CREEP AND LONG-TERM STRENGTH OF LIGHT ALLOYS WITH ANISOTROPIC PROPERTIES

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In this article, we describe the experimental data on the creep and long-term strength of D15AT alloy with anisotropic properties. For creep in the plane stressed state, we generalized the plasticity theories proposed by R. Hill for an anisotropic material with isotropic hardening. The numerical values of the coefficients in the equations of state and in the kinetic equation for damage were determined from the experimental results. The calculated and experimental data on creep of rectangular plates are compared.

We examined the results of creep tests in uniaxial tensile loading flat specimens made of sheets of D16AT material. The specimens were cut along (1) and across (2) the rolling direction and also under an angle of 45° to direction 1 (3). The tests were conducted at constant temperatures (275 and 300°C) and constant tensile load in AIMA-5-2 equipment. For each load level we tested at least three specimens and in each sampling direction tests were conducted at least on three load levels. Some of the test results were used to determine the lateral creep strains. On the whole, we tested 61 specimens with a gauge length of $6.6 \cdot 10^{-2}$ m.

Strain gauges were fixed to the specimens and the main strains were determined from the mean readings of two dial-type displacement indicators. Since the material did not harden, in determining the lateral strains it was possible to restrict our considerations to the data on the variation on the transverse dimensions of the specimens over the time period $\tau < t_*$, where t_* is the fracture time. Prior to the tests, the specimens were measured and after the tests direct measurements were taken to determine the residual changes of the dimensions of the cross section. The fulfillment of the condition of the uniformity of strains along the length of the specimen during time τ was checked.

For various values of the stresses σ_{0i} (i = 1, 2, 3 are the directions of cutting of the specimens, Table 1), Figs. 1 and 2 give the measured and averaged-out results of the tests on the specimens at T = 300°C. Figure 3 shows the averaged-out results of measurements of the strains on the specimens of the same material at T = 275°C.

Table 1 gives the mean values of fracture time t_* and corresponding strain p_* for the specimens for various stresses σ_{0i}.

On the basis of qualitative analysis of the data it may be assumed that the material examined is characterized by anisotropic creep properties.

To evaluate qualitatively the significance of the hypothesis on the anisotropy of the creep properties which is an alternative in relation to the assumption on the isotropy of the properties, the experimental results were statistically analyzed. For example, in comparing the endurances of the specimens at T = 275°C cut out in two main directions (i = 1, 2) it was established that, according to Fischer's test, the variances of the general sets with respect to the corresponding variances of the samples were equal to: $S_2^2/S_1^2 \simeq 1.2 < F_{1-\alpha} = 3.14$ for $\alpha = 0.05$. However, according to the criterion of equality of the mean values of the same two sets using the approximate t-test, we obtain $t = 2.34 > t'_{\alpha k} = 2.1$ for $\alpha = 0.05$; $k = 17$; this confirms the alternative hypothesis of the anisotropy of the creep properties of the examined sheet material at T = 275°C.

The results indicate that at T = 275°C, the material tested shows anisotropic creep properties, whereas at T = 300°C the material is almost completely isotropic. At the same time, the mean fracture strain on each temperature level may be assumed to be constant ($p_* = 0.16$ at T = 275°C and $p_* = 0.18$ at T = 300°C) and independent of the stress and the sampling direction of the specimens. Fracture of the specimens in the final stage took place with comparatively insignificant necking developed over a short period of time, and terminated in fracture.

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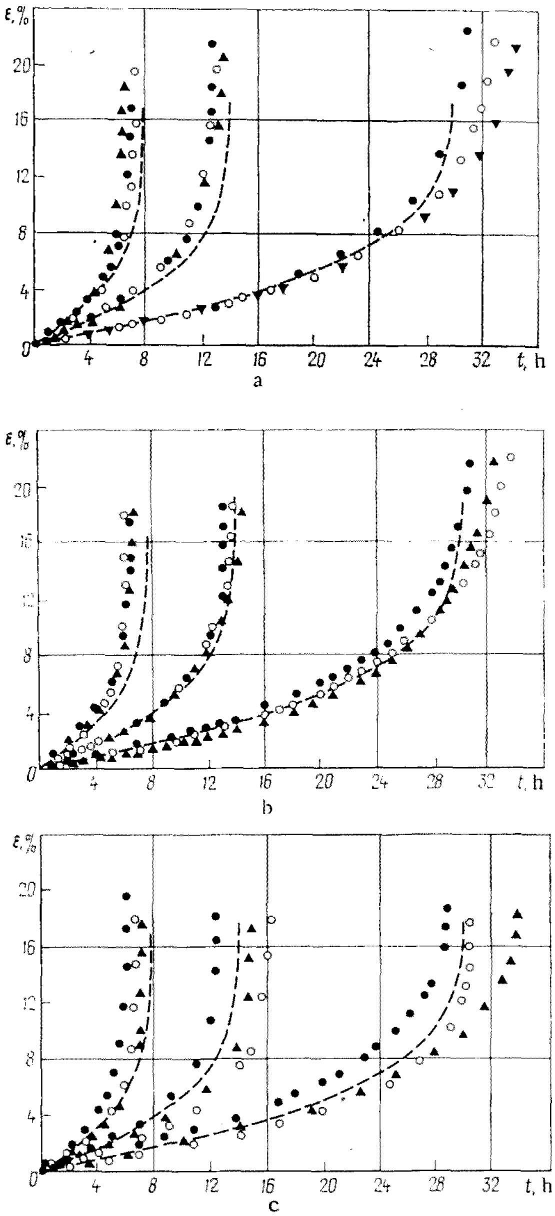

Fig. 1. Results of tests on specimens cut out in the directions 1 (a), 2 (b), and 3 (c) at various stresses and T = 300°C. (Broken lines are the creep curves obtained by integrating Eqs. (1).)

Analytical description of the creep curves up to fracture was carried out using the following dependences [1]

$$\dot{p}_i = A_i\,[(1+p)\sigma_0/(1-\omega^{r_i})]^{n_i}, \quad p(0)=0;$$
$$\dot{\omega} = B_i\,[(1+p)\sigma_0/(1-\omega^{r_i})]^{n_i}, \quad \omega(0)=0, \tag{1}$$

where A_i, n_i were determined on the basis of the data on steady-state creep of the material of the specimens cut out in the i-th direction. For example, at T = 300°C we determined $A_1 \approx A_2 \approx A_3 = 0.34 \cdot 10^{-7}$ MPa^{-n}/h, $n_1 \approx n_2 \approx n_3 = n = 2.93$; at T = 275°C $A_1 = 0.65 \cdot 10^{-9}$, $A_2 = 0.88 \cdot 10^{-9}$, $A_3 = 0.78 \cdot 10^{-9}$ MPa^{-n}/h, $n_1 = n_2 = n = 3.4$.

Averaging out the data obtained in the tests on the specimens of all the batches, we obtained that at T = 300°C, $p_* = 0.18$, and at T = 275°C $p_* = 0.16$.

As a result of integration of Eq. (1) taking into account $\omega(t_*) = 1$ it was established that

$$p(t) = (A_i/B_i)\,\omega(t); \quad p_* = A_i/B_i. \tag{2}$$

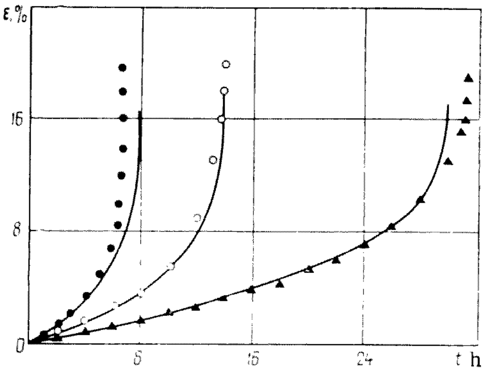

Fig. 2. Averaged-out experimental data for the specimens cut out in the three directions (here and in Fig. 3, the solid lines show the creep curves obtained by integrating Eqs. (1), the points give the averaged-out experimental data).

TABLE 1. Time and Fracture Deformation of Specimens

i	T=275 °C			T=300 °C		
	σ_{0i}, MPa	t_*, h	p_*	σ_{0i}, MPa	t_*, h	p_*
1	84,5	18	0,15	63,6	7	0,16
	74,4	30	0,16	52,9	13	0,18
	63,6	47	0,18	42,4	33	0,20
2	85	12	0,14	64,1	6,5	0,16
	75	22,5	0,16	52,9	14	0,18
	64,1	34	0,18	42,5	32	0,20
3	90	10,5	0,16	63,1	6,5	0,16
	—	—	—	52,6	14	0,18
	63,1	45	0,14	42,1	31	0,20

The results obtained in the calculations using the above equation show that at T = 300°C, $B_1 = B_2 = B_3 = 1.1 \cdot 10^{-7}$ MPa^{-n}/h, at T = 275°C $B_1 = 4.1 \cdot 10^{-9}$; $B_2 = 6 \cdot 10^{-9}$; $B_3 = 5 \cdot 10^{-9}$ MPa^{-n}/h. The parameters r_i were determined from the condition of correspondence between the experimental and theoretical values of fracture time t_{*i}. Equation (1) yields the equality

$$B_i \sigma_{0i}^{n_i} t_{*i} = \int_0^1 [(1-\omega^{r_i})/(1+A_i\omega/B_i)]^{n_i} d\omega \equiv I_i(r). \quad (3)$$

According to the data on creep at T = 300°C, we have $I_1 \approx I_2 \approx I_3 \approx I_m = 0.34$. It should be mentioned that $I_i(r)$ at T = 275°C is almost constant for all directions: $I_1 = 0.267$; $I_2 = 0.302$; $I_3 = 0.298$. After constructing the $I_i(r)$ functions, for I_m we determined the value r_i which was equal to 1.38, i.e., a constant which is independent of temperature and direction of cutting out the specimens.

After integrating the relations (1) using the values of the constants given above, we constructed the creep curves of the material tested.

Both for the isotropic (T = 300°C) and anisotropic (T = 275°C) creep, the calculated and experimental curves were in complete agreement. The fracture time can be calculated from the equation

$$t_{*i} = (A_i \sigma_0^n)^{-1} \int_0^{p_*} [1-(B_i p/A_i)^r]^n \quad (1+p)^{-n}\, dp.$$

It should be mentioned that for the anisotropic material for the same stress σ_0 the fracture time of the specimens cut out in various directions differs. At constant stresses the dependences (1) have the form

$$\dot{p}_i = A_i/[\sigma_0/(1-\omega^r)]^n; \quad \dot{\omega} = B_i\,[\sigma_0/(1-\omega^r)]^n. \tag{4}$$

The fracture time is calculated from the equation

$$t_{*i} = (B_i\sigma_0^n)^{-1}\int_0^1 (1-\omega^r)^n\,d\omega,$$

which gives that $t_{*1}:t_{*2}:t_{*3} = B_1^{-1}:B_2^{-1}:B_3^{-1}$ for the same stress σ_0. If the variability of the stresses in the quantitative respect is taken into account, the results are influenced only slightly. Integration of the relations (4) makes it possible to determine the creep curves differing from those obtained in integrating Eq. (1) by less than 9%; this value fits in the scatter band of the experimental data.

Creep of the orthotropic material in the plane stressed state is considered on the basis of creep theory of the yielding time which generalizes the well-known relations of the isotropic material [1, 2]. The relationship between the components of the tensor of the strain rates and stresses was accepted in the form

$$\left.\begin{aligned}
\dot{\varepsilon}_{11} &= \frac{3}{2}\dot{\Phi}\,[(a_{11}+a_{22})\,\sigma_{11} - a_{11}\sigma_{22} - a_{22}\sigma_{33}]/\sigma_l;\\
\dot{\varepsilon}_{22} &= \frac{3}{2}\dot{\Phi}\,[(a_{33}+a_{11})\,\sigma_{22} - a_{11}\sigma_{11} - a_{33}\sigma_{33}]/\sigma_l;\\
\dot{\varepsilon}_{33} &= \frac{3}{2}\dot{\Phi}\,[(a_{33}+a_{22})\,\sigma_{33} - a_{22}\sigma_{11} - a_{33}\sigma_{22}]/\sigma_l;\\
\dot{\varepsilon}_{12} &= \frac{3}{2}\dot{\Phi}a_{44}\sigma_{12}/\sigma_l; \quad \dot{\varepsilon}_{23} = \frac{3}{2}\dot{\Phi}a_{55}\sigma_{23}/\sigma_l;\\
\dot{\varepsilon}_{31} &= \frac{3}{2}\dot{\Phi}a_{66}\sigma_{31}/\sigma_l,
\end{aligned}\right\} \tag{5}$$

where σ_l^2 is the generalized equivalent stress,

$$\sigma_l^2 = \frac{3}{2}\,[a_{11}(\sigma_{11}-\sigma_{22})^2 + a_{33}(\sigma_{22}-\sigma_{33})^2 + a_{22}(\sigma_{11}-\sigma_{33})^2 + 2a_{44}\sigma_{12}^2 + 2a_{55}\sigma_{23}^2 + 2a_{66}\sigma_{31}^2];$$

$$\dot{\Phi} = g(\omega)\,\sigma_l^n; \quad g(\omega) = (1-\omega^r)^{-n}.$$

The constants included in these dependences were determined on the basis of the experimental data on creep of the specimens cut out in various directions from the sheet material.

To Eq. (5) we added the kinetic equation for the damage parameter

$$\dot{\omega} = g(\omega)\,\sigma_*^n; \quad \omega(0) = 0; \quad \omega(t_*) = 1, \tag{6}$$

where σ_*^2 is the effective stress,

$$\sigma_*^2 = \frac{3}{2}\,[b_{11}(\sigma_{11}-\sigma_{22})^2 + b_{33}(\sigma_{22}-\sigma_{33})^2 + b_{22}(\sigma_{11}-\sigma_{33})^2 + 2a_{44}\sigma_{12}^2 + 2a_{55}\sigma_{23}^2 + 2a_{66}\sigma_{31}^2].$$

In the general case, the constants may be determined from the data on long-term strength or from the creep curves of the specimens, including the section prior to fracture.

We describe one of the possible methods of determining the creep parameters of the materials. For the plane stressed state, the physical dependences have the form

$$\left.\begin{aligned}
\dot{\varepsilon}_{11} &= \frac{3}{2}\dot{\Phi}\,[(a_{11}+a_{22})\,\sigma_{11} - a_{11}\sigma_{22}]/\sigma_l;\\
\dot{\varepsilon}_{22} &= \frac{3}{2}\dot{\Phi}\,[(a_{33}+a_{11})\,\sigma_{22} - a_{11}\sigma_{11}]/\sigma_l;\\
\dot{\varepsilon}_{12} &= \frac{3}{2}\dot{\Phi}a_{44}\sigma_{12}/\sigma_l;\\
\dot{\omega} &= \dot{\Phi}\,(\sigma_*/\sigma_l)^n,
\end{aligned}\right\} \tag{7}$$

where

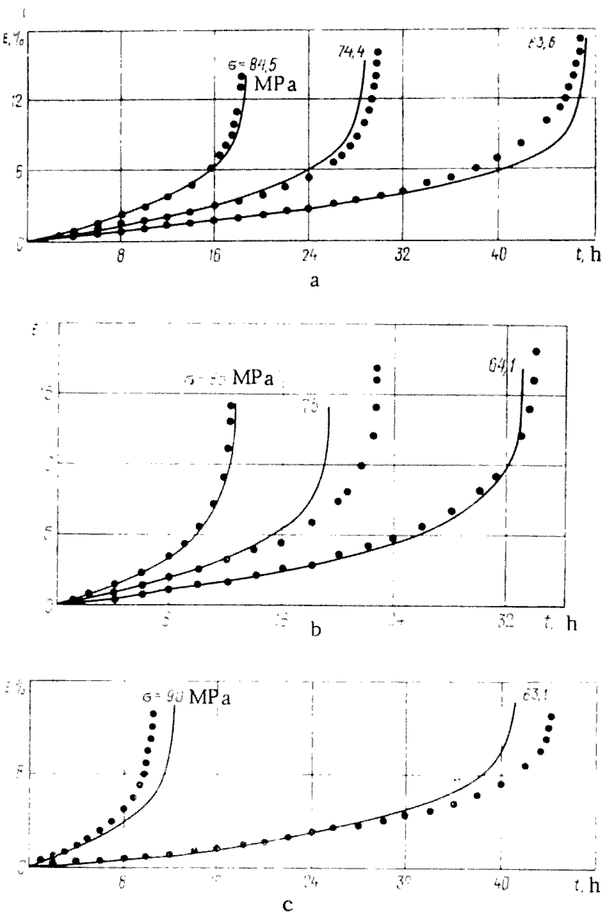

Fig. 3. Results of tests on the specimens cut out in the directions 1 (a), 2 (b), and 3 (c) at various stresses and T = 275°C.

$$\sigma_i^2 = \frac{3}{2}\,[(a_{11} + a_{22})\,\sigma_{11}^2 - 2a_{11}\sigma_{11}\sigma_{22} + (a_{33} + a_{11})\,\sigma_{22}^2 + 2a_{44}\sigma_{12}^2].$$

In the kinetic equation

$$\sigma_*^2 = \frac{3}{2}\,[(b_{11} + b_{22})\,\sigma_{11}^2 - 2b_{11}\sigma_{11}\sigma_{22} + (b_{33} + b_{11})\,\sigma_{22}^2 + 2b_{44}\sigma_{12}^2].$$

For the uniaxial tensile loading of the flat specimens (applied stress is equal σ_0), cut out in the directions 1, 2, and 3, the analytical dependences of the creep curve were obtained from the general physical relations (5). Subsequently, these equations were equated to the dependences used earlier in processing the experimental curves. Thus, the following algebraic system of equations was constructed

$$\left.\begin{aligned}
&3/2\,(a_{11} + a_{22}) = A_1^{2/(n+1)};\\
&3/2\,(a_{33} + a_{11}) = A_2^{2/(n+1)};\\
&3/4\,(a_{22} + a_{33} + 2a_{44}) = A_3^{3/(n+1)};\\
&3/2\,(b_{11} + b_{22}) = (A_1/p_*)^{2/n};\\
&3/2\,(b_{33} + b_{11}) = (A_2/p_*)^{2/n};\\
&3/4\,(b_{22} + b_{33} + 2b_{44}) = (A_3/p_*)^{2/n};\\
&3/2\,(a_{33} + a_{22})^{(n+1)/2} = p_*\,(3/2\,(b_{33} + b_{22}))^{n/2}.
\end{aligned}\right\} \qquad (8)$$

An additional equation is required to close completely this system of equations. For this purpose in tensile loading the specimen cut out in the direction 1 (2) it is sufficient to measure lateral strain $\varepsilon_{2\perp}\,(\varepsilon_{1\perp})$. Consequently, the appropriate physical dependences give

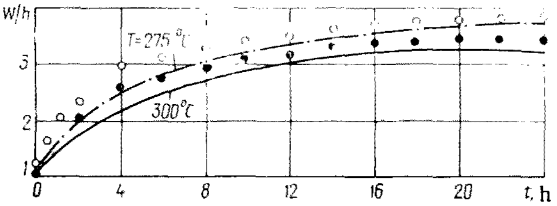

Fig. 4. Increase of deflection in the center of the blade in the creep conditions at various temperatures. (Lines show the experimental data, the points the experimental values.)

$$\dot{\varepsilon}_{2\perp}/\dot{\varepsilon}_1 = -\nu_{21} = -a_{11}/(a_{11} + a_{22});$$
$$\dot{\varepsilon}_{1\perp}/\dot{\varepsilon}_2 = -\nu_{12} = -a_{11}/(a_{11} + a_{33}). \quad (9)$$

In the experiments described above it was determined that $\nu_{12} = 0.42$. The solution of the system of algebraic equations (8), (9) showed that at T = 275°C $a_{11} = 2.13 \cdot 10^{-5}$; $a_{22} = 2.3 \cdot 10^{-5}$; $a_{33} = 2.94 \cdot 10^{-5}$; $a_{44} = 2.2 \cdot 10^{-5}$ $(\mathrm{MPa}^{-n}/\mathrm{h})^{2/(n+1)}$; $b_{11} = 5.4 \cdot 10^{-6}$; $b_{22} = 2.2 \cdot 10^{-6}$; $b_{33} = 4.1 \cdot 10^{-6}$; $b_{44} = 1.76 \cdot 10^{-6}$ $(\mathrm{MPa}^{-n}/\mathrm{h})^{2/n}$; n = 3.4; r = 1.38.

For the material which is isotropic during creep, the physical equations have the form

$$\dot{\varepsilon}_{ij} = \frac{3}{2} A \left[\frac{S_i}{(1-\omega^r)}\right]^n S_{ij}; \quad \dot{\omega} = B \left[\frac{S_i}{(1-\omega^r)}\right]^n,$$

where $S_{ij} = \sigma_{ij} - 1/3(\sigma_{ij}\delta_{ij})\delta_{ij}$; $S_i^2 = 3/2 S_{ij} S_{ij}$.

For the material examined at a temperature of 300°C we obtained $A = 0.34 \cdot 10^{-7}$; $B = 1.9 \cdot 10^{-7}$ $(\mathrm{MPa}^{-n}/\mathrm{h})$; n = 2.93; r = 1.38.

An algorithm of calculating plates in creep was proposed in [3]. To verify the reliability of such an algorithm and of the equations of state examined above, we tested rectangular plates produced from the sheet material examined subjected to creep and loaded with a constant uniform pressure. Experimental examination was carried out in equipment described in [4]. The increase of deflection in the center of the plate whose edges were rigidly fixed in relation to time is shown in Fig. 4.

The numerical results were obtained using the algorithm described in [3]. Calculations were carried out taking into account the geometrical nonlinearity of deformation. The intensity of pressure in all the experiments was maintained constant and equal to 0.025 MPa for T = 300°C and 0.1 MPa for T = 275°C.

As indicated by comparison of the experimental and calculated data, they are in completely satisfactory agreement (within the range of the scatter of the experimental points) and this confirms the validity of the main assumptions and conditions used in the investigations described above.

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