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Evaluation of cyclic instability by mechanical characteristics for structural materials

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1. Introduction

Working conditions and material properties of machines must be analyzed in order to improve their quality, reliability and lifetime. Strain and stress change during the exploitation depend on material type (cyclically hardening, softening or stable), therefore we must know the material type that is chosen for the structures under low cycle loading. The application of particular structural material on certain exploitation conditions is determined by its type.

Hardened steels cyclically soften, tempered or normalized steels are cyclically stable or harden under low cycle loading [1]. Regulation of the temperature and determining of the stress strain curves, in particular at elevated temperature, make the experiments of low cycle loading complicated and expensive. Therefore it is very important that the parameter of cyclic instability (hardening or softening intensity) could be obtained from monotonous tension curves without cyclic loading.

Over 300 structural materials that are used in nuclear power engineering were tested under monotonous tension and symmetric low cycle tension-compression in Kaunas University of Technology together with St. Peterburg Central Research Institute of Structural Materials. The main mechanical, low cycle loading and fracture characteristics of alloyed structural steels, stainless steels and metals of their welded joints with different types of thermal treatment at room and elevated (200-350°C) temperatures were determined during these experiments.

Cyclic instability of welded joint materials, obtained by the same methods and testing equipment, was evaluated according to mechanical properties in this work for 227 structural materials. Various methods of evaluation of cyclic instability have been used in many scientific works, but to the lesser number of materials.

2. Evaluation of cyclic instability of materials according to mechanical properties

Monotonous tension and low cyclic loading are similar by accumulation of plastic strain, therefore the mechanical characteristics can be used for quantitative evaluation of materials. This method was used in the early works of R. Landgraf and A. Romanov.

R. Landgraf [2] determined that at $\sigma_u/\sigma_y > 1.4$ structural materials cyclically harden, at $\sigma_u/\sigma_y < 1.2$ they cyclically soften and at $1.2 < \sigma_u/\sigma_y < 1.4$ they are cyclically stable (Table 1), where σ_y is yield strength and σ_u is ultimate strength of structural materials.

In A. Romanov's and A. Gusenkov's works [3], after testing of 48 structural materials, it was shown, that the relation σ_u/σ_y is not the main factor for the evaluation of cyclic properties. Their proposal was, that the main factor is the relation e_u/e_f. Here e_u is the strain of uniform reduction of area (before necking of specimen) and e_f is the fracture strain under monotonous tension. A. Romanov determined, that at $e_u/e_f < 0.45$ materials cyclically soften, at $e_u/e_f > 0.6$ cyclically harden and at $0.45 < e_u/e_f < 0.6$ are cyclically stable (Table 1). A. Romanov's premise is valuable, because strain, but not stress characteristics more precisely describe the behaviour of materials under low cycle loading. The main drawback of this premise is complicated determination of the strain of uniform reduction of area e_u. Furthermore, e_u is not given in technical manuals, because it is not a standard characteristic of a material.

After the investigation of test results of structural materials (about 300 steels and their weld metals), such zones of cyclic properties were determined in coordinate $Z - \sigma_u/\sigma_y$ (here *Z* is reduction of the area at fracture) [1]: 1) when $\sigma_u/\sigma_y > 1.8$ materials cyclically harden; 2) when $\sigma_u/\sigma_y < 1.4$ and $Z < 0.7$ cyclically soften; 3) when $\sigma_u/\sigma_y < 1.4$ and $Z > 0.7$ are cyclically stable; 4) when $1.4 < \sigma_u/\sigma_y < 1.8$ there is the transition zone, where, independently of *Z*, weak hardening, softening or stable materials are revealed. An additional transition area $0.5 < Z < 0.7$ between stable and softening zones appears for weld materials (Table 1).

3. Mechanical and cyclic characteristics and their relationship

Relationship between stress and strain for the cyclic stress strain curve is described by the equation [1]

$$\bar{\varepsilon}_k = \bar{S}_k + \bar{\delta}_k \qquad (1)$$

where $\bar{\varepsilon}_k$ and $\bar{S}_k$ are cyclic strain and stress range for *k* semicycle respectively; $\bar{\delta}_k$ is the width of hysteresis loop; *k* is the number of cemicycle.

Table 1

Evaluation of cyclic instability of structural materials according to mechanical properties

R.W. Landgraf	$\sigma_u / \sigma_y > 1.4$	materials cyclically harden
	$\sigma_u / \sigma_y < 1.2$	materials cyclically soften
	$1.2 < \sigma_u / \sigma_y < 1.4$	materials cyclically stable
35 materials (steels, aluminium and titanium alloys) were tested. The suggested premise was confirmed for 26 materials		
A. Gusenkov, A. Romanov	σ_u / σ_y	is not the main factor for the determination of cyclic properties of materials
	$e_u / e_y > 0.6$	materials cyclically harden
	$e_u / e_y < 0.45$	materials cyclically soften
	$0.45 < e_u / e_y < 0.6$	materials cyclically stable
	e_u – strain of uniform elongation; e_f – fracture strain	
48 materials (44 steels and 4 aluminium alloys). This premise was very well confirmed for 25 steels.		
M. Daunys, A. Bražėnas, others	$\sigma_u / \sigma_y > 1.8$, independent of Z	materials cyclically harden
	$\sigma_u / \sigma_y < 1.4$, $Z < 0.7$	materials cyclically soften
	$\sigma_u / \sigma_y < 1.4$, $Z > 0.7$	materials cyclically stable
	$1.4 < \sigma_u / \sigma_y < 1.8$, independent of Z	transition zone
	$\sigma_u / \sigma_y < 1.4$, $0.5 < Z < 0.7$	welded metal
106 materials (steels and welded metal of alloyed structural steels and 4 aluminium alloys) were tested		

In Eq. (1) stress and strain are normalized to the stress and strain of proportionality limit, i.e.

$$\bar{S}_k = \frac{S_k}{\sigma_{pl}}; \bar{\varepsilon} = \frac{\varepsilon}{e_{pl}}; \bar{\delta} = \frac{\delta}{e_{pl}} \tag{2}$$

According to the test conditions under low cycle loading with limited strain, $\bar{\varepsilon}_k = const$. Therefore cyclic stress range $\bar{S}_k$ is variable under loading with limited strain (Fig. 1). The same materials can harden, soften or be stable in dependence on the number of cycles and loading level.

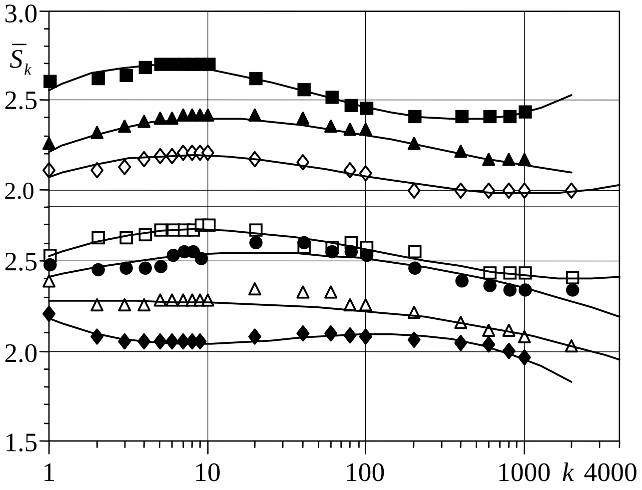

Fig. 1 Dependence of cyclic stress on the number of semicycles for steel 15Ch2MFA under cyclic loading with limited strain

At cyclic straining the behavior of a material is determined by the dependence of cyclic stress $\bar{S}_k$ and the width of hysteresis loop $\bar{\delta}_k$ on the number of cemicycles k. It is shown in the work [4], that the dependence of width of hysteresis loop $\bar{\delta}_k$ on the number of cemicycles k in double logarithmic coordinate makes straight line at cycle straining.

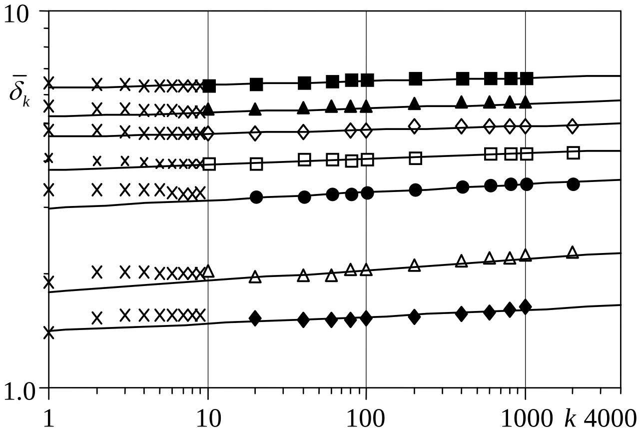

Fig. 2 Dependence of hysteresis loop width on the number of semicycles for softening material (steel 15Ch2MFA), when $k = 1 - 9$ are rejected

According to graphical interpretation of linear regression, the width of hysteresis loop of k-th semicycle

$$lg\,\bar{\delta}_k = lg\,\bar{\delta}_1 + \alpha\,lg\,k \tag{3}$$

or the width of hysteresis loop for cyclically softening materials (Fig. 2)

$$\bar{\delta}_k = \bar{\delta}_1 k^{\alpha} \tag{4}$$

The width of hysteresis loop for cyclically hardening materials (Fig. 3)

$$\bar{\delta}_k = \bar{\delta}_1 k^{-\alpha} \tag{5}$$

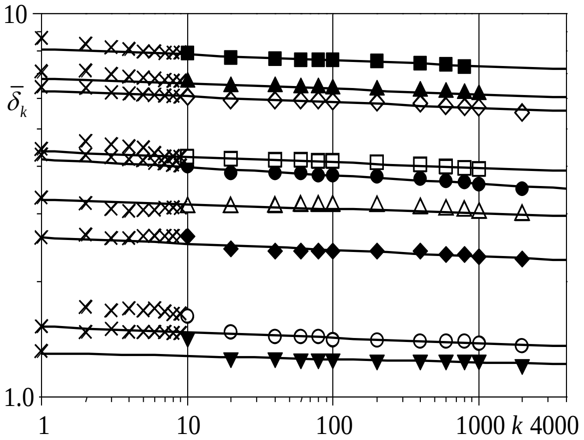

Fig. 3 Dependence of hysteresis loop width on the number of semicycles for hardening material (steel 22KE), when $k = 1 - 9$ are rejected

For cyclically stable materials parameter $\alpha = 0$ and the width of hysteresis loop

$$\bar{\delta}_k = \bar{\delta}_1 \tag{6}$$

When the widths of hysteresis loop for semicycles $\bar{\delta}_1$ and $\bar{\delta}_k$ are determined in coordinate $lg\bar{\delta}_k - lgk$, the parameter for the evaluation of cyclic instability (hardening or softening intensity) is determined by the equation

$$\alpha = \frac{lg\,\bar{\delta}_k - lg\,\bar{\delta}_1}{lg\,k} \tag{7}$$

Parameter α was determined from experimental results of all materials tested at low cycle straining. These materials have been divided into three groups in such manner: if $-0.01 \le \alpha \le 0.01$ the material was nominated as cyclically stable, if $\alpha > 0.01$ – as cyclically softened and if $\alpha < -0.01$ – as cyclically hardened [4, 5].

The values of $\bar{\delta}_k$ were rejected (marked "x") for semicycles $k = 1 - 9$ due to unsettled change of cyclic stress strain curves for these semicycles (Figs. 2 and 3).

In previous works [4-7] the accomplished statistical analysis confirmed that parameter α and modified plasticity $(\sigma_u / \sigma_y)Z$ at room and elevated temperatures were distributed according to the normal law and describe test results in the best way.

After the investigation of 227 test results, the dependences of parameter α on modified plasticity $(\sigma_u / \sigma_y)Z$ for structural steels and their weld metal at room and elevated temperature and 95% confidence intervals (dotted line) for the theoretical regression line are represented in Figs. 4-10. The analytical dependences of parameter α on modified plasticity $(\sigma_u / \sigma_y)Z$ for all investigated materials at room and elevated temperature are given in Table 2.

For the comparison of experimental and calculated results the intervals: $\bar{x} \pm 0.675s$ (probable deviation) with the probability $P \approx 0.50$; $\bar{x} \pm s$ with the probability $P \approx 0.68$ and $\bar{x} \pm 1.96s$ with the probability $P \approx 0.95$ (95% area of normal curve) [6] were determined. Here $\bar{x}$ is the mean value of experimental cyclic instability α of structural materials and *s* is standard deviation.

Table 2

Relationship of cyclic instability parameter and modified plasticity for all investigated materials

Materials	Room temperature	Elevated temperature
Alloyed structural steels	$\alpha = 0.054 - 0.039(\sigma_u / \sigma_y)Z$	$\alpha = 0.047 - 0.025(\sigma_u / \sigma_y)Z$
Weld metal of alloyed structural steels	$\alpha = 0.034 - 0.019(\sigma_u / \sigma_y)Z$	$\alpha = -0.034 + 0.039(\sigma_u / \sigma_y)Z$
Stainless steels	$\alpha = 0.052 - 0.035(\sigma_u / \sigma_y)Z$	$\alpha = 0.036 - 0.030(\sigma_u / \sigma_y)Z$
Weld metal of stainless steels	$\alpha = 0.036 - 0.018(\sigma_u / \sigma_y)Z$	-

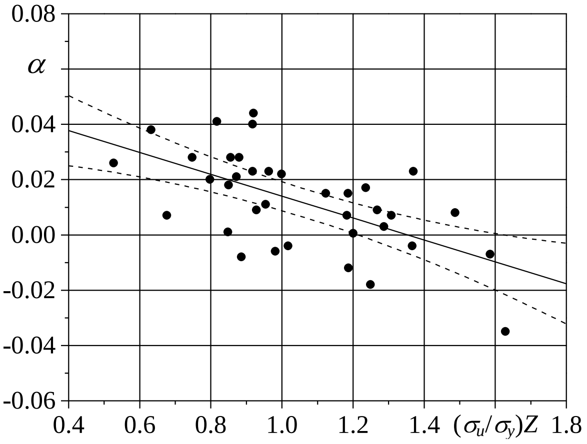

Fig. 4 Dependence of parameter α on modified plasticity for alloyed structural steels at room temperature and 95% confidence intervals (doted lines)

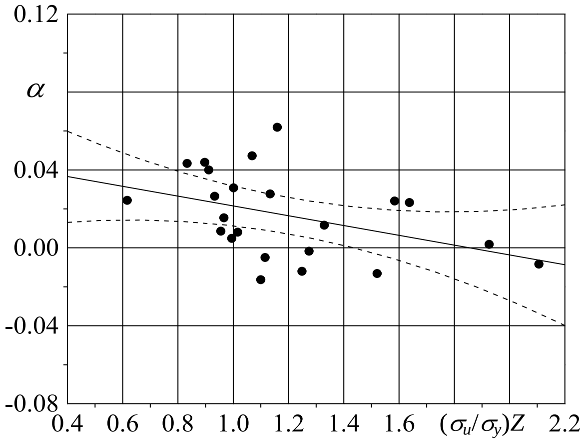

Fig. 5 Dependence of parameter α on modified plasticity for alloyed structural steels at elevated temperature and 95% confidence intervals (doted lines)

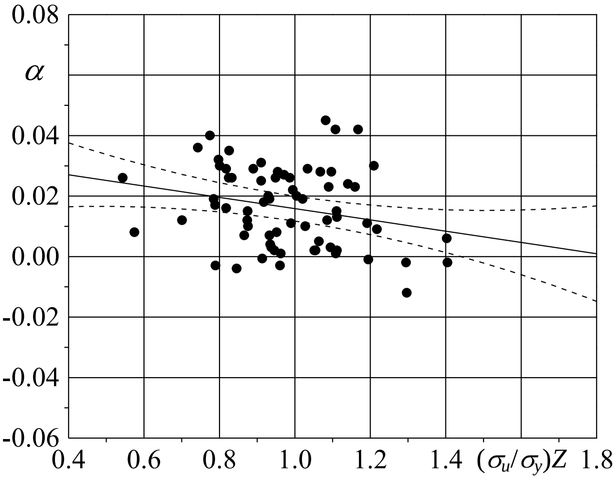

Fig. 6 Dependence of parameter α on modified plasticity for weld metal of alloyed structural steels at room temperature and 95% confidence intervals (doted lines)

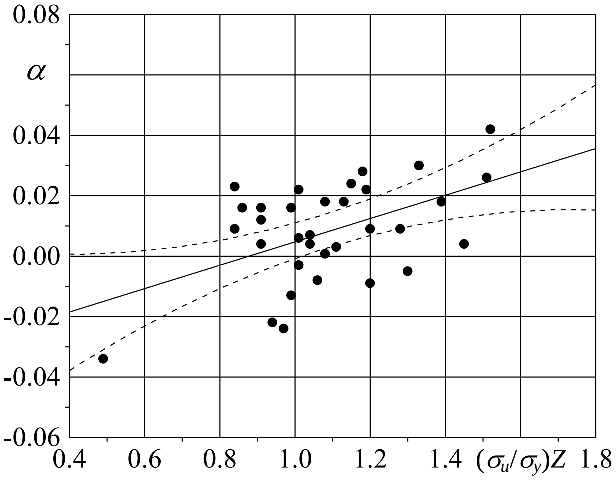

Fig. 7 Dependence of parameter α on modified plasticity for weld metal of alloyed structural steels at elevated temperature and 95% confidence intervals (doted lines)

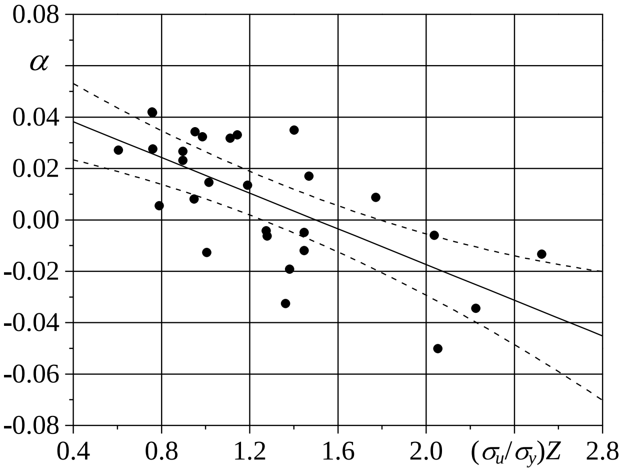

Fig. 8 Dependence of parameter α on modified plasticity for stainless steels at room temperature and 95% confidence intervals (doted lines)

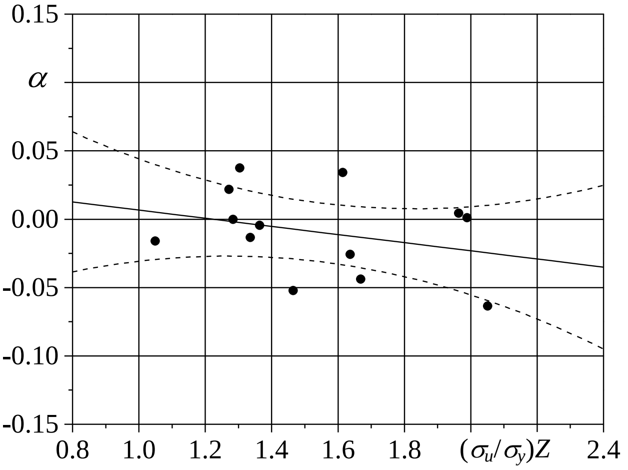

Fig. 9 Dependence of parameter α on modified plasticity for stainless steels at elevated temperature and 95% confidence intervals (doted lines)

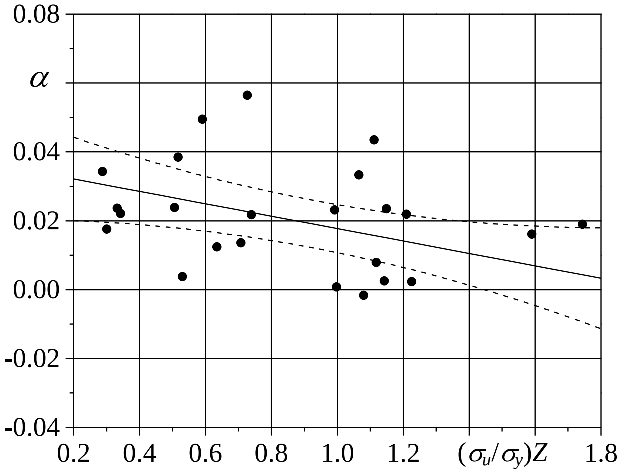

Fig. 10 Dependence of parameter α on modified plasticity for weld metal of stainless steels at room temperature and 95% confidence intervals (doted lines)

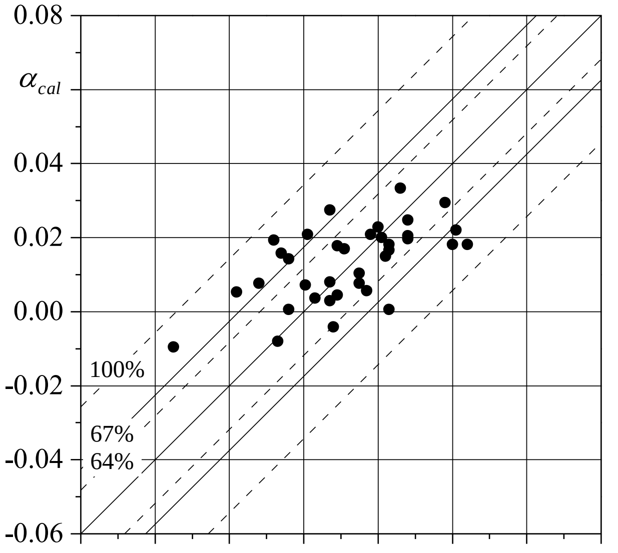

Fig. 11 Comparison of experimental α_{exp} and calculated α_{cal} parameter for alloyed structural steel at room temperature

Table 3

Comparison of experimental and calculated parameter *α* at room and elevated temperature

Number of samples	Materials	Number of samples, when the dispersion between experimental and calculated parameter *α* is in the interval					
		$\bar{x} \pm 0,675s$		$\bar{x} \pm s$		$\bar{x} \pm 1,96s$	
		n	%	*n*	%	*n*	%
36	Alloyed structural steels at room temperature	23	64	24	67	36	100
23	Alloyed structural steels at elevated temperature	10	43	17	74	22	96
69	Weld metal of alloyed structural steels at room temperature	27	39	50	72	66	96
33	Weld metal of alloyed structural steels at elevated temperature	16	48	24	73	33	100
28	Stainless steels at room temperature	18	64	24	86	28	100
13	Stainless steels at elevated temperature	5	38	9	69	13	100
25	Weld metal of stainless steels	13	52	19	76	25	100

The comparison of experimental and calculated (Table 2) parameter *α* for alloyed structural steels at room temperature is shown in Fig. 11, for all investigated materials at low cycle straining are shown in Table 3.

4. Conclusions

1. Parameter *α* characterizes intensity of cyclic hardening or softening rather precisely and can be used for all investigated structural materials at room and elevated temperature.
2. Cyclic instability parameter *α* for all materials and testing temperatures may be evaluated according to modified plasticity.
3. According to scatter of the results of linear relationship between the parameter *α* and modified plasticity, it is likely that it would be more precise when all investigated structural materials were subgrouped according to chemical composition or heat treatment.

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KONSTRUKCINIŲ MEDŽIAGŲ CIKLINIO NESTABILUMO ĮVERTINIMAS PAGAL MECHANINES CHARAKTERISTIKAS

Reziumė

Šiame darbe, apdorojus 227 medžiagų standaus apkrovimo tyrimo rezultatus, įvertintos medžiagų ciklinės savybės pagal mechanines charakteristikas. Atlikus nuodugnią grafinę rezultatų analizę, buvo nustatytas mažaciklio apkrovimo kreivių parametras *α*, kuris pakankamai tiksliai apibūdina medžiagos stiprėjimo (silpnėjimo) intensyvumą. Patikslintos priklausomybės plieno ir jo suvirinimo siūlių medžiagų cikliniam nestabilumui įvertinti pagal modifikuotą plastiškumą $\left(\sigma_u / \sigma_y\right) Z$ kambario ir aukštesnėje temperatūroje.

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EVALUATION OF CYCLIC INSTABILITY BY MECHANICAL CHARACTERISTICS FOR STRUCTURAL MATERIALS

Summary

After the investigation of 227 structural materials at low cycle straining, the cycle properties of structural materials by mechanical characteristics were evaluated. After a thorough analysis of the graphical results, the cyclic stress-strain curves parameter *α*, which characterizes intensity of cyclic hardening or softening of structural materials at room and elevated temperature rather precisely, was determined. Dependences for the evaluation of cyclic instability according to modified plasticity $\left(\sigma_u / \sigma_y\right) Z$ at room and elevated temperature for structural steels and their weld metal were specified.

Keywords: cyclic instability parameter, modified plasticity parameter, reliability.

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