |
| ps | 405 | 1.7556 | -0.0643 | -0.8289 | 5280 |

Material *******’ƒ* *******’ƒ b c 2Nt*

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 *Nt* amounted to ca. 1000 cycles in this case [6]. In addition, it can be stated that shifting of the transition point *Nt* 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 *εαc*.

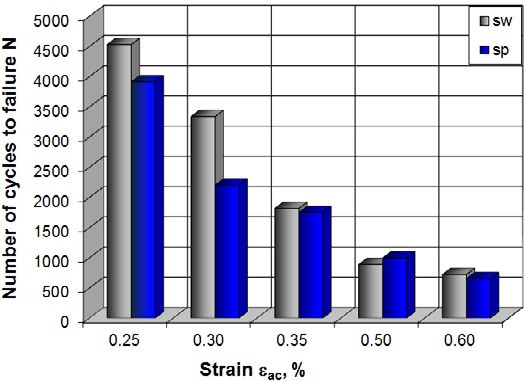


Fig. 5. Fatigue life of GP91 cast steel at the temperature of 550 oC: sw – the as-received condition; ps – after ageing

1. Summary

The paper presents fatigue characteristics of GX12CrMoVNbN9 – 1 cast steel at the temperature of 550 oC 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 oC. 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 *σα* and plastic strain amplitude *εαp* 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.