STATISTICAL EVALUATION OF THE PARAMETERS OF LOW CYCLE FATIGUE CURVE FOR ALLOYED STEELS

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Introduction

Loading with limited strain (particularly in parts and structures near stress concentrators, i.e. in the zones of geometrical parameters change, near cracks, technological, welding and foundry defects) mostly appears in structures and elements of machines, because plastic strains in these areas are limited by adjacent elastic strained zones. In the condition of cyclic loading the elastic strained metal impedes the accumulation of strain in these areas. Therefore the conditions of loading with limited strain in these areas are similar to real constructions and machines.

The parameters of low cycle fatigue curves (fracture parameters of Coffin) and the durability dependence on main mechanical characteristics and their combinations have been investigated already [1]. It has been shown that fatigue curves parameters well correlate with modified plasticity criterion (σ_u / σ_y) Z at room and elevated temperature and conform according to normal distribution.

The aim of the article is to analyze the dependence of Coffin's curves parameters on modified plasticity criterion for grouped *Cr-Ni*, *Cr-Ni-Mo*, *Cr-Ni-Mo-V* alloyed structural steels used in nuclear power equipment at room and elevated (250-550°C) temperature.

Research objective is to determinate the influence of the materials grouping by the alloy elements on the coefficients of the dependence on low cycle fatigue curves parameters for modified plasticity criterion at room and elevated temperature. The results of the investigation into 65 steels at room and 52 steels at elevated temperature were selected from laboratories of Kaunas University of Technology and other countries (Czech, Russia, Hungary) [1, 2].

Research methods are based on experimental, analytical and statistical methods [3].

Parameters of Low Cycle Fatigue Curve

The parameters of fracture under low cycle loading with limited strain are understood as durability or low cycle fatigue curves that are composed in coordinate lg ε – lg N and lg δ – lg N according to the number of cycle till crack N_c or fracture N_f appears. The durability of the materials under loading with limited strain is expressed by Coffin's equation:

$$\delta N^{m} = C \tag{1}$$

where δ is the range of plastic strain or the width of plastic hysteresis loop; N is the number of cycles up to crack formation or fracture; m and C are characteristics of the material, this is proposed by Coffin: $m = 0.5$ and $C = 0.5 ln\,(1/(1 - Z))$, where Z is the reduction of area at fracture.

The stresses and elastic-plastic strains vary during the low cycle loading with limited strain for hardened and softened materials. In a number of works by other authors [4] it was proposed to replace hysteresis loop δ in equation (1) with ε, because the total strain ε remains constant (plastic strain δ changes during the cycle straining) and we have the equation

$$\varepsilon N_f^{m_f} = C_f \tag{2}$$

This equation is correct for the majority of materials, when ε>(3.0-3.5)e_{pr}, then mm_f, CC_f [4], and when ε<(3.0-3.5) e_{pr}, then the durability greatly increases, therefore low cycle fatigue curves are defined in this work by the equation

$$\varepsilon = C_e N^{-m_e} + C_p N^{-m_p} \tag{3}$$

where ε is total elastic plastic strain; m_e, C_e and m_p, C_p, are parameters of low cycle fatigue curves according to elastic and plastic strain.

Analytical and statistical methods were used to determine relationship between modified plasticity criterion and the parameters of low loading fatigue curves for grouped alloyed structural steels.

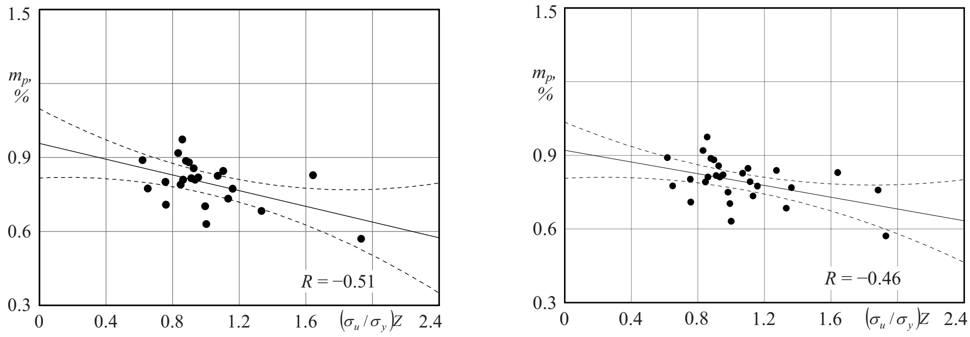
Research results

The materials investigated in this work were sorted by temperature into 2 groups (at room temperature; at elevated temperature) and by chemical composition into 3 groups (*Cr-Ni*; *Cr-Ni-Mo*; *Cr-Ni-Mo-V*). Statistical characteristics of grouped materials for parameters m_e, C_e, m_p, C_p, at room (20°C) and elevated (250–350°C) temperature are given in Table 1.

Table 1. ***Statistical characteristics of parameters m_e, C_e, m_p, C_p according to elastic and plastic strain at room and elevated temperature***

Parameters	**Alloyed structural steels at room temperature**				**Alloyed structural steels at elevated temperature**			
	m_e	C_e	m_p	C_p	m_e	C_e	m_p	C_p
Cr-Ni alloyed structural steels								
Mean value	0.72	172.6	0.16	1.47	0.79	194.7	0.15	1.81
Minimum value	0.49	31.9	0.09	0.94	0.75	8.05	0.10	0.80
Maximum value	0.89	224.4	0.27	2.26	0.84	413.4	0.25	4.58
Median value	0.72	189.9	0.15	1.59	0.78	216.8	0.15	1.32
Correlation coefficient	-0.88	-0.91	-0.67	-0.61	0.18	0.45	-0.75	-0.64
Cr-Ni-Mo-V alloyed structural steels								
Mean value	0.84	227.1	0.13	1.64	0.80	189.1	0.17	2.05
Minimum value	0.62	18.1	0.06	0.69	0.57	23.6	0.07	0.34
Maximum value	1.00	496.5	0.22	3.10	0.97	456.9	0.30	4.85
Median value	0.84	224.7	0.13	1.58	0.81	215.5	0.15	1.68
Correlation coefficient	-0.44	0.47	-0.51	-0.56	-0.51	-0.56	0.58	0.56
Cr-Ni-Mo alloyed structural steels								
Mean value	0.75	180.6	0.09	1.03	0.78	156.0	0.19	2.32
Minimum value	0.53	11.7	0.03	0.46	0.61	32.9	0.05	0.64
Maximum value	0.88	394.2	0.18	1.74	0.95	315.3	0.33	5.46
Median value	0.79	205.5	0.09	1.01	0.78	179.0	0.19	1.87
Correlation coefficient	-0.81	-0.86	0.71	0.62	-0.50	-0.79	0.73	0.70

The statistical analysis carried out in previous works [1, 5] demonstrated that the results of the parameters m_e, C_e, m_p, C_p, well correlate with the modified plasticity criterion $(\sigma_u / \sigma_y)\,Z$ at room and elevated temperature. Dependences of parameter of low cycle fatigue curve m_p on modified plasticity criterion for integrated and *Cr-Ni-Mo-V* alloyed structural steels at elevated temperature and 95% confidence interval ranges (dotted line) to theoretic line are given in Fig. 1.



a *b*

Fig. 1. Dependence of parameter m_p on modified plasticity criterion $(\sigma_u / \sigma_y)\,Z$ at elevated temperature and 95% confidence interval (doted line):
a – for *Cr-Ni-Mo-V* alloyed structural steels; *b* – for integrated group of alloyed structural steels

Correlation analysis is used to determine linear correlations [6]. Pearson's correlation coefficient for grouped *Cr-Ni-Mo-V* alloyed structural steels is better in comparison to integrated group at elevated temperature. Analogical results were obtained for other groups of materials. Therefore we have determined that the results of grouping by the chemical composition influences the stronger linear relationship between the parameters m_e, C_e, m_p, C_p and the modified plasticity criterion $(\sigma_u / \sigma_y)\,Z$ for alloyed structural steels at room and elevated temperature.

Analytical dependences of parameters of low cycle fatigue curve on modified plasticity $(\sigma_u / \sigma_y)\,Z$ for alloyed structural steels at room and elevated temperature are given in Table 2. These dependences of m_e, C_e, m_p, C_p are used to forecast the durability of material by Eq. (3).

The dispersion between experimental and calculated results by Eq. (3) of durability for alloyed structural steels (according to analytical dependences given in Table 2) at room and elevated temperature are given in Table 3. The dispersion of results between experimental $N_f^{\exp}$ durability and calculated N_f^{cal} durability for *Cr-Ni*, *Cr-Ni-Mo*, *Cr-Ni-Mo-*

V steels is lower in comparison to integrated group of alloyed structural steels. Furthermore the dispersion of results between those parameters at elevated temperature is greater than at room temperature. The comparison between experimental $N_f^{\exp}$ and calculated N_f^{cal} durability for *Cr-Ni-Mo-V* and for integrated alloyed structural steels at elevated temperature is shown in Fig. 2.

Table 2. ***Analytical dependences of parameters*** m_e, C_e, m_p, C_p ***on modified plasticity*** (σ_u / σ_y) ***Z at room and elevated (250-350°C) temperature***

Alloyed structural steel at room temperature	Alloyed structural steel at elevated temperature
Cr-Ni alloyed structural steels	
$m_e = 0.352 - 0.175\,(\sigma_u / \sigma_y)\,Z$ $C_e = 3.03 - 1.38\,(\sigma_u / \sigma_y)\,Z$ $m_p = 1.29 - 0.498\,(\sigma_u / \sigma_y)\,Z$ $C_p = 509.1 - 297.3\,(\sigma_u / \sigma_y)\,Z$	$m_e = 0.322 - 0.124\,(\sigma_u / \sigma_y)\,Z$ $C_e = 5.59 - 2.79\,(\sigma_u / \sigma_y)\,Z$ $m_p = 0.764 + 0.015\,(\sigma_u / \sigma_y)\,Z$ $C_p = 11.4 + 145.2\,(\sigma_u / \sigma_y)\,Z$
Cr-Ni-Mo-V alloyed structural steels	
$m_e = 0.243 - 0.122\,(\sigma_u / \sigma_y)\,Z$ $C_e = 3.565 - 2.11\,(\sigma_u / \sigma_y)\,Z$ $m_p = 1.3 - 0.204\,(\sigma_u / \sigma_y)\,Z$ $C_p = 33.4 + 219.8\,(\sigma_u / \sigma_y)\,Z$	$m_e = 0.029 + 0.134\,(\sigma_u / \sigma_y)\,Z$ $C_e = -0.201 + 2.26\,(\sigma_u / \sigma_y)\,Z$ $m_p = 0.957 - 0.163\,(\sigma_u / \sigma_y)\,Z$ $C_p = 363.36 - 175.2\,(\sigma_u / \sigma_y)\,Z$
Cr-Ni-Mo alloyed structural steels	
$m_e = -0.026 + 0.129\,(\sigma_u / \sigma_y)\,Z$ $C_e = 0.109 + 0.974\,(\sigma_u / \sigma_y)\,Z$ $m_p = 1.14 - 0.438\,(\sigma_u / \sigma_y)\,Z$ $C_p = 603 - 473.1\,(\sigma_u / \sigma_y)\,Z$	$m_e = 0.007 + 0.150\,(\sigma_u / \sigma_y)\,Z$ $C_e = -1.001 + 2.78\,(\sigma_u / \sigma_y)\,Z$ $m_p = 0.925 - 0.120\,(\sigma_u / \sigma_y)\,Z$ $C_p = 371.2 - 174.6\,(\sigma_u / \sigma_y)\,Z$

Table 3. ***Comparison of experimental*** $N_f^{\exp}$ ***and calculated*** N_f^{cal} ***durability of alloyed structural steels at room and elevated temperature***

Chemical composition (groups)	Total number of specimens	Number of specimens when dispersion of results between experimental and calculated durability is					
		fourfold		ninefold		sixteenfold	
		number	%	number	%	number	%
Alloyed structural steel at room temperature							
Cr-Ni	161	113	70	129	80	142	88
Cr-Ni-Mo-V	508	313	62	424	83	446	88
Cr-Ni-Mo	94	68	72	75	80	79	84
Integrated group	763	500	66	596	78	629	82
Alloyed structural steel at elevated temperature							
Cr-Ni	110	33	30	61	56	73	66
Cr-Ni-Mo-V	230	133	58	171	74	187	80
Cr-Ni-Mo	102	59	58	78	76	88	86
Integrated group	442	211	48	293	66	335	76

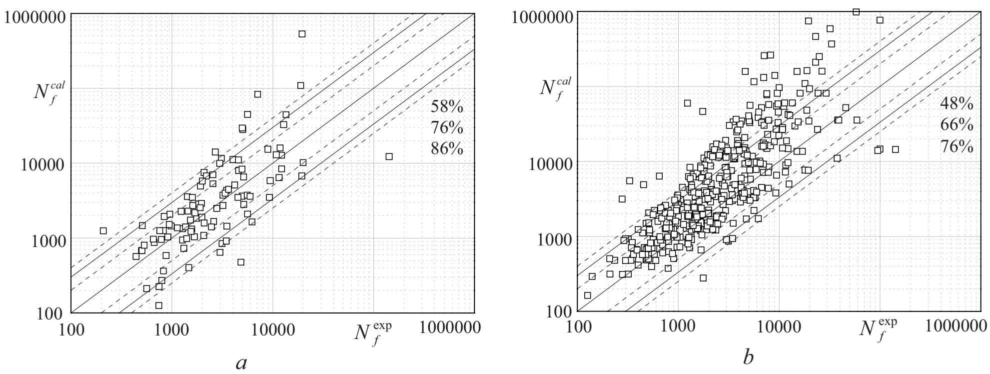


Fig. 2. Comparison of experimental $N_f^{\exp}$ and calculated N_f^{cal} durability at elevated temperature: *a* – for *Cr-Ni-Mo* alloyed structural steels; *b* – for integrated group of alloyed structural steels

Conclusions

1. The mean value of parameter m_p for alloyed structural steels at room and elevated (250-350°C) temperature is greater than Coffin's constant (m=0.5.)
2. The parameters of low cycle fatigue curves m_e, C_e, m_p, C_p for steels correlate with modified plasticity criterion $(\sigma_u / \sigma_y)\ Z$ by linear regression at room and elevated temperature.
3. The dispersion of results between experimental $N_f^{\exp}$ durability and calculated N_f^{cal} durability by Eq. (3) for alloyed structural steels at elevated temperature is greater than at room temperature.
4. The dispersion of the results between experimental $N_f^{\exp}$ and calculated N_f^{cal} durability (when the durability is calculated for integrated group) is 2-16% greater than the dispersion of results for separate three groups at room and elevated temperature.
5. Analytical dependences of low cycle fatigue curve parameters on modified plasticity criterion for *Cr-Ni*, *Cr-Ni-Mo-V*, *Cr-Ni-Mo* alloyed structural steels are correct enough to figure out the durability at room and elevated temperature.
6. Dependencies proposed in this work can be used for preliminary evaluation of durability for alloyed structural steels at low cycle loading.

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Summary

In this work dependence of durability of alloyed structural steels used in nuclear engineering on mechanical characteristics was analyzed. The data of low cycle tests of 74 alloyed steels at room temperature and 52 alloyed steels at elevated temperature were used; the data were obtained at low-cycle fatigue laboratories of Kaunas University of Technology and Czech, Russia, and Hungary. Parameters m_e, C_e, m_p, C_p of low cycle fatigue decomposition curves according to elastic and plastic deformations were identified. Statistical analysis confirmed that decomposition curves parameters and modified plasticity criterion $(\sigma_u / \sigma_y)\ Z$ are random and independent values, they have normal distribution and low-cycle durability has linear correlation with the modified plasticity. Analytical dependences of parameters m_e, C_e, m_p, C_p on modified plasticity at room and elevated temperature are proposed for materials grouped by chemical composition. The comparison of calculated and experimental durability results has shown that the proposed analytical dependencies can be used for preliminary estimation of low cycle durability for *Cr-Ni*, *Cr-Ni-Mo-V*, *Cr-Ni-Mo* alloyed steels.

Keywords: low cycle loading, durability, parameters of Coffin's curves, modified plasticity criterion.

LEGIRUOTŲJŲ PLIENŲ MAŽACIKLIO NUOVARGIO SUIRIMO KREIVĖS PARAMETRŲ STATISTINIS ĮVERTINIMAS

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Santrauka

Straipsnyje analizuojama atominėje energetikoje naudojamų legiruotųjų konstrukcinių plienų ilgalaikiškumo priklausomybė nuo mechaninių charakteristikų. Tyrimui panaudoti 74 legiruotųjų plienų kambario temperatūroje ir 52 plienų aukštesnėje temperatūroje mažaciklio bandymo duomenys, gauti Kauno technologijos universiteto bei Čekijos, Rusijos ir Vengrijos mažaciklio nuovargio laboratorijose. Nustatyti mažaciklio nuovargio suirimo kreivės parametrai me, C_e, m_p, C_p pagal tampriąją ir plastinę deformacijas. Atliktas statistinis tyrimas patvirtino, kad suirimo kreivių parametrai, taip pat modifikuoto plastiškumo kriterijus $(\sigma_u / \sigma_y)\,Z$ yra atsitiktiniai ir nepriklausomi dydžiai, pasiskirstę pagal normalųjį dėsnį, o mažaciklis ilgalaikiškumas tiesiškai siejasi su medžiagų modifikuoto plastiškumo kriterijumi. Pasiūlytos klasifikuotoms medžiagų grupėms parametrų m_e, C_e, m_p, C_p analitinės priklausomybės nuo modifikuoto plastiškumo kambario ir aukštesnėje temperatūroje. Apskaičiuoto ir atliekant eksperimentą gauto ilgalaikiškumo rezultatų palyginimas parodė, kad pasiūlytas metodas gali būti preliminariai pritaikytas tirtų *Cr-Ni*, *Cr-Ni-Mo-V*, *Cr-Ni-Mo* medžiagų grupių mažacikliam ilgalaikiškumui nustatyti.

Prasminiai žodžiai: mažaciklis apkrovimas, Kofino kreivės parametrai, modifikuotas plastiškumo kriterijus.

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