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Statistical evaluation of low cycle durability for corrosion and heat-resistant steels welded joints materials at room and elevated temperature

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1. Introduction

Many structural components contain the zones of geometrical parameters change, shoulders, keyways, oil holes, welded joints and termed notches. When such elements are loaded, local stress and strain concentrations are generated in such zones of geometrical parameters change [1, 2]. Plastic strain in these areas appears in small material volumes. During cyclic loading the cyclic plastic deformation in the area of stress and strain concentrations can severely reduce the durability of the construction. Plastic strains in these areas are limited by adjacent elastic strained zones, therefore the conditions of loading with limited strains in these areas are very similar.

The low cycle loading experiments are very complicated and expensive, particular at elevated temperature because of temperature control and stress strain curves recording. That is why the attempts to obtain characteristics of low cycle loading from monotonous tension curves, hardness or other parameters, but without cyclic loading are made. Heat treatment is widely used in nuclear power equipment and other engineering components. Under low cycle loading tempered or normalized steels cyclically stabilized or hardened, therefore high strength steels are cyclically softened [3].

It is very important to analyze the reliability of structures under low cycling loading. The probabilistic methods of reliability determination of corrosion and heat–resistant steels are analyzed in this work. Durability calculation is based on the statistical method by the use mechanical characteristics and low cyclic loading parameters.

The parameters of low cycle loading fatigue curves according plastic strain m_p and C_p and elastic strain m_e and C_e for corrosion and heat-resistant steels at room and elevated temperatures were determined under tension compression and at symmetric ($R=-1$) strain limited conditions. In works [4, 5] detailed statistical analysis showed that parameters of Coffin curves the best correlate with modified plasticity $\left(\sigma_u/\sigma_y\right)Z$, i.e. the parameter depending on ultimate tensile and yield strengths and reduction of the area at fracture, at room and elevated temperatures. The relationship between the parameters of fatigue curves and mechanical characteristics was conformed according to normal distribution. Only the results of experiments of Kaunas University of Technology laboratory were analyzed. In this work the results of the investigation of 55 corrosion and heat-resistant steels, 36 their weld metals at room (20°C) and 46 corrosion steels at elevated (250°C–550°C) temperatures were selected from materials investigated in the laboratories of Kaunas University of Technology and other countries (Slovakia, Russia, Hungary).

2. Mechanical characteristics and low cycle fatigue curves parameters

The low cycle fatigue characteristics of materials are significant for estimating the reliability and durability of construction elements during exploitation [6]. The parameters of low cycle loading with limited strain are understood as the durability or low cycle fatigue curves, which are composed in coordinates $lg\,\varepsilon - lg\,N$ and $lg\,\delta - lg\,N$ according the number of cycles till crack N_c or fracture N_f appears. The durability of the material under loading with limited strain is expressed by Coffin's equation

$$\delta N^{m_p} = C_p \tag{1}$$

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_p and C_p are characteristics of the material, which are proposed by Coffin: $m_p = 0.5$ and $C_p = 0.5ln\left(1/\left(1-Z\right)\right)$, where Z is reduction of the area at fracture, while S.S. Manson [8] proposed the expression $C_p = \left(ln1/1-Z\right)^{0.6}$.

The hysteresis loop describes cyclic behavior of the material and its resistance to fatigue. Under loading with limited strain, the cyclic hardened, softened or stable materials are damaged of fatigue, because at this loading there is no quasistatic damage. The shape of hysteresis loop vary during the low cycle loading with limited strain for hardened and softened materials, therefore it is proposed to calculate equivalent plastic strain by expression $\delta = \frac{1}{k_c}\sum_{0}^{k_c}\delta_k$ where k_c is the number of semicycles up to crack, or to the applied width of plastic hysteresis loop for durability $k_c/2$ [3].

In work [3] it was proposed to change plastic deformation δ in Eq. (1) by ε, because the range of total strain ε remains constant at cyclic loading with limited strain therefore the durability is proposed to be evaluated by the equation

$$\varepsilon N^m = C \tag{2}$$

This equation, when $\varepsilon > \left(3.0 - 3.5\right)e_{pr}$, is correct for the majority of materials, then, $m_p > m$, $C_p > C$ [3], and when $\varepsilon < (3.0 - 3.5)\, e_{pr}$ the durability greatly increases, therefore low cycle fatigue curves are defined in this work by the equation

$$\varepsilon = C_e N^{-m_e} + C_p N^{-m_p} \qquad (3)$$

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

3. Statistic evaluation of low cycle fatigue parameters

The corrosion and heat-resistant steels and their weld metals [4, 5] investigated in this work were divided according temperature into 2 groups: 1) at room temperature; 2) at elevated temperature. Dependences of the parameters of low cycle fatigue curve m_p, C_p according plastic strain and m_e, C_e according elastic strain on modified plasticity $(\sigma_u/\sigma_y)Z$ for steels at room temperature and 95% confidence interval ranges (dotted line) to theoretic line are given in Fig. 1. Fig. 2 represent the results of parameters m_p, C_p dependences on modified plasticity for steels at elevated temperature.

Figs. 1 and 2 show that the 95% confidence interval ranges (dotted line) to theoretic line are narrower at room temperature comparing with the results at elevated temperature.

Rectangular diagrams of parameters m_p for steels and their weld metals (Fig. 3) show that the scatter interval of the results is not wide (within limits $x_{min} \div x_{max}$). In these diagrams the median values x_{me} for the investigated n number of materials are also represented, which divides the scatter of the results into two equal parts. Defined area (within quartiles limits $x_{0.25} \div x_{0.75}$) describes the 50% scatter of the middle values. Statistical characteristics of low cycle fatigue curve parameters m_p, C_p, m_e, C_e according to elastic and plastic strain at room (20°C) and elevated (250°C - 550°C) temperatures are given in Table 1. Mean values of the parameters are similar to median values; the implication is that here are no strongly outstanding materials. The mean values of scatter results of parameters m_p and C_p according elastic and plastic strain for corrosion and heat–resistant steels at room temperature are greater comparing with the results at elevated temperature, however parameters m_e and C_e are smaller at room temperature than at elevated temperature.

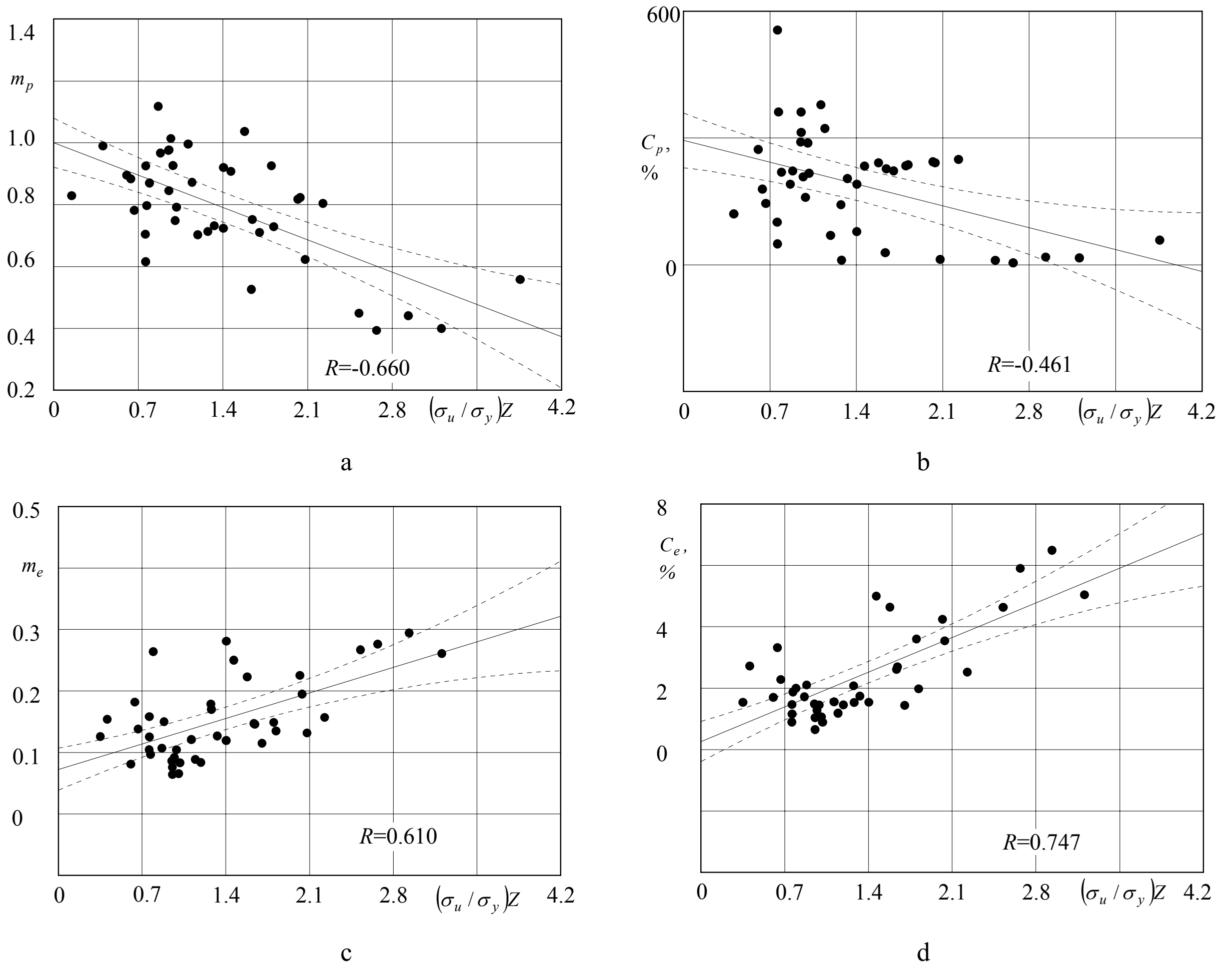
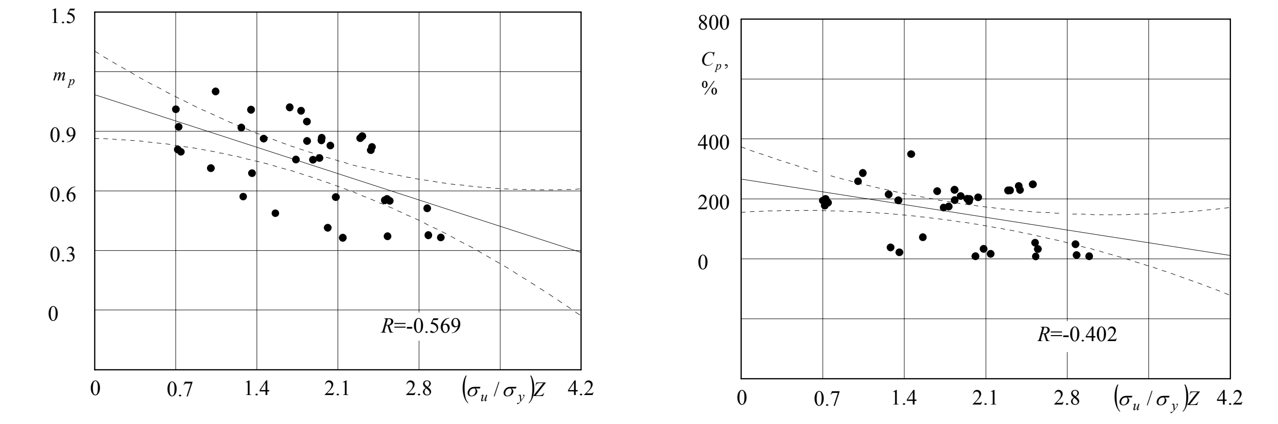
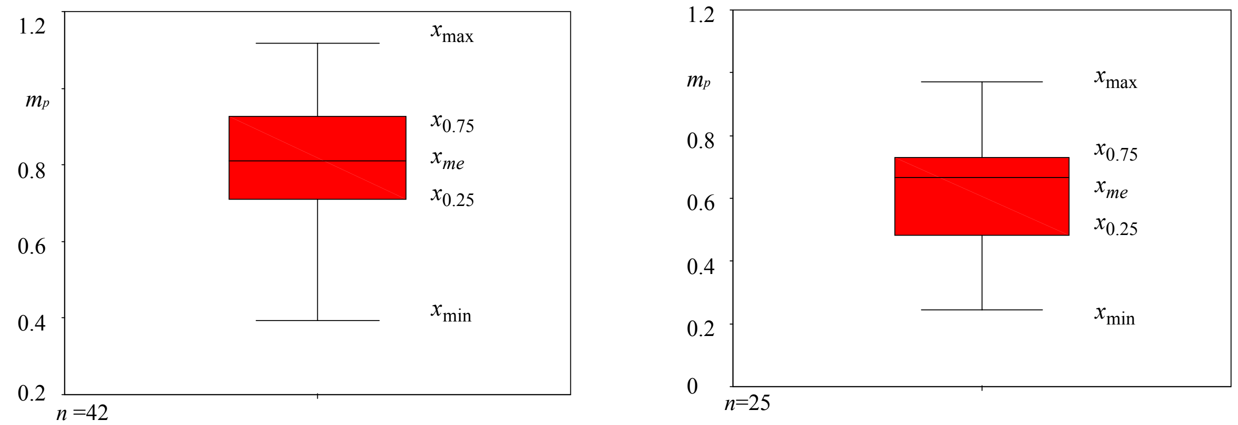


Fig. 1 Dependences of low cycle fatigue curves parameters on modified plasticity $(\sigma_u/\sigma_y)Z$ for steels at room temperature: a- m_p, b - C_p, c- m_e, d - C_e



a b

Fig. 2 Dependences of parameters m_p (a) and C_p (b) on modified plasticity $(\sigma_u/\sigma_y)Z$ for steels at elevated temperature



a b

Fig. 3 Rectangular diagrams of parameters m_p for steels (a) and weld metals (b) at room temperature

Parameter m_p of low cycle fatigue curves for analyzed steels and their weld metals at room and elevated temperatures has left skewness compared with normal distribution, while parameter m_e for those steels at elevated temperature has right skewness. Kurtosis coefficient shows that the results of parameters m_p and m_e for corrosion and heat–resistant steels and weld metals at room and elevated temperatures are spread wider interval comparing with normal distribution.

Correlation analysis is statistical relation strength between analyzed variables, which is expressed by correlation coefficient. Pearson correlation coefficient measures the linear relation strength. Correlation analysis is not used to determine nonlinear correlations. When linear model is not adequate, it is necessary to use nonlinear model.

In previous works the accomplished statistical analysis conformed that the parameters of Coffin curves the best correlate with modified plasticity $(\sigma_u/\sigma_y)Z$ at room and elevated temperatures. The results in Table 2 confirm that the parameters of low cycle fatigue curves m_e, C_e, m_p, C_p for steels, their weld metals and modified plasticity $(\sigma_u/\sigma_y)Z$ at room and elevated temperatures are correlated. Pearson correlation coefficient has the minimum value $|-0.402|$ for corrosion and heat-resistant steels coefficient C_p at elevated temperature and the maximum value $|0.747|$ for those steels coefficient C_e at room temperature.

Analytical dependences of Coffin parameters on modified plasticity for analyzed steels and weld metals at room and elevated temperatures are given in Table 3. The dependences of m_p, C_p, m_e, C_e are used for forecasting the preliminary durability of a material by Eq. (3).

For the comparison of the results of experimental and calculated durability by Eq. (3), which are distributed according to normal low, there were determined such scatter limits: fourfold, ninefold, sixteenfold. The scatter between experimental and calculated durability results for steels and their weld metals (according analytical dependences given in Table 3) at room and elevated temperatures is presented in Table 4. Scatter of the results between experimental N_f^{exp} and calculated N_f^{cal} durability for steels at elevated (250°C - 550°C) temperature is 19% greater than the scatter of the results at room (20°C) temperature. The scatter of comparison results of experimental and calculated durability for steels and their weld metals are similar at room temperature. The comparison between their durability at room temperature is shown in Fig. 4. When N_f^{cal} >10000 the relation N_f^{cal} / N_f^{exp} is greater than 10, it means that in Table 3 proposed analytical dependences are correct to use when N_f^{cal} <10000.

Table 1

Statistical characteristics of low cycling curves parameters m_e, C_e, m_p, C_p at room and elevated temperatures

Parameters	Corrosion and heat-resistant steels at room temperature				Corrosion and heat-resistant steels at elevated temperature				Weld metals of corrosion and heat-resistant steels at room temperature			
	m_p	C_p	m_e	C_e	m_p	C_p	m_e	C_e	m_p	C_p	m_e	C_e
Number of materials	42	42	42	40	36	36	34	29	25	24	23	22
Mean value	0.791	189	0.152	2.40	0.735	154	0.200	2.58	0.608	93.1	0.171	2.38
Median value	0.811	212	0.137	1.81	0.798	193	0.197	2.35	0.665	52.7	0.157	1.63
Minimum value	0.39	4.44	0.06	0.65	0.36	6.05	0.11	0.83	0.24	2.88	0.05	0.51
Maximum value	1.12	555	0.30	6.49	1.10	347.8	0.34	5.08	0.97	348	0.36	6.96
Kurtosis coefficient	-0.06	0.56	-0.46	0.71	-0.94	-1.10	-0.73	0.30	-0.50	1.16	-0.42	0.74
Skewness coefficient	-0.63	0.39	0.78	1.25	-0.38	-0.36	0.52	0.71	-0.19	1.38	0.47	1.32

Table 2

Correlation analysis of parameters m_e, C_e, m_p, C_p and modified plasticity $(\sigma_u/\sigma_y)\cdot Z$ at room and elevated temperatures

Material	Pearson correlation coefficient			
	m_p	C_p	m_e	C_e
At room temperature				
Corrosion and heat-resistant steels	-0.660	-0.461	0.610	0.747
Corrosion and heat-resistant steels weld metals	0.559	0.707	0.545	0.466
At elevated temperature				
Corrosion and heat-resistant steels	-0.567	-0.402	0.501	0.436

Table 3

Analytical dependences of low cycle curves parameters on modified plasticity $(\sigma_u/\sigma_y)Z$ at room and elevated temperatures

At room temperature	At elevated temperature
Corrosion and heat-resistant steels	
$m_p = 1.00 - 0.149(\sigma_u/\sigma_y)Z$ $C_p = 294 - 73.8(\sigma_u/\sigma_y)Z$ $m_e = 0.073 + 0.059(\sigma_u/\sigma_y)Z$ $C_e = 0.260 + 1.61(\sigma_u/\sigma_y)Z$	$m_p = 1.08 - 0.189(\sigma_u/\sigma_y)Z$ $C_p = 266 - 60.7(\sigma_u/\sigma_y)Z$ $m_e = 0.105 + 0.052(\sigma_u/\sigma_y)Z$ $C_e = 1.44 + 0.645(\sigma_u/\sigma_y)Z$
Weld metals of corrosion and heat–resistant steels at room temperature	
$m_p = 0.363 + 0.244(\sigma_u/\sigma_y)Z$ $C_p = -79.7 + 181(\sigma_u/\sigma_y)Z$ $m_e = 0.057 + 0.114(\sigma_u/\sigma_y)Z$ $C_e = 0.147 + 2.26(\sigma_u/\sigma_y)Z$	

Table 4

Comparison of experimental N_f^{exp} and calculated N_f^{cal} durability for corrosion and heat-resistant steels and their weld metals at room and elevated temperatures

Material	Total number of specimens	Number of specimens, when scatter of results between experimental and calculated durability is					
		fourfold		ninefold		sixteenfold	
		number	%	number	%	number	%
At room temperature							
Corrosion and heat–resistant steels	449	142	32	212	47	260	58
Weld metals of corrosion and heat-resistant steels	228	88	31	145	50	173	60
At elevated temperature							
Corrosion and heat-resistant steels	362	58	16	100	28	139	39

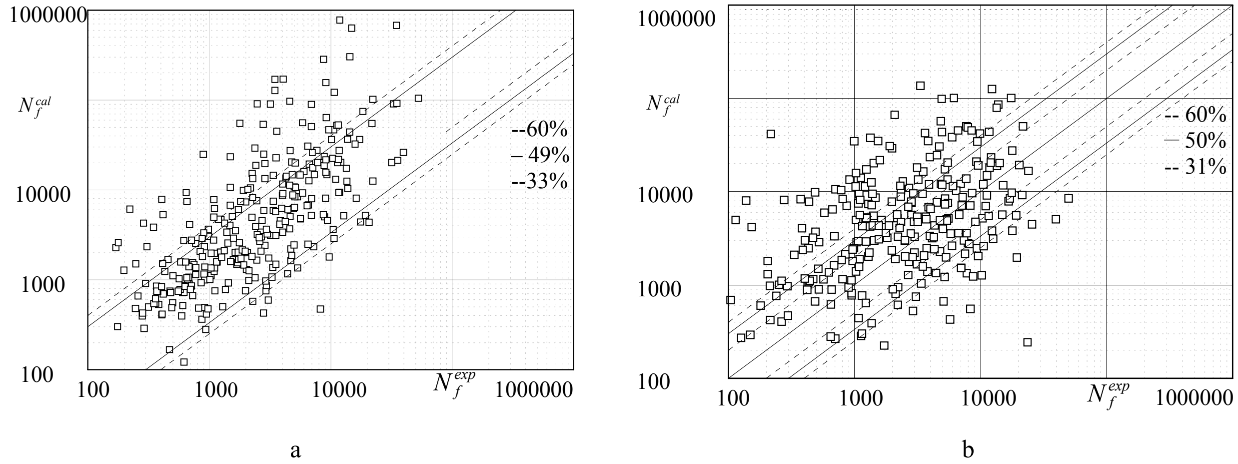


Fig. 4 Comparison of experimental N_f^{exp} and calculated N_f^{cal} durability for corrosion and heat-resistant steels (a) and weld metals (b) at room temperature

4. Conclusions

1. The mean value of parameter m_p for corrosion and heat-resistant steels and their weld metals at room at elevated temperatures is greater than Coffin's suggested constant $m = 0.5$. The obtained mean value at room temperature for steels $m_p = 0.791$, for weld metals $m_p = 0.608$, at elevated temperature for steels $m_p = 0.735$.

2. The parameters of low cycle fatigue curves m_e, C_e, m_p, C_p for steels and their weld metals are correlated with modified plasticity $(\sigma_u/\sigma_y)Z$ by linear regression at room and elevated temperatures.

3. The scatter of the results between experimental N_f^{exp} and calculated N_f^{cal} durability for steels at elevated temperature is 19% greater than the scatter of the results at room temperature. The scatter of the results between experimental and calculated durability for steels and their weld metals are similar at room temperature.

4. Analytical dependences of low cycle fatigue curve parameters on modified plasticity for corrosion and heat-resistant steels and their weld metals are enough correct to figure out the durability at room and elevated temperatures. The scatter of the results is 2-3 times greater than for one material experimental durability at low cycle loading.

5. Dependencies proposed in this work may be used for preliminary durability evaluation of corrosion and heat-resistant steels and their weld metals at low cycle loading.

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KOROZIJAI IR KARŠČIUI ATSPARIŲ PLIENŲ SUVIRINTŲJŲ JUNGČIŲ MEDŽIAGŲ MAŽACIKLIO ILGAAMŽIŠKUMO STATISTINIS ĮVERTINIMAS KAMBARIO IR AUKŠTESNĖJE TEMPERATŪROJE

R e z i u m ė

Straipsnyje analizuojama atominėje energetikoje naudojamų korozijai ir karščiui atsparių plienų ir jų suvirinimo siūlių medžiagų mažaciklio ilgaamžiškumo priklausomybė nuo mechaninių charakteristikų. Tyrimui panaudoti 55 korozijai ir karščiui atsparių plienų, 36 šių plienų suvirinimo siūlių medžiagų kambario temperatūroje ir 46 plienų aukštesnėje temperatūroje mažaciklio deformavimo duomenys, gauti Kauno technologijos universiteto bei Slovakijos, Rusijos ir Vengrijos mažaciklio nuovargio laboratorijose. Nustatytos mažaciklio suirimo kreivės charakteristikos $C_{p,}$, m_p pagal plastinę deformaciją ir C_e, m_e pagal tampriąją deformaciją. Atliktas statistinis tyrimas patvirtino, kad suirimo kreivių parametrai, taip pat modifikuotas plastiškumas $(\sigma_u/\sigma_y)Z$ yra atsitiktiniai ir nepriklausomi dydžiai, pasiskirstę pagal normalųjį dėsnį, ir mažaciklis ilgaamžiškumas tiesiškai koreliuoja su medžiagų modifikuotu plastiškumu $(\sigma_u/\sigma_y)Z$. Pasiūlytos korozijai ir karščiui atsparių plienų ir jų suvirinimo siūlių medžiagų konstantų C_e, m_e, C_p, m_p analitinės priklausomybės nuo modifikuoto plastiškumo kambario ir aukštesnėje temperatūrose. Apskaičiuoto ir eksperimentiškai gauto ilgaamžiškumo rezultatų palyginimas parodė, kad pasiūlytas metodas gali būti pritaikytas preliminariam tirtų medžiagų mažaciklio ilgaamžiškumo nustatymui.

M. Daunys, A. Stulpinaite

STATISTICAL EVALUATION OF LOW CYCLE DURABILITY FOR CORROSIAN AND HEAT-RESISTANT STEELS WELDED JOINTS MATERIALS AT ROOM AND ELEVATED TEMPERATURE

S u m m a r y

In this work low cycle fatigue durability dependence upon mechanical characteristics for corrosion and heat-resistant steels and their weld metals used in nuclear engineering was analyzed. The results of 55 corrosion and heat-resistant steels, 36 their weld metals at room and 46 corrosion and heat-resistant steels at elevated temperatures are obtained in the laboratories of Kaunas University of Technology and in Slovakia, Russia, and Hungary. Parameters of low cycle curves according plastic strain C_p, m_p and elastic strain C_e , m_e for these steels and their weld metals at room and elevated temperatures are analyzed. Statistical analysis confirmed, that fracture characteristics and modified plasticity are independent values, they have normal distribution and durability has linear correlation with the modified plasticity $(\sigma_u/\sigma_y)Z$. Analytical dependences of constants C_e, m_e, C_p, m_p on modified plasticity are proposed for these materials at room and elevated temperatures. The comparison of calculated and experimental durability results showed, that the proposed analytical dependencies may be used for preliminary estimation of low cycle durability of the investigated materials.

М. Даунис, А. Стулпинайте

СТАТИСТИЧЕСКИЙ АНАЛИЗ МАЛОЦИКЛОВОЙ ДОЛГОВЕЧНОСТИ МАТЕРИАЛОВ СВАРНЫХ СОЕДИНЕНИЙ КОРРОЗИОННОСТОЙКИХ И ЖАРОСТОЙКИХ СТАЛЕЙ В УСЛОВИЯХ КОМНАТНОЙ И ПОВЫШЕННОЙ ТЕМПЕРАТУРЫ

Р е з ю м е

В статье анализируется зависимость малоцикловой долговечности от механических характеристик для коррозионностойких и жаростойких сталей и материалов их сварных швов, используемых в атомной энергетике. Для исследования использованы данные малоцикловой усталости 55 коррозионностойких и жаростойких сталей 36 материалов их сварных швов в условиях комнатной температуры и 46 коррозионностойких и жаростойких сталей, в условиях повышенной температуры, полученные в Каунасском технологическом университете, а также в лабораториях малоцикловой усталости Словакии, России и Венгрии. Определены характеристики кривой малоцикловой усталости m_p , C_p по пластической деформации и m_e , C_e по упругой деформации. Проведенные статистические исследования подтвердили, что параметры кривых малоцикловой усталости, также как модифицированная пластичность $(\sigma_u/\sigma_y)Z$, есть случайные и независимые величины, распределенные по нормальному закону, а малоцикловая долговечность имеет линейную корреляцию с модифицированной пластичностью материалов $(\sigma_u/\sigma_y)Z$. Предложены аналитические зависимости констант m_e , C_e , m_p , C_p от модифицированной пластичности в условиях комнатной и повышенной температурах. Сопоставление результатов расчетной и экспериментальной долговечностей показало, что предложенная методика может быть использована для предварительной оценки долговечности при малоцикловом нагружении.

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