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STIFFNESS INCREASE ASSOCIATED WITH FATIGUE OF POLYCARBONATE

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Synopsis

Experimental investigations were made with rod materials of phosgenation process-produced polycarbonate at slow speeds, as 60 cycles or a few cycles per minute. The fatigue under torsion, reversed or fluctuating, was accompanied by rigidity increase in the stress range below the transition of the fatigue fracture mode. The rate of the rigidity increase, expressed by a power of the number of cycles, has been investigated in a term of the exponent in a comparatively earlier stage of fatigue. The value of the exponent depended on the imposed amplitude and consequently on the specimen temperature, which was supposed to be raised by the work due to the fatigue load. But the generated heat must dissipate with time and hence the temperature must depend on the time length for one cycle. Thus, the larger the amplitude was, the rate got the more reduced in Schenck-type machine tests, i.e. the constant time cycle tests, and was the higher under such a condition that a longer time for one cycle was needed for a higher value of the amplitude.

Not so much pronounced changes as with fibrous materials have been observed with the material. This is due to the fact that the changes concentrate on the specimen surface being under a higher stress. It has been confirmed by removing the surface layer repeatedly during fatigue. The smallness of the changes never imply that they can be ignored in considering the fatigue properties of engineering plastics, because a localized fatigue leads the specimen to the ultimate fatigue fracture as well known.

1. Introduction

Mostly the fatigue strengths of engineering plastics have been investigated at the speeds of several hundred or more cycles per minute as in metals and, as a matter of fact with plastics, the results involve the pronounced effect of the temperature raised with the cyclic loads[1]. Although the temperature effect is of a primary importance for practical purposes, it also is interesting to disclose the fatigue mechanism in a field where the temperature rise is very little. As for fibrous materials, the investigations have more advanced in considering the micro-mechanism of fracture[2].

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The present work is the preliminary measurements for an attempt to study the fatigue mechanism. Usually the fatigue mechanism in metals is described in terms of the dislocation. The fracture behaviors of engineering plastics, even those of amorphous structure, often much resemble those of metals. Such explanation for metal fatigue made from the structural standpoint may possibly be replaced by some concept understandable from the standpoint of a mechanics in some sort of a domain of a size of μm by sublating the sub-microstructural standpoint, to get available for plastics fatigue mechanism as well.

2. Preliminaries

The material, the testing machines and the condition of measurement are described in the preceding paper[3].

A preliminary test was made to get a stress-strain diagram of the material when subjected to torsion. Two hollow specimens of the same form but different in length were prepared to exclude the end effect and to evaluate the homogeneous deformation of the material, and after R. Hill[4] the torque-twist relationship was converted to a shearing stress-strain diagram*. Initial values of shearing stresses and strains of the fatigue specimens were calculated by use of the diagram together with the values of each specimen diameter and the initial torque. However, in the present case, the changes in rigidity of the specimens under reversed twisting with the pre-determined amplitudes of the twist angle are given with the ratios of the changes in the torque to the initial (i.e. $\Delta T/T_0$), because the stress-strain relationship itself changes with fatigue[2].

The amplitudes of the twist angle of the torsion bar of the Schenck-type fatigue testing machine were measured with an autocollimator, from which the change 0.1″ could be read in the range $\pm$ 15′. This was very sensitive and gave the most reproducible data, though laborious to make measurement. Some of the data were taken with a couple of dial gauges.

In a Rhiele-type machine which was used for fluctuating torsional load, the torque was read on its dial.

3. Torque increase with strain cycles

The specimens were repeatedly subjected to torsion under the condition of the angle of twist for each being kept constant in its initially determined amplitude. The amplitude of the torque required to twist them increased with repetitions below the transition of the fracture mode[3], where the shearing strain (or stress) was less than about 0.04 (or about 3 kg/mm^2). As a matter of fact, they decreased rather rapidly with approach to their fatigue lives, as shown in Fig. 1; while there appeared no stage of increase in the super-transitional range. The increases in the present case were 4$\sim$5% and seemed to be larger for small-

* It is available for viscoelastic materials also as far as the load is of non-decreasing.

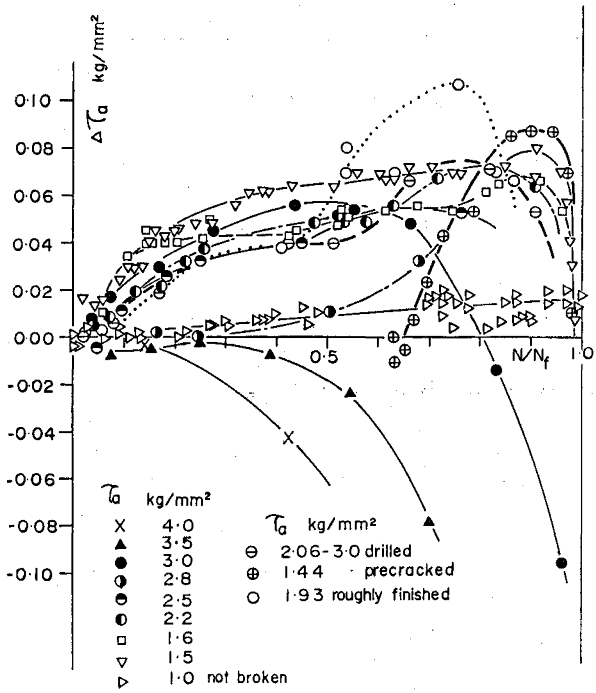

Fig. 1. Changes in rigidity

er strain amplitudes.

There is given a measurement for a specimen subjected to 10^6 cycles of which the stress amplitude is initially 1.0 kg/mm². The cycle ratio there represents the ratio of the imposed cycles to 10^6 in place of the fatigue life, N_f; apparently the rigidity increase is small and does not seem saturated. Supposedly the specimen might have increased in rigidity in about the same rate as for the specimen under the stress 1.5 or 1.6 kg/mm² if the test would have been continued untill fracture. Then, an expected life in such an assumed increasing rate is about 4×10^7 cycles.

On the other hand, the data for a precracked specimen are plotted not against its actual cycle ratios but against the ratios to a life presumed for the specimen to have had if it would have been tested with no pre-made crack. The specimen had had a 0.03 mm deep and 2 mm long precrack made at the mid length by lightly pressing a razor blade placed on the surface at about 50° to the specimen axis, and was subjected to the stress amplitude of 1.4 kg/mm² initially. Naturally it broke in a much less time than a specimen did under about the same stress amplitude, 1.5kg/mm². If the break point is adjusted to coincide with others, then the starting point is located on 0.63 (a thick line in Fig. 1). It could be said that such is a period needed for a crack to appear in a sound specimen and to grow up to the same size as the precrack. The precracked specimen is presumed lacking in a middle stage of fatigue.

The final stage, distinguished from the middle with a slight further increase in rigidity is not always conspicuous. It often becomes clear however, when not the average but the respective values in both directions of torsion are plotted. Presumably it occurs due to the plastic deformation at crack tips. The specimen shows local extension near the crack owing to a lot of fine deformation bands, which on fatigue appear even below the yietd stress of the material. Accordingly the torque increases mechanically in the crack closing direction; it can not be said to be of a substantial nature from a physical point of view.

In a roughly finished specimen, cracks occur comparatively early and much in succession as shown with a dotted line in Fig. 1.

4. The exponent of an initial rigidity increase

Although crack propagation is a matter of primary concern for most of the people who are now studying on fatigue, the writers think that the initial rigidity increase is of an intrinsic nature in order to understand the effect of load repetitions on the strength of materials. For the present we shall state it in a term of the exponent which represents the initial rigidity increase in a simple way, though not the best.

The measurements shown in Fig. 1 are replotted in Fig. 2 on a semi-log

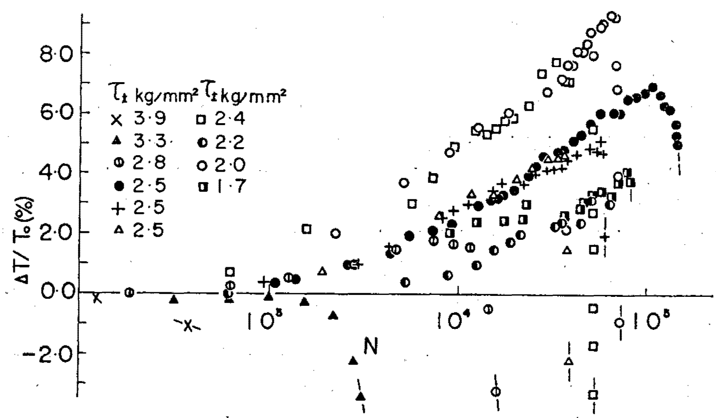

Fig. 2. Changes in rigidity replotted against a semi-log scale

scale, where the final decrease in rigidity, after which break soon follows, is shown with downward running broken lines. After the initial repetitions of several tens, the rigidity rises in an almost linear fashion over a period for the stresses in the subtransitional range. Assuming a relation

$$\frac{\Delta T}{T_0} = m \log_{10} \frac{N}{N_0}$$

in this period, the values of the tangents, m, percent per unit increase of $\log_{10} N$, are plotted against the values of the initial stress amplitudes for the case of reversed torsional loads (Fig. 3). Using m' equal to $0.4343\,m$, an expression

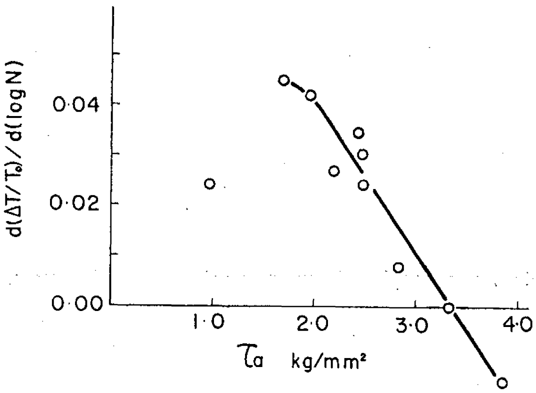

Fig. 3. Rates of rigidity increase (Schenck-type tests)

$$\frac{T_0+\Delta T}{T_0}\simeq\left(\frac{N}{N_0}\right)^{m'}$$

also may be available because an approximate relation

$$\frac{\Delta T}{T_0}\simeq\log_e\left(1+\frac{\Delta T}{T_0}\right)$$

holds for the present case. Here, N_0 is the intercept on the axis of N.

The exponent is exceptionally small for 1.0 kg/mm^2, possibly because for one thing the exponent has been evaluated only in an earlier gently increasing range compared with the life length (the fatigue test was not completed for such a small stress), and for another because the rigidity increase should essentially be the less for the smaller stresses in spite of the fact already described; possibly the small values of m obtained for high stresses may be ascribed to softening due to temperature rise which is the larger for the higher stresses.

The first reason can not be discussed any more by this way of a simple analysis; we now are not investigating on the detail of the process of rigidity increase. The second admits of further consideration. When a Schenck-type machine is used, the time required for one cycle is determined independently of the magnitude of the twist angle. If the test is carried out at a pre-determined twisting speed, the time is proportionate to the imposed amplitude. There are, in a large amplitude, an ample time for heat dissipation as well as much work for heat generation. This is the case of a Rhiele-type testing machine. The exponent m increases with the stress amplitudes, which is shown in Fig. 6, where the parameter is the initial value of the mean stress, τ_m.

Taking into account that our repetition is at slow speeds in any case and

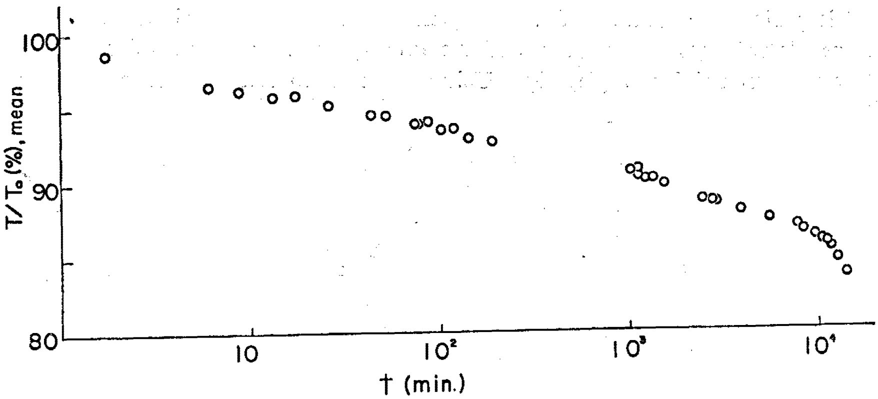

Fig. 4. An example of dynamic relaxation of a mean value

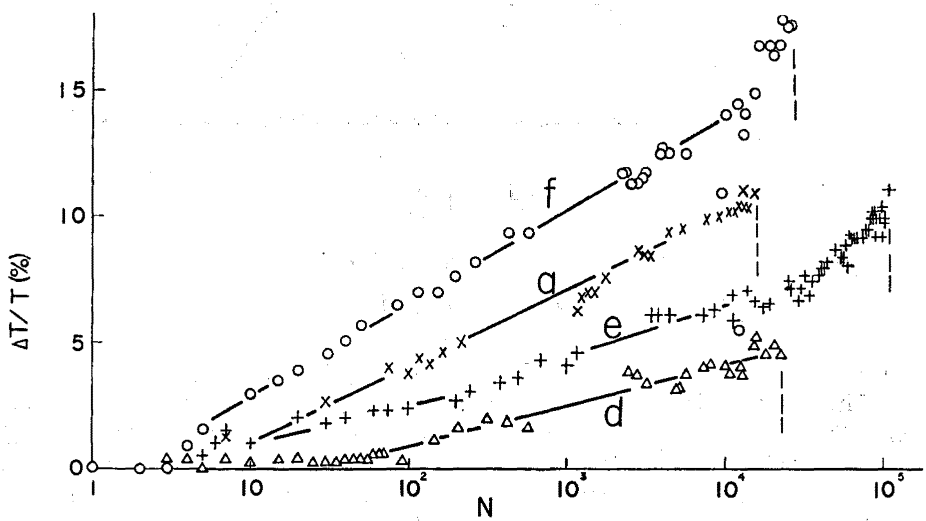

Fig. 5. Rigidity increase (Rhiele- or Instron-type tests)
f, a, e, d refer to Fig. 6

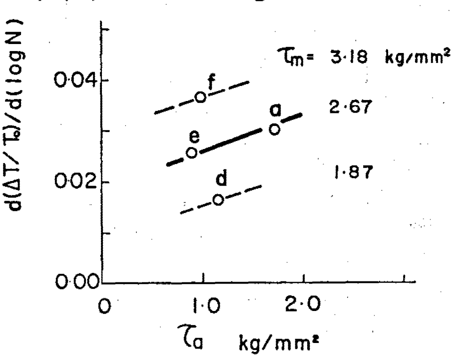

Fig. 6. Rates of rigidity increase as expressed dependent on initial stresses

the temperature rise may be small, we can not but consider the exponent m to be very sensitive to heat.

5. The effect of the twisting speed on m

An experiment has been made for cases of fluctuating torsion with different strain amplitudes and strain rates (Table 1, Fig. 7).

Table 1

	Mean strain, set constant γ_m	Strain amplitude, set constant γ_a	Time for one cycle min	Angular velocity deg/min	Exponent m
a	0.044	0.036	0.88	30	0.025
b	0.044	0.035	0.49	60	0.020
c	0.042	0.016	0.44	32	0.035

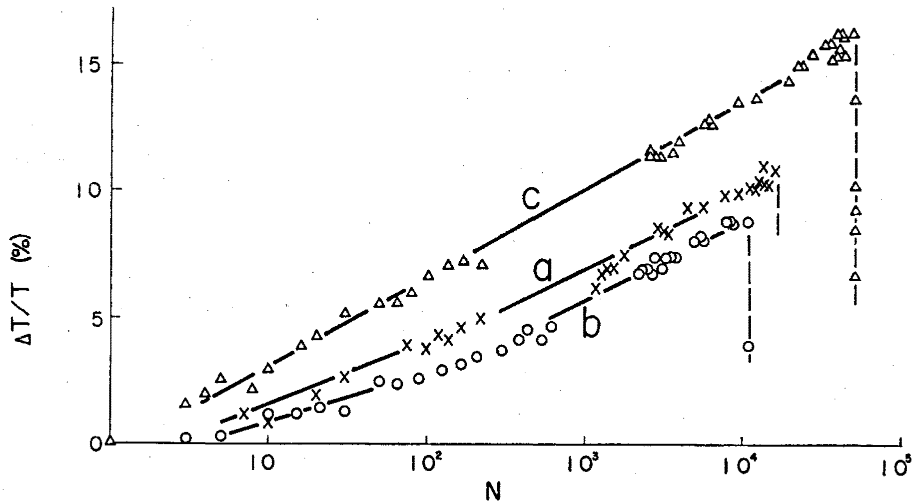

Fig. 7. Effect of twisting speeds on increase rates
a, b, c refer to Table 1

Fluctuating strains for the specimens a and b are equal in magnitude of both the average and the amplitude, but the time required to complete one cycle is less for b than for a; accordingly the specimen b has less time for heat to dissipate and its rigidity increase will be less on account of the stored heat. In the specimen c, on the other hand, the strain amplitude is smaller than that of b, while the time for one cycle is about the same for both specimens. The temperature of c will be at a lower level; thus the rigidity increase rate is larger as shown in Fig. 7. Although the strain amplitude dependence of the rigidity increase in itself can not in a general formula be defined without separating the effect of the temperature rise, it is likely that the relation may be represented as a schematic diagram shown in Fig. 12.

6. The effect of surface treatments on rigidity increase

Repolishing, three times during fatigue testing, was made with a specimen for the purpose of realizing the significance of a layer of some depth on the surface. We began the first process in the same way as for other ordinary ones. When the rigidity increase seemed to approach its saturation (after the cycles of about 20% of the fatigue life), the machine was stopped and the specimen was removed with prudence. Before and after repolishing the surface the diameter was measured. The specimen was reset with prudence again and the amplitudes of torque and twist at restarting were measured. After three times repolishing the specimen was kept on test untill break.
The results of measurement are given with the amount of the removed layer depth and the amplitude in term of the stress at each restart in both Fig. 8 and Table 2. The mode of rigidity change is not much different from each another and the curves can be shifted to overlap as seen in Fig. 8. The life of the final course itself was longer than those of the ordinary ones.

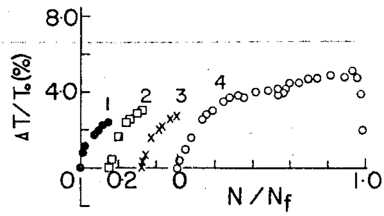

Fig. 8. Effect of surface repolishing
Refer to Table 2

Table 2

	Diameter mm	Removed layer depth mm	Stress amplitude kg/mm²
1	10.295	...	2.51
2	10.246	0.025	2.50
3	10.196	0.025	2.50
4	10.141	0.028	2.48

There is another long-lived specimen which had been treated chemically. A small quantity of methylene dichloride-methyl alcohol solution in the ratio of about two to one was sprayed on the specimen surface, which was dried at once by air blast. The change in the diameter could be disregarded. This was done prior to start testing and repeated three times during fatigue testing. The rigidity, in the present case, seems to continue to increase indifferently to the procedures. The curves of increasing can be naturally connected one after another to form a smooth rising curve.

As for an effect of the pause of loading for the procedure, only a little increase in rigidity was caused as noticed at the points denoted 'stopped' in Fig. 9, each of discontinuances lasted nearly twenty hours. In the ordinary cases

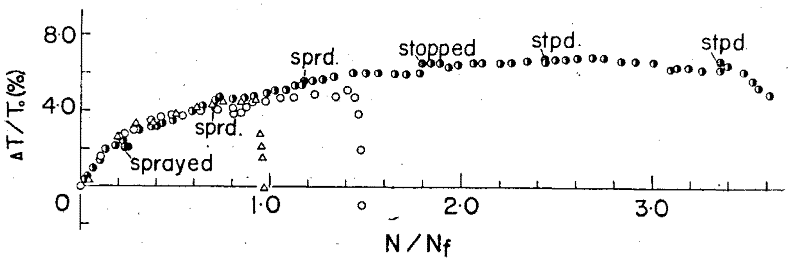

Fig. 9. Effect of surface treatments

△ control
○ repolished

the slightest decrease was observed after a pause of loading.

7. The relation of the strain amplitude and the fracture cycle

As shown in Fig. 1, the rigidity does not so completely cease to increase, that the repeating stress amplitudes can not be defined definitely as Manson did for metals[5]. Only we can take the magnitudes at half the cycles of fracture as a convenient measure and draw a stress-strain diagram, and the components of the elastic and the plastic strains were evaluated on the diagram. We have tried to plot them and to evaluate the tangents as $-1/3$ and $-3/2$ respectively for the plastic strains in the super-transitional and the sub-transitional ranges (Fig. 10).

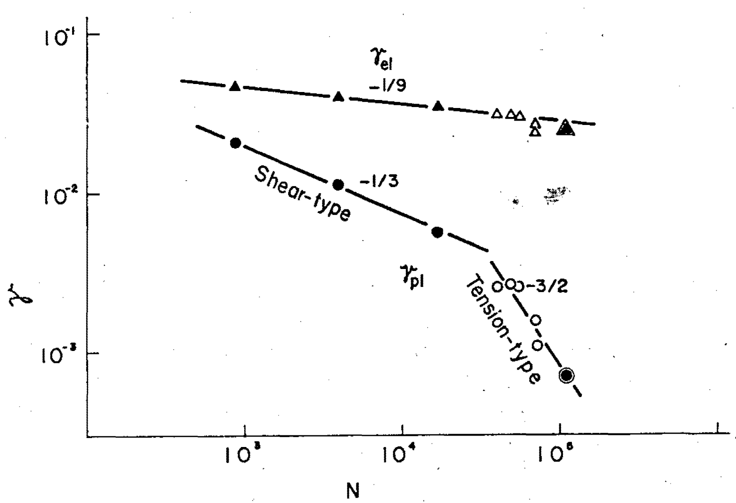

Fig. 10. Relations of repeating plastic strain vs cycle

8. Stress-strain diagrams of a fatigued and an unfatigued specimen

Fig. 11 shows a torque-shearing strain diagram of a specimen fatigued under 12.3×10^4 cycles of the stress fluctuating between 1.7～3.5 kg/mm^2 together with that of an unfatigued control specimen. Their dimensions were 20 mm and 14 mm in the outer and inner diameters and 30 mm in the length of the parallel part. The shearing strain was evaluated with the length of the parallel portion. The control specimen had been pre-conditioned in the same room condition for the same period (about one month) as in fatigue testing. The difference is not so much as in fibrous materials[2]. An imaginable reason for the present, apart from the problem of structural difference of the materials, is that the fibrous materials underwent the loads in the extent to give rise to molecular orientation and that they had a good deal of surface area ratio on account of their fineness. On the surface occurs most of the effect of fatigue even under uniform stress and much more under such particular higher stress values as on the surface in our case. Notwithstanding the effect, averaged on the whole cross sectional area, will not amount to much on account of the smallness of the surface layer depth ratio. Conversely this implies that a small amount of change is possible to lead to local fatigue. We can not side with the people who are of opinion that the increase in rigidity can be ignored in considering the fatigue properties of engineering plastics.

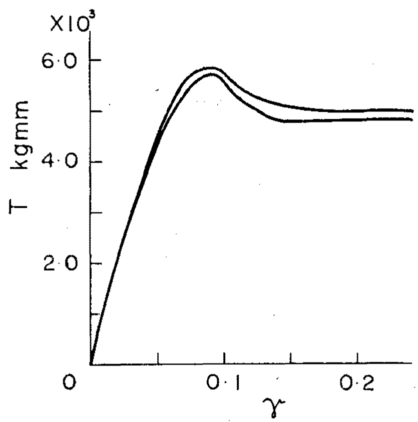

Fig. 11. Torque- shearing strain diagrams
Upper fatigued
Lower unfatigued

9. Conclusion

Phosgenation process-produced polycarbonate increases in rigidity when subjected to repetition of loads in the stress range below the transition of the fatigue fracture mode.

The increase amounts to 4～5% when subjected to reversed torsions on the condition that the imposed strain amplitudes are constant (Schenck-type tests), and is somewhat larger for the low values of the amplitudes. The rates of the rigidity increase also are larger for smaller amplitudes.

In the case of fluctuating torsions with a Rhiele-type torsion testing machine the increase amounts to 5～15% and the rates of increasing rise with the values of the amplitudes, though the magnitudes of the torque fall with time, needless to say, on account of the non-zero mean stresses (Fig. 4).

The difference of their tendencies is due possibly to the difference of the working conditions for both machines that the one takes a constant time for one cycle independently of the amplitude while the other needs the time proportional to its value. Accordingly the specimens in the latter case are at comparatively lower temperatures in larger amplitudes on account of the longer time for the generated heat to dissipate.

Rigidity increase itself may naturally be presumed to be in a higher rate under a larger value of amplitude. However, the situation is reversed when the time required for one cycle remains constant and the specimen temperature is comparatively high as on a Schenck-type testing machine. These circumstances have been described in term of an exponent *m*, and both results in Figs. 3 and 6 give a diagramatic representation as shown in Fig. 12.

An examination was made of the effect of removing the surface layer on the rigidity increase, together with that of a chemical treatment. It may fairly be presumed that the increase in rigidity is produced in a thin layer on the surface particularly when a bulk material is subjected to a stress being high on the surface.

For this reason, it is reasonable that not so much pronounced changes as with fibrous materials were observed with our material.

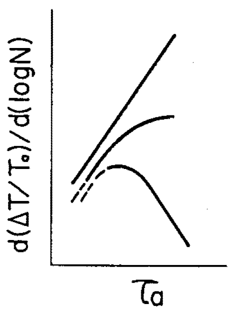

Fig. 12. Schematic general representation of increase rates

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