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ON THE DIFFERENT NATURE OF TIME-DEPENDENT AND TIME-INDEPENDENT IRREVERSIBLE DEFORMATION

O RAZLIČNI NARAVI ČASOVNO ODVISNE IN ČASOVNO NEODVISNE IREVERZIBILNE DEFORMACIJE

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Several current models for elastoviscoplasticity use irreversible deformations without dividing them into time-dependent and time-independent components. This article presents experimental data on the difference in the mode of deformation and in the fracture conditions compared to the actual values. General functional dependences are proposed for the description of the dependence of the material characteristics from the conditions of exposure to high temperature. The interference of creep deformation and momentary deformation in conditions of static and cyclic deformations is investigated. A method is proposed for summing the irreversible deformations, taking into account their difference in nature.

Key words: elastoviscoplasticity, ireversible deformation, time dependence, separation

Več sedanjih modelov elastoviskoplastičnosti uporablja irevezibilno deformacijo brez ločitve v časovno odvisno in v časovno neodvisno komponento. V tem članku so predstavljeni eksperimentalni podatki o tem, da lahko to povzroči pomembno razliko v načinu deformacije in v pogojih preloma. Predlagana je splošna funkcijska odvisnost za opis karakteristik materiala v odvinosti od pogojev obremenitve pri visoki temperaturi. Raziskavna je interferenca deformacije z lezenjem in trenutne deformacije v pogojih statične in ciklične deformacije. Predlagana je metoda za seštetje ireverzibilnih deformacij, ki upošteva razliko v njihovi naravi.

Ključne besede: elastoviskoplastičnost, ireverzibilna deformacija, časovna odvisnost, metoda ločitve obeh

1 INTRODUCTION

Some of the current models of plasticity consider time-dependent irreversible deformations separately from time-independent deformations[1]. At the same time, the parameters of a number of other models for plasticity are time-dependent components of the tensor of plastic deformation. This paper presents experimental data confirming that in a number of cases it is not correct to use the second approach and it is more appropriate to use the models of thermoelastoviscoplasticity (and thermoviscoelastoplasticity, according to the classification of Perzyna[2]) and the division of irreversible deformations into time-dependent and time-independent components. It should be noted that the question about such divisibility (on the basis of the notion of momentary deformation curves introduced by Yu. N. Rabotnov) was resolved positively in experimental studies of different alloys based on iron and nickel. The results of an experimental study pertaining the conditions of a uniaxial stress state were observed mainly for heat-resistant steels and alloys.

2 MICROSTRUCTURAL PECULIARITIES OF DEFORMATION PROCESSES

It is known that because of the different crystallographic orientation of the grains in polycrystalline metal materials, microstresses in such materials differ considerably (also because of the anisotropy of the coefficient of elasticity) from the average stresses both by the value and by the direction of the deviator vector. For this reason, the microplastic deformations differ considerably in terms of value from the average deformation and this induces residual stresses usually referred to as residual stresses of type II, which cause the Bauschinger effect and plastic hysteresis. It is evident that the time-independent microplastic deformations and microcreep deformations may take place both when deforming with stresses higher and lower than the elastic limit and may produce the relaxation of internal stresses of type II. B. I. Rovinsky and V. G. Liuttsau[4] have linked the processes of micro- and macrocreep and have shown that the character of the process of microstress relaxation was similar to that of macrostress relaxation.

Which deformations, microplastic or microcreep, are larger in magnitude in conditions of stresses under the elastic limit (σ_y), including cyclic stresses, is the question that can only be answered on the basis of experimental results. It is known, as proved by the analysis of data on the microdeformations of different materials under single loading[5], that at low temperatures the microplastic deformations are considerably larger. However, in the case of cyclic deformation the process of development of microplastic deformations in many materials is slowed as the number of cycles increases, whereas the rate of accumulation of microcreep deformations under cyclic

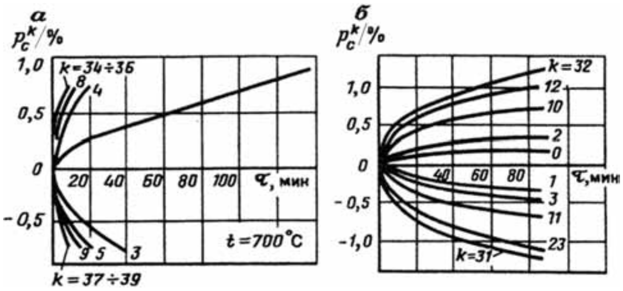

Figure 1: Cyclic creep curves for the alloy EI765 at 700 °C. (a) hard loading cycle, (b) soft loading cycle,
a) τ_c = 290 MPa, $\Delta\varepsilon$ = 1,2 %; b) τ_c = 272 MPa (τ_c – elastic limit)
Slika 1: Krivulje cikličnega lezenja za zlitino EI 765 pri 700 °C. (a) cikel trde obremenitve, (b) cikel mehke obremenitve

alternating loading increases with the number of cycles (**Figure 1**). At high temperatures the microcreep deformations are considerably larger than the microplastic deformations.

These conclusions were confirmed by the author's electron microscope observations of the deformation relief on heat-resistant alloy samples with precipitation strengthening after momentary tension in vacuum under high temperature up to stresses that were considerably lower than the elastic limit (a), after keeping it in such conditions for a short period of time (b) and after a creep test (c). After unloading, the deformation relief of the alloy EI826 (ChN70WMTAlV) formed at 850 °C was investigated after momentary and prolonged loading up to σ = 220 MPa – 0.6 σ_c (**Figure 2**). After a longer loading time (1–4 h) and a creep test, the accumulation of a microcreep deformation of 0.1 % and the intense development of fine slip lines were discovered in the overwhelming majority of grains. (**Figure 2b**). By difference, in conditions of momentary loading (with a rate of 180–2400 %/h) after loading-unloading the packets of slip lines were found in only 30 % of grains (**Figure 2a**).

Particles of the second phase in heat-resistant alloys are efficient barriers for the development of conservative sliding and can be overcome with microplastic deformation only at high stress with the mechanisms of lateral sliding and cutting. At the same time, during prolonged loading at the stress $\sigma < \sigma_e$, the accumulation of creep deformation is controlled by dislocation creep over barriers. Besides, unlike the case of momentary loading, where shearing of grain boundaries (because of the strong off-orientation of the lattice) is not possible, by creep deformation inter-grain sliding may also occur and cause the accumulation of creep damage.

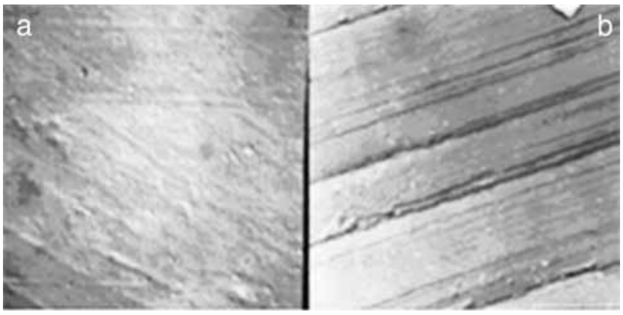

Figure 2: Microstructure of the alloy EI826 after momentary loading (a) and after prolonged loading (b) σ = 220 MPa at 850 °C
Slika 2: Mikrostruktura zlitine EI 826 po trenutni (a) in po podaljšani (b) obremenitvi

Thus, the analysis of the microstructural behavior of materials during deformation shows that it is useful to divide irreversible deformation into creep deformation and time-independent plastic deformation.

3 CREEP DEFORMATION CAPACITY OF MATERIALS

The deformation accumulated in a material at the moment of rupture, is, as a rule, considerably different in the cases for momentary loading and after a creep test. As an example, in **Table 1** the values of the residual elongation for two groups of steels and alloys after a short time deformation up to rupture and after long-term strength tests (in creep conditions) are shown. The alloys of group A have values close to the residual elongation after short-term tension and after a long-term strength test. This confirms the conclusion, considering the deformation at rupture, that for the materials of group B the equal residual deformation accumulated by momentary loading (ε) and in creep (p), may lead to considerably different values of damage ($\varepsilon/\varepsilon_f$ and p/ε_c). Thus, for such materials, the use of irreversible deformations without the separation into time-dependent and time-independent deformations may produce considerable errors in the determination of the margins of safety.

Table 1: Residual elongation after creep and after momentary loading
Tabela 1: Sposobnost za deformacijo v primeru lezenja in trenutne obremenitve

Material	Group	Temperature, °C	Residual elongation (%) under	
			Long-time rupture (100–1000 h)	Momentary tension
22*K*	A	500	21–23	24
15ChM		520	15–31	21
12Ch1MV		500	34–41	21–22
10Ch18N10T		650	9–45	27–37
25Ch2M1V	B	550	1,0	14
EI481		600	1–3	12
EI612		600	1–3	15–25
EI765		700	10–13	20
EI826		800	4–7	14
EI827		800	2–6	18
EP220		900	2–3	10

Table 2: Influence of a long ageing time on the residual deformation
Tabela 2: Vpliv dolgega staranja na rezidualno deformacijo

Material	Temperature and time of preliminary aging		Stress, temperature and time to rupture in the creep test			Residual deformation (%)	
	T/°C	τ/h	σ/MPa	T/°C	τ_f/h	Momentary loading, ε_f	Creep, ε_c
EI787	–	–	350	650	8000	20	1,6
	650	50000	350	650	442	6	15,0
EP99	–	–	200	800	374	50.2	24
	800	5000	200	800	193	5.0	20.4
EP126	–	–	100	800	684	41	28,8
	800	5000	100	800	151	16	10.0
EI481	–	–	300	650	1000	23	4
	650	40000	300	650	72	20	30

4 INFLUENCE OF EXPOSURE TO HIGH TEMPERATURES ON THE DEFORMATION CAPACITY

Special experiments were carried out to determine the influence of preliminary aging without any load on the alloy microstructure and its resistance to deformation in the cases of momentary loading and in creep conditions[6] (**Table 2**). It was found that the microstructural changes caused by long-term aging affect differently the residual elongation after momentary deformation and after creep and, as shown in **Table 2**, on the deformation capacities ε_f and ε_c. Thus, the microstructure of the material is related to its mechanical state, which is a microstructural parameter.

Metallographic studies were also carried out during the deformation of samples of the alloy EI787 after aging for 50000 h at a temperature of 650 °C (state 2) in comparison with the initial state (state 1). For both states of material approximately equal values of yield stress (880 MPa and 900 MPa) were established with tensile tests (in the case of momentary loading). At the same time, the values of the plasticity and the time-to-rupture below 650 °C and a stress of 350 MPa were considerably different (**Table 3**).

Table 3: Influence of microstructure of the alloy EI787 on it deformation characteristics
Tabela 3: Vpliv stanja mikrostrukture zlitine EI787 na deformacijske značilnosti

Temperature of tests, T/°C	650		700	
State	1	2	1	2
Stress, σ/MPa	730–870	460–470	380–460	280–290
Number of grain borders where sliding is observed, (average), %	13.5	4.5	25	13.5
Share of deformation localized on the grain borders, %	3.3	0.5	8.2	1.6
Average value of inter-grain creeping, μm	0.098	0.018	0.326	0.072
Observed microcracks	2	0	10	0

The samples in these two states were deformed at a rate of 1 %/h until a total deformation of 1.9 % was accumulated at 650 °C and until 2.2 % deformation at 700 °C. The assessment of the microstructure in the axial and transverse directions has shown that (see **Table 3**):

- the aging processes decrease the deformation resistance for momentary loading of the alloy EI787;
- the aging process decreases the deformability of the alloy in the region of grain boundaries;
- the deformation capacity with short-term rupture is higher in the initial state than in the aged state, while during long-term rupture it is higher in the initial state than after ageing.

5 PHENOMENOLOGICAL DESCRIPTION OF THE CHARACTERISTICS OF THE MATERIAL

The described experimental data demonstrate that it is useful to expand the principle of development of the creep equation with the microstructural parameters of Rabotnov s_i, $i = 1...n$[3]

$$p^{\bullet}= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),\ .....T,\ \sigma) \qquad (1)$$

for which the inclusion of other material characteristics:

$$\begin{aligned}
\sigma_B &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),\ ....T,\ v)\\
\sigma_{0,2} &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),\ ....T,\ v)\\
\sigma_{lts} &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),\ ....T,\ \sigma)\\
\delta &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),...\ T,\ v) \qquad (2)\\
\Delta\varepsilon &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),...\ T_{max},\ T_{min},\ N,\ \tau_c)\\
S_{0,4} &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),\ ....T,\ v)\\
dl/d\tau &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),...\ T,\ K_1)\\
dl/dn &= F(s_1(\tau,T),s_2(\tau,T),s_3(\tau,T),...\ T,\ K_1)
\end{aligned}$$

where v is the deformation rate, τ_c, T_{max}, T_{min}, N are the cycle period, the maximum and minimum cycle temperature, the number of cycles up to the fatigue crack's appearance during thermo-cyclic loading, and K_1 is the stress-intensity factor.

The problem was formulated[7] and the solution consisting of the determination of indices for the description of the state of the material's microstructure and its physical relation to the parameters $s_1(\tau,T), s_2(\tau,T), s_3(\tau,T)$ was found with the Eqs (1) and (2).

For this reason, for the determination of the margins of safety for components operating at high temperature, it is useful to link the parameters of their strained and stressed state to the material characteristics of the actual microstructure.

Taking into account the different nature of momentary plastic deformation and creep deformation, it is preferable to use models of thermo-visco-elasto-plasticity, where irreversible deformations can be divided. In this case the accumulated damage was determined on the basis of the deformation criteria:

$$D = D_1 + D_2$$
$$D_1 = \varepsilon/\varepsilon_\mathrm{f},\ \ D_2 = p/\varepsilon_\mathrm{c} \tag{3}$$

Having accepted the described approaches to the estimation of the deformation mode and of safety factors, considering the changes in the material's microstructure, it is necessary to have data on the kinetics of change of the characteristics used for a strength calculation in the process of holding the material at high temperature for a long time: yield point $\sigma_{0.2}$, plasticity δ, creep rate $p^{\bullet}$, creep crack-growth rate $\mathrm{d}l/\mathrm{d}\tau$, cyclic deformation resistance $S_{0.4}$, thermal fatigue resistance $\Delta\varepsilon$ and long-term strength σ_lts.

6 INTERFERENCE OF PROCESSES OF CREEP AND MOMENTARY DEFORMATION

For the case of the division of irreversible deformations as a measure of deformation damage to use in calculations, the equivalent irreversible deformation, defined in Eq. (4), can be used:

$$\varepsilon_\mathrm{eq} = \varepsilon + p\varepsilon_\mathrm{f}/\varepsilon_\mathrm{c} \tag{4}$$

In **Figure 3** the influence of creep deformation on the resistance to the momentary deformation of steel EI723 below 550 °C, is shown, which confirms the validity of the Eq.(4).

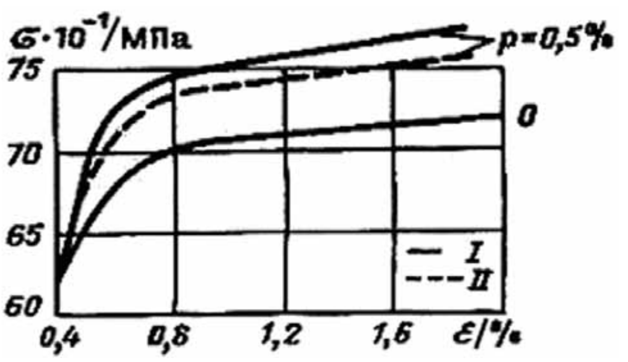

Figure 3: Influence of creep deformations on the resistance to momentary deformation of the steel EI723 at 550 °C, I —— experiment, II- - - - calculation

Slika 3: Vpliv deformacije z lezenjem na odpornost jekla EI 723 proti trenutni obremenitvi

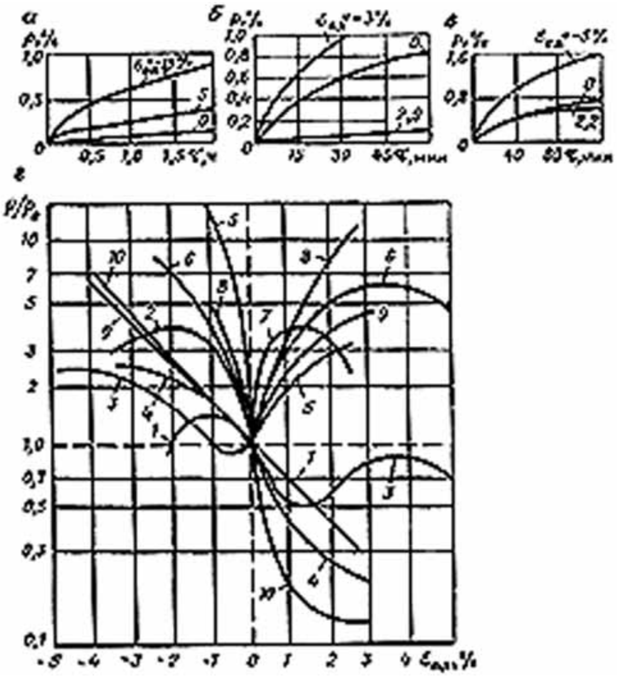

Figure 4: Dependence accumulated deformation related to the creep deformation after preliminary plastic deformation versus creep deformation in the initial state related to the value of the preliminary plastic deformation for different alloys and steels

a) EI765 at 750 °C; σ = 400 MPa, b) 20Ch23N18 at 750 °C, σ = 130 MPa, c) 15Ch12WNMV at 550 °C, σ = 320 MPa, d) 1-EI723 at 550 °C, σ = 550 MPa, τ = 1 h; 2-EI802 at 500 °C, σ = 400MPa, τ = 1 h; 3-EI802 at 550 °C, τ = 1 h, σ = 320 MPa; 4-20X23H18 at 750 °C, σ = 130 MPa, τ = 1 h; 5-EI765 at 750 °C, σ = 400 MPa, τ = 1 h; 6-EI765 at 700 °C, σ = 600 MPa, τ = 1 h; 7-EI698 at 700 °C, σ = 500 MPa, τ = 100 h; 8-EI698 at 750 °C, σ = 420 MPa, τ = 1 h; 9-EI607 at 650 °C, σ = 520 MPa, τ = 1 h; 10-20Ch23N18 at 800 °C, σ = 60 MPa, τ = 50 h

Slika 4: Razmerje akumulirana deformacija z lezenjem proti trenutni deformaciji v odvisnosti od razmerja deformacija z lezenjem proti predhodni plastični deformaciji za različne zlitine in jekla

The influence of momentary plastic deformation on the creep resistance depends on both the alloy composition and the direction of the preliminary deformation. In **Figure 4** the curves of the dependence of the accumulated creep deformation after preliminary plastic deformation related to the creep deformation in the initial state on the value of the preliminary plastic deformation at the same temperature are shown The experiments were carried out with ε varying from –5 % to +5 %. It was shown that even with a similar direction of deformation different alloys behave differently – some alloys get stronger and others become softer. In the case of a different direction of deformation, all the materials get stronger.

For the cyclic alternating deformation the character of the interference of creep deformation and momentary plastic deformation has specific features. A series of cyclic deformation tests was carried out for three levels of deformation amplitude with hard loading both in cyclic tension-pressure and in cyclic torsion. The values of the cyclic elastic limits were determined in cycles

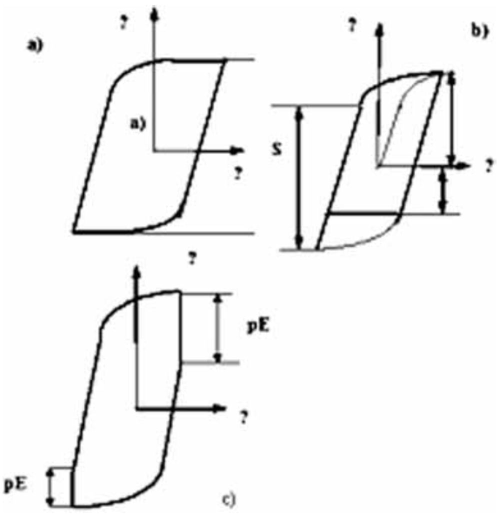

Figure 5: Cycles with the creep in bipolar semi-cycles (a,b) and in one semi-cycles (c)

Slika 5: Cikli z lezenjem v bipolarnih pol ciklih (a,b) in v eneme pol ciklu (c)

without creep, with creep in both semi-cycles, and with creep in one semi-cycle[8]. The creep deformation in the cycle did not exceed 1%. **Table 4** shows the values of the cyclic creep limit in relative units $\overline{S}_e^{(\kappa)} = S_e^{(\kappa)}/\sigma_e^{(0)}$, observed after the stabilization of the curves of cyclic deformation.

Table 4: Values of cyclic elasticity limit $\overline{S}_c^{(\kappa)}$

Tabela 4: Vrednosti ciklične meje elastičnosti $\overline{S}_c^{(\kappa)}$

Material	T/°C	$\overline{S}_c^{(\kappa)}$	
		Without creep	With creep in both semi-cycles
20Ch23N18	400	4.3	1.8
EI868	600	2.0–2.9	1.8
	700	2.5	1.8
EI765	700	1.9	1.4–1.7
EP220	900	1.9	1.3

The acceleration of creep from cycle to cycle is observed in case of cyclic deformation with creep in one semi-cycle (**Figure 5**). It was also found that the creep has a softening effect on the curve of cyclic deformation in the next semi-cycle: 1) the cyclic elastic limit decreases by the value ($S_{\max}/2$) – σ_{creep} (σ_{creep} – sample ageing stress); 2) during this aging partial annealing occurs, which lowers the cyclic strengthening. The analysis of experimental data has shown that the curves of deformation after creep on different levels may be described as central-like (curves with a constant relation in different points) with the similarity coefficient $\alpha_?$ in relation to the curve of deformation for the cycle without creep (with the same deformation amplitudes):

$$\alpha_c = A + B\,\sigma_{\text{creep}}/\sigma_c \qquad (5)$$

where A and B are temperature-dependent coefficients of the materials.

7 CONCLUSIONS

1. On the basis of results of experimental studies it was determined that the division of irreversible deformation into time-dependent and time-independent is necessary and expedient.
2. A general form of correlation was proposed for the description of the dependence of the material characteristics for the conditions of long-term exposure at high temperature.
3. Particularities of the interference of creep deformation and momentary deformation in conditions of static and cyclic deformation were established experimentally.
4. A method was proposed for the summing of the irreversible deformations, taking into account the difference in their nature.

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