UDK 669.14.018:620.172.251 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 45(6)523(2011)

CHARACTERISTICS OF CREEP IN CONDITIONS OF LONG OPERATION

ZNAČILNOSTI LEZENJA PRI DOLGOTRAJNI UPORABI

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Prejem rokopisa – received: 2011-07-28; sprejem za objavo – accepted for publication: 2011-10-20

The creep of materials is considered in various temperature ranges: at low, at elevated and at high temperatures. Different approaches of extrapolation of experimental data for creep curves are shown. For the available isochronous curves of steels R2M and EP291, the coefficients for the upgraded formula Soderberg were obtained. The isochronous creep curves and the curves with a partition into first and second stages were constructed by using the coefficients obtained. Calculation of the coefficients was performed using the computational mathematics package MathCad and OriginPro. The Arrhenius equation for description of the temperature dependence of creep rate in a narrow temperature range is presented.

The results of this work are a new method of determining the extrapolated values of material creep resistance relating to long-life, a verification of this method for experimental data of the steels R2M and EP291.

Key words: steel, creep, isochronous curves, creep curve, Norton formula, Soderberg formula, Arrhenius equation for a creep rate, steels R2M, EP291, 20Cr12WNiMoV

Lezenje materialov je obravnavano za različna območja temperatur: pri nizki, povišani in visoki temperaturi. Prikazani so različni načini ekstrapolacije eksperimentalnih podatkov s krivulj lezenja. Za razpoložljive izohrone krivulje za jekli R2LM in EP291 so bili določeni koeficienti za izboljšavo Soderbergove enačbe. Izohrone krivulje in krivulje z delitvijo na prvo in drugo stopnjo so oblikovane z upoštevanjem prve in druge faze in z uporabo določenih koeficientov. Koeficienti so izračunani z uporabo matematičnih izračunov na podlagi matematičnih paketov MathCad in OriginPro. Arheniusova enačba za odvisnost hitrosti lezenja od temperature je prikazana za ozko območje temperature.

Rezultati tega dela sta nova metoda za določanje ekstrapoliranih vrednosti odpornosti materiala proti lezenju pri dolgi uporabi in verifikacija metode na podlagi eksperimentalnih podatkov za jekli R2M in EP291.

Ključne besede: jeklo, lezenje, izohrone krivulje, krivulje lezenja, Nortonova enačba, Soderbergova enačba, Arheniusova odvisnost za hitrost lezenja, jekla R2M, EP291, 20Cr12WNiMoV

1 INTRODUCTION

The use of isochronous curves of creep in the strength calculations of details for power plants and necessary demands of increasing resource of these details up to 300 000 h or more, requires the need of resolving of several problems connected with the processing of experimental data of creep.

Considering the features of the steel creep in conditions of insignificant residual strain, the stress change over time can be neglected.

In these conditions creep should be considered in various temperature ranges:

a) At low temperatures. Creep is characterized by the first stage of transient creep. For example, further course of the creep process is almost inhibited with increasing time, leading to a lack of long damage at stresses less than the yield stress (**Figure 1a**);
b) At elevated temperatures. As test results of various materials show the rate of steady creep depends on the duration of tests: more time, lower slope of the creep curve. In this connection it should be recognized, that the adequacy of isochronous creep curves, obtained by extrapolation, is very low (**Figure 1b**). The corresponding curves are lower than those, which were obtained by direct experiment. It gives a conservative estimate of the deformation process details by soft loading. However, when the processes of stress relaxation are defined (hard load – uneasiness strain) and when the durability assessment is determined in accordance with the equivalent stress, we find higher values of durability and safety margins. These conditions are the material behavior at stress raisers, the stress relaxation at the high temperature fasteners, the redistribution of stresses in the steam pipeline bending, in the blades and turbine disks;
c) At high temperatures, as it is well known, the processes of diffusion creep take place without the first stage of creep (**Figure 1c**).

The second stage of creep is followed by the third (the stage of accelerated creep) depending on the deformation ability of the material and the stress level at the elevated and high temperatures.

2 EXPERIMENTAL

Consequently, using the experimental data of creep at the terminal duration, different approaches for the extrapolation should be taken into account.

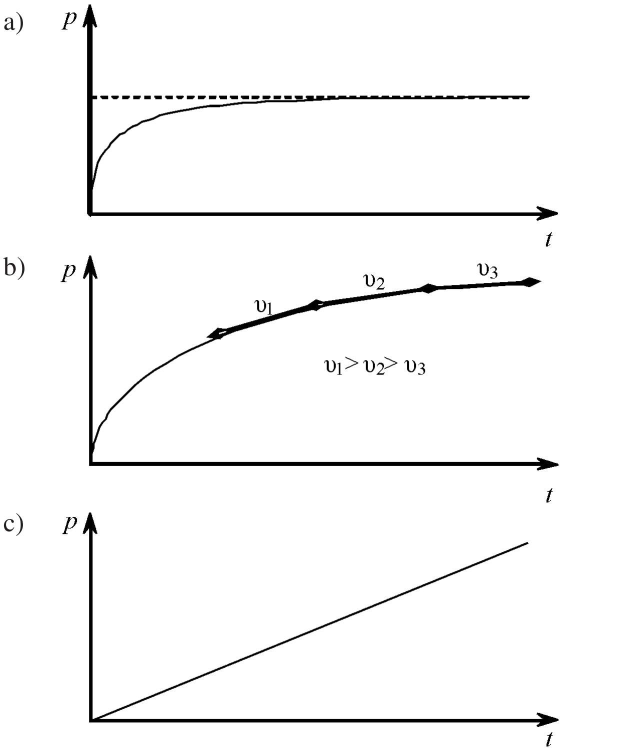

Figure 1: Schematic diagram of creepa) at low b) at elevated c) at high temperature

Slika 1: Shematična krivulja lezenja a) pri nizki, b) pri povišani in c) pri visoki temperature

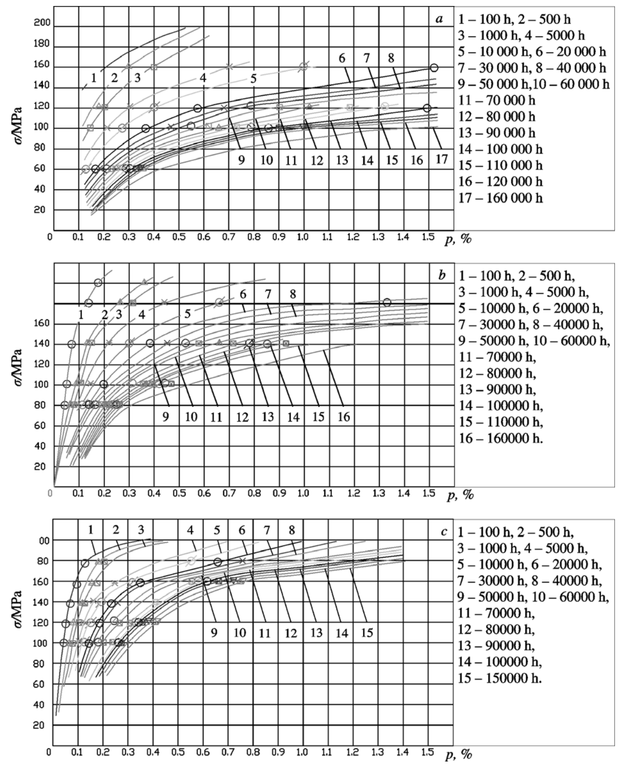

Figure 2: Approximation of the experimental creep data of the steel R2M at 500 °C (a), 525 °C (b) and 550 °C (c), presented in [1]

Slika 2: Aproksimacija eksperimentalnih podatkov za jeklo R2M pri 500 °C (a), 525 °C (b) in 550 °C, ref. [1]

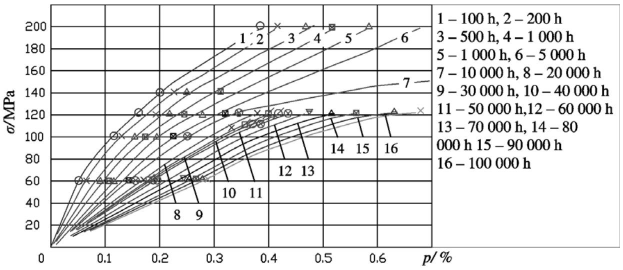

Figure 3: Approximation of the experimental creep data of the steel EP291 at 550 °C, presented in [1]

An adequate description of creep at low temperatures can be obtained by using the expression:

$$\dot{p} = a \cdot c \cdot \exp(-c \cdot t) \tag{1}$$

where: $a = A \cdot \sigma^{k}$, $c = C \cdot \sigma^{l}$ (σ – stress, t – time, A, C, k, l – constants, depending on temperature). For high temperatures, the Norton formula gives the consistent results:

$$\dot{p} = b \tag{2}$$

where: $b = B \cdot \sigma^{m}$ (σ – stress, B, m – constants, depending on temperature).

3 THE RESEARCH RESULTS

At elevated temperatures, at which details power plants operate usually, the use of sum (1) and (2) for determining the rate of creep:

$$\dot{p} = a \cdot c \cdot \exp(-c \cdot t) + b \tag{3}$$

is possible for time not exceeding the experimental. To solve the problem of extrapolation of the creep data of long duration, the experimental data of long duration have been used. These data have been received by A. A. Chizhik for the steel R2M pearlitic at 50 °C, 525 °C, 550 °C (**Figure 2**), the steels of martensitic class 18Cr11MoVNbNi (EP291) (**Figure 3**) and 20Cr12WNiMoV (**Figure 4**) at 550 °C [1].

Dependence of the duration of the first and second stages of creep has been determined in accordance with the test base for steel R2M (**Figure 5**) as well as for steel EP291.

Taking this in consideration, the use of the Norton formula with coefficients derived from a relatively short

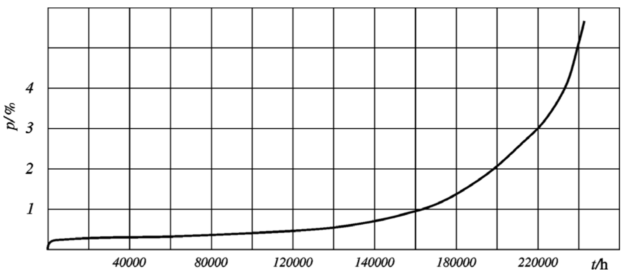

Figure 4: Creep curve of the steel 20Cr12WNiMoV at 550 °C

Slika 4: Krivulja lezenja za jeklo 20Cr12WNiMoV pri 550 °C

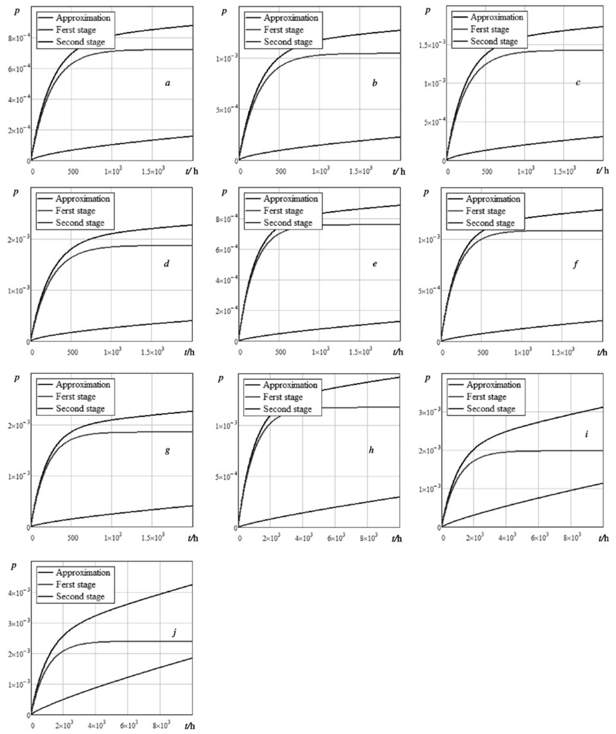

Figure 5: Duration of the first and second stages of creep for the steel R2M at 500 °C (*a* – 100 MPa, *b* – 120 MPa, *c* – 140 MPa, *d* – 160 MPa), 525 °C (*e* – 80 MPa, *f* – 100 MPa, *g* – 120 MPa), 550 °C (*h* – 60 MPa, *i* – 100 MPa, *j* – 120 MPa)

Slika 5: Trajanje prve in druge faze lezenja za jeklo R2M pri 500 °C (a- 100 MPa, b- 120 MPa, c- 140 MPa, d- 160 MPa), 525 °C (e- 80 MPa, f- 100 MPa, g- 120 MPa), 550 °C (h- 6a MPa, i- 100 MPa, j- 120 MPa)

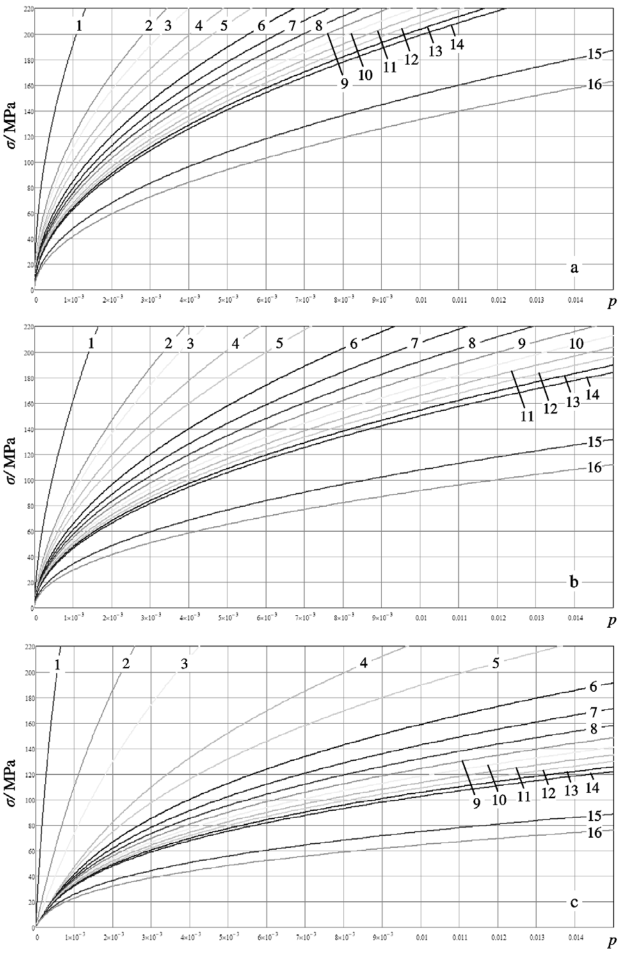

Figure 6: Isochronous curves of steel R2M at 500 °C (*a*), 525 °C (*b*) and 550 °C(*c*) 1 – 100 h; 2 – 500 h; 3 – 1 000 h; 4 – 5 000 h; 5 – 10 000 h; 6 – 20 000 h; 7 – 30 000 h; 8 – 40 000 h; 9 – 50 000 h; 10 – 60 000 h; 11 – 70 000 h; 12 – 80 000 h; 13 – 90 000 h; 14 – 100 000 h; 15 – 300 000 h; 16 – 500 000 h.

Slika 6:. Izohrone krivulje za jeklo R2M pri 500 °C (a), 525 °C (b), in 550 °C (c). 1 – 100 h; 2 – 500 h; 3 – 1 000 h; 4 – 5 000 h; 5 – 10000 h; 6 – 20 000 h; 7 – 30 000 h; 8 – 40 000 h; 9 – 50 000 h; 10 – 60 000 h; 11 – 70 000 h; 12 – 80 000 h; 13 – 90 000 h; 14 – 100 000 h; 15 – 300 000 h; 16 – 500 000 h.

duration of data, can give very significant errors in the calculation regarding the operation of equipment with very long lifetime (more than 100 000 h) both due to the neglect of the first stage of creep and the overrated values of the exponent *m*. The various attempts of description of this phenomenon led to the need to modify the Soderberg formula as:

$$p = a_1 \cdot \sigma^{a_2} \cdot (1 - \exp(-c_1 \cdot \sigma^{c_2} \cdot t)) + b_1 \cdot t^{b_2} \cdot \sigma^{b_2} \cdot t \quad (4)$$

where: (σ – stress, t – time, a_1, a_2, b_1, b_2, b_3, c_1, c_2 – constants depending on temperature).

The expression for the creep rate is:

$$\dot{p} = a_1 \cdot \sigma^{a_2} \cdot c_1 \cdot \sigma^{c_2} \cdot (1 - \exp(-c_1 \cdot \sigma^{c_2} \cdot t)) + b_1 \cdot t^{b_2} \cdot \sigma^{b_2} \quad (5)$$

Table 1: Values of the coefficients of equation (4)

Tabela 1: Vrednosti koeficientov enačbe (4)

	R2M						18Cr11MoVNbNi (EP291)	
	500 °C		525 °C		550 °C		550 °C	
	I	II	I	II	I	II	I	II
a_1	6.322E-8	1.402E-7	6.942E-7	1.314E-6	1.717E-5	1.043E-5	7.383E-6	6.626E-6
a_2	2.028	1.854	1.596	1.448	1.031	1.126	1.202	1.203
b_1	1.435E-10	8.803E-11	5.510E-11	9.066E-11	3.217E-12	4.293E-12	1.768E-7	2.059E-7
b_2	–3.752E-1	–3.915E-1	–2.784E-1	–2.914E-1	–1.843E-1	–1.554E-1	–5.973E-1	–6.215E-1
b_3	1.988	2.121	2.091	2.017	2.643	2.515	1.070	1.087
c_1	9.341E-5	6.374E-5	1.181E+8	6.662E-7	1.016E-3	1.175E-3	1.294E-5	2.718E-5
c_2	7.793E-1	8.868E-1	-5.270	-5.148	0	0	1.214	1.197
SD	1.937E-2	1.776E-2	2.796E-2	2.718E-2	1.290E-2	1.088E-2	6.917E-2	7.044E-2

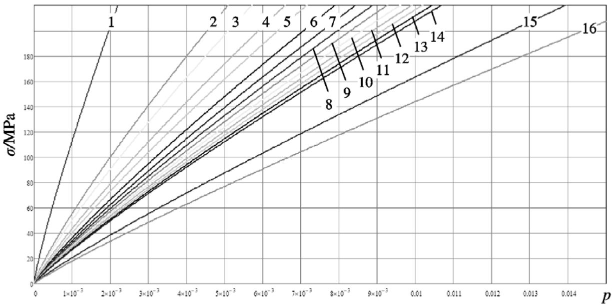

Figure 7: The isochronous curves of steel EP291 at 550 °C 1 – 100 h; 2 – 500 h; 3 – 1 000 h; 4 – 5 000 h; 5 – 10 000 h; 6 – 20 000 h; 7 – 30 000 h; 8 – 40 000 h; 9 – 50 000 h; 10 – 60 000 h; 11 – 70 000 h; 12 – 80 000 h; 13 – 90 000 h; 14 – 100 000 h; 15 – 300 000 h; 16 – 500 000 h
Slika 7: Izohromne krivulje za jeklo EP291 pri 550 °C 1 – 100 h; 2 – 500 h; 3 – 1 000 h; 4 – 5 000 h; 5 – 10 000 h; 6 – 20 000 h; 7 – 30 000 h; 8 – 40 000 h; 9 – 50 000 h; 10 – 60 000 h; 11 – 70 000 h; 12 – 80 000 h; 13 – 90 000 h; 14 – 100 000 h; 15 – 300 000 h; 16 – 500 000 h

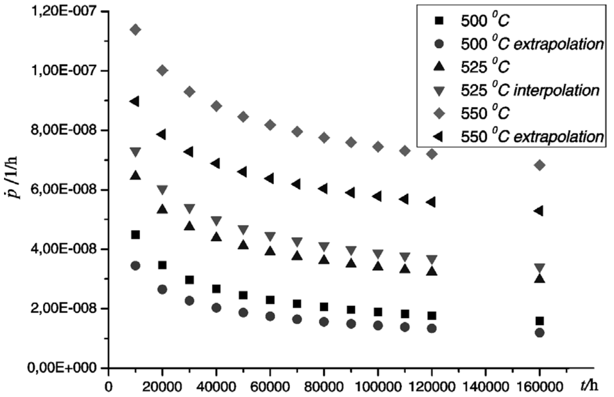

Figure 8: Comparison of experimental values of creep rate for the steel R2M with the extrapolated and interpolated values
Slika 8: Primerjava eksperimentalnih hitrosti lezenja za jeklo R2M z ekstrapoliranimi in interpoliranimi vrednostmi

The values of the coefficients of equation (4) for the investigated materials are given in **Table 1**. The coefficients are calculated in accordance with the minimum standard deviation for the experimental points and the proposed approximation. Calculation of the coefficients has been performed by means of the computational mathematics package MathCad and OriginPro.

The standard deviation has been used for comparing the results obtained during the calculation of the creep deformation with the original data calculated from:

$$SD = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{y_i - y}{y_i} \right)^2 \tag{6}$$

In some cases, the dependence (4) for certain values of the coefficients may give an inadequate representation of the isochronous curves of creep that has double bends. For example, this situation occurred during processing the experimental data for the steel R2M at 550 °C. In case of these incorrect results on the basis of the analysis, it is necessary to use of $c_2 = 0$ in equation (4).

Data in **Table 1** show, that SD values are at low level. The isochronous creep curves of steel have been built according to the values of the coefficients listed in **Table 1** (**Figure 6**).

Comparing **Figures 2 and 3** with **Figures 6 and 7**, we can see significant differences in the type of curves. It is related to the effectiveness of the proposed approximation by means of the dependence (4) and the use directly the experimental points for finding the values of the coefficients, rather than curves.

Unfortunately, methods of calculation that have been used for the calculated construction of the isochronous creep curves, were based on the unique experimental data of long duration obtained for a metal melting and these methods didn't make provision for the scatter of

Table 2: Creep rate
Tabela 2: Hitrost lezenja

t/ h	100 MPa					
	T = 500 °C	*T* = 500 °C extrapolation	*T* = 525 °C	*T* = 525 °C interpolation	*T* = 550 °C	*T* = 550 °C extrapolation
100	2,876E-07	1,538E-07	5,725E-07	7,713E-07	1,891E-06	1,070E-06
500	1,448E-07	2,392E-08	1,923E-07	4,535E-07	1,280E-06	2,490E-07
1 000	1,073E-07	1,590E-08	1,258E-07	3,124E-07	8,251E-07	1,454E-07
5 000	5,821E-08	4,107E-08	7,823E-08	9,236E-08	1,405E-07	1,023E-07
10 000	4,488E-08	3,451E-08	6,450E-08	7,310E-08	1,139E-07	8,969E-08
20 000	3,460E-08	2,650E-08	5,318E-08	6,039E-08	1,002E-07	7,860E-08
30 000	2,972E-08	2,270E-08	4,750E-08	5,401E-08	9,296E-08	7,276E-08
40 000	2,668E-08	2,034E-08	4,385E-08	4,990E-08	8,816E-08	6,888E-08
50 000	2,454E-08	1,867E-08	4,121E-08	4,693E-08	8,461E-08	6,602E-08
60 000	2,291E-08	1,742E-08	3,917E-08	4,463E-08	8,182E-08	6,376E-08
70 000	2,163E-08	1,642E-08	3,752E-08	4,278E-08	7,952E-08	6,192E-08
80 000	2,057E-08	1,561E-08	3,615E-08	4,123E-08	7,759E-08	6,036E-08
90 000	1,968E-08	1,492E-08	3,499E-08	3,992E-08	7,592E-08	5,903E-08
100 000	1,892E-08	1,433E-08	3,397E-08	3,878E-08	7,446E-08	5,785E-08

the data depending on the characteristics of melting and the variations in the mode of heat treatment. Thus the use of these methods in practice requires the application of certain stocks in the deformations (or the stresses).

Next step was getting a universal dependence of isochronous curves on temperature for any values (in a relatively narrow temperature range). The Arrhenius equation was used to describe the temperature dependence of creep rate in a narrow temperature range.

$$\dot{p}^{c} = \dot{p}_{0} e^{-\frac{U}{RT}} \tag{7}$$

where
U – activation energy of creep,
$R = 8{,}32 \cdot 10^{-3}$ kJ/mol·K – gas constant,
$\dot{p}_0$ – constant.

Table 2 and **Figure 8** show the values of creep rate obtained in the experiment by means of extrapolation and interpolation on temperature.

The comparison of the experimental values of the creep rate with the extrapolated and interpolated values on temperature in dependence on time, showed that their differences were 3–30 % and quite acceptable.

4 CONCLUSION

The new method of determining the extrapolated values of material creep resistance related to long-life was proposed.

The verification techniques relating the experimental data obtained previously for the steels R2M and EP291 by A. A. Chizhik were made.

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