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APPLYING THE KINETIC THEORY OF STRENGTH TO DETERMINING LIFE OF LIGHT ALLOYS AFTER PRELIMINARY PLASTIC DEFORMATION

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Residual plastic strains can occur in light-alloy structural elements as a result of the action of a complex of service loads (especially at points of stress concentration) and also in connection with certain fabrication processes involving bending, stretching, various types of cold forging, etc.

The temperature conditions and the amount of plastic deformation determine the previous history of the material and may have an important influence on the resistance of the alloy to static and variable loads. It has been experimentally established that the nature of the effect of plastic deformation depends on many factors: the composition of the alloy, the conditions of preliminary deformation, and the load-temperature conditions of the subsequent tests. Depending on the circumstances, the strength properties of the material may increase, decrease, or remain unchanged.

The extensive use of plastically deformed materials has led to many attempts to determine experimentally the optimum plastic strain. However, the purely experimental approach is very laborious and does not always give reliable results for the favorable degree of plastic deformation.

We have investigated the effect of the degree of preliminary plastic tensile deformation on the long-time strength of Duralumin at various temperatures and stresses and have estimated the possibility of determining the long-time strength under these conditions on the basis of the kinetic theory of strength.

As the material for investigation we used sheets of commercial hardened and naturally aged D16AT alloy 3 mm thick. All the sheets were taken from the same melt. The specimens were cut parallel to the direction of rolling. The mechanical properties of the material in the starting state (as delivered) were as follows: ultimate strength $\sigma_u = 48.6$ kg/mm², yield point $\sigma_{0.2} = 36.4$ kg/mm², relative elongation $\delta = 14.3\%$.

The mechanical characteristics were determined and the preliminary plastic deformation (2, 4, 6, and 8%) was produced at room temperature in a GURM-10 hydraulic tensile testing machine. The specimens subjected to plastic deformation were finished specimens which after cold-hardening had not undergone any further mechanical working. Due to the specially designed recording instrument, the plastic deformation could be carried out with a high degree of accuracy. The spread of the valves at each plastic strain level did not exceed 0.01-0.03%. After preliminary deformation the specimens were tested to destruction in creep at temperatures of 125, 150, 175, and 200°C and stresses of 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, and 42 kg/mm².

The tests were conducted on redesigned DST-5000 machines; undeformed specimens were also tested to destruction. Altogether 235 specimens were tested.

The test conditions and the corresponding values of the stress rupture life for various levels of preliminary plastic deformation (PPD) are indicated in Table 1, from which it is possible to judge the complex influence of the preliminary plastic deformation on the long-time strength. Thus, at 125 and 150°C and stresses σ = 34, 36, 38, 40, and 42 kg/mm², PPD

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leads to an increase in τ; at 150 and 175°C and stresses σ = 28, 30, and 32 kg/mm^2, PPD does not have much effect on τ, whereas at 175 and 200°C and stresses σ = 18, 20, 22, 24, and 26 kg/mm^2 τ is reduced.

The variable effect of PPD on the creep rupture life can be explained in terms of the kinetic theory of strength. According to this theory [1, 2], the relation between τ, σ, and T can be described by the expression [1]

$$\tau = \tau_0 \exp\, [(U_0 - \gamma\sigma)/RT], \tag{1}$$

where τ_0, U_0, and γ are coefficients; R is the universal gas constant; and T is absolute temperature, in °K.

The coefficients τ_0, U_0, and γ are ascribed a particular physical significance. The pre-exponential coefficient τ_0, which is approximately equal to 10^{-13} sec, is identified with the period of vibration of the atoms in the solid. U_0, which has the dimension of energy, is considered to represent the activation energy corresponding to breakage of the interatomic bonds; U_0 varies from one material to another but is not much affected by a change of structure. The coefficient γ is the structure-sensitive factor. It reflects the stress concentration at the points of local fracture development. The lower the local stress concentrations the stronger the material and the smaller γ. From this standpoint PPD should reduce the stress concentration and lower the value of γ, thereby increasing the rupture life. On the other hand, loading to produce plastic deformation should reduce the long-time strength, since the accumulation of damage is regarded in [1] as a process irreversible in time. The interaction of these two opposing processes results in PPD having different effects on the stress rupture life.

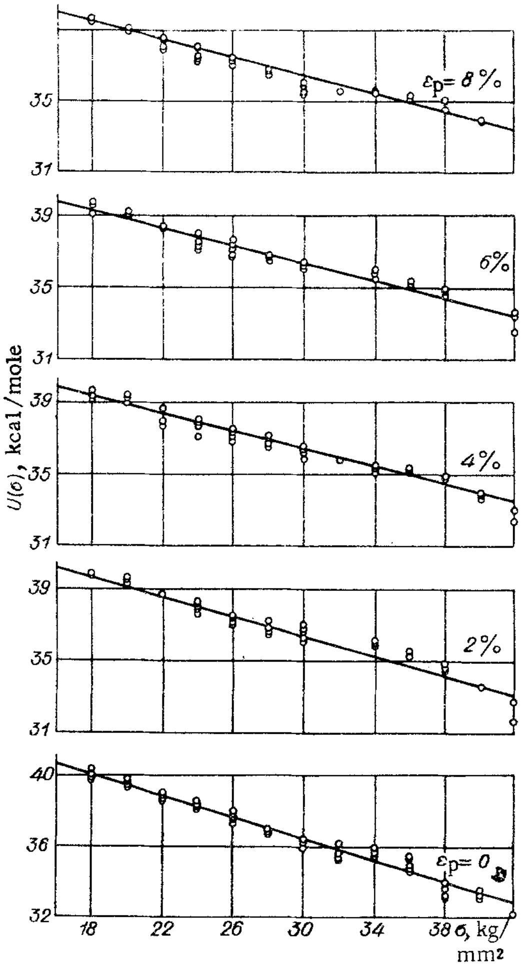

Fig. 1

TABLE 1

Test conditions	Time to rupture τ, h				
	$\varepsilon_p=0$	$\varepsilon_p=2\%$	$\varepsilon_p=4\%$	$\varepsilon_p=6\%$	$\varepsilon_p=8\%$
$T=125°C$ $\sigma=42$ kg/mm²	16	7; 26	19, 42; 48	66; 61; 60; 23;	
$T=125°C$ $\sigma=40$ kg/mm²	44; 89; 55	84	92; 87; 97		94; 66
$T=150°C$ $\sigma=38$ kg/mm²	5; 5; 8; 9; 14	22; 26; 10	28; 24; 24	26; 21; 24; 33	38; 36; 23
$T=150°C$ $\sigma=36$ kg/mm²	26; 25; 31; 32; 36; 48; 54	41; 61	44; 47	45; 48	46; 49; 52
$T=150°C$ $\sigma=34$ kg/mm²	46; 54; 57; 71; 72; 86	79; 91; 85	70; 74; 83; 97	74; 70; 88	58; 64
$T=150°C$ $\sigma=32$ kg/mm²	127; 56; 48; 124		102		68
$T=175°C$ $\sigma=30$ kg/mm²	10; 12; 13	12; 14; 21; 26; 14; 22	12; 12; 18; 13; 9; 12	14; 13; 12; 12; 14; 13	9; 8; 11;6; 9
$T=175°C$ $\sigma=28$ kg/mm²	21; 23; 27 35	21; 38; 30; 21; 25	22; 36; 25; 28	19; 20; 24	20; 14; 21
$T=175°C$ $\sigma=26$ kg/mm²	87; 43; 71; 49; 70; 68	33; 30; 42; 43; 41	26; 41; 44; 55	40; 41; 29; 35; 42; 65	39; 30; 29
$T=175°C$ $\sigma=24$ kg/mm²	95; 96	76	72; 88; 98	75; 94; 73	39; 51; 75
$T=200°C$ $\sigma=24$ kg/mm²	9; 9; 13; 17; 19; 20	6; 7; 12; 11	7; 9; 10; 7; 4; 9; 10; 9	11; 8; 7; 6	5; 10; 6
$T=200°C$ $\sigma=22$ kg/mm²	18; 20; 22; 26; 27	21	9; 9; 20	17; 14; 17; 17;	12; 15; 15 11; 11
$T=200°C$ $\sigma=20$ kg/mm²	53; 54; 46; 62	52; 46; 37	31; 37; 40; 27	29; 37; 35; 30	24; 31; 30
$T=200°C$ $\sigma=18$ kg/mm²	99; 133; 114 78	70; 56	38; 40; 66	34; 61; 51	52; 40; 51

If Eq. (1) holds for a material subjected to PPD, then from the relation

$$U(\sigma) = U_0 - \gamma\sigma = 2.3RT \lg (\tau/\tau_0),$$

obtained from (1), we can calculate $U(\sigma)$, taking $\tau_0 = 10^{-13}$ sec and using experimentally measured values of τ. The graph of $U(\sigma)$ versus σ should be a straight line for various τ, σ, and T.

The results of plotting the experimental data in $U(\sigma)-\sigma$ coordinates at various values of the PPD ε_p are presented in Fig. 1. To give an idea of the scatter, the data have been plotted separately for each specimen. The straight lines are based on a least squares analysis. The fact that the points lie quite close to the straight lines indicates that Eq. (1) is valid for these particular experimental conditions. By extrapolating the straight lines to the ordinate axis we found the value of U_0, and from their slope the coefficient γ. The values of U_0 and γ for various ε_p are given in Table 2, from which it is clear that PPD has

TABLE 2

ε_p, %	U_0, kcal/mole	$\frac{\text{kcal} \cdot \text{mm}^2}{\text{mole} \cdot \text{kg}}$
0	45,4	0,30
2	44,5	0,27
4	43,9	0,25
6	43,8	0,25
8	44	0,25

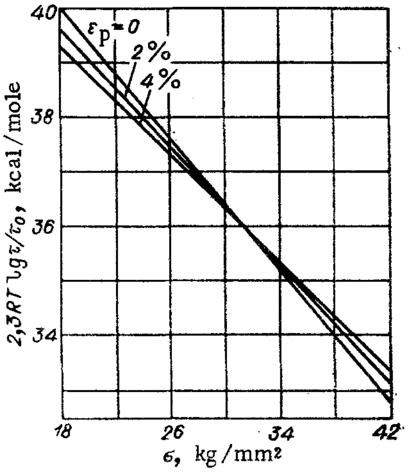

Fig. 2

most effect on the structure-sensitive coefficient γ. The value of γ was reduced by 10% at $\varepsilon_p = 2\%$ and by 16.7% at $\varepsilon_p = 4\%$. Further increases in PPD had no effect on γ (the structure was stabilized). The values of U_0 were reduced by 2-3.5%.

Changes in the coefficient γ explain the variable effect of PPD on the long-time strength. In $U(\sigma)$—σ coordinates the straight lines of plastically deformed specimens intersect the straight line of the undeformed material (Fig. 2). Accordingly, in the region of lower stresses (σ = 18, 20, 22, 24, 26 kg/mm^2) and relatively high temperatures (175, 200°C) the long-time strength decreases after PPD, whereas at sufficiently high stresses (σ = 34, 36, 38, 40, and 42 kg/mm^2) and lower temperatures (125, 150°C) the long-time strength is greater for the plastically deformed material.

The validity of Eq. (1) makes the determination of the long-time strength after PPD less laborious and more reliable as compared with the strictly experimental approach.

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