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INFLUENCE OF ELEVATED TEMPERATURE ON LOW CYCLE PROPERTIES OF WCLV/1.2344 STEEL

Key words

Low cycle fatigue, cyclic softening, fatigue life.

Abstract

In this paper the results of low cycle fatigue tests of hot-work tool WCLV (1.2344) steel carried out at the temperatures of 20ºC and 600ºC were presented. These results are used for numerical modelling of the wearing course of forging tools. This analysis was performed by means of hysteresis loop parameters recorded during tests. It was stated that the elevated temperature influences fatigue life and changes of hysteresis loop parameters in the function of loading cycles. At the temperature of 600ºC, changes in the parameters were significantly higher than at 20ºC. It make more difficult to calculate the fatigue life of objects operating at elevated temperatures, because material data determined during tests reflects only the momentary properties of steel.

Introduction

Fatigue life calculations of structural components are related to the fatigue damage cumulating process [1, 2]. To do the calculations, a knowledge about basic material data and the loading program are necessary. For the loading of low cycle fatigue, a fatigue diagram in coordination of ε-$2N_f$ is approximated with the Manson-Coffin-Basquin equation [3, 4] as follows:

$$\varepsilon_{ac} = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^b + \varepsilon_f{}'\left(2N_f\right)^c \tag{1}$$

Material data are required during calculations to construct an analytical description of a hysteresis loop, among other things. One of the simplest ways to obtain a description of the hysteresis loop is a use of a cyclic stress strain curve. For analytical description of this diagram, the Ramberg–Osgood model [5] is mostly used in a form as follows:

$$\frac{\Delta\varepsilon_c}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{2}$$

where

n' – cyclic hardening exponent,

K'– strength coefficient of cyclic strain diagram,

E – Young's modulus.

Parameters of n' and K' are determined during fatigue tests [6], but the constant value of E is determined during tensile tests. During the determination of n' and K', it is assumed that plastic strain ε_{ap} is a power function of σ_a in the form of the following [6]:

$$\varepsilon_{ap} = \left(\frac{\sigma_{as}}{K'}\right)^{\frac{1}{n'}} \tag{3}$$

where σ_{as} and ε_{ap} – hysteresis loop parameters from the stabilization period.

Parameters from equations (1-3) are determined during empirical tests from the "stabilization period." Based on the analysis of data from literature, it can be stated that the stabilization state is very rare and lasts a very short time or does not exists at all [7]. There exist many hypotheses about steel properties in the area of low cycle fatigue [7]. Factors that have an influence on the course of the softening or hardening processes are as follows: loading program (e.g., overloads), loading magnitude, temperature, etc. During modelling of technical objects created at elevated temperatures, analytical models are used that were prepared for room temperatures. In many cases, this produces problems regarding the different course of softening or hardening processes at elevated temperatures [8, 9].

The goal of this work is to determine the influence of temperature on the cyclic properties of WCLV/1.2344 steel. An additional aim is to evaluate the effects of changes of cyclic properties of steel at elevated temperatures on the final elaboration of experimental tests results.

1. Description and test methods

Cylindrical specimens with threaded heads according to a standard were prepared for the tests [6]. Specimens were made of hot working tool steel of WCLV (1.2344) following heat treatment, typical for this steel: hardening and triple tempering. The hardness of specimens was in the range of 50–50.5 HRC.

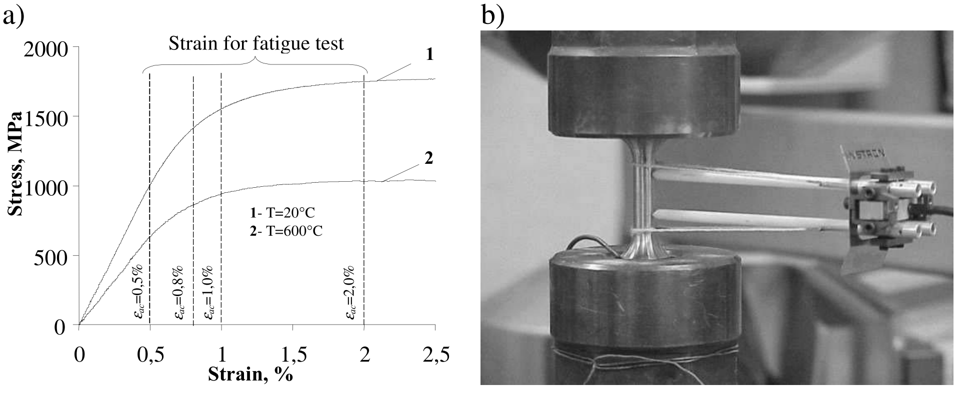


Fig. 1. a) Diagram of tensile test of steel WCLV for different temperatures, b) specimen mounted in holders with an extensometer and thermocouple

In order to define the levels of variable total strain, tensile tests were performed before fatigue tests. Analysis of results (Fig. 1a) allowed the selection of four levels of variable total strain ε_{ac} = 0.5%; 0.8%; 1.0%; and, 2.0%. Fatigue tests were performed in conditions of a controlled total strain of ε_{ac} = constant and with an asymmetry coefficient of R = -1.

Tensile and fatigue tests were carried out at temperatures referred to working conditions of dies and tools made of WCLV/1.2344 steel (20 and 600°C). For tests at the temperature of 600ºC, a heating chamber–test machine Instron 8502 was used. Extension of specimen was measured by means of an extensometer with a measuring range of 3.75 mm and base of 12.5 mm, and a thermocouple was used for the specimen temperature measurements (Fig. 1b).

2. Test results

During low cycle fatigue tests at the temperatures of 20ºC and 600ºC, cyclic softening of tested steel was observed. The level of material softening was highly influenced by the test temperature and the level of variable strain ε_{ac}. In Fig. 2, exemplary diagrams of stress amplitude σ_a as the function of the number of loadings for two temperatures ($T = 20$°C and $T = 600$°C) are presented.

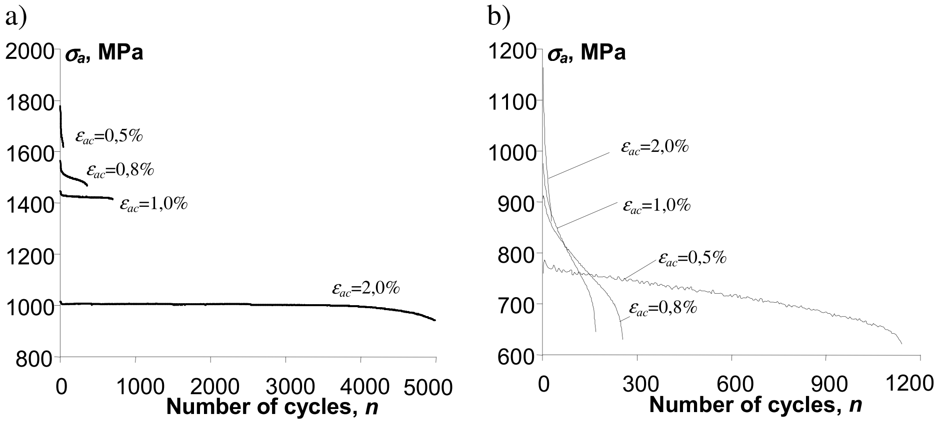


Fig. 2. Changes in stress σ_a as a function of number of cycles: a) $T = 20$ºC, b) $T = 600$ºC

For the evaluation of the influence of strain ε_{ac} on the level of softening, a change coefficient $\Delta\sigma_{wzgl}$ was introduced as proposed in [10] in the following form:

$$\Delta\sigma_{wzgl} = \frac{\Delta\sigma_i}{\Delta\sigma_1} \tag{4}$$

where $\Delta\sigma_i$ – range of stress at i loading cycle,
$\Delta\sigma_1$ – range of stress at first loading cycle.

Figure 3 presents diagrams of $\Delta\sigma_{wzgl}$ as a function of relative life n/N (n – actual number of loading cycles at level of ε_{aci}, N – fatigue life at level of ε_{aci}).

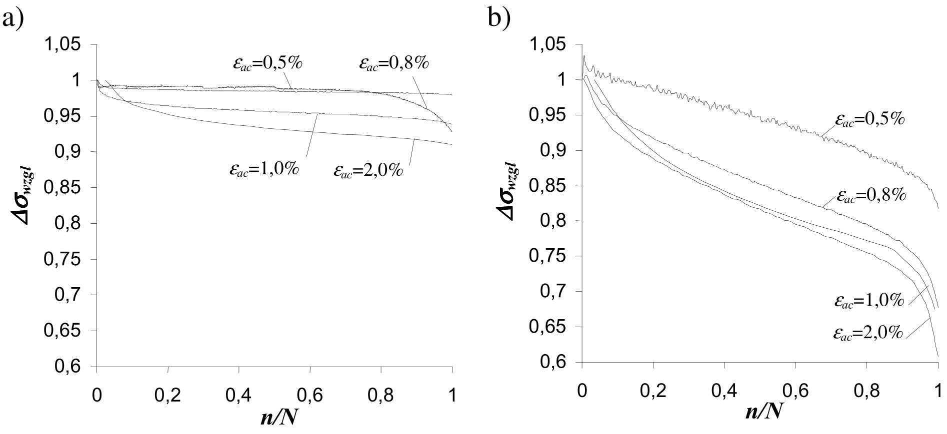


Fig. 3. Changes in $\Delta\sigma_{wzgl}$ at four levels of total strain: a) T = 20ºC, and b) T = 600ºC

Diagrams of $\Delta\sigma_{wzgl}$ confirms softening of steel at the temperature of 20ºC and at the temperature of 600°C ($\Delta\sigma_{wzgl}$<1). The level of the softening of steel for both temperatures increases with increasing the total strain ε_{ac}. For the same levels of total strain, a magnitude of softening (changes in $\Delta\sigma_{wzgl}$) at elevated temperatures is significantly higher than at room temperature. Changes in the hysteresis loop parameters as a function of the number of loading cycles and the lack of a clear stabilization period make it difficult to develop the obtained test results.

In this paper, comparative analysis was performed of hysteresis loops obtained for the same levels of total strain for both temperatures. Regarding the continuous changes in cyclic properties for both temperatures and the lack of a stabilization period for comparison, hysteresis loops from half of the fatigue life (n/N = 0.5) were taken into consideration. In Fig. 4, exemplary loops obtained at temperatures of 20 and 600°C for two levels of total strain (ε_{ac} = 0.5%, ε_{ac} = 2.0%) are presented. In accordance with expectations, the range of stress $\Delta\sigma$ for loops obtained at the temperature of T = 600ºC is clearly lower than at the temperature of 20ºC. For the range of plastic strain $\Delta\varepsilon_{ap}$, the situation is reversed. With increasing temperature, the range of the plastic strain $\Delta\varepsilon_{ap}$ increases.

Based on the comparative analysis of loops in Figs. 4a and 4b, it can be stated that the increase of plastic strains ($\Delta\varepsilon_{ap}$) at the temperature of 600ºC is clearly higher than at low levels of total strains. For an analytical description of the relationship between stress σ_a and strain ε_{ap}, equation (3) was used. Results of the approximation of parameters σ_a and ε_{ap} at two temperatures are collected in Fig. 5.

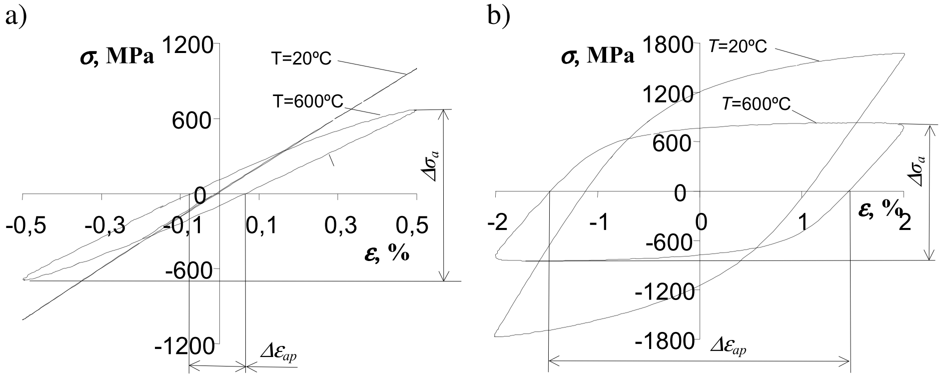
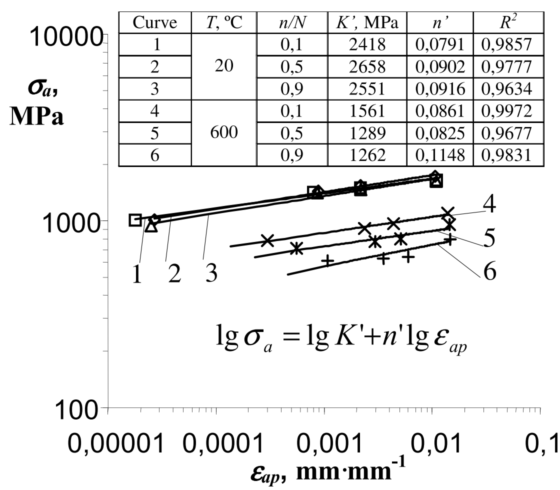


Fig. 4. Hysteresis loops at two temperatures: a) $\varepsilon_{ac} = 0.5\%$, and b) $\varepsilon_{ac} = 2.0\%$



Curve	T, ºC	n/N	K', MPa	n'	R^2
1	20	0,1	2418	0,0791	0,9857
2		0,5	2658	0,0902	0,9777
3		0,9	2551	0,0916	0,9634
4	600	0,1	1561	0,0861	0,9972
5		0,5	1289	0,0825	0,9677
6		0,9	1262	0,1148	0,9831

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

Fig. 5. Results of approximation of loop parameters at different periods

In order to illustrate the scale of simplification carried out during assuming loop parameters from the period of $n/N = 0.5$, the results of the approximation of the loop parameters for $n/N = 0.1$ and $n/N = 0.9$ were added (Fig. 5). Regarding the changes in hysteresis loop parameters (σ_a and ε_{ap}) as a function of the number of loading cycles at the temperature of 600ºC values of the coefficient K' and the n' exponent of the equation (3) depends on the period of life that was considered to determine σ_a and ε_{ap}. At this temperature, a clear description of relation between stress σ_a and strain ε_{ap} is difficult to make.

Due to significantly lower changes in hysteresis loop parameters at room temperature (Fig. 2), material data of n' and K' marginally depend on the fatigue life period in which they were determined. Independent of the life period, they are similar.

Data on *n'* and *K'* are used, among others, during the modelling of strains and stresses. For an analytical description of strains, equation (2) was used. For example, in Fig. 6, the results of changes in the hysteresis loop parameters and their influence on the cyclic strain diagram position are shown. In this figure, the positioned hysteresis loops obtained at different fatigue life periods for levels of total strain ε_{ac} = 2.0% are shown.

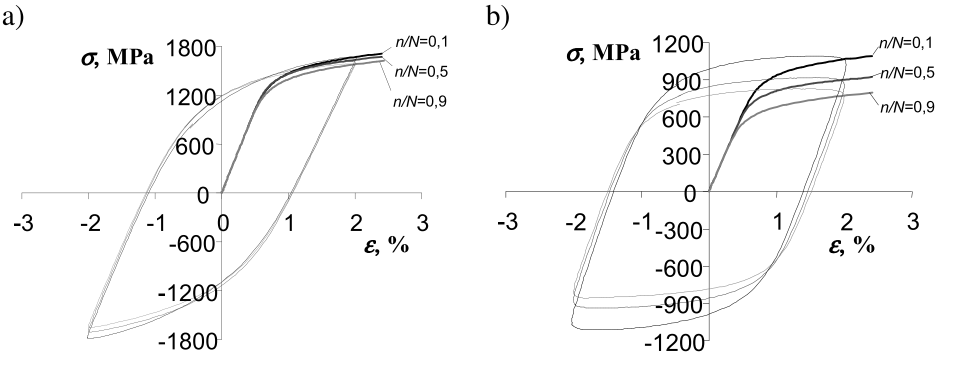


Fig. 6. Cyclic strain diagrams: a) T = 20°C, and b) T = 600°C

As expected, at the temperature of 20ºC, cyclic strain diagrams have similar courses that are independent of the life period *n/N*. This situation is different at the temperature of T = 600ºC, where these diagrams are significantly different. There exist variations of material data values at different periods of fatigue life. Therefore, the results obtained from tests and calculations obtained at elevated temperatures may by characterized by a significant differentiation. It was confirmed for materials operated at room temperature, among others in [7].

Apart from higher changes of cyclic properties at a temperature of 600ºC, the influence of elevated temperatures on fatigue life was indicated during tests. Cyclic diagrams in a bi-logarithmic coordination system were approximated by the equation (1). Regarding the lack of a stabilization period in the equation (3), coefficients and exponents were determined for hysteresis loop parameters from half of the fatigue life (*n/N* = 0.5). Fatigue diagrams obtained as a result of approximation by equation (3) of fatigue tests results for two temperatures are shown in Fig. 7.

Based on diagrams, it can be stated that test temperature significantly influences the fatigue life. Its impact depends on level of total strain and is low in the area of the highest strains (ε_{ac} = 2.0%), and it increases with a lowering strain level.

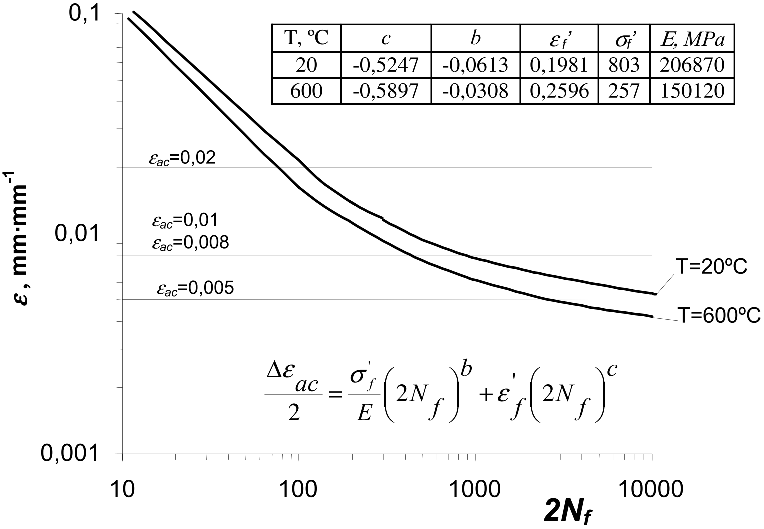


Fig. 7. Fatigue diagrams at temperature of 20ºC and 600ºC

The higher influence of elevated temperature on fatigue life observed on the lowest strain levels may be explained by significantly higher changes in plastic strains $\Delta\varepsilon_{ap}$ on these levels at the temperature of 600ºC in relation to plastic strains $\Delta\varepsilon_{ap}$ at the highest strains (Fig. 4a).

Summary

WCLV (1.2344) steel is a material which cyclically softens during low cycle fatigue tests, independent of temperature. The softening occurs on all levels of strain and increases with increasing strain.

Significantly larger changes of cyclic properties take place at elevated temperatures than at room temperature. Larger changes in cyclic properties and the lack of a stabilization period make uncertainties about fatigue life calculations of structural components operating at elevated temperatures with use of material data determined from half of the fatigue life ($n/N = 0.5$). The data reflects only momentary properties of the material.

Elevated temperature influences the fatigue life. Temperature influence on the fatigue life depends on level of strain. It is low in the area of high strains ($\varepsilon_{ac} = 2.0\%$) and increases with lower levels of strain.

During operation of technical objects at elevated temperatures, there exist interactions connected with simultaneous changes in loading and temperature involving the process of oxidation and wear. Tests presented in this paper were carried out in conditions of isothermal constant amplitude loadings (ε_{ac} = const and T = const). In order to formulate detailed conclusions regarding the cyclic properties of WCLV/1.2344 steel, further works should consider changes in loading and temperature occurring during tests. The obtained results should also serve for fuller analysis of forged tools damages. Determined detailed data (parameters) may be very useful during numerical modelling for tools life and forge instrumentation.

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Wpływ podwyższonej temperatury na właściwości niskocyklowe stali WCLV/1.2344

Słowa kluczowe

Zmęczenie niskocyklowe, osłabienie cykliczne, trwałość zmęczeniowa.

Streszczenie

W pracy zamieszczono wyniki niskocyklowych badań zmęczeniowych stali WCLV 1.2344 w temperaturze 20ºC oraz 600ºC. Analizę wyników prowadzono przy wykorzystaniu parametrów pętli histerezy rejestrowanych w trakcie badań. W pracy stwierdzono, że podwyższona temperatura ma wpływ na trwałość zmęczeniową oraz zmiany parametrów pętli w funkcji liczby cykli obciążenia. W temperaturze 600ºC zmiany parametrów są zdecydowanie większe niż w temperaturze 20ºC. Utrudnia to prowadzenie obliczeń trwałości obiektów poddanych eksploatacji w temperaturze podwyższonej. Wyznaczone podczas badań dane materiałowe odzwierciedlają bowiem jedynie chwilowe właściwości stali.