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Fatigue Resistance of GX12CrMoVNbN9-1 Cast Steel after Ageing Process

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In the present paper, low cycle fatigue behaviour of GX12CrMoVNbN9-1 (GP91) cast steel is presented. Fatigue tests were performed under isothermal conditions at room temperature and at 550 °C and 600 °C, on five levels of total strain amplitude value ε_{ac} = 0.25 % ÷ 0.60 %. The cast steel subject to investigation was in the as-received condition (after heat treatment) and after 8000 hours of ageing at the temperature of 600 °C. Performed research has shown an insignificant influence of the ageing process on mechanical properties of GP91 cast steel, determined with the static test of tension. Analysis of the performed tests has proved that GP91 cast steel in the as-received condition and after ageing process was characterized by strong cyclic softening without a clear period of stabilization of the hysteresis loop parameters. The fatigue lifetime curves at each temperature were obtained based on Basquin and Coffin-Manson equations. The process of ageing of GP91 cast steel contributed to a decrease in its fatigue life N_f from a few to a few dozen percent, and the level of fatigue life was dependent on the value of strain amplitude ε_{ac}. It has also been stated that the fatigue life N_f of GP91 cast steel is determined by its plastic properties, and the degree of changes in fatigue life N_f was dependent not only on the temperature of testing, but also on the value of strain amplitude ε_{ac}.
Keywords: GP91 cast steel, low cycle fatigue, ageing process.

1. INTRODUCTION

The GX12CrMoVNbN9-1 (GP91) cast steel belongs to a new group of high temperature creep resisting materials introduced into the power industry. The GP91 cast steel is characterized by high properties, higher than those of so far used low alloy cast steels, which allows using these casts in the power plants designed for work at the so-called supercritical parameters [1, 2].

Cast steels in power industry play a crucial role as construction material used for making components of steam turbines, such as turbine cylinders, valve chambers, T-pipes, etc. During the service, when starting up and shutting down the power units, steel casts are exposed to the effects of changing thermal and mechanical loads which often exceed the value of yield strength. Frequently, the cyclic changing effect of temperature and load contributes to the occurrence of deformations and fractures of fatigue character after a certain number of cycles. Failures, and in extreme cases, complete damages of the casts are connected with low cycle fatigue life (LCF), or thermomechanical fatigue, which according to [3] constitute ca. 65 % of all damages of turbines.

The basic requirement that is set for heat resisting steels/cast steels, designed for work in the power industry, is retaining stable microstructure and at the same time certain mechanical properties for long time of service. The effect of temperature and time, also in the conditions of creep and also stress, is the cause of gradual degradation of microstructure of the serviced steels/cast steels, which also leads to the changes in their properties [4, 5]. Introducing new materials into the power industry requires constructing comprehensive characteristics that determine the usefulness and potential possibility of using the modern high-temperature creep resisting steels/cast steels. For this purpose, proper characteristics, such as fatigue characteristics, are necessary for the new grades of steels and cast steels, determining a gradual decrease in their mechanical properties during the service [6, 7].

2. MATERIAL AND METHODOLOGY OF RESEARCH

The material for research was martensitic GX12CrMoVNb9-1 (GP91) cast steel. The investigated samples were in the as-received condition, i. e. after heat treatment and after 8000 hours of ageing at the temperature of 600 °C. The description of microstructure of the examined cast steel in the as-received condition and after ageing is presented in the work [8]. The investigated samples were subject to low cycle fatigue at room temperature and elevated temperature of 550 °C and 600 °C, at five levels of total strain amplitude ε_{ac} = 0.25, 0.30, 0.35, 0.50 and 0.60 %. Fatigue tests were preceded by static tests of tension carried out at the above-mentioned temperatures. The description of methodology of fatigue tests and initial results of researched is included in the work [9, 10]. Fatigue tests were preceded by static tests of tension carried out at the above-mentioned temperatures. According to the standard guidelines [11], the occurrence of a bend on the hysteresis loop was assumed to be the criterion for the end of fatigue tests. The tests were performed by means of testing machine, the Instron 8502 type, equipped with a heating chamber.

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Table 1. Mechanical properties of GP91 cast steel at room temperature, at 550 °C and 600 °C in the as-received state *(sw)* and after ageing process *(pw)***,** with standard deviation for the given mean value included in brackets

Parameter	Temperature of testing, °C					
	room		550		600	
	sw	*pw*	*sw*	*pw*	*sw*	*pw*
$YS_{0.2}$, MPa	488 (7.17)	485 (8.06)	339 (5.33)	332 (4.79)	303 (5.33)	297 (5.24)
TS, MPa	632 (7.93)	644 (5.29)	395 (7.58)	386 (4.47)	338 (7.21)	331 (4.30)
El., %	26 (0.53)	19 (0.32)	47.3 (0.61)	48.8 (0.49)	63.5 (1.27)	63.8 (0.96)
E, MPa	206870 (2276)	202800 (3245)	161460 (2099)	163013 (1793)	150120 (2852)	142180 (1991)
Norma [12]	$YS_{0.2min}$ = 450 MPa, TS_{min} = 600 MPa		$YS_{0.2}{}^{550}{}_{min}$=270 MPa, $TS^{550}{}_{min}$=330 MPa		$YS_{0.2}{}^{600}{}_{min}$= 215 MPa, $TS^{600}{}_{min}$=260 MPa	

3. TEST RESULTS

3.1. Static tests

Low cycle fatigue of GP91 cast steel in the as-received condition and after the process of ageing were preceded by the static test of tension. The obtained mechanical properties of the examined cast steel are given in Table 1.

Performed research has shown that mechanical properties of the cast steel after the process of ageing, determined with the static test of tension, at room and elevated temperature (550 °C and 600 °C), were similar as the properties determined in the as-received condition and higher than the required minimum. The obtained results on mechanical properties and literature data [4, 5] allow to assume that the service of the investigated cast steel will result in a slow reduction of its strength properties, similarly as in the case of "older" grades of cast steel used in the power industry.

It should also be mentioned that according to [13], the yield strength *YS* (or yield strength $YS_{0.2}$) determined for the examined material using the static test of tension, necessary for the qualification of scopes of low – or high cycle fatigue, is the approximate criterion not corresponding to the process of damage of the examined material in the conditions of cycle loads (Table 2). the proper criterion of assessment of the low cycle fatigue scope is the cyclic yield strength determined from the graph of cyclic strain (*YS'*, $YS_{0.2}'$).

Table 2. Comparison of the values of yield strength (*YS*) determined from the curve of static tension ($YS_{0.2}$) and cyclic strain ($YS_{0.2}'$)

T = 20 °C		*T* = 600 °C	
$YS_{0.2}$, MPa	$YS_{0.2}'$, MPa	$YS_{0.2}$, MPa	$YS_{0.2}'$, MPa
488	436	303	210

3.2. Fatigue tests

The analysis of fatigue characteristics of GP91 cast steel in the as-received condition and after the process of ageing, in the conditions of cyclic loads, were performed using the most important parameters of hysteresis loop, including: the amplitude of plastic strain ε_{ap} and the amplitude of stress σ_a.

Low cycle fatigue tests of GP91 cast steel, both in the as-received state and after the ageing process, at all temperatures covered in the experiment, have shown a growth of width of hysteresis loop ε_{ap}, and at the same time intense decreasing of the stress amplitude value σ_a. This indicates cyclic softening of the investigated cast steel during the process of low cycle fatigue. The intensity of cyclic softening increased together with the growth of temperature of the fatigue test. Examples of hysteresis loops for the strain amplitude ε_{ac} = 0.25 % and 0.60 % are illustrated in Figs. 1 and 2.

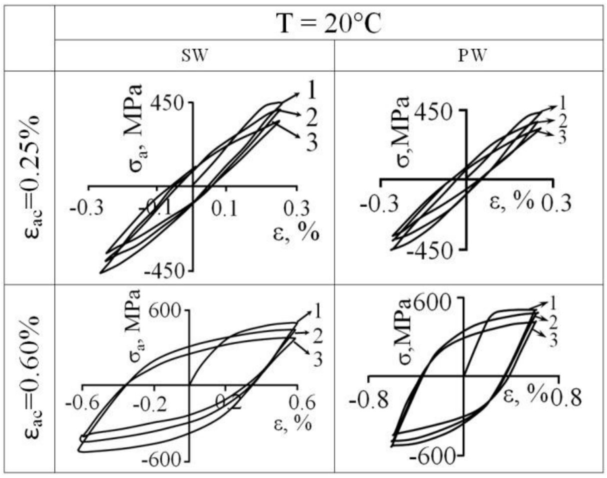


Fig. 1. Examples of hysteresis loops for the cast steel in the as-received state (*sw*) and after ageing process (*pw*) obtained at the temperature of 20 °C: 1 – loop in the first cycle; 2 – loop at half the fatigue life; 3 – loop for the last cycle

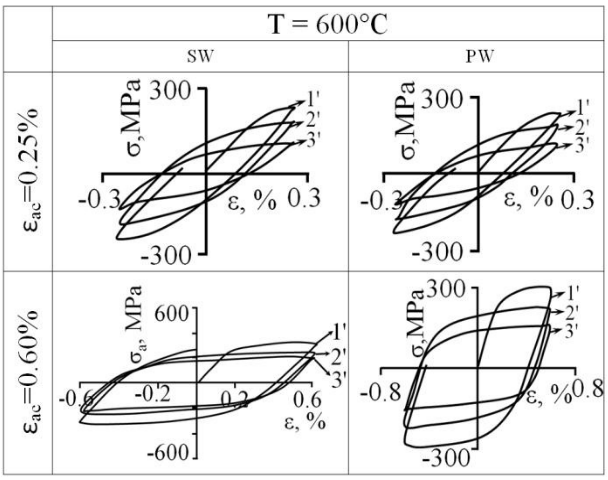
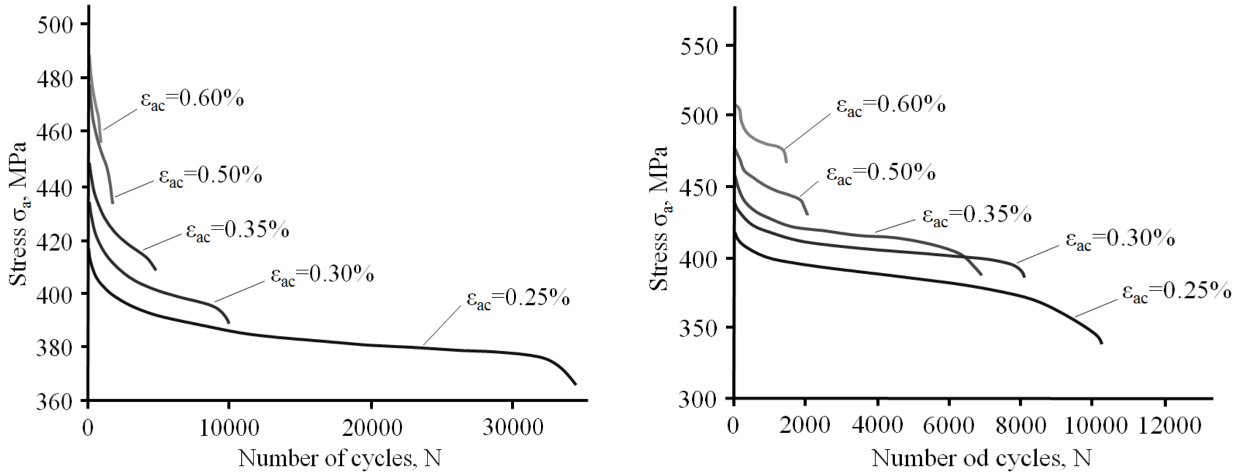


Fig. 2. Examples of hysteresis loops for the cast steel in the as-received state (*sw*) and after ageing process (*pw*) obtained at the temperature of 600 °C: 1 – loop in the first cycle; 2 – loop at half the fatigue life; 3 – loop for the last cycle



a b

Fig. 3. Change in the hysteresis loop parameters in the function of the number of cycles N for the value of strain amplitude ε_{ac} = 0.25 % – 0.60 % of GP91 cast steel at room temperature: a – as-received state, b – after ageing

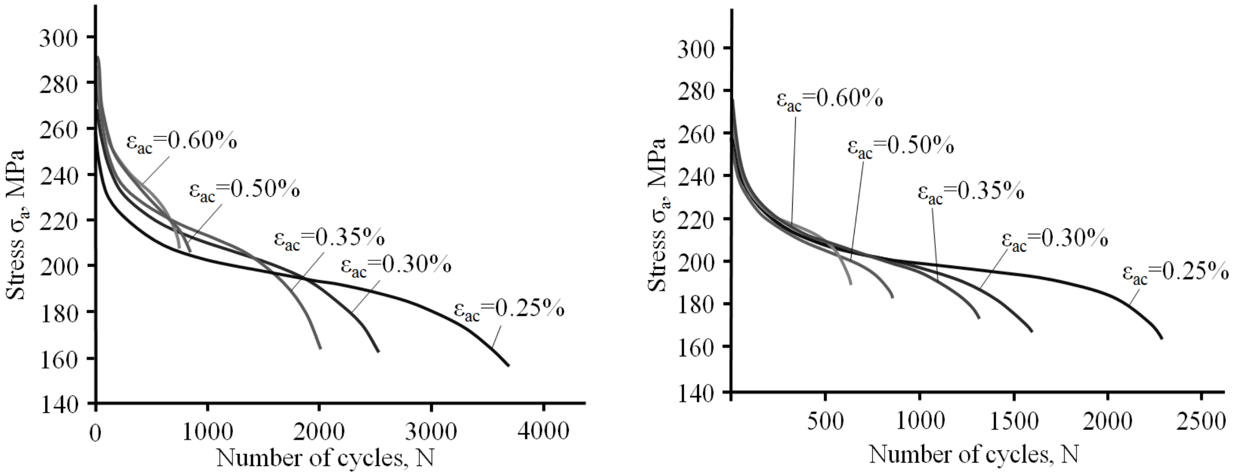


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Fig. 4. Change in the hysteresis loop parameters in the function of the number of cycles N for the value of strain amplitude ε_{ac} = 0.25 % – 0.60 % of GP91 cast steel at the temperature of 600 °C: a – as-received state, b – after ageing

Cyclic softening of the examined cast steel, without a clear period of stabilization of the hysteresis loop parameters in the subsequent phases of cyclic strain, continued at the temperature of testing until the moment when a crack occurred (Figs. 3 and 4). The above test results prove cyclic exhausting of fatigue resistance of the examined cat steel. Cyclic softening of the cast steel during the low cycle fatigue process indicates decreasing of stress amplitude values σ_a necessary to achieve the same unchangeable value of strain.

Cyclic softening that occurs during low cycle fatigue was also observed in high-temperature creep resisting martensitic 9 % ÷ 12 % Cr steels. In these steels, contrary to the investigated cast steel, a clear period of stabilization of the hysteresis loop parameters – the amplitude of stress σ_a and strain ε_{ac} was visible [7].

The lack of a clear period of stabilization of the hysteresis loop parameters (Figs. 3, 4) makes the analytic description of fatigue characteristics of the examined cast steel considerably difficult. Due to the lack of the clear period of stabilization of hysteresis loop parameters and their changes in the function of the number of stress cycles N, the necessary data for the analytic descriptions of characteristics of the investigated cast steel were determined at the number of cycles N corresponding to half the number of cycles until failure, i. e. $0.5N_f$.

The dependence between stress σ_a and strain ε_{ap} was described with equation (1) according to the recommendation included in the standard [11]:

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

where K' – cyclic strain curve coefficient (MPa), n' – strain curve exponent.

The graphs obtained as a result of approximation of the loop parameters (stress amplitude σ_a and plastic strain amplitude ε_{ap}) from the periods corresponding to half the fatigue life (N/N_f = 0.5) are shown in Fig. 5, whilst Table 3 includes the values of parameters (n' and K').

Mutual position of the strain curves of the cast steel in the as-received condition (dashed line in Fig. 5) and after the ageing process (solid line in Fig. 5) is a consequence of differentiated values of the hysteresis loop parameters for the examined cast steel (Figs. 1 and 2). A decrease (for the same values of strain amplitude ε_{ac}) in the stress amplitude

σ_a and a simultaneous increase in the plastic strain amplitude ε_{ap} are the reason why the graphs obtained for the cast steel after ageing process lie below the graphs obtained for the cast steel in the as-received state (Table 3).

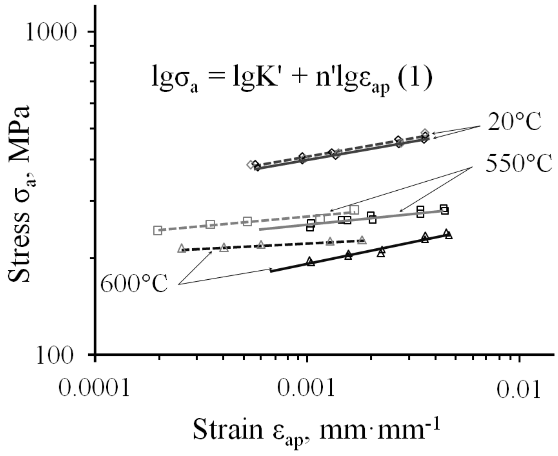

Fig. 5. Influence of the temperature of testing on the graphs of strain of GP91 cast steel after ageing process (interpreted in the text)

The values of parameters n' and K' – the basic materials characteristics used during the calculations of low cycle load changes – in the case of materials not revealing the period of stabilization, depends on the degree of fatigue damage for which they were determined. In the work [10, 13], it has been proved that the values of parameters n' and K' depend on the number of changing load cycles for which they were estimated. The values of these parameters determined at half the fatigue life ($N/N_f = 0.5$) are not average values for the whole fatigue test, which in the authors' opinion indicates the scale of the simplification that was made and can lead to considerable errors. This remark gains particular meaning in the case of the description of fatigue properties of materials at elevated temperature, in which the scope of these changes is bigger than at room temperature.

The results obtained during the fatigue tests at constant strain amplitude ε_{ac} were used when preparing the graphs of fatigue life of the examined cast steel. The fatigue life of GP91 cast steel was described using the Mansona-Coffina-Basquina equation (MCB) (2) [14, 15].

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

where b – fatigue life exponent, c – cyclic strain exponent, ε_f' – fatigue life coefficient (MPa), ε_f' – plastic strain coefficient, E Young modulus determined from the static test of tension (MPa), $2N_f$ number of reversals to failure.

The values of coefficients and exponents obtained for the examined GP91 cast steel, necessary for the mathematical description of fatigue life expressed with the MCB equation (2), are given in Table 4. Performed analysis of the obtained characteristics of GP91 cast steel in the as-received condition (Fig. 6) shows that the abscissa $2N_t$ of the point of intersection of the curves $\varepsilon_{ae} = f(2N_f)$ and $\varepsilon_{ap} = f(2N_f)$ in the analysed cases amounted to 3700 and around 5700 cycles, respectively, for the room and elevated temperature (550 °C and 600 °C) – Table 4.

This indicates that the process of cyclic strain of the investigated cast steel, with the values of total strain ε_{ac} applied during fatigue tests, for all the temperatures applied in the experiment, will run at the dominant role of plastic component of strain ε_{ap}. Therefore, it can be assumed that for these values of strain ε_{ac}, the resistance to cyclic strain of the GP91 cast steel will mostly depend on its plastic properties. Similar dependence was also observed in the case of high-temperature creep resisting martensitic steels, such as P91 and P92, however the point of intersection N_t for these steels amounted above 1000 cycles [6, 7].

In the case of the cast steel after ageing process, the point $2N_t$ amounts to about 5300 for room temperature and for 550 °C, and 4558 cycles for the temperature of 600 °C (Figs. 6, 7), which shows that the abscissa N_t, i.e. the point of intersection of the curves of strain elastic component ε_{ae} and plastic component ε_{ap}, lies in the so-called area of low cycle fatigue (similarly as in the as-received condition) – Table 4. This proves that the process of cyclic strain of the examined cast steel, like in the as-received condition, ran at the dominant role of the plastic component of strain ε_{ap}.

Table 3. Comparison of the coefficients of equation (1) for the cast steel in the as-received state *(sw)* and after ageing process *(pw)*

	Temperature, °C								
	20			550			600		
	K', MPa	**n'**	R^2	K', MPa	n'	R^2	K', MPa	n'	R^2
sw	879	0.1130	0.9786	416	0.0743	0.9564	496	0.1384	0.9603
pw	898	0.1147	0.9553	490	0.1086	0.9223	302	0.0630	0.9112

Table 4. Comparison of mathematical models of low cycle fatigue life of GP91 cast steel in the as-received condition (*sw*) and after ageing (*pw*)

Temperature, °C	σ'_f, MPa		ε'_f		b		c		$2N_f$	
	sw	pw	sw	pw	sw	pw	sw	pw	sw	pw
20	880	1055	0.1244	2.5917	–0.0673	–0.09554	–0.4842	–0.8198	3700	5389
550	526	405	0.8136	1.7556	–0.0553	–0.06428	–0.7279	–0.8289	5717	5280
600	248	227	2.2102	9.9614	–0.0222	–0.03014	–0.8514	–1.0669	5700	4558

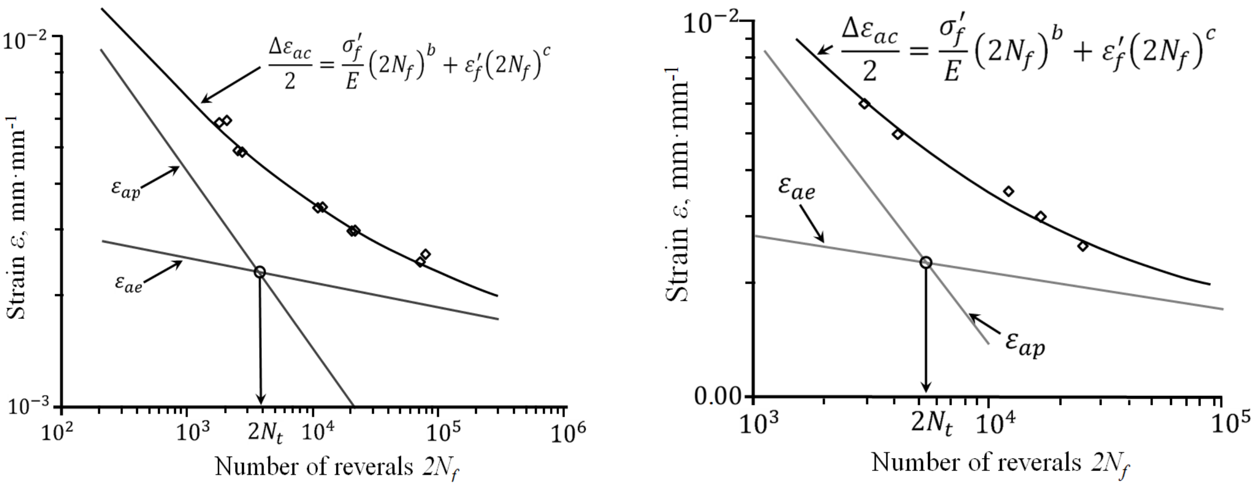

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Fig. 6. Curves of low cycle fatigue life of GP91 cast steel at room temperature: a – as-received state, b – after ageing

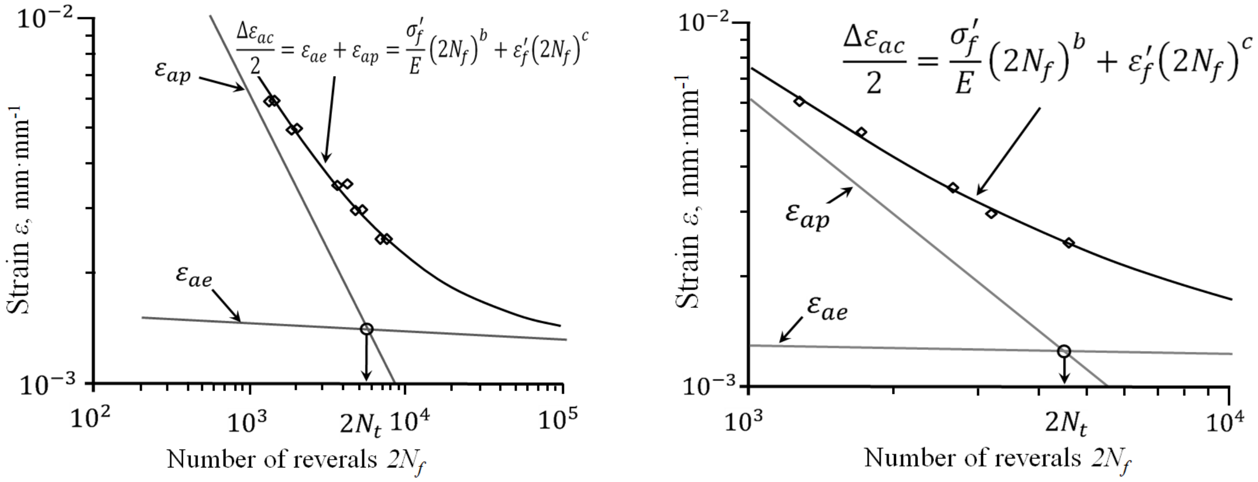

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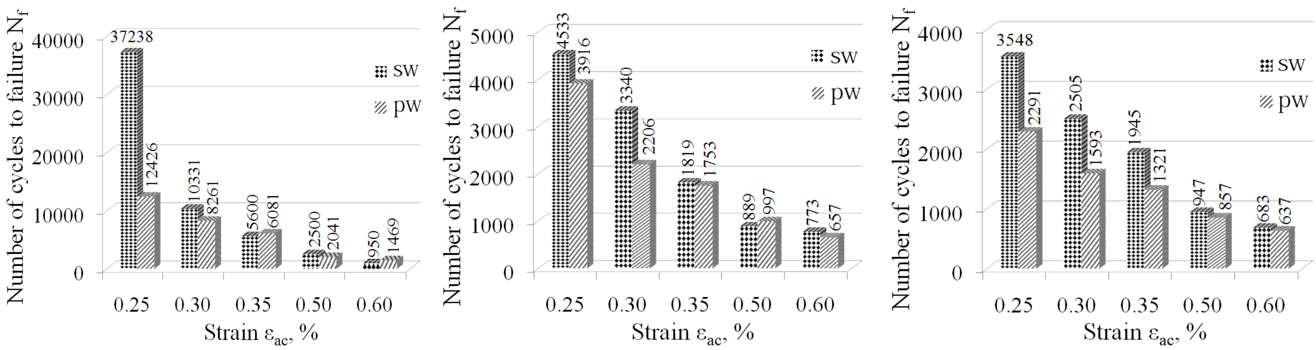
Fig. 7. Curves of low cycle fatigue life of GP91 cast steel at temperature of 600 °C: a – as-received state, b – after ageing



a b c

Fig. 8. Comparison of low cycle fatigue of GP91 cast steel in the as-received state (sw) and after ageing (pw) at: a – room temperature; b – 550 °C; c – 600 °C

Thus it can be concluded that for the values of strain ε_{ac}, assumed during the tests, the resistance to cyclic strain of the cast steel mostly depends on its plastic properties.

According to the data [16], an increase in the absolute value of cyclic strain exponent *c* observed in the examined cast steel can indicate a change in the mechanism of decohesion of the steel subject to low cycle fatigue, from the transcrystalline mechanism into the intercrystalline one.

Fatigue life of GP91 cast steel after the process of ageing in comparison with the as-received condition is presented (depending on the temperature of testing) in Fig 8. The presented graphs show a significant influence of the temperature, as well as total strain amplitude value ε_{ac} on the fatigue life of the investigated cast steel. Comparison of the low cycle fatigue characteristics of GP91 cast steel in the as-received state and after ageing

Table 5. Fatigue characteristics of GP91 cast steel at room temperature

Strain amplitude ε_{ac}, %	Room temperature					
	As-received state			After ageing		
	N_f	σ_a, MPa	ε_{ap}, %	N_f	σ_a, MPa	ε_{ap}, %
0.25	950	386	0.058	1469	384	0.054
0.30	2500	404	0.094	2041	405	0.097
0.35	5600	416	0.130	5600	415	0.140
0.50	10331	449	0.266	8261	448	0.274
0.60	37238	463	0.352	12426	482	0.355

Table 6. Fatigue characteristics of GP91 cast steel at the temperature of 550 °C

Strain amplitude ε_{ac}, %	Temperature 550 °C					
	As-received state			After ageing		
	N_f	σ_a, MPa	ε_{ap}, %	N_f	σ_a, MPa	ε_{ap}, %
0.25	9066	249	0.102	3916	232	0.107
0.30	6079	257	0.146	2206	245	0.156
0.35	3637	261	0.197	1753	250	0.205
0.50	1777	273	0.338	997	257	0.346
0.60	1445	278	0.437	657	277	0.440

Table 7. Fatigue characteristics of GP91 cast steel at the temperature of 600 °C

Strain amplitude ε_{ac}, %	Temperature 600 °C					
	As-received state			After ageing		
	N_f	σ_a, MPa	ε_{ap}, %	N_f	σ_a, MPa	ε_{ap}, %
0.25	3548	193	0.104	2291	198	0.126
0.30	2505	260	0.156	1593	202	0.173
0.35	1945	208	0.221	1321	204	0.226
0.50	947	237	0.356	857	208	0.368
0.60	683	235	0.451	637	218	0.473

process is presented in Tables 5 – 7. Due to the lack of a clear period of stabilization of the hysteresis loop parameters (Figs. 3, 4), the value of stress σ_a was determined from the period corresponding to half the fatigue life ($N/N_f = 0.5$).

The process of ageing of GP91 cast steel, stimulating the changes that occur in its microstructure during the service, contributed to a decrease in fatigue life of the examined cast steel at room temperature and elevated temperature of 550 °C and 600 °C, from few to a few dozen percent, compared to the as-received state. At the same time, it has been noted that the process of low cycle strain of the investigated cast steel, at a given temperature of experimenting, occurred at similar values of stress σ_a and plastic strain ε_{ap}. Cyclic softening and the decrease in fatigue life N_f of the examined cast steel result from the advantage of the softening processes over the processes of matrix strengthening, revealed by: a decrease in the dislocation density, increase in the mean diameter of subgrains and a reduction of the stabilizing effect of $M_{23}C_6$ carbides (a decrease of pinning effect of $M_{23}C_6$ carbides) on the dislocation microstructure as a result of their coagulation [6, 9]. The above recovery and polygonization process of matrix, similarly as in the case of fatigue life N_f, depends on the temperature and value of strain amplitude ε_{ac} [9].

In paper [17], the degree of softening of GP91 cast steel was determined for particular values of strain amplitude ε_{ac}, using the softening coefficient δ (stress coefficient δ_σ and strain coefficient δ_ε. Performed calculations have shown that the degree of softening expressed with the coefficients δ_σ and δ_ε is bigger in the case of the cast steel after ageing than for the cast steel in the as-received condition (after heat treatment). The value of coefficient δ_σ and δ_ε grows as the temperature of testing rises. Moreover, it has been stated that from among the two analyzed parameters of hysteresis loop (σ_a, ε_{ap}), the coefficient δ_ε was characterized by a smaller range of changes. In the authors‘ opinion, this confirms that in the area of low cycle fatigue, it is justified to make calculations of fatigue life with a strain-based approach.

4. CONCLUSIONS

1. The process of ageing had an insignificant influence on the change in mechanical properties of GP91 cast steel, determined with the static test of tension, at both room and elevated temperature (550 °C and 600 °C).

2. In the as-received condition, as well as after the ageing process, at both room and elevated temperature, GP91 cast steel is characterized by strong cyclic softening without a clear period of stabilization of the hysteresis loop parameters.
3. Fatigue life N_f of the examined cast steel is determined by its plastic properties.
4. The process of ageing of GP91 cast steel contributed to a decrease in its fatigue life N_f from a few to a few dozen percent at the temperature of testing, compared to the as-received condition. The degree of changes in fatigue life N_f of the examined cast steel was dependent not only on the temperature of testing, but also on the value of strain amplitude ε_{ac}.
5. Decrease in the fatigue life of GP91 cast steel depends on the changes in the microstructure – matrix softening process.

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