ANALYTICAL DESCRIPTION OF THE IRREVERSIBLE DEFORMATION OF METALS DURING THERMOCYCLING

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A theory of the nonisothermal deformation of metals was developed in [1]. This theory also describes the deformation of a loaded body in the case of temperature oscillations. Below, we use this theory to analytically describe irreversible deformation due to the thermocycling of a metallic specimen which is free of external laods.

1. Growth Coefficient. Experiment and Theory. The relative irreversible (plastic) deformation in one complete cycle of thermal loading will be referred to as the growth coefficient γ, in accordance with [2]. As was noted in [2], about 10-20 cycles are usually sufficient for γ to assume a steady value. In addition, since it rarely exceeds $5 \cdot 10^{-5}$ 1/cycle, then the relative change in dimensions after this number of cycles will be no greater than 0.1%. Thus, it does not make sense to consider the dependence of the shape change on the number of previous cycles when the specimen is subjected to several thousand or tens of thousands of thermal cycles and undergoes a dimensional change of tens or hundreds of percent.

An analysis of numerous experiments led the authors of [2] to the conclusion that γ is determined mainly by the temperature interval and region and the time the specimen spends at the upper and lower temperatures of the interval. Given sufficiently rapid thermal cycling, it is almost independent of the heating and cooling rate. In any case, the rate of cycling is not the main determining factor, since it can be ignored in calculations and the change in temperature can be assumed to be instantaneous.

Equations (6.5) and (6.6) obtained in [1] are reproduced below:

$$\varepsilon_*^{\mathrm{p}} = \varepsilon_0^{\mathrm{p}} + B|\Delta T|/c; \tag{1.1}$$

$$c\varepsilon^{\mathrm{p}} = c\Delta\varepsilon_*^{\mathrm{p}} + K\alpha_* t + \frac{B}{\beta}\left[Kt - \left(1 - \frac{K}{\beta}\right)(1 - \exp(-\beta t))\right]|\Delta T|, \tag{1.2}$$

where ε^{p}, $\varepsilon_0^{\mathrm{p}}$, $\varepsilon_*^{\mathrm{p}}$ are the total plastic strain and the plastic strains at the beginning and end of the temperature jump, respectively; ΔT is the instantaneous increment in temperature; t is time; B, K, α, β, and c are material constants.

In accordance with these formulas, the instantaneous change in the temperature of a specimen, in the form of a thin-walled cylindrical tube, which is free of external loads and is textured when subjected to uniaxial loading results in the plastic strain

$$\Delta\varepsilon_T^{\mathrm{p}} = \frac{B}{c}\left[1 + \frac{1}{\beta}(1 - \exp(-\beta t))\right]|\Delta T|. \tag{1.3}$$

In accordance with (1.3), at the moment of the temperature jump ($t = 0$, $\Delta T \neq 0$), strain increases to a finite value $\Delta TB/c$. Then, at $\Delta t \neq 0$, $\Delta T = 0$, there is a further increase in strain at a decaying rate. This is consistent with the experimental data [2]. Let one complete thermal cycle consist of an instantaneous increase in temperature, holding at a fixed maximum temperature, an instantaneous decrease in temperature, and holding at a constant minimum temperature. In this case, (1.3) describes the increment in strain during a thermal half-cycle (jump in temperature and its holding at the new level). Assuming that in the second half-cycle the strain increment obeys the same law as in the first half-cycle, we write the growth coefficient as follows in accordance with (1.3)

$$\gamma = A[1 + D(1 - \exp(-rt))]|\Delta T| \tag{1.4}$$

(A is a parameter of the material; D and r are constant coefficients).

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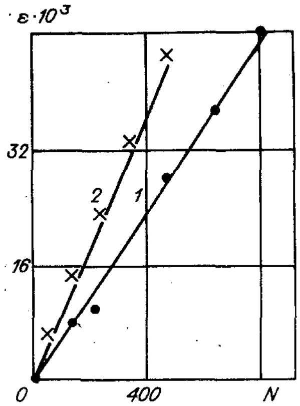

Fig. 1

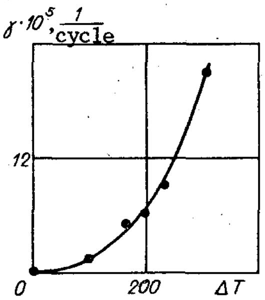

Fig. 2

It follows from [1] that A may depend on the temperature interval and on the absolute values of the upper and lower temperatures of the cycle. Thus, A can be found from a thermocycling experiment without holds at the upper and lower cycle temperatures, i.e., with the thermal cycles occurring instantaneously. In this case, D = 0 in (1.4). This means that $\gamma_i = A|\Delta T|$.

In the experiments described in the literature, the lower temperature of the cycle is generally kept constant while the upper temperature is changed [2]. Nearly exponential temperature dependences of γ have been obtained. It was shown in [2] that for thermally activated materials (by which we mean polycrystalline aggregates) the form change during thermal cycling occurs due to anisotropy of the coefficient of thermal expansion (uranium, zinc, cadmium, tin, etc.). Complete agreement with the test data is obtained if we assume that A depends on the dispersion of the activation energy and the upper temperature of the cycle: $A = a\exp(-\Delta Q/(RT))$, so that

$$\gamma_i = a \exp[-\Delta Q/(RT_1)]|\Delta T|; \tag{1.5}$$

$$\gamma = a \exp[-\Delta Q/(RT_1)][1 + D(1 - \exp(-rt))]|\Delta T|. \tag{1.6}$$

Here, a is a constant coefficient; ΔQ is the dispersion of activation energy; R is the universal gas constant; T_1 is the upper (maximum) temperature of the cycle.

We find the constant coefficients D and r from the experimentally determined change in γ in relation to the hold at fixed T_1. This increment γ is represented by the difference in its values in Eqs. (1.5) and (1.6)

$$\Delta\gamma = Da \exp[-\Delta Q/(RT_1)][1 - \exp(-rt)]|\Delta T|. \tag{1.7}$$

2. Growth Coefficient of Zinc. The formulas obtained above will be used to describe the growth coefficient of a typical representative of thermally anisotropic materials – zinc. Experimental data on the dependence of γ for zinc on the factors mentioned in Part 1 was presented in [3]. It follows in particular from this information that without a hold at a fixed temperature (T_1 = 533 K and ΔT = 250 K) $\gamma_i = 4 \cdot 10^{-5}$ 1/cycle. Inserting this value into (1.5) and considering that ΔQ = 3.5 kcal/mole for zinc, we find $a = 4.3 \cdot 10^{-6}$ 1/(K·cycle). The changes obtained experimentally [3] for γ due to holds at fixed T_1 are described well by Eq. (1.7) at D = 2.125 and $r = 9.87 \cdot 10^{-3}$ sec^{-1}.

Thus, the theoretical formula takes the form

$$\gamma = 4{,}386 \cdot 10^{-6} \exp(-764{,}74/T_1)[1 + 2{,}155(1 - \exp(-9{,}87 \cdot 10^{-3} t))]|\Delta T|. \tag{2.1}$$

Having used this formula, we can analytically describe the plastic strain of a thin-walled zinc tube which is free of external loads while being subjected to thermal cycles in the temperature range 283-483 K with different holds in the high-temperature zone (T_1 = const): 1) at t_1 = 120 sec, T_1 = 483 K and ΔT = 200 K from (1.8) $\gamma_1 = 5.622 \cdot 10^{-5}$ 1/cycle; 2) at t_2 = 600 sec, T_1 = 483 K and ΔT = 200 K from (1.8) $\gamma_2 = 9.085 \cdot 10^{-5}$ 1/cycle. If we multiply γ_1 and γ_2 by the corresponding number of cycles N, we obtain the strain with holds t_1 = 120 sec (line 1 in Fig. 1) and t_2 = 600 sec (line 2). The points and x' show the test results reported in [2].

Let us also examine the dependence of γ on the temperature interval in the case when the hold at the upper cycle temperature is long enough for all relaxation processes to occur during this time. It follows from Eq. (2.1) that a hold of 15-20 min at fixed T_1 is sufficient. Let us study the case $t_* = 20$ min. We take the following temperature intervals: $\Delta T = 100$, 200, and 300 K. As in the experiments in [3], we take the same value for the lower temperature in all of the cycles: $T_0 = 283$ K. Then $T_1 = 383$, 483, and 583 K for all of the chosen temperature intervals. Inserting the values of T_1 and ΔT into Eq. (2.1) at $t = t_* = 1200$ sec, we obtain the corresponding growth coefficients: $\gamma_1 = 1.37 \cdot 10^{-5}$, $\gamma_2 = 7.1 \cdot 10^{-5}$, $\gamma_3 = 20 \cdot 10^{-5}$ 1/cycle.

A line is drawn through the theoretical values of the growth coefficient in Fig. 2. The experimental results are shown by points. The positions of the points shows that the results obtained theoretically agree completely with the experimental data.

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BEHAVIOR OF RUBBER IN SHOCK WAVES AND RAREFACTION WAVES

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There is no literature data on the properties of filled elastomers under shock-loading conditions. Despite this, rubber-like materials are used to damp pulses from shock compression and to solve other practical problems. The behavior of such materials under normal conditions is distinguished by several specific features [1, 2]; it is interesting to determine the degree to which these features of filled elastometers are manifest during intensive shock loading.

The present article reports results of the recording of the shock compression, unloading, and dynamic tension of vacuum-treated white rubber of grade 7889.

The specimens were cut from a sheet 1 cm thick. The measured density of the specimens was 1.34 g/cm³. The speed of sound at atmospheric pressure was 1.5 km/sec. Tests in simple tension conducted at a rate of 10^{-2}-10^{-3} $\sec^{-1}$ showed that the initial Young's modulus of the rubber lies within the range 2-3 MPa, while the true breaking stress $S_n = 88$ MPa. At the moment of rupture, the relative elongation of the working part of the specimen was 609%. The permanent set after rupture was about 10%.

Plane shock waves (SW) were created in the specimens by strikers 2-7 mm thick made of aluminum or organic glass, as well as by the explosive detonation of lenses in direct contact with the specimen. The strikers were propelled by explosive devices described in [3, 4]. The pressure associated with the shock compression was varied by changing the velocity of the strikers and by using shields with different dynamic stiffnesses. The shields were placed between the striker and the specimen. We used manganin transducers to record the pressure profile P(t) in the specimen at the boundary with the shield and at a prescribed distance from it. We also used the method of Doppler laser interferometry [5, 6] to record the velocity profiles of the rear surface of the specimens u(t) in cases when the pressure pulse exited into a barrier with a low dynamic stiffness or into air.

Figure 1 shows results of measurements of the evolution of pressure profiles 1-4 in the rubber. These results are for the loading conditions shown in Table 1. No qualitative features connected with the specific properties of the rubber were seen on the P(t) profiles in the investigated range of pressures from 2 to 6 GPa. The incompleteness of the unloading

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