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HEAT GENERATION IN POLYCARBONATE DUE TO PULSATING TENSILE LOAD

By

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Experimental investigation was made of fatigue of polycarbonate subjected to pulsating stress of comparatively small amplitudes at low rates of repeating (one cycle per second or less). The temperature rise associated with load repetition under such conditions was shown to be only 0.2 °C or thereabouts above room temperature, and was considered to be in correlation with stiffness increase. Fatigue fracture occurred without any unstable increase in the temperature. The heat energy produced under the load was evaluated and compared with the work required for the material to cold draw at room temperature, and with the fracture surface energy of polymethyl methacrylate. Results of the preliminary measurements have been presented in the appendices. They are the temperature change per unit stress increase of tension, compression or torsion, that related to a tensile stress-strain diagram, and those under pulsating compression, torsion and bending.

1. Introduction

There is a loose thought that fatigue fracture of plastics is caused by temperature rise due to repetition of load. It is admittedly valid at high stresses and/or high rates of repeating, but not necessarily so; fatigue fracture occurs also when the specimen temperature does not rise much, under such conditions of low stresses at low rates of repeating that the temperature rise converges to a level 0.1 - 0.2 °C above room temperature. The comprehension of an inherent mechanism of fatigue fracture will be possible when we advert to a temperature rise in amorphous regions of a microscopic scale which is thought to be of a size of cristallites or physically crosslinked blocks of segments;[1] which, we imagine, form due to the action of repeating load, rather irregularly interposing amorphous regions among them. At any rate we can not at present measure the local temperature of such restricted regions.

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We have begun with giving a relation that how much heat energy the material could produce by the time it had been used up; according to some author the material could be considered to be a negative engine, being given mechanical work, to generate heat.

2. Material used and temperature measurement

Plates of 5 mm thickness obtained from the market were used. They were, after shaping and polishing, heat-treated in a silicone oil bath of 140°C for 5 hours and cooled at a rate of 0.1 °C/min. The specimens were of dimensions of 5 × 20 × 50 mm at their parallel part for test. Our air conditions are 23 °C and 50 % RH.

Thermocouple Sheets, Philips PR6452A/00, were used for measuring the temperature of the specimen surfaces. The sheets are 0.2 mm thick inclusive of protection papers on both sides, and the copper-constantan couples are of 0.08 mm thickness. One or two of the Couple Sheets were held on the specimen surface with an adhesive tape of thickness of 0.33 mm, and used in series together with a dummy sheet for each active, being held on another specimen under no load. The temperature change was recorded through a microvoltmeter; meters as well as recorders of low drift were chosen. Fig. 1 shows one of the records, as seen in which the temperature sinusoidally changes with the tensile load pulsation and it increases in its average from below to above room temperature. On account of this we made preliminary measurements of temperature change of the materials undergoing monotonically increasing loads, the results of which are presented in an appendix of this paper.

The average temperature was thought not subject to the influence of time lag of response of the Couple Sheets because the average temperature rose gradually enough. The temperature increased during the incipient stage of

Table 1

No.	σ_{amp} kg/mm²	σ_{mean} kg/mm²	λ sec/cycle	$-\theta_0$ C°	$\alpha\times10^3$ °C/cycle	$\beta\times10^3$ 1/sec	N_f cycles
1	1.09	2.91	6.7	0.230	0.680	2.90	14,661
2	1.38	2.15	8.0	0.180	0.921	2.88	5,200
3	1.53	3.37	10.0	0.204	2.74	2.20	3,247
4	1.62	2.98	10.5	0.280	3.10	2.45	2,593
5	1.98	2.96	18.75	0.280	3.90	2.54	1,700
6	2.00	2.95	12.7	0.283	3.45	2.94	1,700
7	2.11	3.41	19.3	0.250	5.14	2.06	1,520
8	2.15	2.87	7.8	0.294	2.64	2.85	1,332
9	2.76	3.72	26.9	0.300	16.62	2.88	576
10	2.84	3.39	18.2	0.275	13.90	2.88	688

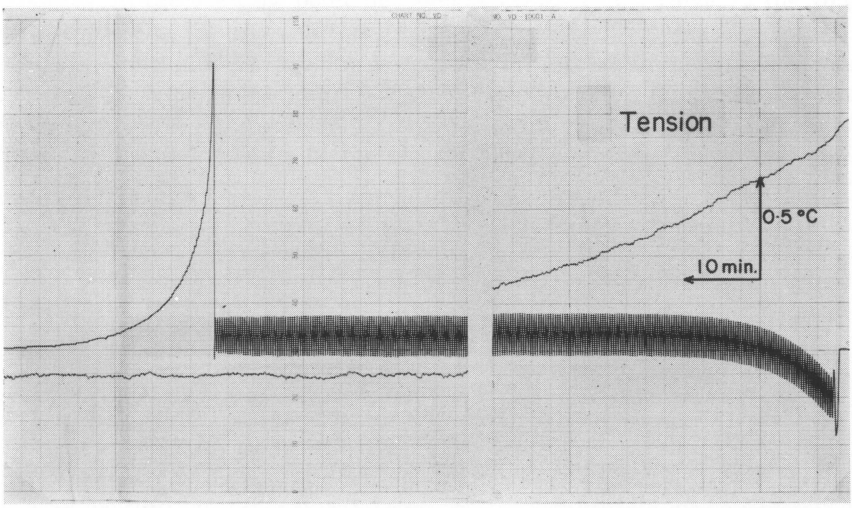

Fig. 1 Temperature change of a plate specimen under pulsating load. It begins at the right. The left half is the end part, where the specimen broke and the temperature had a sudden rise.

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several tens of cycles. The value of the average temperature in the first cycle was determined from the measurements of the ensuing cycles by extrapolating to the starting point and denoted $-\theta_0$ °C in Table 1; the figures show the decreases from room temperature. Specimen temperatures, when the stress amplitudes and the cycling speeds are low, cease to increase and remain at a slightly high temperature 0.1 - 0.2 °C above room temperature; Immediately after break they suddenly rise on account of a compressive stress wave having reached the location of the Couple Sheet from the broken section.

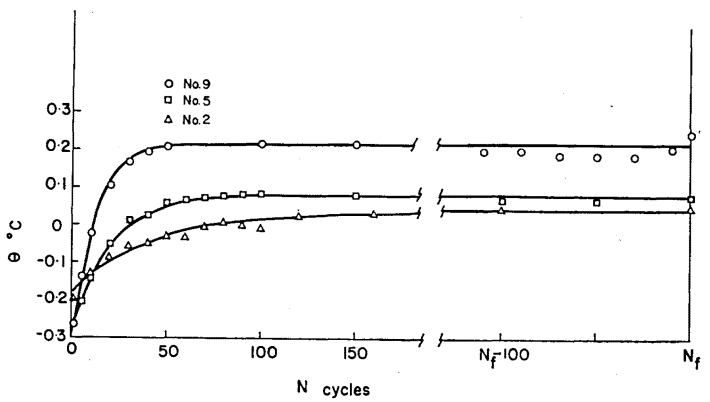

Fig. 2 Average temperature increases represented for three stress values (cf. Table 1).

Cycling begins at the left hand side and the last 100 cycles to fracture is shown at the right end, representing the room temperature with 0°C.

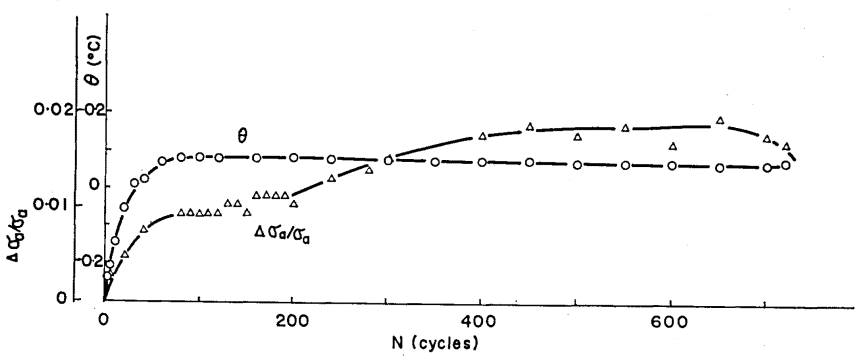

Fig. 3 Correlation of increases in temperature and in stiffness.

Stiffness is represented with the increase in stress amplitude under a preset strain amplitude.

3. Adjustment of measurements of temperature

The temperature increase is associated with dissipation of heat to the surroundings and is subjected to the influence of the time length λ required for each stress cycle. Using factors α and β for heat generation and dissipation respectively, the increase of temperature has been formulated as follows.

$$d\theta = \alpha dN - \beta\theta dt$$

Here the temperature θ gives the value above room temperature and dN, dt are incremental cycles and time respectively for an incremental temperature rise, $d\theta$. The above mentioned period, λ, stands for dt/dN. The equation is integrated as

$$\theta = \frac{\alpha}{\beta\lambda}(1-e^{-\beta\lambda N}) + \theta_0 e^{-\beta\lambda N}$$

Table 1 gives the values for them, under pulsating tension of respective constant strain amplitudes. The fatigue lives N_f also are given in the column at the right end of the table.

The obtained temperatures are shown in Fig. 2 for examples of three kinds of magnitude of the initial stress amplitude. Increase in stiffness, that is, increase in the stress amplitude under the condition of a preset strain amplitude, has in addition, been measured in each case.[2)]

The temperature seems to reach a steady state at such a stage that the increase in stiffness gets saturated (Fig. 3).

4. Heat generation factor α and stress amplitude σ_a

Fig. 4 shows the relation of α and σ_a. On account of our formulation, β should be dependent only on the geometry of the specimens, and α on the magnitude of stresses. Naturally β's were nearly of the same value as expected because of the same form of our specimens for this experiment. The variation of α is found likely to be subject little to the magnitude of the mean stresses and mostly to that of the amplitudes. According to our another experiment on plain bending of plate specimens, the values of α have been much less than those presented here. The result has, however, been regarded due to the smallness of the effective work done by bending stresses compared with uniform tensile stresses and not due to the zero mean stresses in the experiment of bending.

It is, however, not possible to pursue the same line of thought in a case of a large value of the mean stress, in which the imposed stress draws near the yield stress of the material and the circumstances get different. A tendency of the specimen temperature somewhat to rise toward the fracture is seen in one subjected to comparatively high stress in Fig. 2.

5. Heat generation factor α and fatigue life N_f

The relation of α and N_f could be formulated as

$$(\alpha - a)N_f \simeq 7.0 \ (°C)$$

where $a = 1.43 \times 10^{-4}$ °C/cycle, but it hardly improve on fitting of another linear equation $\alpha N_f =$ constant given in Fig. 5. Although the above given formula suggests the existence of an endurance limit for the value of $\alpha = a$, our evidence is not enough to infer it.

Converting the value of α to generated heat energy

$$Q = \alpha c \rho \ (\text{cal/cm}^3\text{cycle})$$

is obtained for one of the specimens, No. 10, as an example, by use of the values of the specific heat $c = 0.28$ (cal/gr°C) and the specific weight $\rho = 1.2$.

On the other hand, a net value of the mechanical input in the uniform parallel portion of the specimen was evaluated as $A = 3.8 \times 10^5$ (erg/cm^3 cycle) from the hysteresis loops of the pulsating load and extension. The heat energy Q evaluated from α is found nearly half the magnitude of A. The mechanical input A gives about 3×10^8 (erg/cm^3) or so when accumulated untill fracture. The value is roughly a constant independent of the magnitude of stresses, when $\alpha N_f =$ constant is approved.

We obtained a value 4×10^8 (erg/cm^3) of the mechanical work required for cold drawing polycarbonate at room temperature, at which the draw ratio was about 1.7 for our material.[3] The proximity of both values may suggest an implicit relation between fractures due to the repeating and the increasing load in spite of the decided difference in the quantity of extension at fracture.

Fracture surface energy of polymethyl methacrylate when broken under an increasing load had been evaluated to be 3.6×10^5 (erg/cm^2) and the depth of the fracture surface layer to be the order of magnitude of a half micron.[4] If we would ignore the difference of both materials, the above mentioned work 3×10^8 (erg/cm^3) should give a fracture area 8.3×10^2 (cm^2/cm^3) of the same layer depth and of the same fracture surface energy and it could be assumed that so much latent fracture interfaces of crosslinked blocks of the linear dimension of several ten microns should be present in the fatigue fractured specimen.

G. Jacoby et al. made measurements of fatigue crack growth for polycarbonate. It has not been the subject of our study.[5]

Appendix 1

An SN-curve from our data is shown in Fig. A·1. It seemed from the data of a few specimens that the material had somewhat larger lives when not heat-treated but as polished.

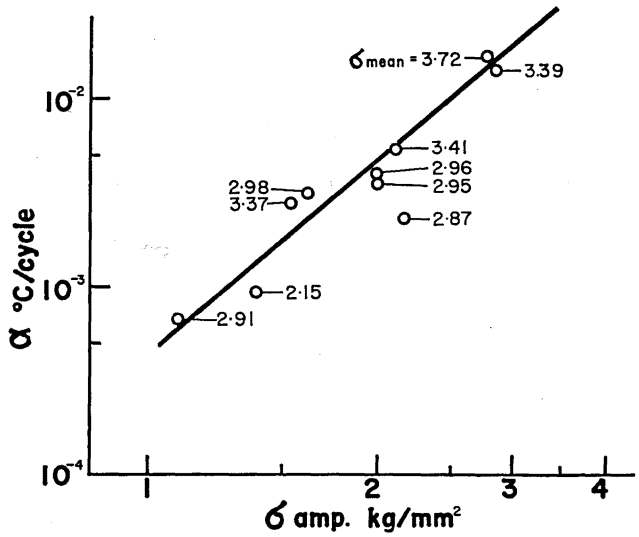

Fig. 4 Relation of heat generation factors and stress amplitudes. Annexed figures denote the mean stress values.

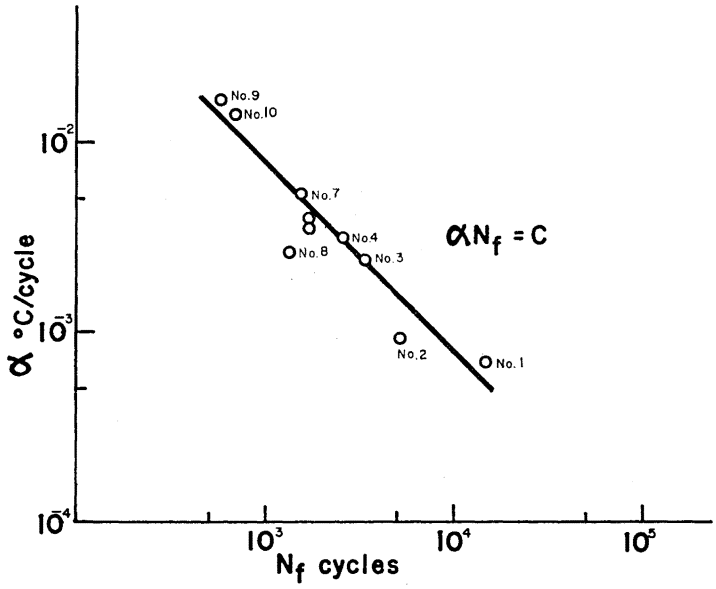

Fig. 5 Heat generation factors and fatigue lives.

Appendix 2

Temperature changes were measured of the specimens subjected to statical loads, which were made increased to some stress levels and held there. Several load rates were chosen. The temperature rise delayed at higher rates because of the lag of response. The results are shown in Figs. A·2·1 through A·2·3, from which the temperature change with the stress in the range of the material being almost in elasticity have been found to be -0.08 (°Cmm²/kg) for tension and 0.16 (°Cmm²/kg) for compression; for torsion of hollow cylindrical specimens it is 0.015 for below and 0.06 (°Cmm²/kg) above 3 (kg/mm²).

The obtained temperature decrease per unit stress of tension is about 60 % in magnitude of a value calculated from a thermodynamical equation, [6]

$$\frac{\partial \theta}{\partial \sigma} = \frac{\alpha_l T}{Jc\rho}$$

where α_l = linear thermal expansion coefficient, 6×10^{-5} (/°C), $c\rho$ = specific heat per unit volume, $0.28 \times 1.2 \simeq 0.34$ (cal/cm³°C), and T = absolute temperature (°K).

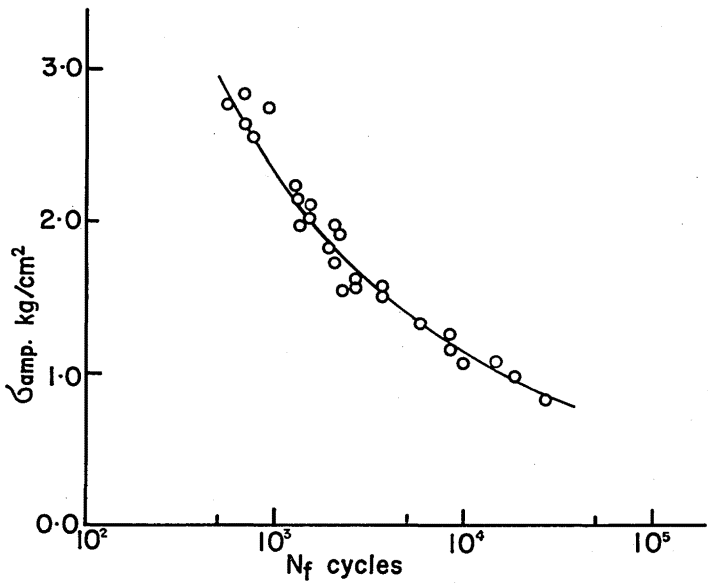

Fig. A·1 SN-curve for heat-treated polycarbonate.

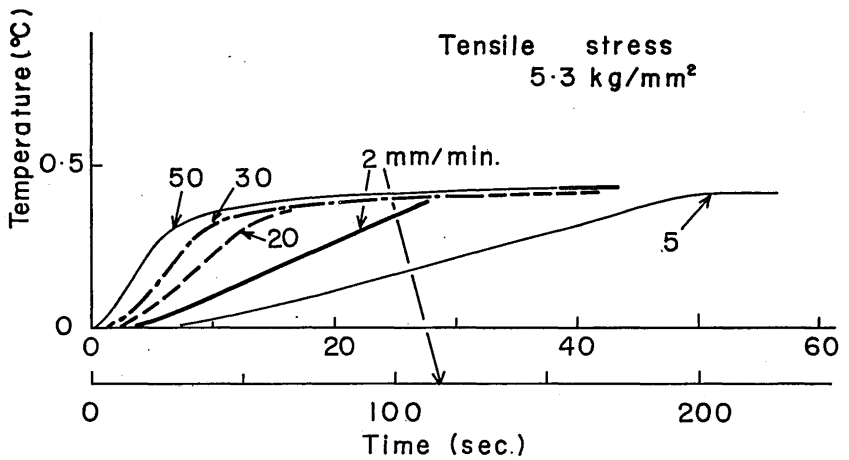

Fig. A·2·1

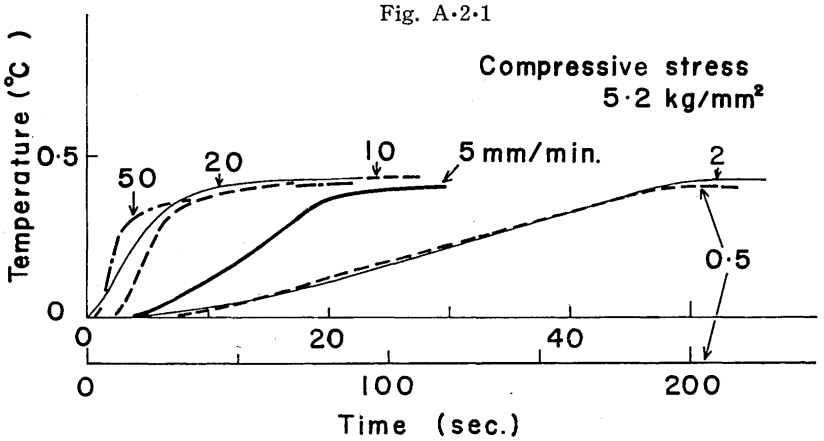

Fig. A·2·2

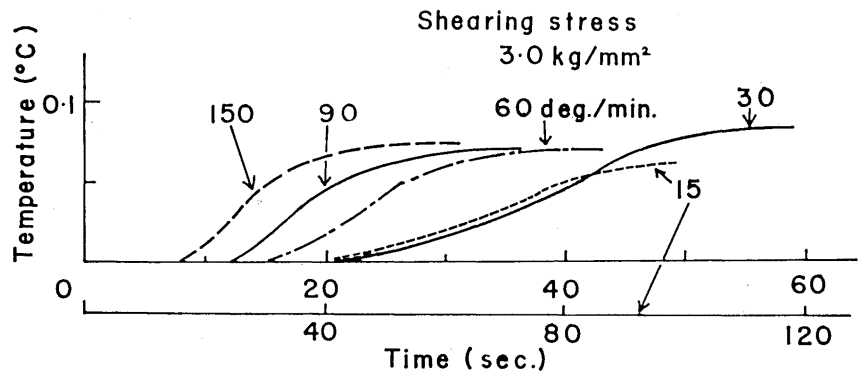

Fig. A·2·3

Figs. A·2·1 through A·2·3 Transient temperature decrease or increase of stressed specimens, depending on stressing rates but independent of the stress values themselves in the final stage.

The temperature ceases to decrease somewhere at a stress where the stress-strain relation deviates from linearity, and soon tends to increase. It is followed by a rapid rise associated with necking. After accomplishment of the orientation, as seen from a curve θ_3 in Fig. A·2·4, the temperature rather tends to decrease again possibly because of dissipation of heat. There is not much increase on both end portions having a larger sectional area, but only a sudden increase appears immediatedly after the specimen breaks. It is due no doubt to an impulsive stress wave of compression caused by the break; it is quantitatively verified.

Fig. A·2·5 gives the relation of stresses vs. temperature changes in three kinds of load.

Appendix 3

Fig. A·3·1 shows an incipient temperature rise and succeeding temperature change under pulsating compression. When the stress amplitude is not high compared with the mean stress, the mean temperature converges to a lower level than the initially raised temperature. Another measurement is given in

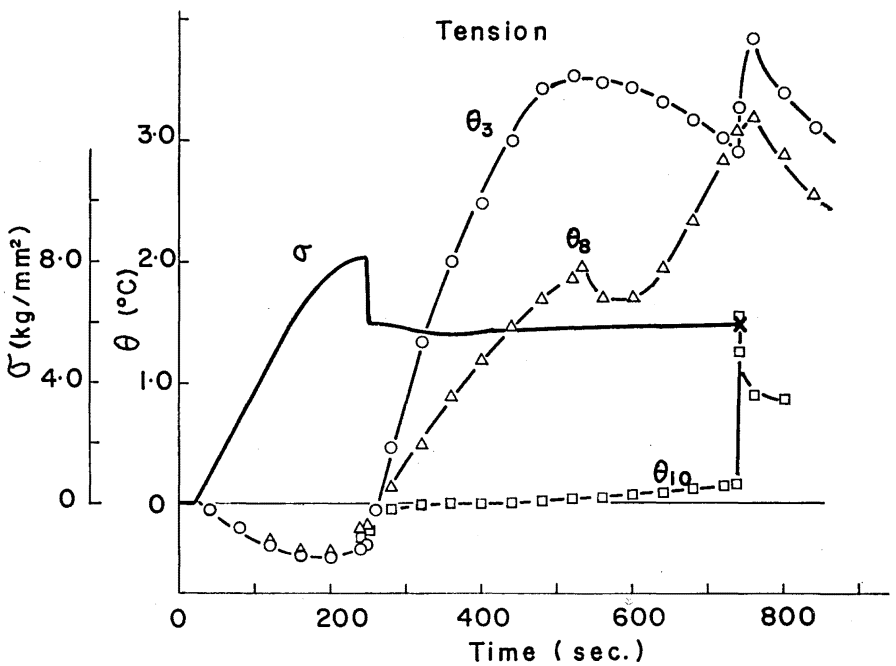

Fig. A·2·4 Temperature change interrelated to change in monotonically increasing extension.
#3 is a site 5 mm distant from the section to break, #8 is 25 mm distant, and #10 35 mm but very near one of grips.

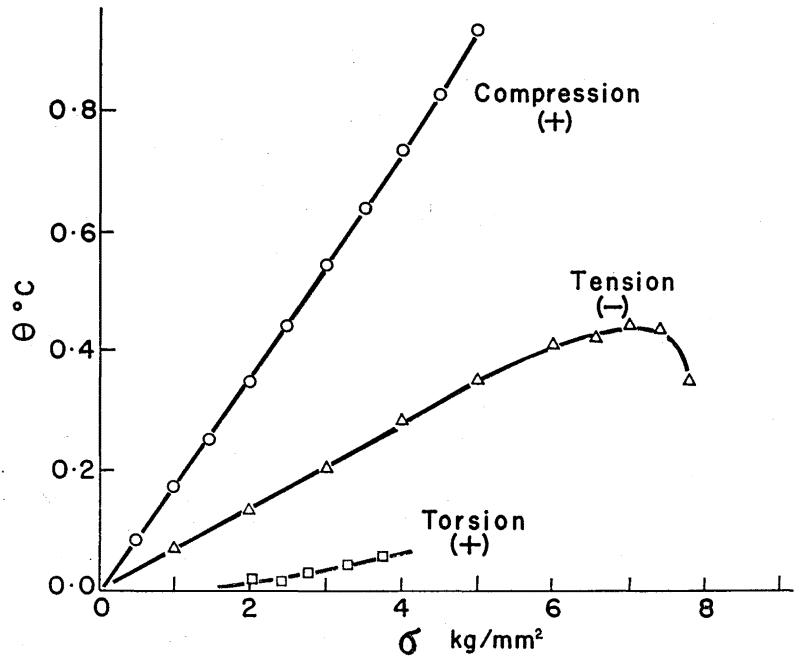

Fig. A·2·5 Stresses and temperature changes of polycarbonate.

Fig. A·3·2 together with the stress increase measured at the same time.

Fig. A·3·3 is a record of the temperature change in a hollow cylindrical specimen under pulsating torsion, from which the difference between the temperatures of the outside and the inside surfaces is known. Fig. A·3·4 is that of a plate specimen under plain bending. The small amplitude of the temperature cycles is due to a high rate of repetition, 1 cycle/sec, compared with other kinds of load. The result is well understandable when a solution of the problem of heat conduction is referred to,[7] considering the thermal diffusivity of the protective layer of the thermocouple sheet and the time constant of the recorder. Reasonable values of amplitude reduction as well as of the phase angle lag are given.

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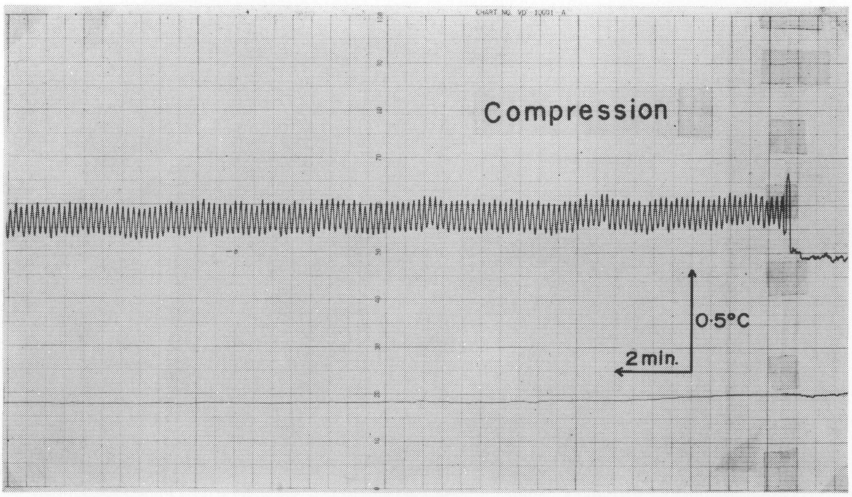

Fig. A·3·1

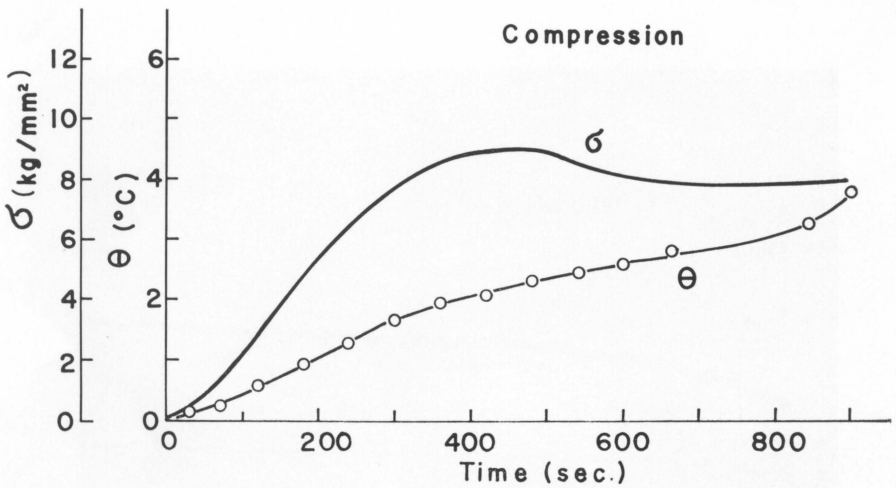

Fig. A·3·2

Figs. A·3·1 through A·3·4 Temperature changes under pulsating loads of compression, torsion, and plain bending.

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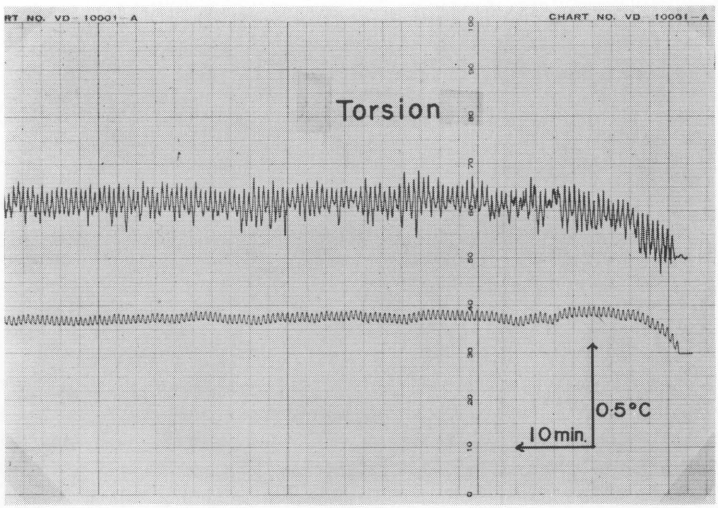

Fig. A·3·3

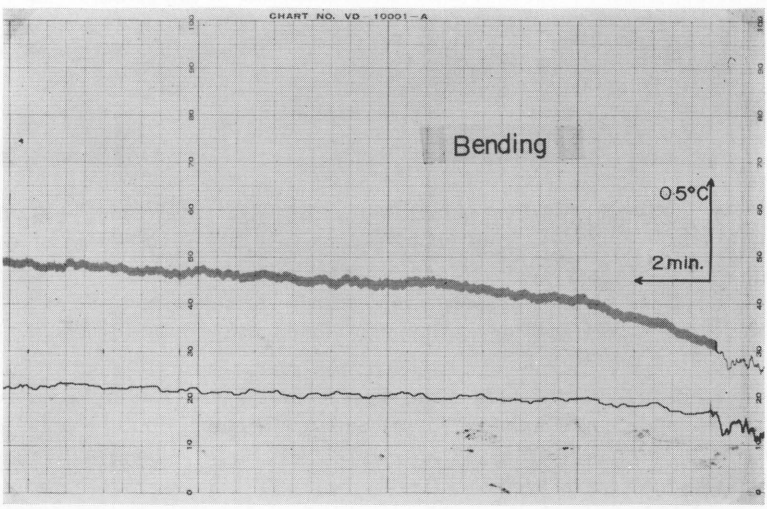

Fig. A·3·4