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Low cycle fatigue of GX12CrMoVNbN9-1 cast steel

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ABSTRACT

Purpose: The purpose of the paper is to characterise low cycle fatigue of high – chromium martensitic 9%Cr cast steel for advanced steam power plants.

Design/methodology/approach: The research on fatigue life within the scope of small amount of cycles to failure at room temperature was carried out on high - chromium, martensite GX12CrMoVNbN9-1 cast steel. Fatigue tests were performed for the assumed five levels of controlled amplitude of total strain ε_{ac} i.e. 0.25; 0.30; 0.35; 0.50 and 0.60%. The loads applied in the performed experiment oscillated sinusoidally with the stress ratio R = -1 and frequency f = 0.2Hz. Fatigue tests were run by means of Instron 8501 hydropulser. Tests pieced for fatigue tests were round and threaded.

Findings: The investigated cast steel is strongly weakened during low cycle fatigue. The period of stabilization was not revealed during the cyclic loading of GP91 cast steel. Moreover, it has been proved that the course of weakening process of the cast steel does not depend on the level of strain. In the examined cast steel's weakening process three stages can be distinguished which are characterized by a different weakening speed.

Research limitations/implications: The present study is focused on the influence of low cycle fatigue on the fatigue life of GX12CrMoVNbN91 cast steel at room temperature. The investigated cast steel is characterized by the lack of stabilization period, which makes the research results considerably difficult to work out.

Originality/value: The fatigue characteristics of GX12CrMoVNbN9-1 cast steel is presented within the scope of small amount of cycles to failure. Fatigue life of the investigated cast steel was described using the equations of Ramberg-Osgood and Manson-Coffin-Basquin.

Keywords: Metallic alloys; Fatigue; 9% Cr cast steel

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PROPERTIES

1. Introduction

Changing loads of construction elements may result in elastic-plastic strains. They are the cause of hysteresis loops forming in each of the stress cycles. Under the changing load the characteristic loop quantities are generally subject to variation.

When peak stresses decrease in the following stress cycles, at the stable value of total strain ε_{ac} or plastic strain ε_{ap}, the material is subject to cyclic weakening. However, the cyclic strengthening occurs when the stresses are on the rise. For many materials the changes in hysteresis loops appear to a certain number of stress cycles after which they stabilize at some level, giving a state of saturation determined by the value of saturation stress σ_{an} or saturation strain ε_{an}. The state of saturation is in some cases attainable after a few dozen or a few hundred stress cycles. For a majority of construction materials the saturation state is most frequently obtained after 1/3 of the number of cycles to failure, and sometimes after half the cycles to failure [1,2].

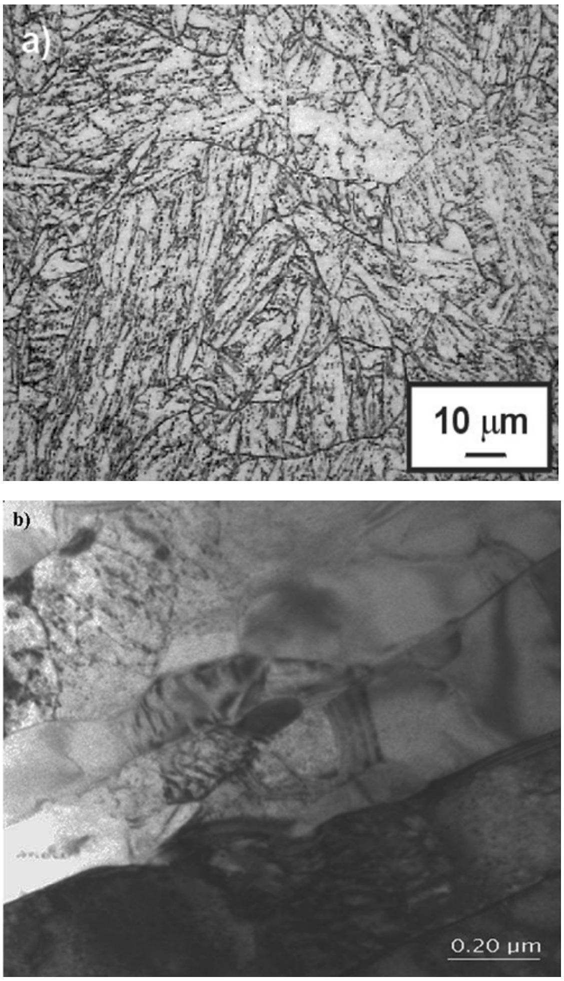

Fig. 1. Microstructure of GP91 cast steel after heat treatment (explanation in the text), a) OM; b) TEM, thin foil

On the basis of experimental tests run at various levels of amplitude of total or plastic strain, the characteristics of material behaviour are being determined within the scope of low cycle strength, i.e. for large strains of material resulting from high level of cyclic loading. In practice such characteristics are a source of essential information necessary for constructing elements of machines and appliances working under the changing load in the conditions of high stress level [1,3,4].

Predictable behaviour of the material within the scope of low cycle fatigue is possible only as the approximate one with a large degree of uncertainty. In general, the material strengthening can be expected when the ratio of tensile strength R_m to the clear yield strength or proof stress R_e (R_m/R_e) is higher than 1.4, whereas its weakening - with the ratio of $R_m/R_e < 1.2$. [1,4-7]. As for the low cycle strength, the behaviour of most metals, particularly alloy steels, is dependent on the history of loading and heat treatment. Therefore, the same material can have various levels of saturation stress or saturation strain [4,7,8].

A significant phenomenon appearing in the elements of steam turbines serviced at elevated temperatures is low cycle fatigue occurring at low frequency of changes, e.g. during repeated putting the power units into and out of operation and their and loading changes. According to literature data [9-13] fatigue, and especially low cycle fatigue, constitutes ca. 65% of the damages in massive turbine cylinders and valve chambers.

The paper presents the research results ranging over low cycle fatigue of the high-chromium martensitic GX12CrMoVNbN9-1 (GP91) cast steel. The GP91 cast steel is designed for service in power units working under the so-called supercritical parameters. The paper provides characteristics of behaviour of the cast steel under the conditions of cyclic loading with a tension-compression effect at room temperature and high levels of total strain. Moreover, the results of research in the system of total strain amplitude - stress amplitude were described with the Ramberg-Osgood dependence. These results were the basis for plotting a graph of the Manson-Coffin-Basquin fatigue life.

2. The investigated material and methodology of research

The material under research was GX12CrMoVNbN9-1(GP91) cast steel with chemical composition included in Table 1. The cast steel for investigation was heat treated: 1040°C/12 h/oil+ 760°C/12 h/air+750°C/8 h/furnace. The investigation of GP91 cast steel's microstructure in the initial state (after heat treatment) was performed by means of an optic microscope, Axiovert 25 and high-resolution transmission electron microscope, (HREM) JOEL JEM-3010. Metallographic microsections prepared in a conventional way (through grinding and polishing) were etched using Vilella's reagent. Thin foil for transmission microscopy was prepared by window thinning method using 10% perchlore acid in methanol as electrolyte. Particles of secondary phases were extracted in carbon replicas. Moreover, the identification of particles was carried out with the usage of thin foils. They were analyzed using selected area electron diffraction (SAD).

Extraction replicas were prepared from well polished and carbon coated specimens using Vilella's reagent. An example of microstructure of the investigated cast steel after heat treatment (in the as-received condition) is illustrated in Fig. 1. 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 after the above-mentioned treatment consisted of lath martensite with large dislocation density as well as the polygonized ferrite grains. 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 high chromium, martensite cast steel and martensite steel microstructure has been shown in [e.g. 14-16]. Mechanical properties of the GX12CrMoVNbN9-1 (GP91) cast steel cast steel in as received condition (after heat treatment) have been shown in Table 2.

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

Table 2.
Mechanical properties of GX12CrMoVNbN9-1 (GP91) cast steel in as received condition (after heat treatment)

Mechanical properties			
$Rp_{0.2}$, MPa	Rm, MPa	A, %	E MPa
488	640	24	205 339

Tests pieced for fatigue tests were round and threaded (Fig. 2). The tests were carried out at room temperature for the assumed five levels of controlled amplitude of total strain ε_{ac} = 0.25, 0.30, 0.35, 0.50 and 0.60%. The applied loading was oscillating sinusoidally with the stress ratio R = -1 and frequency f = 0.2 Hz. The fatigue tests were run by means of Instron 8501 hydropulser.

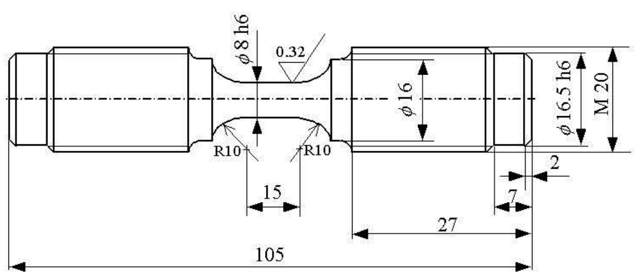

Fig. 2. Test piece for fatigue tests within the scope of small number of cycles

3. Results and their disccusions

Fig. 3 shows examples of hysteresis loops obtained at four levels of strain amplitude ε_{ac} = 0.25; 0.35; 0.50 and 0.60 %. What can be noticed on the basis of performed research is a decrease in the value of stress amplitude - σ_a in the following stress cycles and growth of plastic strain amplitude - ε_{ap}.

Such changes were observed for all the assumed levels of total strain amplitude - ε_{ac}.

For their description Fig. 4 shows graphs of changes in the hysteresis loop parameters (ε_{ac}, ε_{ap}) in the function of the stress cycles number for five strain levels assumed in the research. The obtained graphs prove that the loop shape undergoes changes observed in Fig. 3. Analysis of the graphs of changes in stress (Fig. 4a) and strain (Fig. 4b) allows to notice their qualitative similarity, which consists in the occurrence of three similar stages at different levels of strain. They are illustrated in Fig. 4 on the example of stress and strain curves obtained at one level of strain ε_{ac} = 0.25%. Occurring in the below order, these are:

Stage I in which the cast steel is subject to intense weakening. It is proved by a fast decrease in stress σ_a in the following stress cycles and at the same time an increase in strain ε_{ap}. The weakening speed of the cast steel is decreasing along with the growth of load cycles number (damage extent). Duration of this stage depends on the level of strain and ranges from ca. 5% of all cycles to the crack N_f at the strain level ε_{ac} = 0.25%, to ca. 30% at the level ε_{ac} = 0.6%.

Stage II in which the stress amplitude σ_a goes on to decrease uniformly with the simultaneous growth of amplitude ε_{ap}. Linear character of the changes in the analyzed parameters shows that the weakening speed is constant at this stage. Its duration decreases along with the growth of strain level ε_{ac} and amounts to ca. 90% of the cycles to the crack N_f at the level ε_{ac} = 0.25%, to ca. 30% of the cycles N_f at the level ε_{ac} = 0.6%.

Stage III in which the material is subject to further weakening (fall of the stress level σ_a and simultaneous growth of ε_{ap}) with the growing speed till the moment of total crack of the test piece. At this stage the fatigue crack of the test piece is initiated and continues to develop. Duration of this stage diminishes along with an increase in the strain amplitude level ε_{ac} from ca. 10% of the cycles to the crack N_f at the level ε_{ac} = 0.25%, to around 5% of the cycles N_f at the level ε_{ac} = 0.6%.

The graphs (Fig. 4) presenting the basic parameters of hysteresis loops prove the lack of stabilization period of cyclic properties of the cast steel. Thus it is considerably difficult to arrive at the research results. For this reason, the relations between parameters of loops σ_a and ε_{ap}, being essential for the analytic description, were taken from the period corresponding to half the fatigue life (n/N = 0.5 N_f). For the analytic description of the relation between stress σ_a and strain ε_{ap} the below power function was adopted:

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

where:
K' - strain curve factor,
n' - strain curve exponent.

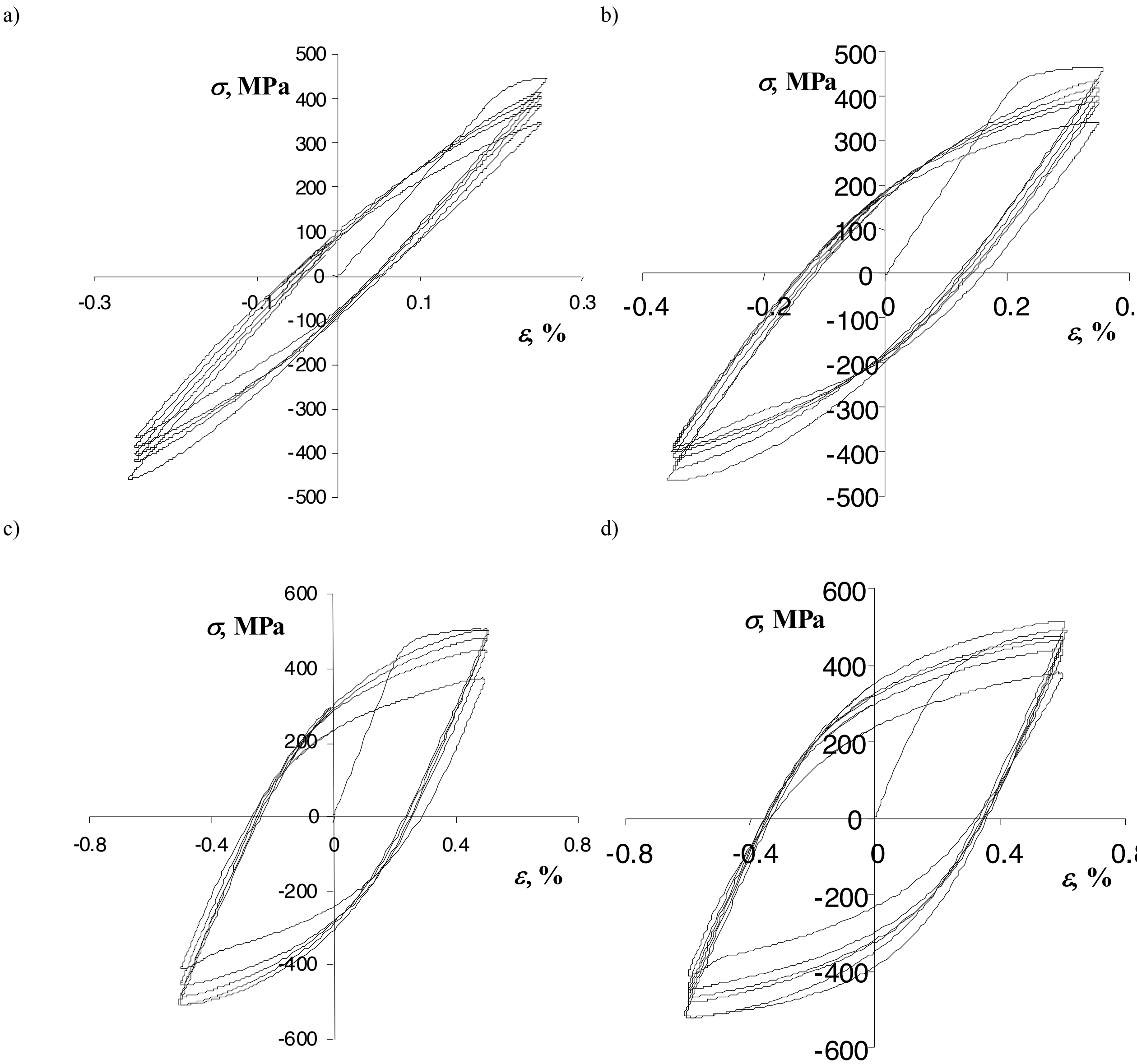

Fig. 3. Hysteresis loops at the amplitude of total strain ε_{ac}: a) 0.25%; b) 0.35%; c) 0.50%; d) 0.60%

Strain curve obtained as a result of approximation of the loop parameters (σ_a, ε_{ap}) with an equation (2) from the periods corresponding to half the fatigue life of the GP91 cast steel is presented in Fig. 5. The parameters of equation (2) were used in the description of cyclic strain curve.

The curve of cyclic strain (Fig. 5) of the examined cast steel was approximated with an equation proposed by Ramberg-Osgood, whose first part concerns the scope of elastic strains and the second one - plastic strains [1]:

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

where:

E - Young module; MPa.

Figure 6 presents hysteresis loops assumed for the analytic description of the cast steel material data obtained from the life period $n/N_f = 0.5$. Additionally, the figure includes the curve of cyclic strain described by equation (2) as well as the curve of static tension.

The cyclic strain curve, drawn through the vertices of hysteresis loops, lies below the static (monotonic) tensile curve. This dependence applies to strains bigger than ca. 0.1% (Fig. 5). The position of the mentioned curves towards one another supports the previous statement about cyclic weakening of the examined cast steel.

On the basis of results of the fatigue tests a graph of fatigue has been plotted. For the analytic description of the graph the Manson-Coffin-Basquin equation was used [1,6,8]:

$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ae}}{2} + \frac{\Delta\varepsilon_{ap}}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (3)$$

where:

b - fatigue life exponent,
c - cyclic strain exponent,
σ'_f - fatigue life factor, MPa,
ε'_f - cyclic plastic strain factor.

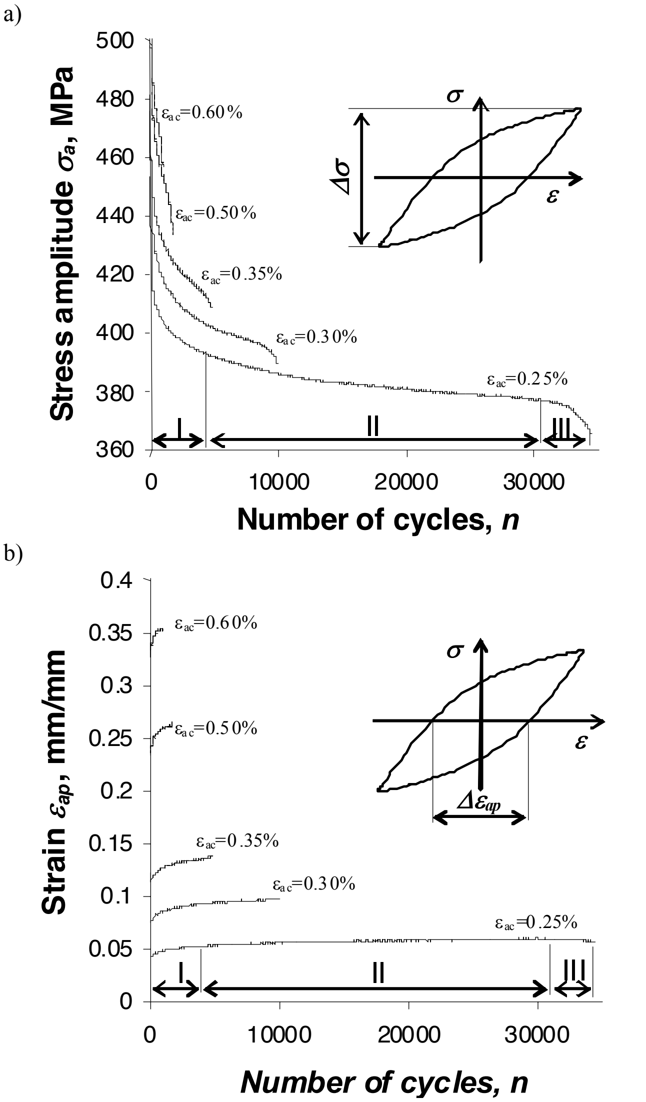

Fig. 4. Changes of the hysteresis loop parameters at five levels of strain: a) σ_a=f(n), b) ε_{ap}=f(n)

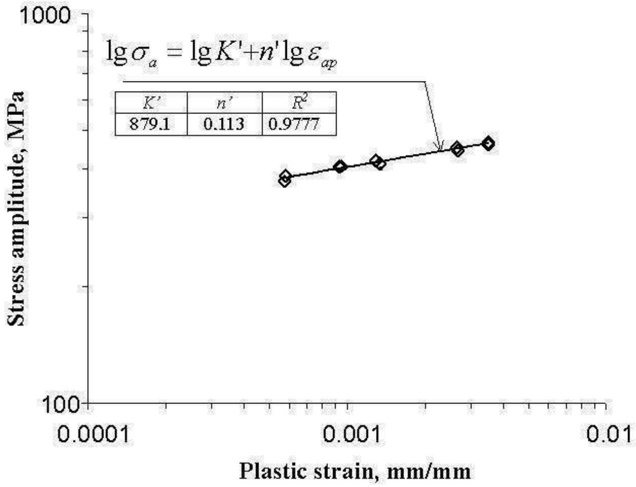

Fig. 5. The strain curve for GX12CrMoVNbN9-1

The values of hysteresis loop parameters and fatigue life obtained in the tests are shown in Table 3

Table 3.
Results of fatigue tests

ε_{ac}, %	ε_{ae}, %	ε_{ap}, %	Number of reversals to failure, $2N_f$	Saturation stress σ_a,MPa
0.60	0.249	0.351	2 000	466
0.60	0.248	0.352	1 800	460
0.50	0.235	0.264	2 400	452
0.50	0.232	0.267	2 600	445
0.35	0.220	0.130	11 600	420
0.35	0.216	0.134	10 800	412
0.30	0.205	0.093	20 322	402
0.30	0.205	0.095	21 000	405
0.25	0.191	0.058	70 952	381
0.25	0.191	0.058	78 000	370

The values of saturation stress obtained for the investigated cast steel at the total strain level of 0.6% are similar to the results achieved for P91 steel. Fatigue life of the GP91 cast steel for this level of strain is over three times as low as that of P91 steel [17].

The curve of fatigue life for GP91 cast steel at room temperature plotted after approximation of research results with an equation (3) is presented in Fig. 7, with the parameters of equation included (3).

Table 4 presents coefficients obtained from the curve approximation (Fig. 7) of the fatigue tests results within small amount of cycles to failure of GP91 cast steel, according to the equation (3). Moreover, Table 4 includes the values of coefficients of the Ramberg-Osgood equation for the examined material (2).

Table 4.
Factors obtained for equations Ramberg-Osgood and Manson-Coffin-Basquin

K'	n'	E	σ'_f	ε'_f	b	c	$2N_t$
MPa	-	MPa	MPa	-	-	-	-
879.1	0.112973	205339	879.8	0.1244	-0.06737	-0.48427	3700

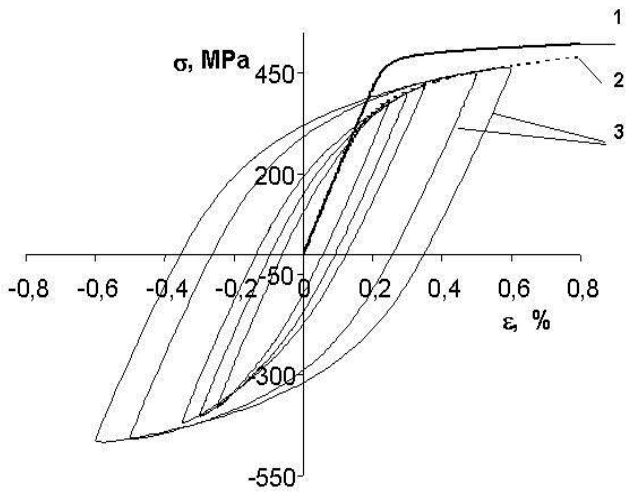

Fig. 6. Position of the curves of static tension and cyclic strain: 1- static tension curve; 2 - cyclic strain curve; 3 - hysteresis loops

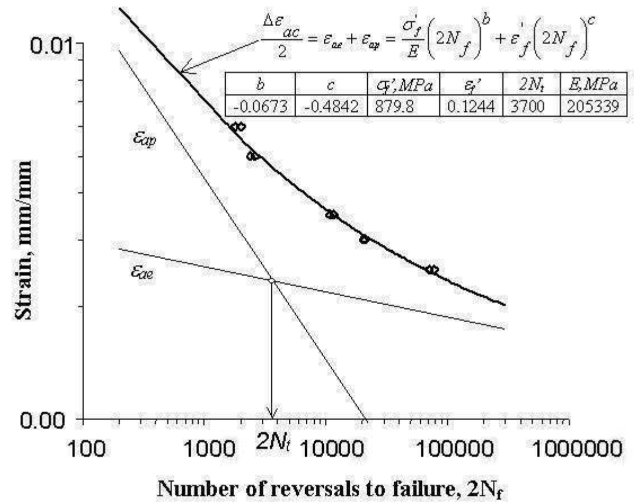

Fig. 7. Curve of the cast steel fatigue life

4. Summary

The research covered the tests of martensitic GX12CrMoVNbN9-1 (GP91) cast steel within the scope of small number of stress cycles to failure. Fatigue tests of the cast steel were carried out at room temperature. During low cycle fatigue the investigated cast steel becomes significantly weaker. In the case of GP91 cast steel $R_m/R_{p0.2}$ = 1.3, there is no experimental evidence for the reference index of the material behaviour towards weakening.

The course of weakening process of the cast steel does not depend on the level of strain. In the weakening process there are three distinguishable stages which are characterized by a different weakening speed.

The lack of stabilization period of GP91 cast steel makes it considerably difficult to arrive at the research results. For this reason during the work on results some parameters were adopted as representative at five levels of strain. These were the parameters of loops from the period corresponding to half the number of cycles to crack in the test piece $n/N_f = 0.5$. It should be noted that the material data obtained thus characterize only momentary properties of the cast steel from one period of fatigue life. Failing to consider the weakening of the cast steel while calculating fatigue life may lead to diversity of results obtained on the basis of the fatigue life calculations and tests.

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Nomenclature

ε_{ac} – total strain amplitude
ε_{ap} – plastic strain amplitude
ε_{as} – plastic strain amplitude
ε_{an} – saturation strain
σ_a – stress amplitude
σ_{an} – saturation stress
N_f – number cycles to the crack
n- numer of cycles

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