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INFLUENCE OF TEMPERATURE ON LOW CYCLE PROPERTIES OF MARTENSITIC CAST STEEL

The paper presents the results of research on low cycle properties of high-chromium martensitic GX12CrMoVNbN9-1 (GP91) cast steel. The tests of fatigue strength were carried out at two temperatures: room temperature and at 600°C. At both temperatures the occurrence of cyclic softening of the cast steel was observed, revealing no clear stabilization period. Moreover, it has been proved that the fatigue life is influenced by the temperature which depends on the level of strain. The greatest influence was observed for the smallest strain levels applied in the research.

1. Introduction

Calculations of fatigue life of structural elements entail the issue of summing up fatigue defects and the necessity of adopting appropriate hypothesis of the cumulation of fatigue damage [1÷3]. Due to the phenomena of material strengthening or softening, which occur during the low cycle fatigue of metals, and due to the frequent lack of a clear stabilization period of cyclic properties, the process of cumulating damage becomes difficult already during the calculations of life of structural elements subject to changing loads at room temperature [4]. However, it gets considerably complicated when it stops being dependent only on the material properties or loading program and its course starts to be influenced by the changeable room temperature [5÷9]. The changes in cyclic properties occurring at that time are the result

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of interaction of the processes characteristic for low cycle mechanical fatigue and thermal fatigue.

On the basis of low cycle fatigue tests carried out at room temperature [6], we could state that considering the changes in cyclic properties during calculations of life of construction elements makes it possible to significantly reduce the discrepancies between tests and calculations results. On the basis of low cycle fatigue tests run at room temperature [4], it has been noted that, when during the calculations we take into account the life of structural elements which are subject to changing loads at room temperatures, the discrepancies between the results of calculations and tests can be reduced to a considerable extent. Taking into account the fact that at elevated temperature the scope of changes in cyclic properties can often be broader [6, 10], one can assume that this factor can also contribute to the improvement in the conformity between the results of calculations and tests.

The aim of this paper is quantitative assessment of the influence of temperature on the course of changes in cyclic properties of martensitic cast steel. The research was performed by comparing the changes in the basic parameters of hysteresis loop recorded at the same levels of strain at two diverse temperatures.

2. Experimental procedure

Test samples for research were made of martensitic GX12CrMoVNbN9-1 cast steel. The shape and dimensions of the test samples were assumed according to the [11] standard requirements (Fig. 1).

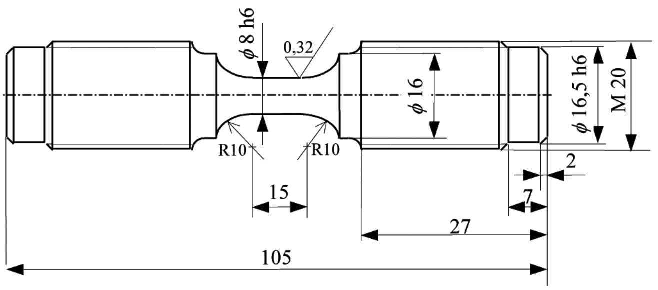


Fig. 1. The shape and dimensions of test samples used during the tests

The tests of fatigue life were preceded by the static tensile test. They were carried out on the test samples used for fatigue tests (Fig. 1). Elongation of a test samples was measured by means of an extensometer of 12.5 mm base and 3.75 mm measuring range. The static tensile test was carried out at the temperatures of 20 and 600°C. The fatigue tests were run at five levels of total strain amplitude ε_{ac} = 0.25; 0.30; 0.35; 0.50; 0.60%. The levels of strain were assumed after the analysis of results from the tensile test (chapter 3.2). The fatigue tests were performed under the conditions of controlled total strain (ε_{ac} =const). Graphical interpretation of parameters assumed for the analysis in the study is illustrated in Fig. 2. The strains of test samples were measured using the extensometer during the tensile test. The fatigue tests, similarly as the static tests, were carried out at the temperatures of 20 and 600°C. The frequency of loading f was equal to 0.2 Hz. Assumed as the criterion for the end of fatigue tests was the occurrence of a deformation on the hysteresis loop arm in the compression half-cycle (appearance of a kink). Moreover, the instantaneous values of loading force and strains of a test sample were recorded during the tests.

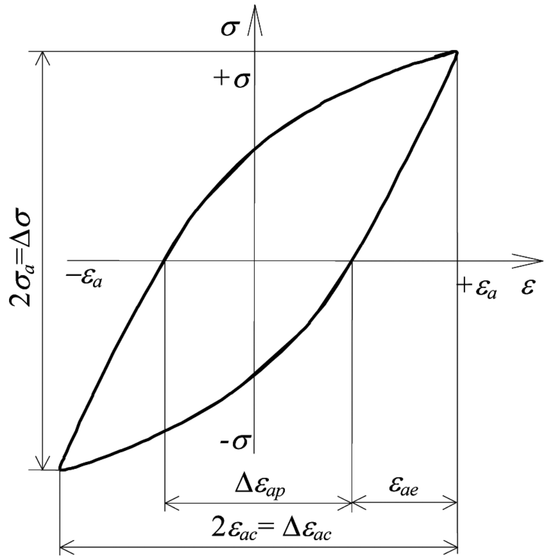


Fig. 2. Hysteresis loop and its basic parameters

3. Research results and their analysis

3.1. Microstructure

The original microstructure of the investigated cast steel subjected to normalizing (1040°C/12h/oil), tempering (760°C/12h/air) and stress relief annealing (750°C/8h/furnace) is shown in Fig. 3.

The examined 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

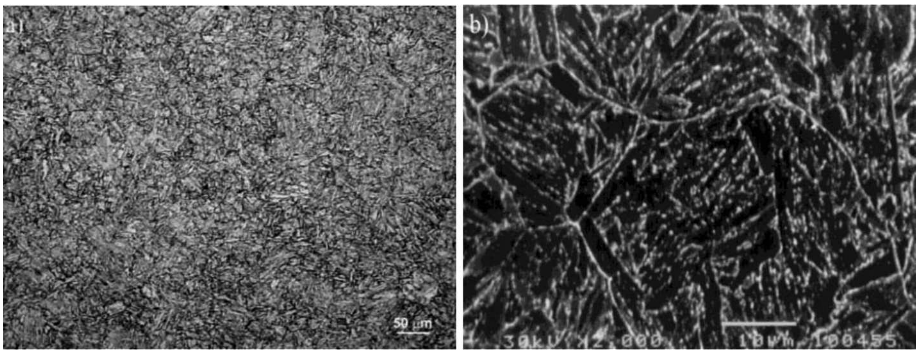
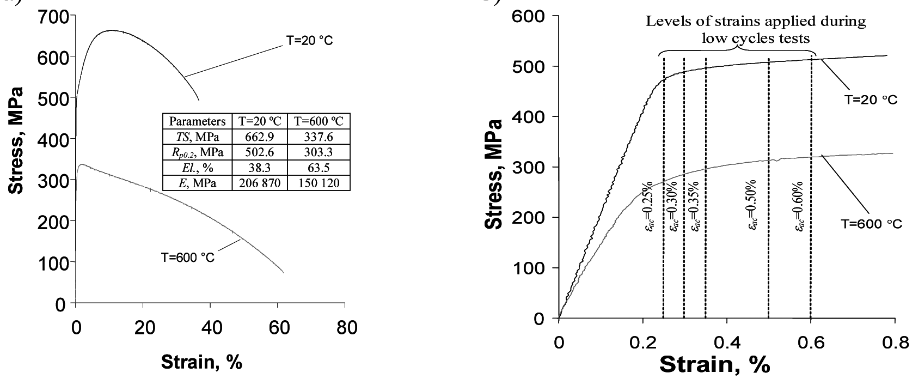


Fig. 3. Microstructure of GP91 cast steel in as – received state: a) OM; b) SEM; nital etched

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 the heat treatment, which indicates that this cast steel was fully martensitic. Description of the high chromium, martensite cast steel and martensite steel microstructure has been shown in [e.g. 12, 13].

3.2. Static tests

Tension curves in the linear coordinate system: elongation of a test sample strain ε vs. stress σ and the tabulated results of static test of tension are shown in Fig. 4a (full range of strains). Stresses in the test sample subject to stretching load were calculated dividing the instantaneous values of loading force recorded during the test by the initial section of a test sample. The tension curves (Fig. 4) were subject to analysis in order to determine the basic strength parameters. Fig. 4b presents fragments of tension curves limited to the elongation interval of 0.8% in which the levels of strain assumed for the fatigue tests are marked.



Parameters	T=20 °C	T=600 °C
TS, MPa	662.9	337.6
$R_{p0.2}$, MPa	502.6	303.3
El., %	38.3	63.5
E, MPa	206 870	150 120

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

According to the expectations, the temperature of testing influenced significantly the strength properties of GP91 cast steel determined during the tensile test. The tensile strength TS and yield strength $R_{p0.2}$ at the temperature of 600°C decreased by about 50% and 40%, respectively, compared to the values obtained at room temperature. Whereas raising the temperature of testing resulted in an increase in the values of the reduction of area and elongation.

3.3. Fatigue tests

The analysis of the cyclic properties of the test samples made of GX12CrMoVNbN9-1 cast steel under the conditions of changing loads was performed using the most important parameters of hysteresis loop, having a direct influence on the results of study. According to [11], the following parameters were included: plastic strain amplitudes ε_{ap} and stress amplitudes σ_a. Their values were determined on the basis of instantaneous values of the force loading a test sample and its strains, recorded during the tests. The test control conditions (ε_{ac} =const) assumed during the research made it possible to analyze the changes in cyclic properties of the examined cast steel in the function of the number of stress cycles, using two parameters of hysteresis loop, i.e. σ_a and ε_{ap} (Fig. 2).

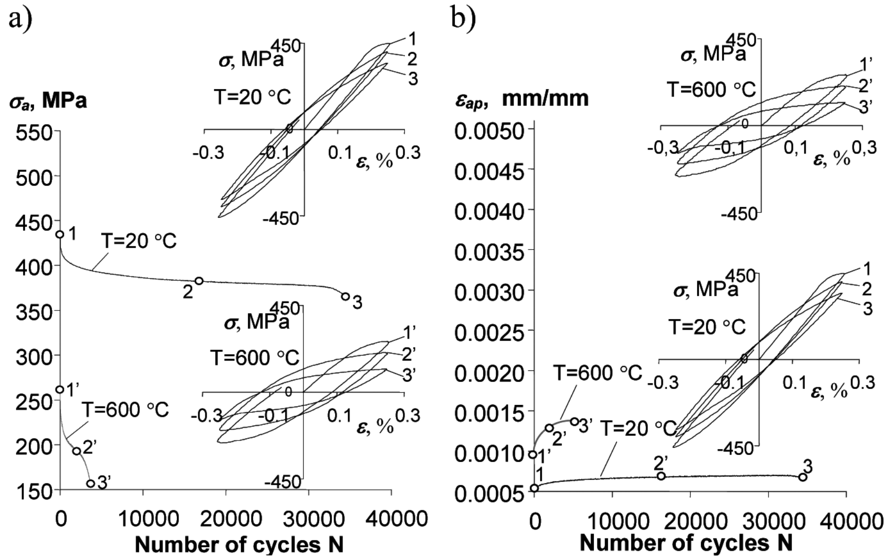


Fig. 5. Changes in the loop parameters at the level ε_{ac} =0.25%: a) $\sigma_a = f(n)$, b) $\varepsilon_{ap} = f(n)$

During fatigue tests, the changes of σ_a and ε_{ap} in the function of stress cycles number were observed. The changes were very similar at all strain levels. In order to discuss the influence of temperature on cyclic properties,

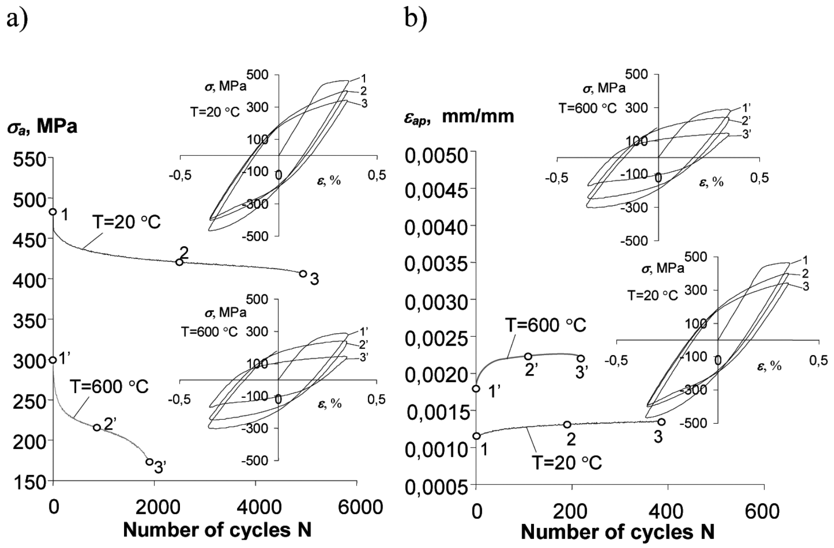


Fig. 6. Changes in the loop parameters at the level ε_{ac} =0.35%: a) $\sigma_a = f(n)$, b) $\varepsilon_{ap} = f(n)$

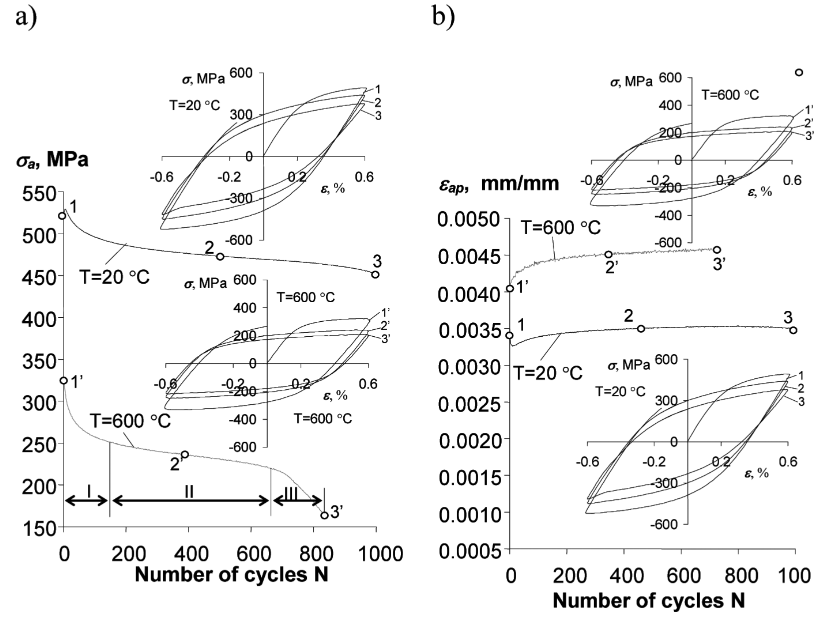


Fig. 7. Changes in the loop parameters at the level ε_{ac} =0.60 %: a) $\sigma_a = f(n)$, b) $\varepsilon_{ap} = f(N)$

Fig. 5÷7 present examples illustrating the course of changes in σ_a and ε_{ap} in the function of cycles number at three levels of total strain ε_{ac}(ε_{ac1} =0.25%, ε_{ac3} =0.35%, ε_{ac5} =0.60%). Additionally, the figures show the loops of hysteresis from three periods of life. 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 a given level of strain. The extent of cast steel softening during the research was assessed in various life periods, comparing the instantaneous value of these parameters with their initial value. For the assessment of the extent of material softening within the entire fatigue test, the softening coefficient δ was applied, as proposed, inter alia, in [6, 12]. The values of softening coefficient δ for the cast steel in the fatigue test was calculated from the following relation:
for the stress description (δ_σ)

$$\delta_\sigma = \frac{\sigma_{a0} - \sigma_{ak}}{\sigma_{a0}} \cdot 100\% \tag{1}$$

and for the strain description (δ_ε)

$$\delta_\varepsilon = \frac{\varepsilon_{apk} - \varepsilon_{ap0}}{\varepsilon_{ap0}} \cdot 100\% \tag{2}$$

Interpretation of the loop parameters present in equation (1) and (2) is illustrated schematically in Fig. 8.

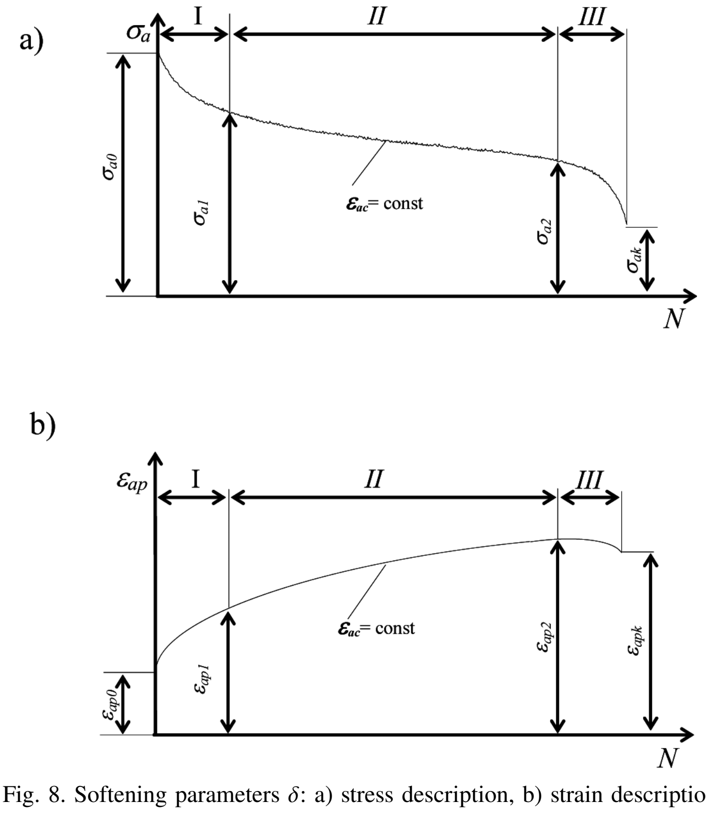


Fig. 8. Softening parameters δ: a) stress description, b) strain description

Analysis of the plotted graphs (Fig. 5÷7) allows us to conclude that the instantaneous cyclic properties (parameters of hysteresis loop) depend on the extent of fatigue damage (number of stress cycles) an temperature. In the courses of hysteresis loop parameters, there are three distinctive stages visible, marked in Fig. 8 as I, II and III.

Stage I – the cast steel is subject to strong softening. At the assumed level of total strains, there is a significant reduction in stress ($\sigma_{a0} - \sigma_{a1}$) and a growth of plastic strains ($\varepsilon_{ap1} - \varepsilon_{ap0}$). Duration of this stage depends on the level of strain and the temperature of testing. The considerable change in cyclic properties at this stage of fatigue can be attributed to the process of dislocation annihilation.

Stage II – the cast steel undergoes further softening. There is a slight reduction in stress ($\sigma_{a1} - \sigma_{a2}$) and growth of strain ($\sigma_{a2} - \sigma_{a1}$). The decrease in stress is significantly smaller compared to stage I. Changes in the mentioned parameters are caused due to further defects being generated in crystal lattice. There is an evolution of defects to the established stable level that is not reached during the fatigue test. Further defects in the crystal lattice reduce the stress and cause an increase in plastic strains. Duration of this stage is dependent on the level of strain and the temperature of testing.

Stage III – evident reduction in stress ($\sigma_{a0} - \sigma_{a1}$) and decrease in plastic strains. The stress and plastic strain reduction occurring at this stage is caused by initiation, propagation, and merging of micro fractures. A primary crack is initiated and it develops into a fatigue crack. Duration of this stage also depends on the level of strain and temperature.

The occurrence of the above-mentioned stages can also be seen on the graphs of changes in stress $\sigma_a = f(N)$ as well as on the graphs of changes in plastic strain $\varepsilon_{ac} = f(N)$. Cyclic strain of the investigated cast steel influences its cyclic properties, in particular: cyclic softening of the material, results mostly from the changes running in the microstructure, such as the observed growth of subgrain size, fall of the dislocation density and the process of coagulation of $M_{23}C_6$ carbides. Quantitative description of these parameters of microstructure is provided in detail in the work [13]. On the basis of graphs presented in Fig. 5÷7, we can conclude that the extent of changes in the loop parameters at particular strain levels is influenced by both: temperature and level of strain.

The results of calculations of coefficients δ_σ and δ_ε (equations 1 and 2) for particular levels of strain amplitude ε_{ac} and temperature of testing are presented in Fig. 9.

The values of softening coefficients δ_σ and δ_ε (Fig. 9) depend on the level of strain, as well as the temperature of testing. Both parameters of hysteresis loop (ε_{ap} and ε_{ac}) are similarly sensitive to changes in the cyclic properties. At the temperature of 20°C the value of δ_σ ranges from ca. 13% for the strain level ε_{ac} = 0.60% to ca. 20% at the level of ε_{ac} = 0.25%.

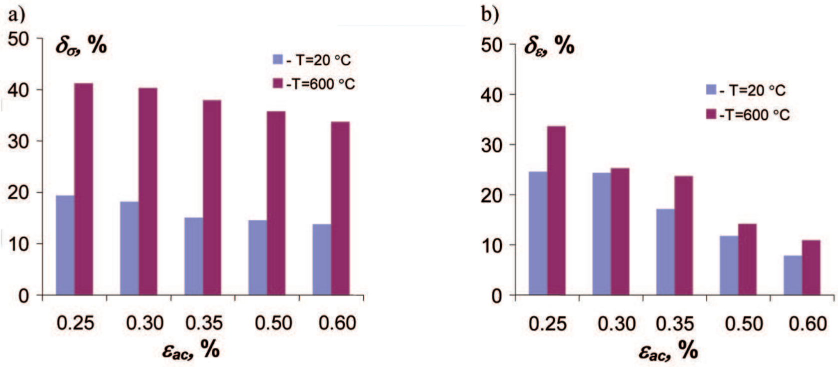


Fig. 9. Changes in the loop parameters at the temperature of 20 and 600°C: a) δ_σ, b) δ_ε

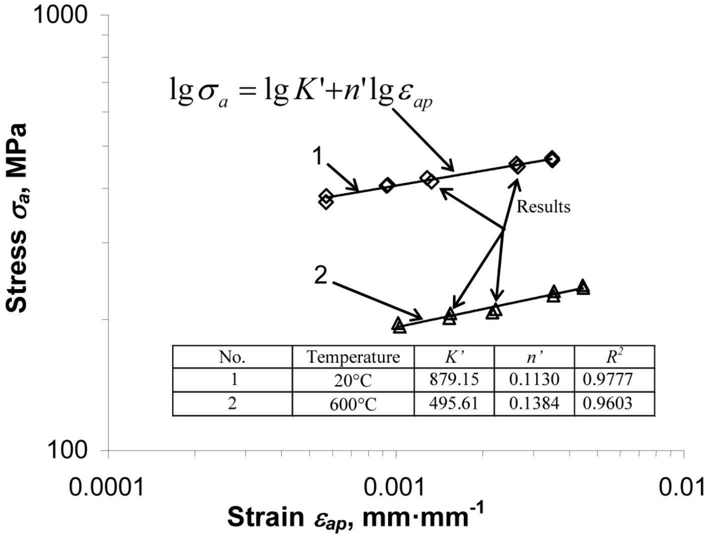
At the temperature of 20°C the value of δ_ε amounts from ca. 8% for the highest strain level to ca. 25% at the level of ε_{ac} = 0.25%. At the temperature of 600°C the extent of cast steel softening is definitely higher in comparison with the course of this process at the temperature of 20°C. The value of δ_σ ranges from 35% (ε_{ac} = 0.60%) to 40% (ε_{ac} = 0.25%). Whilst the value of δ_ε coefficient at the same levels of strain ranges from 10% to 35%. Greater changes running in the cyclic properties of the steel, whose chemical composition and microstructure is similar to that of the investigated cast steel, at the temperature of 600°C are also confirmed by the literature findings [7, 10].

The lack of a clear stabilization period of cyclic properties 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 were assumed from the period corresponding to half the fatigue life N/N_f = 0.5 (points 2 and 2' in Fig. 5÷7 of stress and strain changes). For the analytical description of dependence between stress σ_a and strain ε_{ap} the following equation was adopted:

$$\lg \sigma_a = \lg K' + n' \lg \varepsilon_{ap} \tag{3}$$

where: σ_a – stress amplitudes, MPa;
K' – strain curve coefficient, MPa,
n' – strain curve exponent.

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 (3). Graphs plotted as the result of approximation of the loop parameters (σ_a and ε_{ap}) from the periods corresponding to half the fatigue life are presented in Fig. 10.



No.	Temperature	K'	n'	R^2
1	20°C	879.15	0.1130	0.9777
2	600°C	495.61	0.1384	0.9603

Fig. 10. 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 Fig. 5÷7 are reflected in the respective positions of the obtained graphs of strain (Fig. 10).

Cyclic softening of the cast steel test samples, observed during the tests with constant amplitude at the temperatures of T=20°C and T=600°C, is also proved by the position of graphs of cyclic and static strain. Examples of graphs of static and cyclic strain as well as the loops of hysteresis from the period corresponding to half the fatigue life (N/N_f =0.5- item 2 and 2' in Fig. 5÷7) are presented in Fig. 11. The cyclic strain graphs were approximated with the equation below proposed by Ramberg-Osgood:

$$\varepsilon_{ac} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \tag{4}$$

where: E – Young's modulus, MPa

Regardless of the temperature of testing, the curves of cyclic strain are located below the curves of static strain. The above-mentioned fact proves the cyclic softening of the examined cast steel, irrespective of the temperature of testing 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 3 and 4 describe only the instantaneous properties

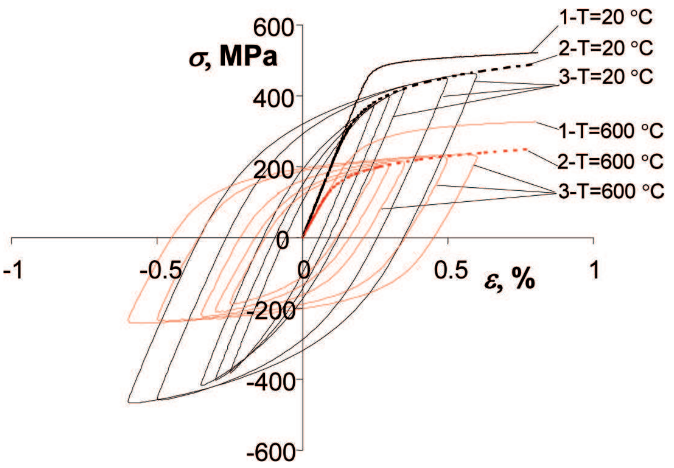
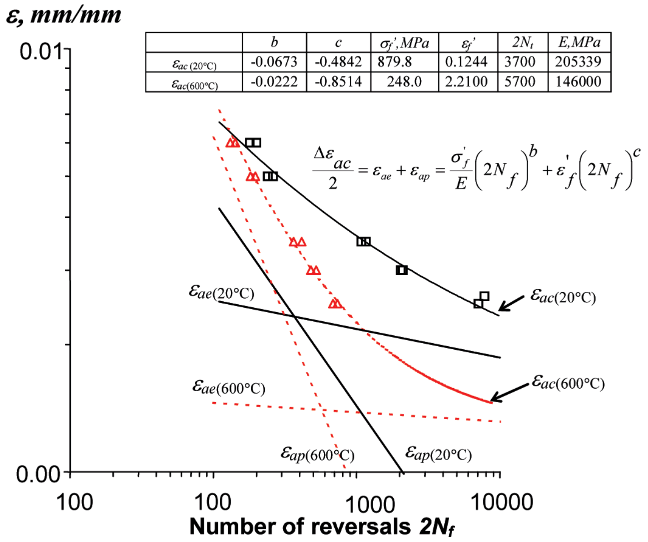


Fig. 11. Position of the graphs of static and cyclic strain obtained at the temperature of 20 and 600°C: 1 – static tension curve, 2 – cyclic strain curve, 3 – hysteresis loops



	b	c	σ_f',MPa	ε_f'	$2N_t$	E,MPa
$\varepsilon_{ac\,(20°C)}$	-0.0673	-0.4842	879.8	0.1244	3700	205339
$\varepsilon_{ac(600°C)}$	-0.0222	-0.8514	248.0	2.2100	5700	146000

$$\frac{\Delta\varepsilon_{ac}}{2} = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c$$

Fig. 12. Comparative graphs of fatigue life of the examined cast steel

determined for half the fatigue life N/N_f =0.5. What was also discovered during the research was a significant influence of temperature on the fatigue life. According to [11], the fatigue graphs in a bilogarithmic system were approximated with the following equation (5):

$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ae}}{2} + \frac{\Delta\varepsilon_{ap}}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{5}$$

where : σ_a – stress amplitude, MPa

E – Young's modulus (determined in the tensile test), MPa;

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

The values of parameters n', K' and E used for the description of graphs of cyclic strain were taken from the table in Fig. 4 and Fig. 10.

The fatigue graphs obtained as the result of approximation of the fatigue tests results conducted at two temperatures are shown in Fig. 12.

On the basis of the presented graphs we can state that the temperature of testing influences the fatigue life significantly. This influence is dependent on the level of total strain amplitude. It is minor in the area of the largest realized strains and increases as the level of strain is falling.

4. Conclusions

The analysis of the results of fatigue tests of martensitic cast steel allows us to formulate the following conclusions:

1. Martensitic cast steel during low cycle fatigue at the temperature of 20 and 600°C is subject to cyclic softening and does not reveal any clear period of stabilization. In the changes of cyclic properties, three characteristic stages can be distinguished and they are characterized by a diverse speed of softening.
2. The extent of changes in the cyclic properties is influenced by the level of strain and temperature. At the temperature of 600°C, the extent of changes in cyclic properties is definitely greater than at the temperature of 20°C. At both temperatures, the degree of changes in cyclic properties is decreasing as the total strain increases.
3. The fatigue life of martensitic cast steel is influenced by both: the strain level and the temperature of testing. The influence of temperature on the fatigue life depends on the level of strain. It is small in the area of very big loads and grows together with the decrease in the strain level.
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 temperatures of 20 and 600°C makes it difficult to determine the basic material data. Their values depend on the period of fatigue life assumed for their determining. When assumed based on the period corresponding to half the fatigue life, the material parameters reflect only the instantaneous cyclic properties of the cast steel from this life period.
5. Significant changes in the cyclic properties of the cast steel at elevated temperatures are the reason why, if one relies on constant material data, the results of calculations of the fatigue life of structural elements subjected to changing loads at elevated temperatures, are bound to raise doubts.

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Wpływ temperatury na własności niskocyklowe staliwa martenzytycznego

Streszczenie

W pracy przedstawiono wyniki badań właściwości niskocyklowych wysokochromowego, martenzytycznego staliwa GX12CrMoVNbN9-1. Badania trwałości zmęczeniowej przeprowadzono w dwóch temperaturach: temperaturze pokojowej i 600°C. W badanych temperaturach stwierdzono występowanie cyklicznego osłabienia staliwa bez wyraźnego okresu stabilizacji. Stwierdzono ponadto istotny wpływ temperatury na trwałość zmęczeniową, który zależy od poziomu odkształcenia i jest największy dla najmniejszych realizowanych poziomów odkształcenia.