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Low cycle fatigue of GX12CrMoVNbN9-1 cast steel at elevated temperature

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Materials

ABSTRACT

Purpose: The purpose of the paper is to characterize the low cycle fatigue of high - chromium martensitic GX12CrMoVNbN9-1 cast steel from the perspective of the strain and energy criterion.

Design/methodology/approach: The tests of fatigue strength within the scope of small amount of cycles to failure at room temperature and elevated temperature (400, 550 and 600°C) were carried out on GX12CrMoVNbN9-1 cast steel. The fatigue tests were run for five assumed levels of controlled amplitude of total strain εac (0.25; 0.30; 0.35; 0.50 and 0.60%). The loading applied in the experiment oscillated sinusoidally with the stress ratio R = -1 and frequency f = 0.2 Hz. The fatigue tests were performed by means of Instron 8501 hydropulser. Tests pieces for the fatigue tests were round and threaded.

Findings: The examined cast steel during low cycle fatigue is subject to intense weakening. The period of stabilization was not revealed during the cyclic loading of the cast steel, neither at room temperature, nor elevated one. Moreover, it has been proved that the extent of changes in the cyclic properties is influenced by the level of strain and temperature.

Practical implications: Obtained results of the tests are indispensable for the formulation of necessary characteristics of high-temperature creep resisting steels and cast steels.

Originality/value: The paper presents the fatigue characteristics of GX12CrMoVNbN9-1 cast steel within the scope of small amount of cycles to failure. The fatigue characteristics of the examined cast steel was developed for both: room temperature and elevated temperature - 400, 550 and 600°C. Fatigue life of the investigated cast steel was described using the equations of Ramberg-Osgood and Manson-Coffin-Basquin, and presented from the perspective of the energy criterion.

Keywords: Metallic alloys; Fatigue; Mechanical properties

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1. Introduction

Development of the contemporary power industry is strictly connected with the issues of environmental protection, especially with aiming to limit the emission of CO_2 into the atmosphere. One of the ways to reduce the emission of pollutants is raising the efficiency of power units through an increase in the parameters of steam, i.e. temperature and pressure. Increasing steam parameters in power units is possible due to the development and introduction of new grades of high-temperature creep resisting materials into the power industry, inter alia: multicomponent high-chromium steels and cast steels [1,2]. One of the new high-temperature creep resisting materials introduced into the power industry is GX12CrMoVNbN9-1 (GP91) cast steel. It was developed on the basis of chemical composition of P91 steel, thus the chemical composition, as well as microstructure and mechanical properties of these materials are similar. Application of high-chromium martensitic cast steel instead of low alloy Cr-Mo or Cr-Mo-V cast steels used so far makes it possible to raise the temperature of steam by 30-50°C [3,4]. One of the main mechanisms of damages in the massive casts of turbine cylinders and valve chambers is thermal-mechanical fatigue which constitutes ca. 65% of all turbine damages. Failures occurring during low-cycle fatigue cause plastic strains and cracks of the steel castings. Such failures are the cause of expensive and long-lasting downtimes due to repairs. Therefore, in order to forecast the safe operation time for elements and pressure installations of a boiler, it is necessary to work out adequate fatigue characteristics of the new grades of high-temperature creep resisting steels and cast steels [4,5]. On analyzing the literature findings, it can be noticed that not only nationwide but also worldwide there is a tendency toward building a comprehensive characteristics describing the usefulness and potential application of the new steel and cast steel grades of high-temperature creep resisting properties [6,7]. The paper presents the results of low cycle fatigue tests of GX12CrMoVNbN9-1 (GP91) cast steel at room temperature and elevated temperature of 400, 550 and 600°C.

2. Methodology of research

The material used for testing was GX12CrMoVNbN9-1(GP91) cast steel after heat treatment: 1040°C/12h/oil 760°C/12h/air + 750°C/8h/furnace. Chemical composition of the cast steel is included in Table 1.

Table 1.
Chemical composition of GP91 cast steel, %mass

C	Si	Cr	Mo	V	Nb	N
0.12	0.31	8.22	0.90	0.12	0.07	0.04

Example of the microstructure of the examined cast steel after heat treatment (in the as-received condition) is illustrated in Fig. 1. The investigated cast steel in the as-received condition was characterized by a typical microstructure for this group of steels/cast steels with 9-12%Cr - the microstructure of high-tempered martensite with numerous precipitations of $M_{23}C_6$ carbides and MX nitrides. The microstructure of GP91 cast steel after the above-mentioned treatment consisted of lath martensite with large dislocation density as well as the polygonized ferrite grains. No δ-ferrite was detectable after heat treatment, which indicates that this cast steel is fully martensitic. The $M_{23}C_6$ carbides were precipitated mostly on grain boundaries of former austenite grain and the boundaries of subgrains/martensite laths. However, the fine dispersive precipitations of the MX type were precipitated mainly on the dislocations inside martensite laths. Description of the microstructure of the cast steel can be found in [e.g. 8,9].

The test pieces used for fatigue tests were round and threaded (Fig. 2). Fatigue tests were carried out on a testing machine of the Instron 8502 type with the strain control (ε_{ac}=const). The tests were performed at room temperature and the temperature of 400, 550 and 600°C.

Loading applied during the tests was oscillating sinusoidally with the strain ratio R=-1. The tests were conducted at six levels of total strain amplitude ε_{ac}: 0.25; 0.30; 0.35; 0.50, 0.60 and 0.8%.

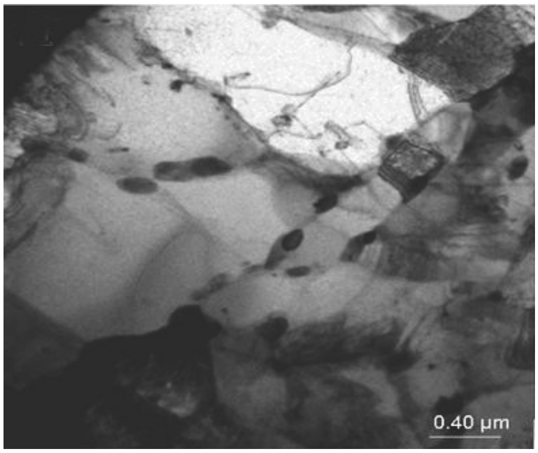


Fig. 1. Microstructure of GP91 cast steel after heat treatment (explanation provided in the text), TEM, thin foil

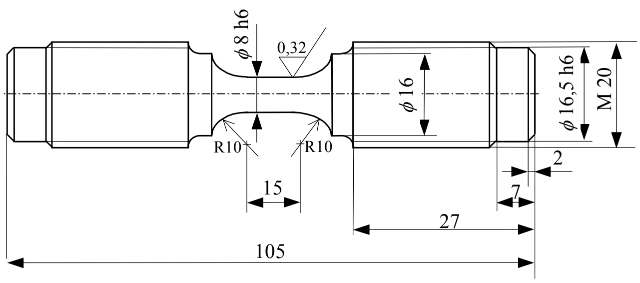


Fig. 2. Test piece for research

The frequency of load changes f during the tests amounted to 0.2 Hz. Assumed as the criterion for the end of a fatigue test and at the same time as the fatigue life N_f at a given strain level, was the number of cycles at which the occurrence of deformation on the hysteresis loop arm in the compression half-cycle was observed. The analysis of fatigue properties of GP91 cast steel under the conditions of changing loads was performed using the parameters of hysteresis loop which included: ε_{ac}, ε_{ap}, σ_a and the energy of plastic strain ΔW_{pl}. Their values were determined on the basis of the values of loading force and strains recorded during fatigue tests. Graphical interpretation of the parameters assumed for the analysis is shown in Fig. 3.

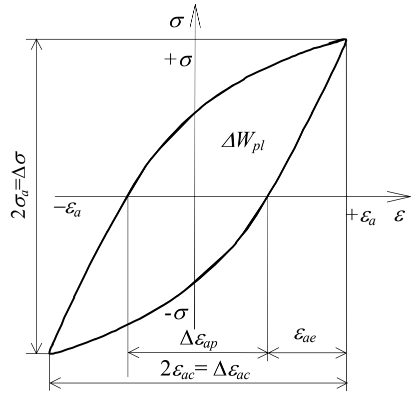


Fig. 3. Hysteresis loop an its basic parameters

The recorded values of strain amplitude σ_a, ε_{ap} and ΔW_{pl} in the following stress cycles allowed to plot graphs of the changes in characteristic parameters of hysteresis loop in the function of the number of stress cycles *n*. Characteristic quantities of the loop determined for half the number of cycles to crack were used for developing the basic fatigue characteristics of a cast steel. Obtained data were also used to define the slopes of regression lines applied for the description of dependence between stress σ_a and strain ε_{ap}.

3. Research results and their analysis

3.1. Static tests

The fatigue tests were preceded by a static tests of tension at the temperature applied during the fatigue tests. Stress in the test piece, which was subject to stretching load, was calculated dividing the instantaneous values of loading force recorded during the test by the area of initial section of a test piece. Tension curves (Fig. 4) were analyzed in order to determine the basic strength parameters. Fig. 4b shows a fragment of the tension curve limited to the elongation of 0.8%, including the levels of strain assumed for the fatigue tests. The basic strength properties of the investigated cast steel are given in Table 2.

Table 2.
Mechanical properties of GP91 cast steel depending on the temperature of testing

Parameter designation	Parameter values depending on the temperature			
	20°C	400°C	550°C	600°C
YS, MPa	503	419	339	303
TS, MPa	663	536	395	338
$E_{12.5}$, %	38.3	29.1	47.3	63.5
RA, %	63.4	49.1	82.7	87.3
R_u, MPa	1890	2031	2382	2787
E, MPa	206870	182100	161460	150120

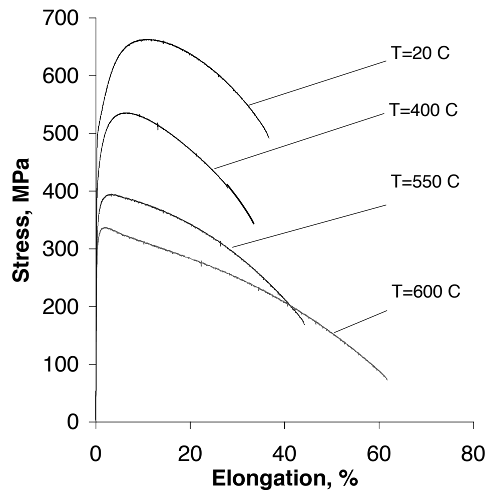
According to the expectations, the temperature of testing has a significant influence on GP91 cast steel's mechanical properties determined during the static tensile test. For instance, tensile strength and yield strength at elevated temperature have decreased by around 50% (600°C), 40% (550°C) and 20% (400°C), respectively, in comparison with the values obtained at room temperature. Whilst raising the temperature of testing results in the growth of both: reduction of area and elongation values.

3.2. Fatigue tests

a) influence of temperature on the changes in hysteresis loop parameters

Analysis of the cyclic properties of GP91 cast steel in the conditions of changing loads was performed using the parameters of hysteresis loop which have a direct influence on the achieved results.

a)



b)

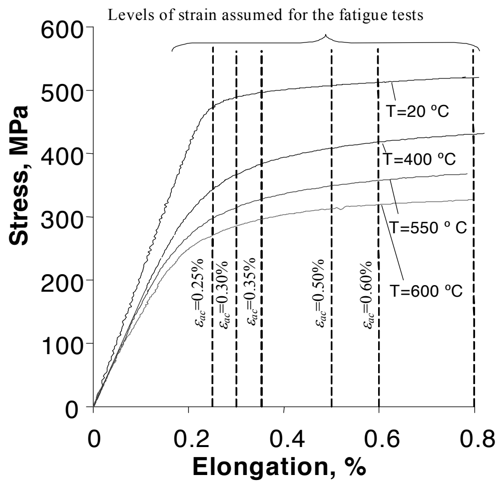


Fig. 4. Tension curves: a) complete curves, b) levels of strain applied during low cycle tests

They include the plastic strain amplitude ε_{ap}, stress amplitude σ_a and energy of plastic strain ΔW_{pl}. Their values were determined on the basis of the values of force loading a test piece and its strains which were recorded during instantaneous tests. Changes observed during the research concerned hysteresis loop parameters in the function of the number of stress cycles. The character of the changes at all levels of strain was very similar. In order to discuss the influence of the temperature on cyclic properties, Fig. 5-6 include examples of the courses of changes in σ_a, ε_{ap} and ΔW_{pl} in the function of the number of cycles at two levels of total strain ε_{ac} (ε_{ac1}=0.25%, ε_{ac5}=0.60%) for room temperature and for 600°C.

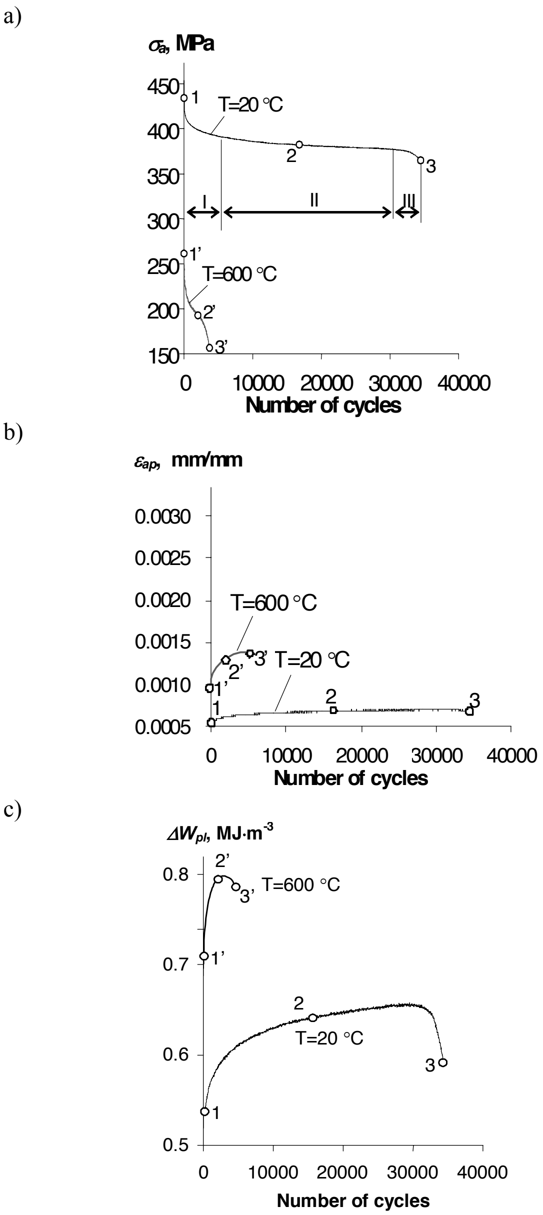


Fig. 5. Changes in the loop parameters at the level ε_{ac}=0.25%: a) σ_a=f(n), b) ε_{ap}=f(n), c) ΔW_{pl}=f(n)

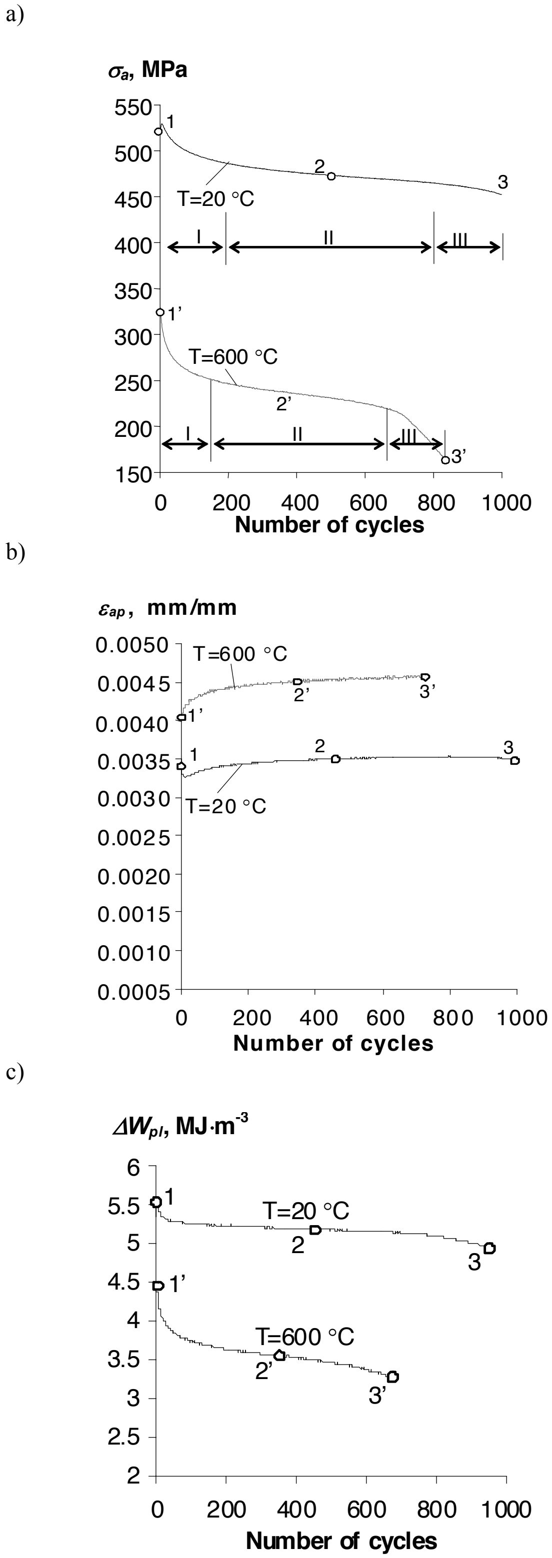


Fig. 6. Changes in the loop parameters at the level ε_{ac}=0.60%: a) σ_a=f(n), b) ε_{ap}=f(n), c) ΔW_{pl}=f(n)

On the basis of analysis of the plotted graphs it can be concluded that the instantaneous cyclic properties (parameters of hysteresis loop) depend on the extent of fatigue damage (number of stress cycles) and temperature. All parameters of hysteresis loop assumed for the analysis are characterized by the occurrence of changes and the lack of a clear stabilization period. In the courses of parameters of hysteresis loop there are three characteristic stages distinguishable, marked only in the case of changes in stress. (Figs. 5a and 6a) [10,11]:

Stage I – the material is subject to evident weakening. Characteristic feature for this stage is high speed of weakening which decreases along with the growth of the number of stress cycles. Duration of stage I depends on the level of strain and the temperature of testing;

Stage II – the parameters of hysteresis loop are subject to slight changes only. The weakening speed, as well as the length of this stage also depends on the level of strain and testing temperature;

Stage III – the material is subject to further weakening. The speed of weakening rises at this stage. Moreover, at this stage a crack of the test piece is initiated and continues to develop until the moment when a fatigue crack occurs. Duration of this fatigue stage, similarly as in the previous cases, depends on the level of strain and temperature as well.

The occurrence of the abovementioned stages can also be seen on the graphs of changes in stress $\sigma_a=f(n)$, stain $\varepsilon_{ap}=f(n)$, as well as on the graphs of changes in the energy of plastic strain ΔW_{pl}=f(n). Moreover, on the basis of graphs presented in Figs. 5-6 it can also be noted that the extent of changes in the loop parameters at particular strain levels is influenced by both: temperature and the level of strain. The degree of changes is definitely higher on higher strain levels than on the lower ones.

b) influence of temperature on the analytic descriptions of cyclic properties

The lack of a clear stabilization period of cyclic properties in the examined cast steel makes the analytical description of its cyclic properties considerably difficult.

Due to the observed changes in hysteresis loop parameters in the function of a number of stress cycles, the values of hysteresis loop parameters indispensable for analytical descriptions of properties can be assumed out of the period corresponding to half the fatigue life n/N=0.5 (points *2* and *2'* in Figs. 5-6 changes of stress σ_a, strain ε_{ap} and energy ΔW_{pl}). In order to demonstrate the changes in loop shape, Figs. 7-8 include hysteresis loops from three various life periods marked schematically in Figs. 5-6. These were: loop no. *1* for the first cycle, loop no. *2* from the period corresponding to half the fatigue life and loop no. *3* for the last cycle at the given strain level - for the tests at the temperature of 20°C and the respective *1'*, *2' 3'*-for the tests at the temperature of 600°C.

For the analytic description of the dependence between stress σ_a and strain ε_{ap} the following equation was adopted [11,12]:

$$\lg \sigma_a = \lg K' + n' \lg \varepsilon_{ap} \qquad (1)$$

where: K' – strain curve coefficient, MPa,
n' – strain curve exponent.

a)

b)

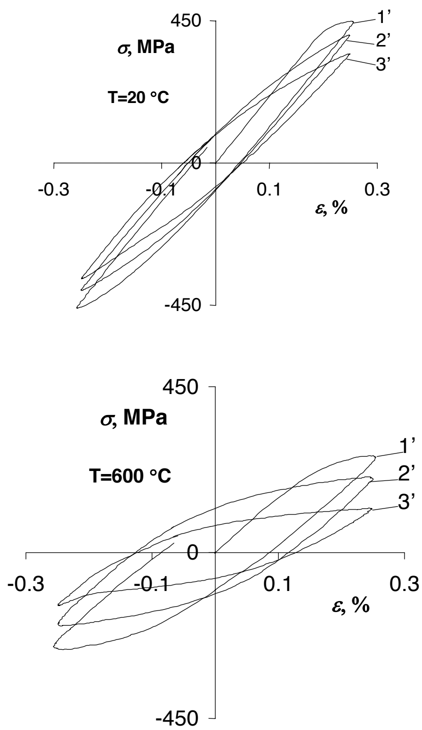


Fig. 7. The loops of hysteresis from various life periods at the strain level of ε_{ac}=0.25%: a) 25ºC, b) 600ºC

a)

b)

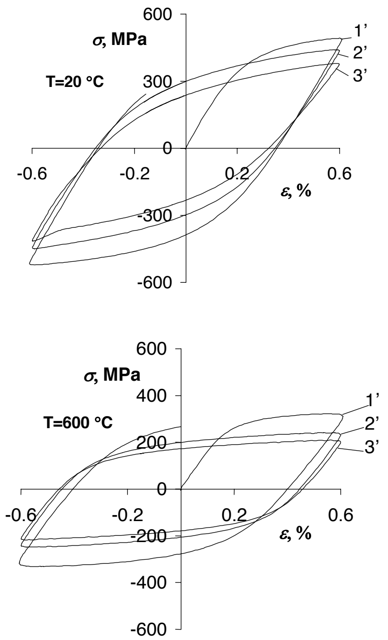
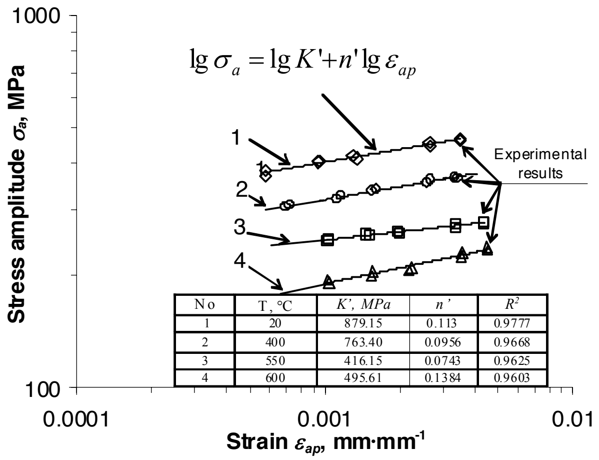


Fig. 8. Hysteresis loops from various periods of life at the strain level of ε_{ac}=0.60%: a) 20ºC, b) 600ºC

The values of hysteresis loop parameters σ_a and ε_{ap} obtained during all of the tests were worked out with the method of least squares by determining the coefficients and exponents of a regression line described with the equation (1). Graphs plotted as a result of approximation of the loop parameters (σ_a and ε_{ap}) from the periods corresponding to half the fatigue life are shown in Fig. 9.



No	T, °C	K', MPa	n'	R^2
1	20	879.15	0.113	0.9777
2	400	763.40	0.0956	0.9668
3	550	416.15	0.0743	0.9625
4	600	495.61	0.1384	0.9603

Fig. 9. Graph of strain for GX12CrMoVNbN9-1 cast steel

Higher values of plastic strain amplitude ε_{ap} and at the same time lower levels of stress amplitude σ_a at the same levels of total strain ε_{ac} presented in Figs. 5-6 are reflected in the respective positions of the obtained graphs of strain (Fig. 9).

Cyclic weakening of the cast steel test pieces observed during the tests with constant amplitude at room temperature and elevated temperature is also proved by the position of graphs of cyclic and static strain. Examples of the graphs of static and cyclic strain obtained during the research are shown in Fig. 10. The cyclic strain graphs were approximated with an equation proposed by Ramberg-Osgood as given below:

$$\varepsilon_{ac} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \tag{2}$$

Fig. 10 also includes the loops of hysteresis from the period corresponding to half the fatigue life (the *2* points in Figs. 5-6).

Regardless of the temperature of testing the curves of cyclic strain are located below the curves of static tension. This fact proves the cyclic weakening of the examined cast steel irrespective of the testing temperature and the level of changing strain.

It should be emphasized that due to the changes in the hysteresis loop parameters in the function of the number of stress cycles, equations (1) and (2) describe only the instantaneous properties of the cast steel determined for half the fatigue life n/N=0.5 (the 2 points in Figs. 5 and 6). In order to illustrate the influence of the life period assumed for analytic descriptions, Fig. 11 includes the curves of cyclic strain plotted on the basis of the results of tests at room temperature and three periods of fatigue life corresponding to the points: 1-(n/N=0.1) 2-(n/N=0.5) and 3-(n/N=0.9)

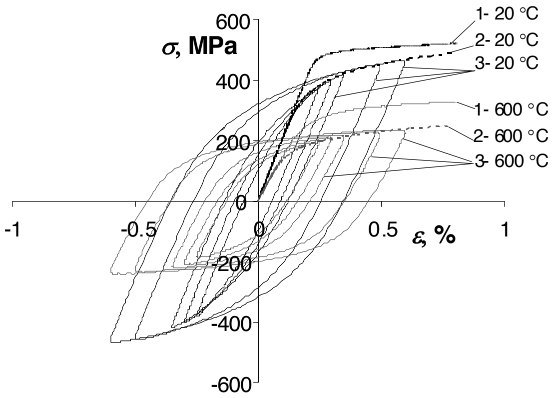


Fig. 10. Graphs of static and cyclic strain: 1-static tension curve, 2-cyclic strain curve, 3- hysteresis loops

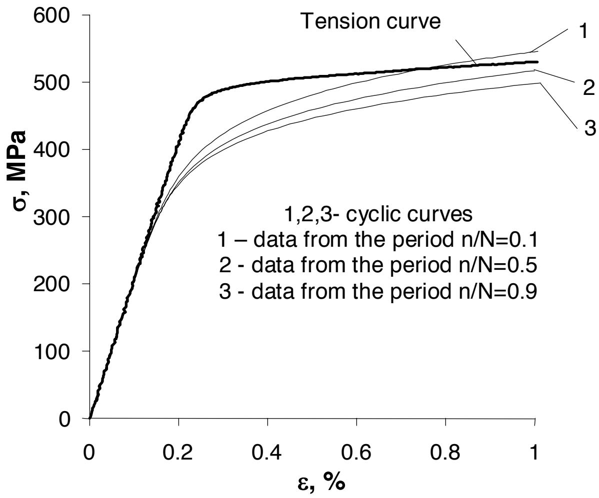


Fig. 11. The curves of cyclic strain for GP91 cast steel at room temperature

On the basis of the cyclic strain curves given in Fig. 11 it can be noted that in the case of lack of the stabilization period of cyclic properties the only data used for the calculations of fatigue life are the instantaneous material data. Such an approach may cause e.g. significant diversity of the life results obtained through calculations and tests. This remark gains a particular meaning in the case of a description of cyclic properties of a cast steel at elevated temperature at which the scope of changes in the cyclic properties is larger compared to room temperature.

c) influence of the temperature on fatigue life

The tests have also revealed a significant influence of the temperature on the fatigue life [13]. This influence is reflected in the position of the plotted fatigue graphs. The fatigue graphs in a bilogarithmic system were approximated with the Morrow equation, i.e.:

$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ae}}{2} + \frac{\Delta\varepsilon_{ap}}{2} = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^b + \varepsilon_f^{'}\left(2N_f\right)^c \quad (3)$$

where:

- b – exponent of the fatigue life,
- c – exponent of the cyclic strain,
- σ_f' – coefficient of the fatigue life,
- ε_f – coefficient of the plastic strain,
- E–- Young's modulus determined from the tensile test.

The results of research are shown in Fig. 12 in the form of graphs of fatigue life [13,14]. To maintain clarity, the figure lacks the markings of regression lines which describe changes in the plastic strains ε_{ap} and elastic strains ε_{ae} in the function of the number of reversals $2N_f$ obtained at the temperature of 400 and 550ºC.

T	b	c	σ_f',MPa	ε_f'	$2N_t$
20°C	-0.0673	-0.4842	879.8	0.1244	3700
400°C	-0.0601	-0.5845	659.4	0,3456	4620
550°C	-0.0553	- 0.7279	384.5	0.8136	5717
600°C	-0.0222	-0.8514	248.3	2.21	5700

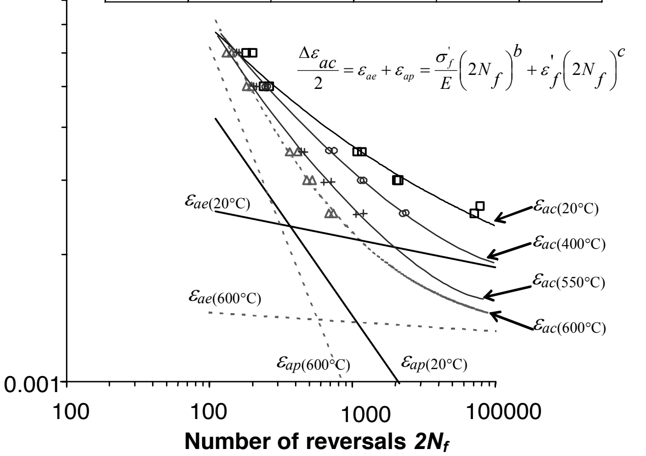


Fig. 12. Diagram of fatigue life of GP91 cast steel at room temperature and at elevated temperature

The presented graphs allow to conclude that the influence of temperature on the fatigue life depends on the level of total strain amplitude. This influence is slight in the areas of the largest realized strains and increases as the level of strain is falling. Fig. 13 provides a graphic illustration of the influence of temperature and total strain amplitude on the fatigue life.

d) cumulatiom of strains and energy

Higher influence of temperature on the life in the area of slight strains can be demonstrated by a diverse course of cumulation of fatigue damages. Elementary parameters relating to one stress cycle, which can be subject to summation during cyclic loading, can be the parameters of hysteresis loop, e.g. the scope of plastic strains $\Delta\varepsilon_{ap}$ or the energy of plastic strain ΔW_{pl} (Fig. 3).

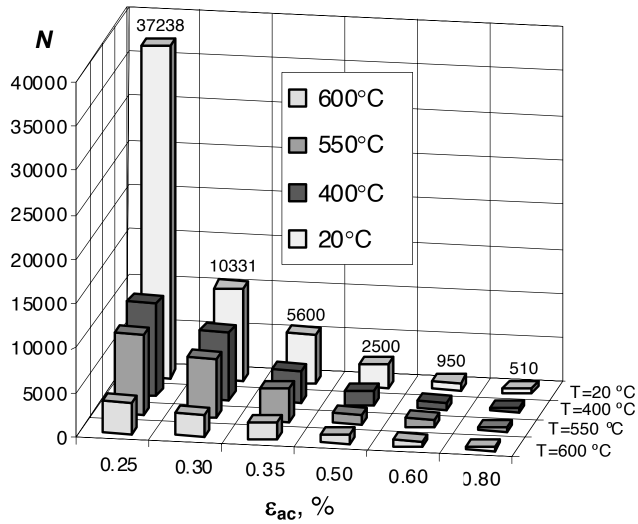


Fig. 13. Influence of the strain level ε_{ac} on the fatigue life of GP91 cast steel

Summing up the values of the abovementioned parameters in the following stress cycles allowed to determine their boundary values corresponding to the moment of a test piece crack. The work includes analyzing the influence of temperature on the very course of summing (cumulation) of these parameters, as well as on the cumulated values of these parameters till the moment of the test piece crack. The calculations of energy ΔW_{pl} were made using the values of loading force and strains of a test piece registered during the fatigue tests, for particular cycles of loading. Each cycle of loading (loop) was described with 200 points. The value of strain energy was calculated with the method of loop integrating from the independence given below [15,16,17]:

$$\Delta W_{pl} = [\sum_{i=1}^{n-1} \frac{1}{2}(\sigma_i + \sigma_{i+1})(\varepsilon_{i+1} - \varepsilon_i)] + (\sigma_n + \sigma_1)(\varepsilon_1 - \varepsilon_n) \quad (4)$$

where:

n – the number of hysteresis loop points (n=200)

The scheme of the course of energy calculations ΔW_{pl} is presented in Fig. 14.

Presented in Figs. 5 and 6, the influence of temperature on the level of basic parameters of hysteresis loop is highlighted also in the graphs of cumulation of plastic strains $\Delta\varepsilon_{ap}$ and the unit energy ΔW_{pl}. Fig. 15 illustrates examples of the courses of plastic strains cumulation obtained at one level of strain (ε_{ac}=0.60%) and four temperature.

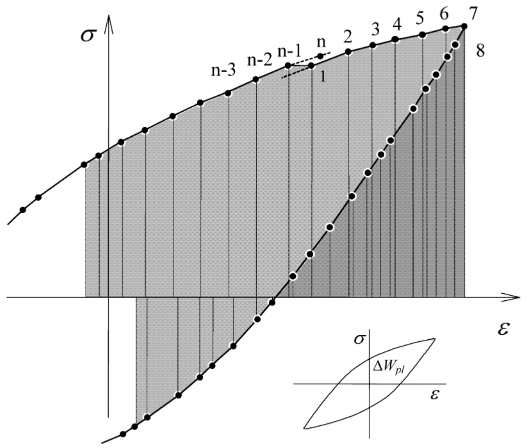


Fig. 14. Scheme of the numerical calculation of hysteresis loop area

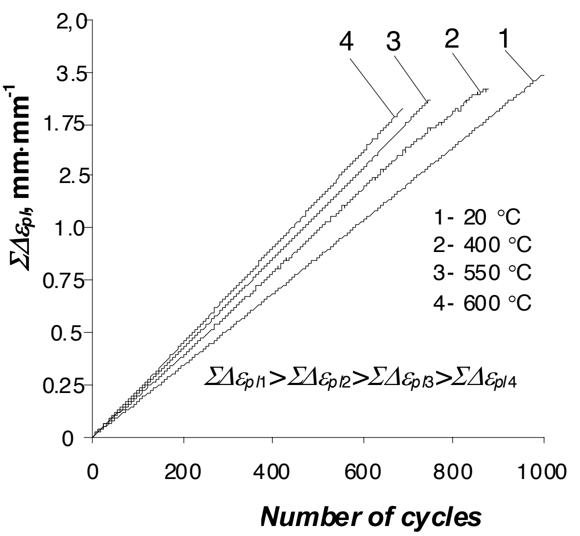


Fig. 15. Influence of temperature on the level of cumulated plastic strain at the level of ε_{ac}=0.60%

Growth of the scope of plastic strains $\Delta\varepsilon_{pl}$ within one cycle together with the growth of temperature (Figs. 5, 6) is the cause of a change in the position of graphs of strains cumulation. As results from the plotted graphs (Fig. 15), the level of cumulated plastic strain in the test piece till its crack $\Sigma\Delta\varepsilon_{ap}$ gets decreased along with the temperature rise. Lowering of the level of cumulated plastic strain together with the temperature increase was observed at all of the strain levels.

However, the influence of temperature on the level of cumulated energy $\Sigma\Delta W_{pl}$ in the test piece till crack is quite different. On the strain level of ε_{ac}=0.60% along with the rise of temperature, the cumulated energy in the test piece decreases (Fig. 16). Such dependence between the temperature and cumulated energy occurs at all levels of strain [16,17].

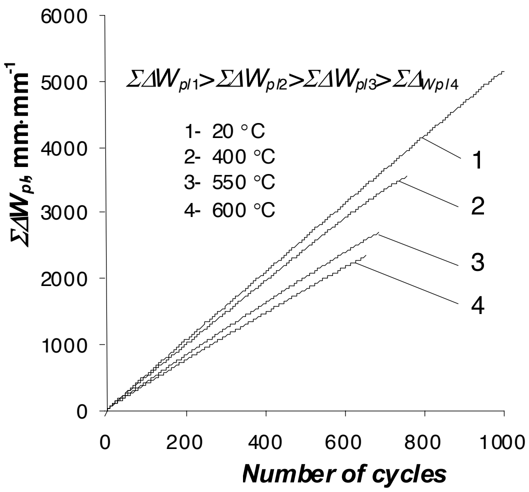


Fig. 16. Influence of the temperature on the level of strain energy $\Sigma\Delta W_{pl}$ cumulated at the level of ε_{ac}=0.60%

In order to illustrate the quantitative influence of the temperature on the level of cumulated strain $\Sigma\Delta\varepsilon_{ap}$ and unit energy $\Sigma\Delta W_{pl}$, Figs. 17 and 18 provide the results of research obtained at six levels of strain.

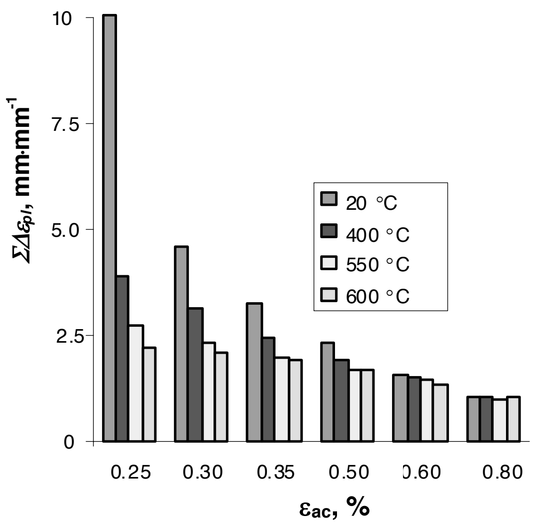


Fig. 17. Influence of the temperature and strain on the cumulated plastic strain $\Sigma\Delta\varepsilon_{ap}$

On the basis of the obtained data (Fig. 18) it can be noted that both: plastic strain $\Sigma\Delta\varepsilon_{ap}$ and the energy of plastic strain $\Sigma\Delta W_{pl}$ cumulated in the test piece till the moment of its cracking depend on the level of strain and temperature. The biggest influence of the temperature on both analyzed parameters occurs in the area of the lowest levels of strain. Whilst the influence of temperature on the boundary values of strain $\Sigma\Delta\varepsilon_{ap}$ and energy $\Sigma\Delta W_{pl}$ is slight for the lowest strain levels covered in the research.

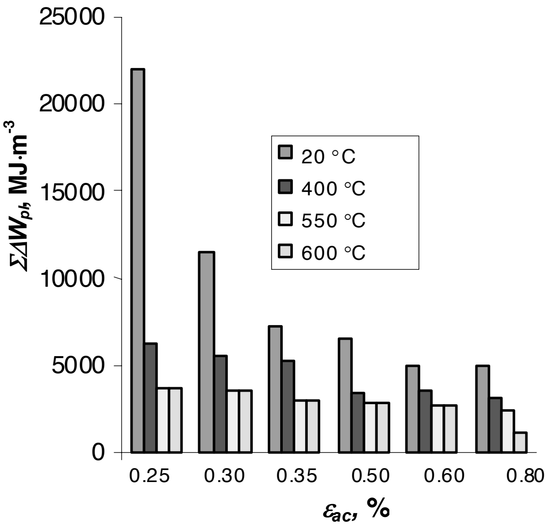


Fig. 18. Influence of the temperature and strain on the energy of plastic strain $\Sigma\Delta W_{pl}$

Similar values of these parameters for diverse temperature constitute a proof of a minor influence of elevated temperature on the life in the area of slight levels of strain.

4. Conclusions

Performed analysis of the fatigue tests results for martensitic cast steel allows to formulate the following conclusions:

1. Martensitic GX12CrMoVNbN9-1 cast steel during low cycle fatigue at room temperature and at elevated temperature is subject to cyclic weakening and does not reveal any clear period of stabilization. In the changes of cyclic properties there are three characteristic stages distinguishable and they are characterized by a diverse speed of weakening.
2. The extent of changes in the cyclic properties is significantly influenced by the level of strain and temperature. At elevated temperature the changes in cyclic properties are definitely bigger than at room temperature. At room temperature and elevated temperature the degree of changes in cyclic properties is decreasing together with an increase in the total strain.
3. The fatigue life of martensitic cast steel is influenced not only by the strain level, but also by the temperature of testing. Influence of the temperature on the fatigue life is dependent on the level of strain. It is slight in the area of very big loads and grows as the level of strain decreases.
4. The occurrence of changes in cyclic properties (parameters of hysteresis loop) and the lack of clear stabilization period of the cast steel at the investigated temperature makes it difficult to determine the basic material data. Their values depend on the period of fatigue life assumed for their calculation. Being assumed from the period corresponding to half the fatigue life makes them reflect only the instantaneous cyclic properties of the cast steel from this specific life period.
5. Growth of the testing temperature by 50°C, i.e. from the temperature of 550°C to 600°C results in a decrease in the fatigue life from 5 to 60% depending on the amplitude of total strain ε_{ac}. This indicates that the casts made of the examined cast steel working under the conditions of low cycle loads, in the case of slight increase in temperature, are at risk of heavy loss of the service properties.
6. The temperature of testing has a considerable influence on the basic parameters of hysteresis loop, such as the scope of plastic strain $\Delta\varepsilon_{ap}$ and unit energy ΔW_{pl}. The temperature of testing also affects the cumulated values of these parameters till the moment of a test piece crack ($\Sigma\Delta\varepsilon_{ap}$ and $\Sigma\Delta W_{pl}$). Cumulated to the moment of test piece cracking: strain $\Sigma\Delta\varepsilon_{ap}$ and energy $\Sigma\Delta W_{pl}$ are not constants at a given temperature, but they depend on the level of strain. They reach the highest values for the lowest levels of strain. It is precisely at these levels that influence of temperature on these parameters is the most evident.
7. Significant changes in the cyclic properties of the cast steel at elevated temperature are the reason why the results of calculations of the fatigue life of construction elements subject to changing loads at elevated temperature, being based on constant material data, are bound to raise doubts.

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