Influence of Form of Loading and Heating Cycle on Resistance to Long-Term Low-Cycle Fracture

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Summary

In connection with the investigation of the regularities of long-term low-cycle fracture, strain-kinetic criteria of strength, taking into account the influence of nonisothermality, strain ageing of materials, combinations of loading and heating cycle and sign of stresses at the extremum cycle temperature and long-term dwell, have been proposed and experimentally established.

The results of the investigation of low-cycle strength of structural materials of the type 18Cr-9Ni (steel I), 18Cr-12Ni-1,0Ti-Al (steel II), Cr-Mo-V (steel III) are discussed. The influence on durability of operation factors such as phasing of loading and heating cycles, range of temperature changes in the cycle ets. - is established. It is shown that the material life at specified strain amplitude substantially depends on abovementioned loading factors and may be lowered by the factor of 10 comparing with the experimental results at isothermal loading. Dependences for damage evaluation are given.

The basing of the methods of low-cycle fatigue estimation of components, working under conditions of variable and elevated temperatures, demands the development and experimental grounding of the conditions of reaching the limiting state in fracture (crack forming) taking into account different working factors: presence of dwells in the cycle, frequency of loading, phasing of loading and heating cycles, range of temperature changes in the cycle, etc [1,2] . For studying the effect of the above mentioned factors of loading on the limiting number of cycles before fracture, testing of a number of structural materials, used for pressure vessels in chemical and energetic machine building, has been performed. Austenitic stainless steel I which is cyclically stabilizing material with marked dependence of plasticity on time, heat-resistant cyclically softening steel of the type III and stainless cyclically hardening steel II characterized by stable plasticity have been investigated. These materials were tested at constant and variable temperature in modes with controlled strain amplitude and controlled stress amplitude [3] .

In non-isothermic tests, loading was performed at cophasal and counterphasal variations of the temperature in the cycle (Fig. 1). Temperature conditions of testing are presented in table I. In all the cases the strain varied according to the linear low, the temperature varied both linearly and in steps when passing the zero value of the load.

The performed program of tests showed that for steels of the type I and II the life at a given strain amplitude largely depends on the mode of loading and heating. The cycles with cophasal variation of strain and temperature led to the lowering of life up to factor of 10 in comparison with the results of isothermic tests; for counterphasal cycles the obtained data were near to the results at constant temperature (Fig.2,a,b).

For the steel III at non-isothermic loading, life was 1,5 - 2 times lower for modes with cophasal variation of temperature and strain (Fig. 2,c).

On the basis of obtained data for the estimation of damage in the cycle at non-isothermic loading the following relation was suggested [3] :

$$\Delta d_f = \int_{\Sigma} \alpha(T)\,\varepsilon_p\, d\varepsilon_p + \int_{\Sigma^+} \lambda(T)\,\varepsilon_p\, d\varepsilon_p - \int_{\Sigma^-} \lambda(T)\,\varepsilon_p\, d\varepsilon_p \qquad (1)$$

where Σ is the integration region corresponding to the complete cycle of the variation of strain and temperature; Σ^+ - tension half-cycle ($\sigma > 0$) and Σ^- - compression half-cycle ($\sigma < 0$). In this expression the function $\alpha(T)$ is determined from tests in isothermic conditions, when the last two integrals are equal and give zero. In this case $\Delta d_f = \alpha(T)\,\varepsilon_p^2$. If damage in one cycle at base temperature T_o is 1/No (No - is the number of cycle up to the appearance of the crack), for any temperature T

$$\alpha(T) = \frac{N_o}{N}\,\alpha(T_o) \quad . \qquad (2)$$

The function $\lambda(T)$ is determined from non-isothermic tests in which the

temperature level is constant but different for half-cycles of tension and compression (temperature is varied when passing zero value of the load). From (1) and (2) we derive:

$$\lambda(T) = \frac{2N_o}{N} \alpha(T_o) - \left(1 + \frac{\alpha(T)}{\alpha(T_o)}\right) \alpha(T_o) + \lambda(T_o) .$$

The curves $N_o/N - T$, which were used for the calculation of the function $\lambda(T)$ of steels I and II are shown in Fig. 3. In this figure N_o corresponds to the temperature $T_o = 150^\circ$ for steel I and $T_o = 200^\circ$ for steel II.

Equation (1) was used for the calculation of damage of steel II in cycles with linear variation of temperature and strain in the time, Fig. 1,b. The results of the calculation are in good accordance with the value of damage estimated on experimental data of specimen lives as shown in table II. In this table I_1, I_2 and I_3 are accordingly the first, the second and the third integrals in equation (1). $\Delta d_f^{(c)}$ and $\Delta d_f^{(e)}$ - are damages calculated on eq. (1) and on experimental value of lives, devided on damage in cycle with temperature $T = 200^\circ C$ = const. It should be noted that if $I_3 > I_2$ experimental lives of specimens do not increase, so only the first integral in eq. (1) must be accounted at the estimation of damage in this case.

In the general case of non-isothermic loading both fatigue and quasi-static damage can accumulated in materials. As it is shown in [4] for steel I in this condition the linear summation of these compenents of total damage is possible. The criterium relation is given in the form of the following equation:

$$d_f + d_s = 1$$

where d_f is defined using eq. (1) as $d_f = \Delta d_f \cdot N$

and $$d_s = \int_0^{e_f} \frac{de_{ir}}{\varepsilon_f(t)}$$

where e_{ir} is one - sided accumulated deformation in static and cycle loading, $\varepsilon_f(t)$ - is plasticity of monotonous loading (available plasticity) or creep plasticity, e_f - is one-sided accumulated deformation at the fracture moment (crack appearance).

For steel I value $\varepsilon_f(t)$ under non-isothermic loading was defined using the parameter of Larsen-Miller. The following procedure was used. A non-isothermic deformation cycle (Fig. 1) was separated into a number of intervals (for example 10) i.e. $\Delta t = 0{,}1\, t$ cycle. It was supposed the process took place at the constant temperature $T(t)$ at each time interval. The computer integration gives an opportunity to determine a parameter value P at non-isothermic loading. The agreement between the calculated values for non-isothermic loading and experimental data for constant temperatures is enough satisfactory (Fig. 4). The method mentioned permits to determine the material available plasticity at any non-isothermic conditions on a basis of elasticity data of material in isothermic conditions.

For nonageing materials of the types III and II creep plasticity at constant and variable temperature was equal (Fig. 5).

The calculation of total damage for non-isothermic loading with controlled stress amplitude when the accumulation of fatigue and quasistatic damages is possible shows a satisfactiry agreement between the data and the deformation-kinetic criterion of creep low-cycle fatigue non-isothermic strength (Fig. 6). The total damage value is located in the scatter band from 0,5 - 1,5, which indicates the possibility of using the equations (1) and (2) for strength calculation at non-isothermic loading.

References

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[2] Gussenkov A.P. "Strength at isothermic and non-isothermic low-cycle loading". M., "Nauka", 1979.

[3] Kazantsev A.G. "Estimation fatigue damage of long-term low-cycle isothermic and non-isothermic loading". Problems of strength, 1981, v. 6.

[4] Gussenkov A.P., Kazantsev A.G. "Strain-kinetic criteria of long-term low-cycle fatigue at non-isothermic loading". Proceedings of the VIIth Congress on material testing , Budapest, 1978.

Table I

Temperature conditions of testing

Material	T = const, °C	T = var
I	500, 550, 600, 650, 700	150 ⇄ 650 modes a,b, c,f, Fig. 1.
II	600	200 ⇄ 600 modes b,c, Fig. 1. 200 ⇄ 700 mode b, Fig. 1.
III	100, 500	100 ⇄ 500 mode b, Fig. 1.

Table II

Value of fatigue damage for different types of non-isothermic loading

T °C	I_1	I_2	I_3	$\Delta\alpha_f^{(c)}$	$\Delta\alpha_f^{(e)}$
200 ⇄ 700	1,06	5,7	1,31	5,45	5,9
200 ⇄ 600	1,02	2,27	0,72	2,57	3,16
400 ⇄ 700	1,13	7,64	3,08	5,69	5,18
600 ⇄ 700	1,24	11,0	8,5	3,74	2,81

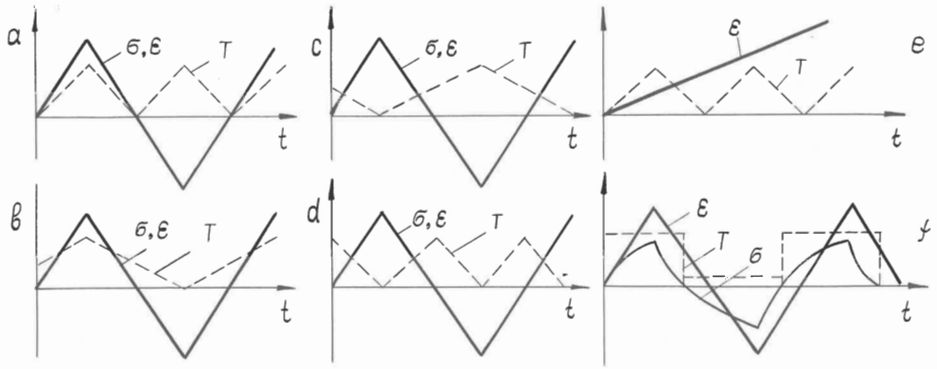

Fig. 1. Modes of the nonisothermic loading.

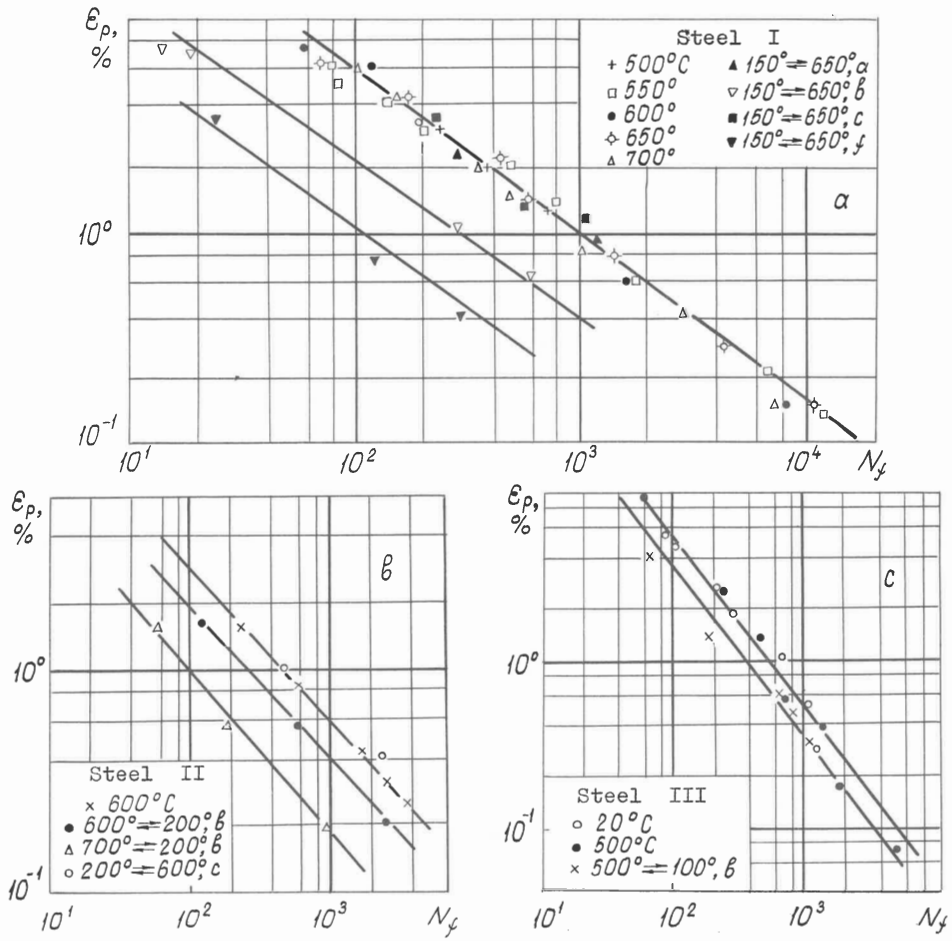

Fig. 2. Fatigue low-cycle curves of isothermic and nonisothermic loading steels 18Cr-9Ni (a), 18Cr-12Ni-1,0Ti-Al (b) and Cr-Mo-V (c).

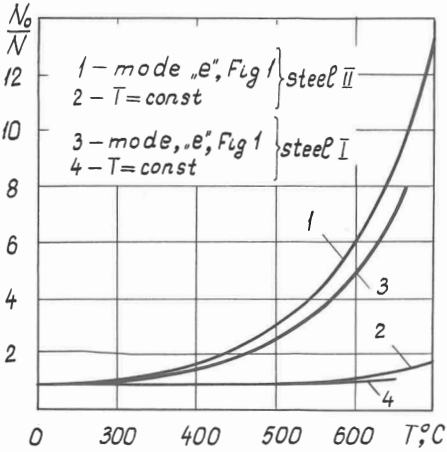

Fig. 3. Relations between N_0/N and maximal temperature of cycle for isothermic and nonisothermic loading of the steels 18Cr-9Ni and 18Cr-12Ni-1,0Ti-Al.

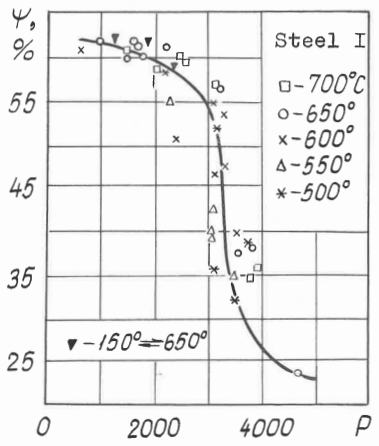

Fig. 4. Parametric curve of the creep plasticity $\Psi - P$ for steel 18Cr-9Ni.

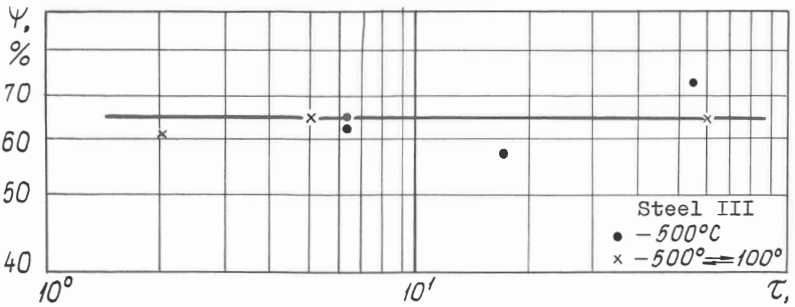

Fig. 5. Relations between isothermic and nonisothermic creep plasticity of the steel Cr-Mo-V and fracture time.

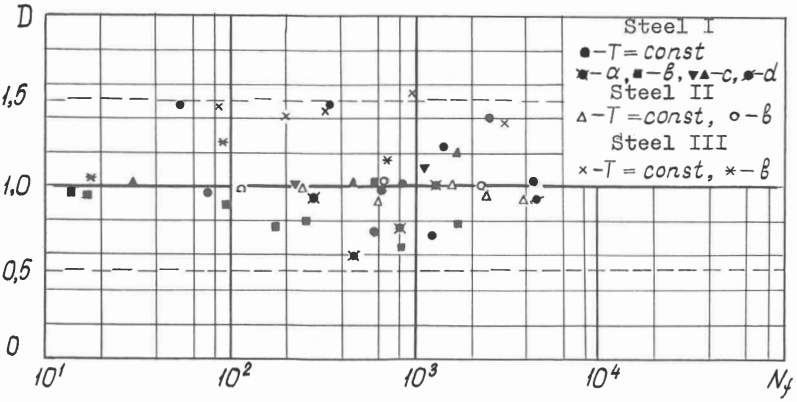

Fig. 6. Total accumulated damage for different modes of the nonisothermic loading.