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FAILURE OF ORGANIC GLASS AFTER ALTERNATING LONG-TERM AND CYCLIC LOADING

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The Palmgren–Meiner hypothesis of accumulation of damage, or the rule of linear summing of damage, was suggested for describing failure under conditions of fatigue [1]. For the case of two-stage loading by stresses σ_1 and σ_2 this hypothesis can be formulated as follows.

First the specimen is loaded by stress σ_1 for N_1 cycles, then it is tested at stress σ_2 for N_2 cycles. At the level of the stress σ_2 the tests are continued up to failure of the specimen. We assume that N_{1R} and N_{2R} are the numbers of cycles under stresses σ_1 and σ_2, respectively, and then N_1/N_{1R} and N_2/N_{2R} are the proportions of damageability in the process of the first and second loading, respectively. According to the Palmgren–Mainer hypothesis

$$\frac{N_1}{N_{1R}}+\frac{N_2}{N_{2R}}=1. \quad (1)$$

An analogous hypothesis for static testing (creep) was formulated by Robinson [2]. Within the time t_1 the specimen is tested under stress σ_1, then the tests are continued at stress σ_2 to failure within time t_2. If we denote by t_1/t_{1R} and t_2/t_{2R} the proportions of damageability in the first and second loading, respectively, then in accordance with Robinson's assumptions

$$\frac{t_1}{t_{1R}}+\frac{t_2}{t_{2R}}=1, \quad (2)$$

where t_{1R}, t_{2R} are the time to failure under stresses σ_1 and σ_2, respectively.

When long-term and cyclic stresses alternate, the hypothesis of accumulation of damage is written in the following form:

$$\frac{t}{t_R}+\frac{N}{N_R}=1, \quad (3)$$

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TABLE 1. Damageability of Organic Glass under Conditions of Long-Term and Cyclic Loading at σ = 50 MPa (t_R = 95 min, N_R = 892 cycles). First Loading Cyclic

N, cycles	N/N_R	t, min	t/t_R	$t/t_R+N/N_R$
10	0,011	17	0,178	0,189
20	0,022	41	0,43	0,452
20	0,022	18	0,189	0,211
30	0,033	25	0,26	0,293
40	0,044	20	0,21	0,254
40	0,044	28	0,29	0,338
50	0,056	21	0,22	0,276
60	0,067	31	0,326	0,393
60	0,067	44	0,463	0,53
70	0,078	32	0,336	0,414
80	0,089	54	0,568	0,657
80	0,089	25	0,263	0,349
100	0,112	54	0,568	0,68
200	0,224	1	0,01	0,234
400	0,448	1	0,01	0,458
800	0,9	29	0,3	1,2

TABLE 2. Damageability of Organic Glass under Conditions of Long-Term and Cyclic Loading at σ = 50 MPa (t_R = 95 min, N_R = 892 cycles). First Loading Long-Term

t, t_{min}	t/t_R	N, cycles	N/N_R	$t/t_R+N/N_R$
5	0,05	886	0,993	1,043
10	0,105	2233	2,503	2,608
20	0,211	727	0,815	1,026
30	0,316	480	0,538	0,854
30	0,316	330	0,370	0,686
30	0,316	1128	1,26	1,576
40	0,421	150	0,168	0,589
40	0,421	174	0,195	0,616
40	0,421	1533	1,719	2,14
50	0,526	1172	1,314	1,84
60	0,632	623	0,698	1,33
70	0,737	1076	1,206	1,943
70	0,737	70	0,078	0,815
80	0,842	1470	1,648	2,49
85	0,895	45	0,05	0,945
90	0,947	20	0,022	0,969

TABLE 3. Damageability of Organic Glass under Conditions of Long-Term and Cyclic Loading at σ = 43 MPa (t_R = 560 min, N_R = 4468 cycles). First Loading Cyclic

N, cycles	N/N_R	t, min	t/t_R	$t/t_R+N/NR$
500	0,112	1182	2,111	2,223
1000	0,224	1132	2,021	2,244
1500	0,336	2164	3,864	4,2
2000	0,448	1860	3,321	3,768
2500	0,559	311	0,555	1,114
3000	0,671	220	0,393	1,064
3500	0,783	614	1,096	1,879
3500	0,783	676	1,028	1,811
4000	0,895	644	1,15	2,045
4200	0,940	288	1,05	1,99
4228	0,946	341	0,608	1,555
5000	1,12	1757	3,1	4,22
4000	0,895	80	0,143	1,038

where t is the time of testing the specimen under long-term loading by stress σ; N is the number of load cycles with the same stress; t_R, N_R are, respectively, the time and number of cycles to failure at stress σ.

By now a large amount of experimental data are known which yield a systematic deviation from the hypothesis of linear summing of damage. The principal shortcoming of this hypothesis

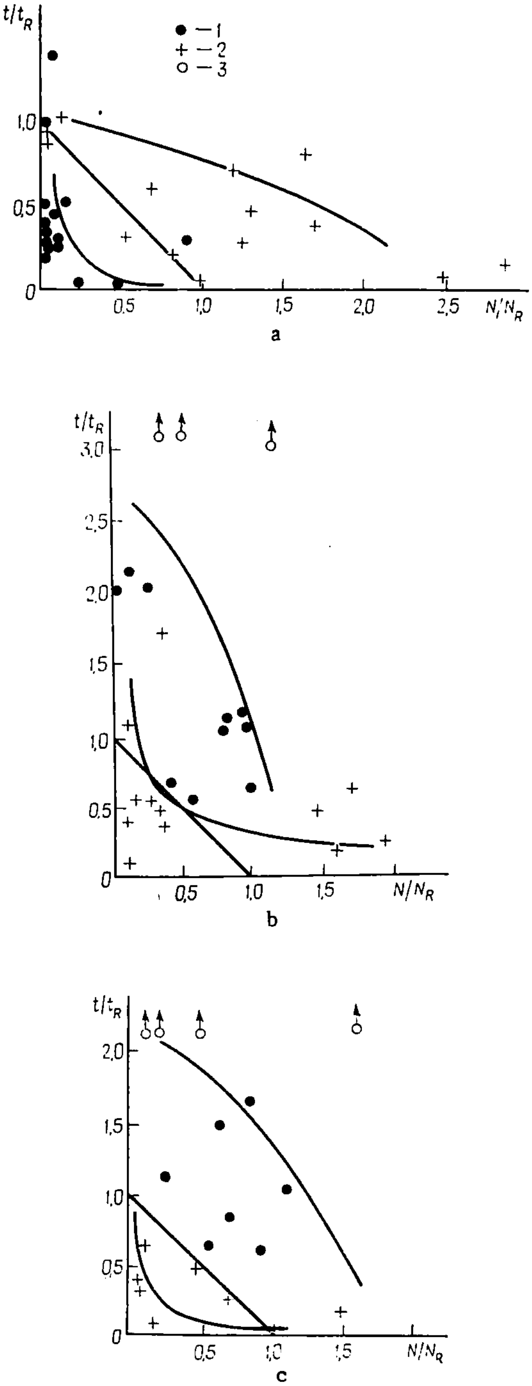

Fig. 1. Accumulation of damage in alternating long-term and cyclic loading at stresses σ = 50 MPa (a), 43 MPa (b), and 34 MPa (c): 1) first loading is cyclic; 2) first loading is long-term; 3) the experimental dots lie outside the graph. (The straight line corresponds to the hypothesis of linear summing of damage.)

is that it ignores the effect of the alternation of different stress levels or the alternation of static and cyclic loading. Different variants of the hypotheses of nonlinear damage were therefore suggested [3, 4].

The present work deals with the experimental evaluation of the strength of organic glass subjected successively to long-term and cyclic loading. The experiments were carried out at room temperature with flat specimens having the following dimensions: gauge length

TABLE 4. Damageability of Organic Glass under Conditions of Long-Term and Cyclic Loading at σ = 43 MPa (t_R = 560 min, N_R = 4468 cycles). First Loading Long-Term

t, min	t/t_R	N, cycles	N/N_R	$t/t_R+N/N_R$
50	0,089	1950	0,436	0,525
50	0,089	522	0,116	0,205
100	0,179	7125	1,59	1,769
150	0,268	8610	1,92	2,188
200	0,357	1629	0,364	0,721
200	0,357	596	0,133	0,49
250	0,446	6408	1,43	1,876
250	0'446	1547	0,346	0,792
300	0,536	805	0,18	0,716
300	0,536	1155	0,258	0,794
350	0,625	1400	0,313	0,938
350	0,625	7431	1,66	2,285
400	0,714	2610	0,584	1,298
500	0,893	2588	0,579	1,472
600	1,071	547	0,122	1,93
700	1,25	368	0,082	1,332
800	1,429	2928	0,655	2,084
1000	1,786	1574	0,35	2,136

TABLE 5. Damageability of Organic Glass under Conditions of Long-Term and Cyclic Loading at σ = 34 MPa (t_R = 350 h, N_R = 14,554 cycles). First Loading Cyclic

N, cycles	N/N_R	t, h	t/t_R	$t/t_R+N/N_R$
2000	0,14	1440	4	4,14
3000	0,2	1008	2,8	3
4000	0,27	403	1,15	1,42
12000	0,89	180	0,5	1,39
7000	0,5	1392	4	4,5
8000	0,55	215	0,614	1,159
10000	0,68	290	0,828	1,515
12000	0,89	200	0,6	1,49
15000	1,03	380	1,08	2,11
20000	1,37	217	0,617	1,987
23000	1,6	1054	3	2,6

TABLE 6. Damageability of Organic Glass under Conditions of Long-Term and Cyclic Loading at σ = 34 MPa (t_R = 350 h, N_R = 14,554 cycles). First Loading Long-Term

t, h	t/t_R	N, cycles	N/N_R	$t/t_R+N/N_R$
30	0,085	2537	0,174	0,259
65	0,185	21636	1,486	1,671
91	0,26	10433	0,71	0,97
120	0,342	718	0,05	0,39
140	0,4	227	0,015	0,415
163	0,46	7118	0,489	0,95
212	0,605	2725	0,187	0,792
260	0,742	54	0,0037	0,745

60 mm, width 10 mm, thickness 5 mm. Under conditions of creep, the specimens were tested on presses UP7 made by the experimental workshop of the Leningrad University. Deformations were measured with instruments TsTM-5. Cyclic loading was effected on machines MR-500T-2 with symmetrical tensile cycle at a frequency of 10 cycles/min.

The results of the experiments, carried out at three stress levels: 50, 43, and 34 MPa, are presented in Fig. 1 (according to the data of Tables 1-6). In accordance with these data, the deviations from regularity of the linear summing of damage (to this regularity corresponds the line connecting the points with the coordinates (0, 1), (1, 0)) are considerable, and the endurance of specimens for the given stress level depends substantially on the alternation of cyclic and long-term loading. Such a conclusion is in good agreement with the data provided by other authors [5]. On the other hand we want to draw attention to the following circumstance not previously discussed in the literature.

Let us examine the accumulation of damage when a stress σ = 50 MPa acts. It follows from Fig. 1a and Tables 1, 2 that the initial cyclic loading causes loss of strength of the material, and the summary damage $t/t_R + N/N_R < 1$. The material gains in strength in reverse alternation of the loading and with $t/t_R + N/N_R > 1$.

With transition to the stress level σ = 43 MPa (Fig. 1b and Tables 3, 4) the pattern changes; at a lower stress level (σ = 34 MPa) — Fig. 1c and Tables 5, 6 — the accumulation of damage is completely opposite to the case σ = 50 MPa. In fact, according to Fig. 1c and the data of Tables 5, 6, the initial cyclic loading causes a considerable increase in strength of the material, and summary damage $t/t_R + N/N_R > 1$. With opposite alternation of the loading, the material loses strength, and summary damage $t/t_R + N/N_R < 1$.

It is accepted to believe [5] that preliminary cyclic aging strengthens the material. In accordance with the data presented above, this assertion is not correct for all stress levels. Preliminary cycling with relatively large stress amplitudes causes loss of strength of the material. Then, with decreasing stresses, the situation changes, and cyclic aging strengthens the material. Thus the process of accumulation of damage is nonmonotonic [1, 6].

It is becoming of great practical importance to determine the stress level at which the transition from loss to gain of strength occurs because the hypothesis of linear summing of damage applies solely to this stress level. When the formulation of the hypotheses of the summing of damage is approached theoretically, it must be taken into account that the summary damage $t/t_R + N/N_R$ is some nonmonotonic function of the stress σ.

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