VARIATION OF SELECTED CYCLIC PROPERTIES DEPENDING ON TEMPERATURE OF THE TEST

M. KUREK, T. LAGODA, K. WALAT

Opole University of Technology, Poland

Determination of fatigue life involves many factors, among them temperature in which the structure is working. Based on the literature data, the authors present the influence of temperature on cyclic properties of the selected materials. Further analysis proves that, in the case of alloyed steels, temperature affects some quantities characterizing fatigue parameters.

Keywords: *temperature, cyclic properties, fatigue.*

The determination of the fatigue life of a structural component is a complex task. It should include all the factors strongly influencing the fatigue life, namely the structure shape, material properties, configuration and type of loadings, the structure state and environmental factors like temperature. The impact of high temperature on materials strength is the current problem [1, 2], as well as the analysis of fatigue life and fatigue crack development, including determination of fatigue characteristics [3].

Alloyed steels, as one of the strongest materials, are used in machines and structures elements that need to be durable and reliable. However, relatively high costs of production prevent these steels from application on a wide scale.

According to [4], the fatigue limit of a component is a function of the fatigue limit of material (σ_{f0}) plus some modifying factors including the temperature factor:

$$\sigma_f = \sigma_{f0} \times K_T \times K_a \times K_b \times K_c \times K_e \times K_f , \tag{1}$$

where σ_f is the fatigue limit of mechanical component; σ_{f0} is the fatigue limit of a material laboratory-tested sample.

In this equation the temperature factor K_T can be calculated by using different relations:

$$K_T = \begin{cases} 1 \ \text{for} \ T \le 70°\text{C}, \\ \dfrac{3100}{2460+9T} \ \ \text{for} \ T > 70°\text{C}. \end{cases} \tag{2}$$

Other author [5] proposed that equations should follow the type:

$$K_T = \sigma_{u(T_i)} / \sigma_{u(20°\text{C})} , \tag{3}$$

where $\sigma_{u(T_i)}$ is the ultimate tensile strength at test temperature and $\sigma_{u(20°\text{C})}$ is the ultimate tensile strength at room temperature.

Influence of temperature on the material properties, including cyclic ones, is of key-importance in food, chemical and power industries. The materials considered in this paper focus on high-alloy steels, which are applied in many elements and structures working at elevated temperatures, such as heat exchangers or tubes for heaters. Authors analyse the influence of temperature on different cyclic properties of the selected materials, using literature data.

Experimental data. The data from literature [6–13] were used in the analysis. The considered materials were divided into three groups: low-alloy steels (10CrMo910,

Corresponding author: M. KUREK, e-mail: ma.kurek@po.opole.pl

13CrMo44, 16CrMo54, and 30CrMoNiV511), high-alloy steels (X5NiCrTi2615, X10CrNiTi189, X10CrNiNb189, X15Cr13) and cast irons (X15CrNiSi2520).

To describe the fatigue properties, a well-known equation proposed by Manson–Coffin–Basquin (MCB) the strain-life curve (σ_a–N_f) is used:

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c, \tag{4}$$

where $\varepsilon_{a,t}$ is total strain amplitude expressed by the sum of elastic strain amplitude $\varepsilon_{a,e}$ and plastic strain amplitude $\varepsilon_{a,p}$, $2N_f$ are a number of half-cycles, E is the Young's modulus, σ'_f, b are coefficient and exponent of the fatigue strength, ε'_f, c are coefficient and exponent of the plastic strain.

Two other models are also widely applied, namely the model proposed by Basquin [14] for the graph (σ_a–N_f)

$$\sigma_a = \sigma'_f(2N_f)^b \tag{5}$$

and the model proposed by Ramberg–Osgood (RO) for the cyclic hardening curve (σ_a–ε_a)

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \sigma_a / E + \left(\sigma_a / K'\right)^{1/n'} \tag{6}$$

where σ_a is stress amplitude, K' is coefficient of cyclic strength, n' is exponent of cyclic hardening.

Equations (4) and (5) are used for determination of a number of cycles to the fatigue crack initiation. Eq. (6) is widely applied for assessing the elastic-plastic stresses and strains, including the material behaviour under cyclic loading.

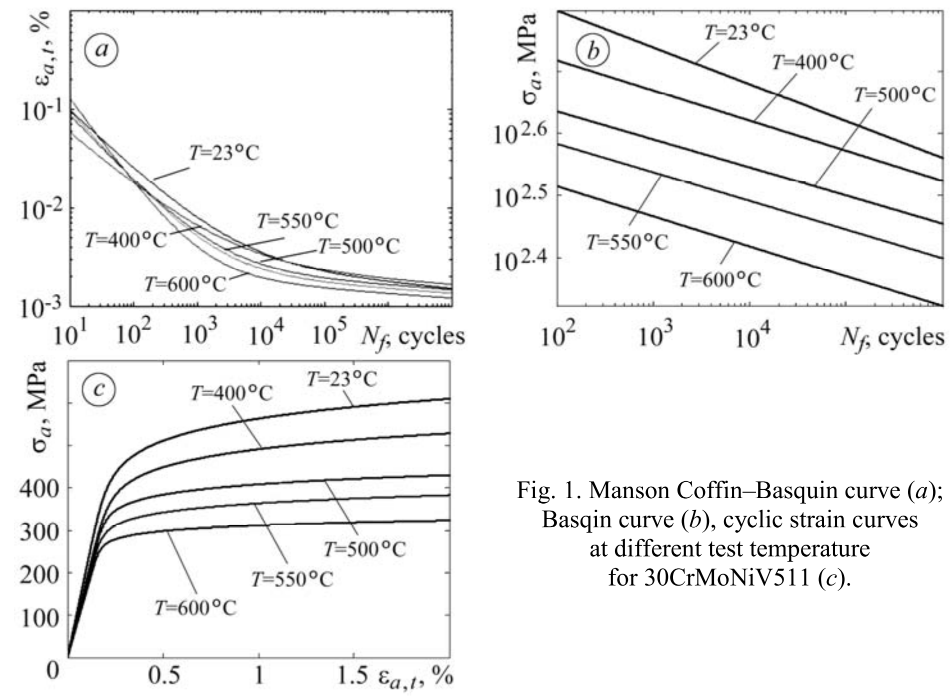

Fig. 1. Manson Coffin–Basquin curve (*a*); Basqin curve (*b*), cyclic strain curves at different test temperature for 30CrMoNiV511 (*c*).

According to Eq. (4), the relation between total strain amplitude and number of cycles also changes for different temperatures, as shown in Fig. 1*a*. According to Eq. (5), the relation between stress amplitude and number of cycles also changes for different temperatures, as shown in Fig. 1*b*. The relation between stress amplitude and total strain amplitude for different temperature according to Eq. (6) is shown in Fig. 1*c*. At a higher temperature the stress and strain distribution changes.

In the main part of this paper the cyclic yield point R'_e, the cyclic hardening exponent n', the coefficient of cyclic strength K', the coefficient of fatigue strength σ'_f, the exponent of fatigue strength b, the coefficient of fatigue plastic strain ε'_f and the exponent of fatigue plastic strain c are considered.

Influence of test temperature *T* on cyclic properties for the selected structural materials. *Low-alloy steels*. The influence of test temperature T on cyclic properties for low-alloy steels is presented in Fig. 2.

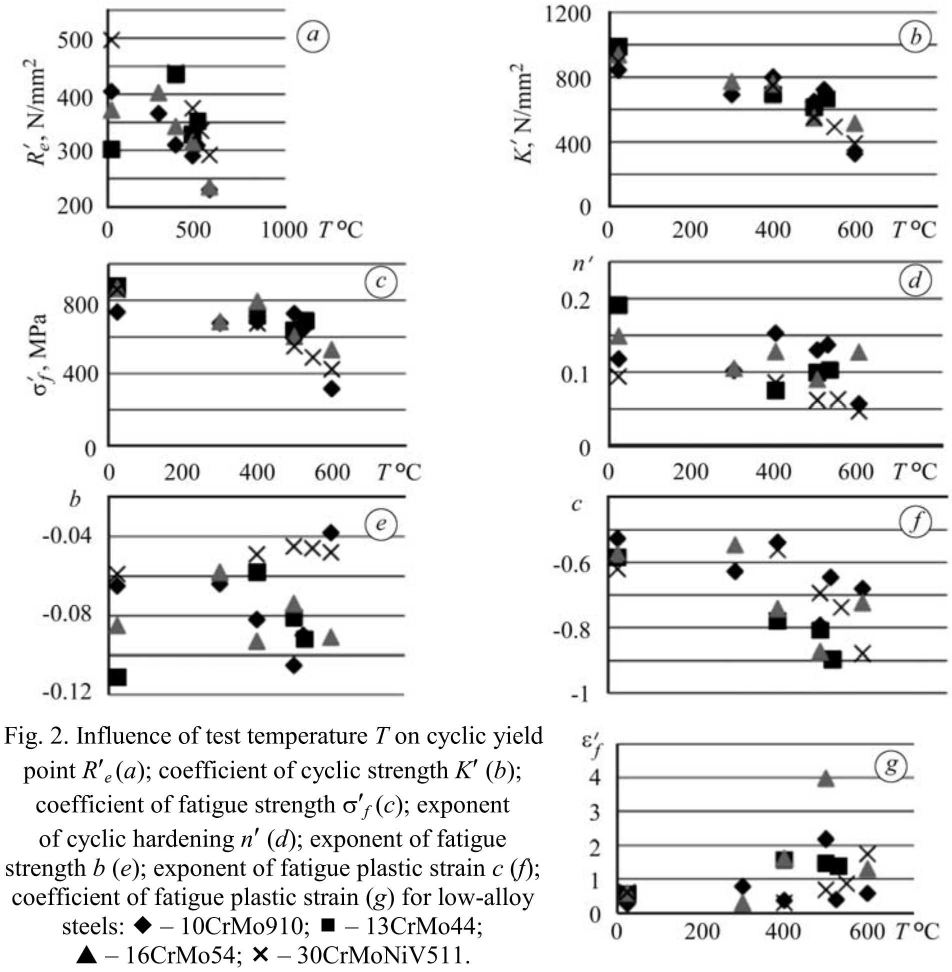

Fig. 2. Influence of test temperature T on cyclic yield point R'_e (a); coefficient of cyclic strength K' (b); coefficient of fatigue strength σ'_f (c); exponent of cyclic hardening n' (d); exponent of fatigue strength b (e); exponent of fatigue plastic strain c (f); coefficient of fatigue plastic strain (g) for low-alloy steels: ◆ – 10CrMo910; ■ – 13CrMo44; ▲ – 16CrMo54; ✕ – 30CrMoNiV511.

Table 1. Coefficients from Eq. (7) for low-alloy, high-alloy steels and irons

Material	*a*	*d*	*e*
10CrMo910 [3]	–0.0004	0.0296	405.42
13CrMo44 [3]	–0.0021	1.217	275.57
16CrMo54 [3]	–0.001	0.396	364.65
30CrMoNiV511[4]	–0.001	0.2713	491.32
X5NiCrTi2615 [5]	–0.002	1.053	689.34
X10CrNiTi189 [6]	0.0003	–0.2781	233.22
X10CrNiNb189 [7]	0.0004	–0.3481	283.09
X15Cr13 [8]	–0.0009	0.061	495.77
X15CrNiSi2520 [7, 10]	–0.0002	0.1016	285.18
GG30 [9]	–0.0021	1.3773	230.45
GGV-30 [9]	0.0009	–0.7161	454.01
GGG-40 [9]	0.0012	–0.803	469.84
GGG-60 [9]	0.0004	–0.2537	500.62

Table 1 contains values of the coefficients of the equation:

$$R'_e = aT^2 + dT + e \tag{7}$$

for the considered group of the materials.

Table 2 contains values of coefficients of the equation:

$$K' = aT + d \tag{8}$$

for low-alloy steels.

Table 2. Coefficients from Eq. (8) for low-alloy steels

Steel	a	d
10CrMo910 [3]	–0.6	907,96
13CrMo44 [3]	–0.711	999.05
16CrMo54 [3]	–0.75	981.27
30CrMoNiV511 [4]	–0.81	955.04

From analysis of the data from Fig. 2, it appears that cyclic properties vary together with increase of the test temperature. In most cases the considered material constants (R'_e; K'; n'; σ'_f; c) decrease with increasing temperature from the ambient temperature to a higher one.

At the initial phase of temperature increase, the cyclic parameters values often increase and then slowly decrease, with the exception of the coefficient of fatigue plastic strain ε'_f with its values increase.

High-alloyed steels. The *i*nfluence of test temperature T on cyclic properties for high-alloy steels is shown in Fig. 3. Table 3 contains values of the coefficients of the equation:

$$K' = aT^2 + dT + e. \tag{9}$$

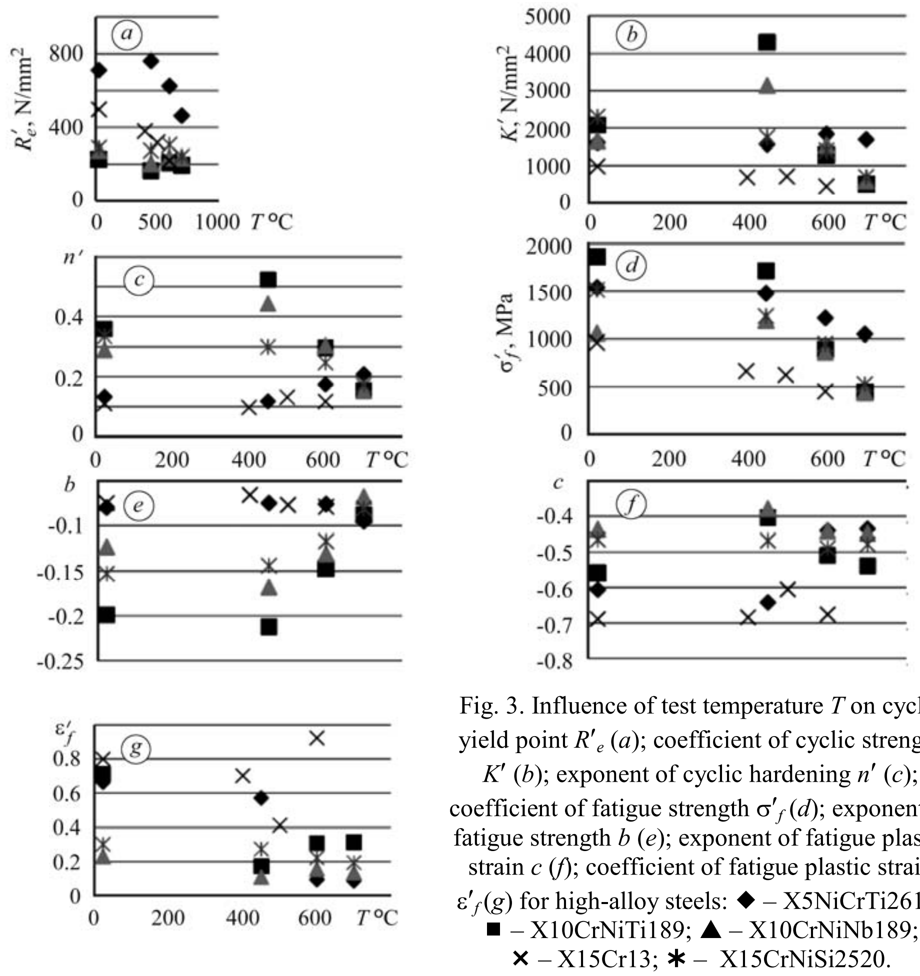

Fig. 3. Influence of test temperature T on cyclic yield point R'_e (a); coefficient of cyclic strength K' (b); exponent of cyclic hardening n' (c); coefficient of fatigue strength σ'_f (d); exponent of fatigue strength b (e); exponent of fatigue plastic strain c (f); coefficient of fatigue plastic strain ε'_f(g) for high-alloy steels: ◆ – X5NiCrTi2615; ■ – X10CrNiTi189; ▲ – X10CrNiNb189; ✕ – X15Cr13; ✱ – X15CrNiSi2520.

Table 3. Coefficients from Eq. (9) for high-alloy steels

Steel	*a*	*d*	*e*
X5NiCrTi2615 [5]	0.0005	0.17	1613
X10CrNiTi189 [6]	–0.028	17.49	1737.9
X10CrNiNb189 [7]	–0.0119	12.47	1403
X15Cr13 [8]	–0.0011	0.149	987.6
X15CrNiSi2520 [7, 10]	–0.0046	1.1	2271.8

Based on the presented figures, it appears that the tested cyclic properties vary also in the case of high-alloy steels. The cyclic parameters decrease as the test temperature increases, like in the case of low-alloy steels. In most cases, it concerns such parameters as R'_e; K'; σ'_f.

Cast iron. The Influence of test temperature T on cyclic properties for cast irons is shown in Fig. 4. Table 1 contains coefficients of Eq. (7) for cast irons.

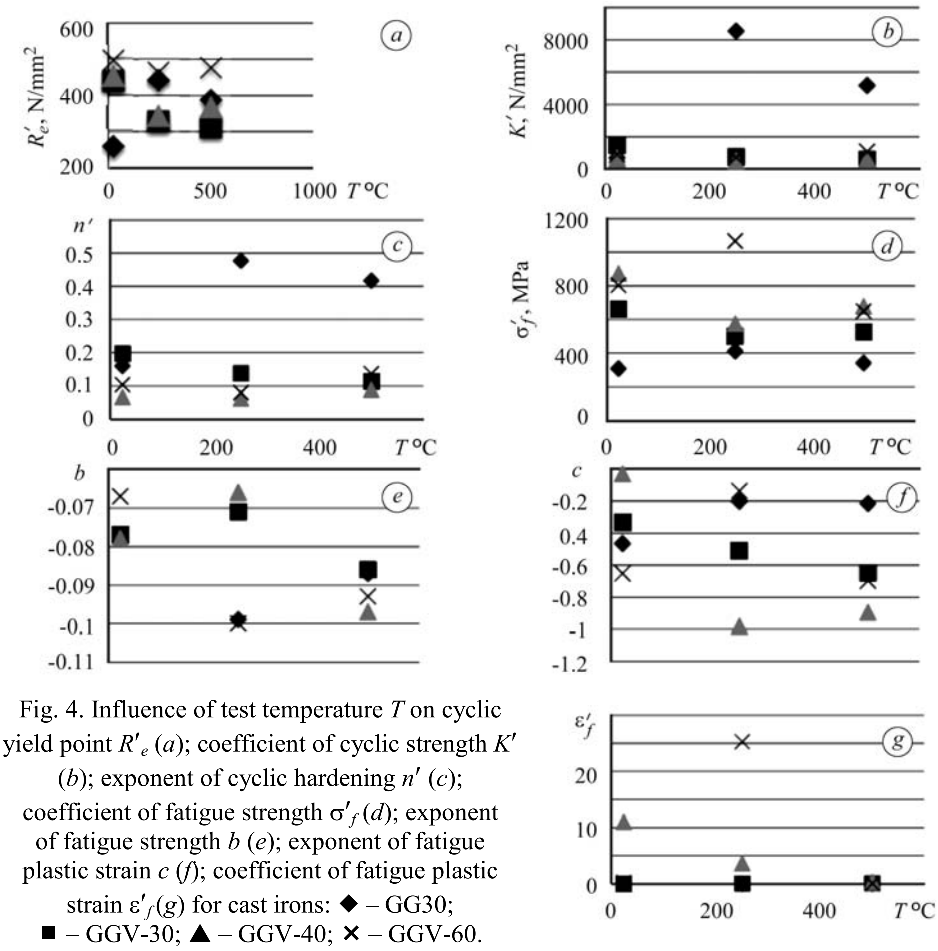

Fig. 4. Influence of test temperature T on cyclic yield point R'_e (*a*); coefficient of cyclic strength K' (*b*); exponent of cyclic hardening n' (*c*); coefficient of fatigue strength σ'_f (*d*); exponent of fatigue strength *b* (*e*); exponent of fatigue plastic strain *c* (*f*); coefficient of fatigue plastic strain ε'_f(*g*) for cast irons: ◆ – GG30; ■ – GGV-30; ▲ – GGV-40; ✕ – GGV-60.

For cast irons the test temperature does not influence the values of the parameters R'_e; K'; σ'_f; ε'_f and n'. The mentioned properties do not vary or change their values insignificantly when temperature increases. For the remaining cyclic properties the variation of the parameters depends on the test temperature.

From the analysis it appears that in the case of using the steel working at elevated temperature and under variable loading it is necessary to include changes of fatigue characteristics depending on temperature. It can be very important while assessing the fatigue life of structures made of such steels.

CONCLUSIONS

The analysis of some cyclic properties variability depending on the temperature for the selected structural materials is presented. From the analysis of the obtained results, it appears that operation of machines and devices at elevated temperature can cause the decrease of strength and reliability of the elements of machines and devices. Cyclic properties of low-alloy steels such as R'_e; K'; n'; σ'_f; c decrease as the temperature increases (with the exception of fatigue plastic strain coefficient ε'_f, which increases). Cyclic properties of high-alloy steels also vary depending on the test temperature. The material constants, such as R'_e; K'; σ'_f, decrease as the test temperature increases. No significant changes of cyclic parameters in cast irons were noted.

РЕЗЮМЕ. Констатовано, що умови експлуатації елементів машин і пристроїв, які використовують в енергетиці, характеризуються змінами температури від кімнатної до дуже високої. Це призводить до істотної зміни механічних властивостей досліджуваних матеріалів. В результаті аналізу зміни вибраних циклічних властивостей залежно від температури встановлено основні закономірності для низьколегованих сталей і високолегованих чавунів.

РЕЗЮМЕ. Констатировано, что условия эксплуатации элементов машин и устройств, которые используют в энергетике характеризуются изменениями температуры от комнатной до весьма высокой. Это приводит к существенному изменению механических свойств исследуемых материалов. В результате анализа изменения избранных циклических свойств в зависимости от температуры установлено основные закономерности для низколегированных сталей и высоколегированных чугунов.

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