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Factors Affecting Dynamic Durability of Polycarbonate under Bending, Torsional, and Impacting Fatigue and in Cavitation Erosion and Dynamic Solvent Cracking Conditions

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Synopsis

To understand influences of various factors on dynamic durability of engineering plastics, effects of average molecular weights of samples, molding variables, preparing methods of specimens, and fillers on plane and rotational bending, torsional, and impacting fatigue and cavitation erosion and solvent cracking of polycarbonate were studied. From the experimental results, the following tendencies are observed as a whole in case of polycarbonate: The extent of influence of the factors on dynamic durability varies depending on the type of testing. Increase in molecular weight has a favorable effect on dynamic durabilities. Influence of molding conditions is remarkable: especially, deficient drying of resin pellets before molding decreases dynamic durability noticeably, and specimens prepared by injection molding have much better durabilities than those by machining from extruded sheet. Polyethylene blending has an unfavorable effect on durability, except for Izod-type impact strength and solvent cracking. Reinforcement by glass fiber has a favorable effect on fatigue under constant load and solvent cracking, but has unfavorable effect on fatigue under constant deformation and cavitation erosion.

INTRODUCTION

In order to use plastics materials widely as mechanical elements in industries such as railways, it is necessary to understand their dynamic durability. However, experimental investigations of dynamic durabilities of plastics have been relatively few in number. Though there are several reports on factors affecting fatigue of plastics, each of these reports deals with influence of a single factor such as testing speed,[1,2] temperature,[3,4] or fillers for thermosetting plastics.[5,6] A survey of factors affecting dynamic durabilities for plastics has not yet been attempted.

It is the purpose of this study to clarify the influence of various factors on dynamic durability. Polycarbonate was selected as the testing material as it is one of the most widely used plastics material in engineering and in addition an important material in railways. The types of test of dynamic durability employed in this study are concerned with plane bending, rotational bending, torsional and impacting fatigue, cavitation erosion, and dynamic solvent cracking. The testing apparatus used for measuring several types of fatigue and solvent cracking has been developed or improved by the authors. The

TABLE I
Specifications of Specimens

Factor	Average molecular weight			Molding variables					Specimen preparation method		Filler		
	Low MW ①	Medium MW ②	High MW Ⓢ		Optimum condition Ⓢ	Lower temp. of mold ③	Lower temp. of cylinder ③'	Imperfect drying of pellets ④	By injection Ⓢ	By extrusion and machining ⑤	Unfilled Ⓢ	PE blended ⑦	Glass fiber filled ⑧
MW of pellets before injection	2.25 × 10^4	2.5 × 10^4	3 × 10^4	Temp. of mold, °C	110–120	50–60	110–120	110–120	3 × 10^4	3 × 10^4	3 × 10^4	3 × 10^4	3 × 10^4
				Temp. of cylinder °C	270	270	250	270					
MW of specimens after injection	2.14 × 10^4	2.33 × 10^4	2.59 × 10^4	Drying time of pellets, hr	6	6	6	1	2.59 × 10^4	—	2.59 × 10^4	—	2.10 × 10^4
Sample source[a]	L-1225	L-1250	K-1300			K-1300			K-1300	K-1300	K-1300	KE-1300[b]	G-1030[c]

[a] Polycarbonate for injection molding: commercial grade of Panlite supplied by Teijin Chemicals Limited.
[b] PE content: a small quantity.
[c] Glassfiber content about 30%; average length after molding about 0.5 mm.

TABLE II
Apparatus Used and Testing Conditions

Type of testing	Apparatus	Specimen (Fig. 1)	Testing conditions[a]	References
Tensile strength	Instron-type testing machine	—	speed of testing = 10 cm/min	—
Plane bending fatigue				
Const. dynamic load	improved ASTM-D671 type	(A)	stress amplitude = ±2.8 kg/mm²	7
Const. dynamic deflection	developed "pentacle machine"		testing speed = 1500 cpm dynamic deflection = ±2.7 mm testing speed = 1000 cpm	8
Rotational bending fatigue	improved R. R. Moore type	(B)	stress amplitude = ±5.8 kg/mm² testing speed = 1500 rpm	9
Torsional				
Strength	developed "MO-U machine"	(B)	testing speed = 5°/sec	
Fatigue			alternating angle = 17 ± 17° testing speed = 600 cpm	10
Impacting				
Strength	Izod type			—
Fatigue	improved dropping weight type	(C)	dropping distance = 10 mm testing speed = 30 cpm	—
Cavitation				
Degradation	sonic shear stability tester ASTM	dioxane solution	frequency = 12 KHz	—
Erosion	sonic vibratory cavitation tester	(D)	frequency = 6.7 KHz (in water)	—
Solvent cracking				
Under nonload	closed glass vessel	(E)	in acetone 70% aqueous solution	—
Under static load	developed "LPN apparatus"		initial tension = 1.3 kg/mm	11
Under Vibration	modified LPN	(E')	initial acceleration = 3 G frequency = 25 Hz	12

[a] At ambient temperature.

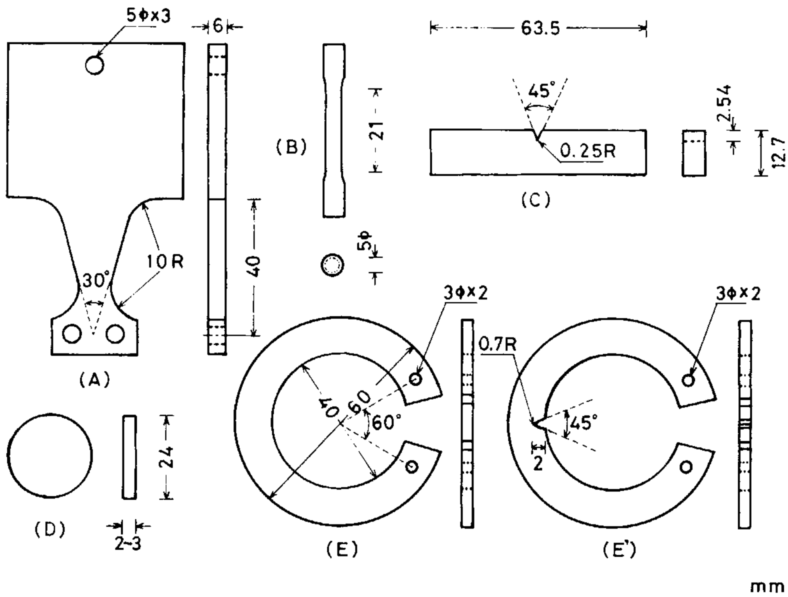

Fig. 1. Dimensions of test specimens.

specimens used here for studying influence of several factors are shown in Table I. Experimental methods and testing conditions are tabulated in Table II, and Figure 1 shows dimensions of these specimens.

PLANE BENDING FATIGUE

Two types of fatigue testing were selected for measuring the effect of several factors on strength of polycarbonate under plane bending fatigue. One was a test under constant amplitude of force based on ASTM-D671, and the other was under constant amplitude of deflection. To study the fatigue under constant amplitude of force, a DTF displacement meter was introduced to a revised testing machine based on ASTM-D671, so that it became

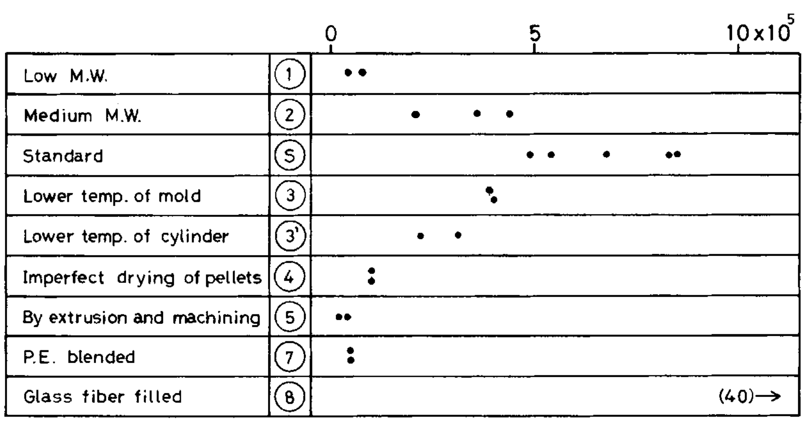

Fig. 2. Number of cycles to failure under repeated bending in constant stress amplitude.

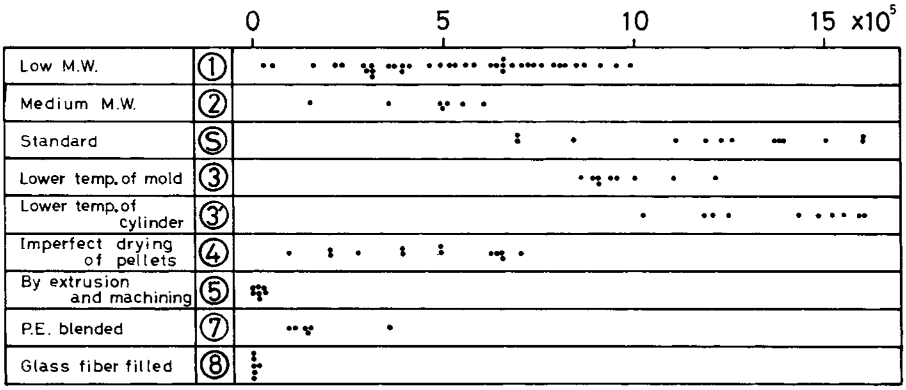

Fig. 3. Number of cycles to failure under repeated bending in constant deflection amplitude.

possible to measure continuously dynamic deflection of a testing specimen. Specifications of this testing machine are as follows: maximum load, ±25 kg; maximum deflection limit, ±10 mm; speed of testing, 1500 cpm; attachment, dynamic deflection detector.

In this study, dynamic durability was evaluated by comparing the number of cycles to failure under repeated bending in ±2.8 kg/mm^2 (bending stress amplitude of force). The results are shown in Figure 2.

Fatigue test in constant amplitude of deflection was carried out by making use of a new testing machine called "pentacle fatigue testing machine" constructed in trial by the authors. This testing machine gives repeated constant amplitude of deflection and it is capable of testing five test specimens simultaneously by a double eccentric shaft mechanism. Specifications of this testing machine are as follows: dynamic deflection range, ±0.9–7 mm; maximum force, ±20 kg (each shaft); testing speed, 300–1500 cpm; attachments, chamber with temperature controller, dynamic force detector, ultraviolet lamps for irradiation, chucks for compressive fatigue testing.

Dynamic durability was compared by the number of cycles to failure under repeated bending in ±2.7 mm (dynamic deflection at specimen's end) by the testing speed of 1000 cpm. Experimental results are shown in Figure 3.

ROTATIONAL BENDING FATIGUE

A revised fatigue testing machine was used here. It is adapted to plastics testing and constructed in trial by the authors based on R. R. Moore's type of four-point loading.

Considerable points of improvement are as follows: (1) Specimen size has been made so small that it can be prepared by injection molding. (2) Maximum deflection limit of specimen is made large, because the rigidity of plastics is very low as compared to metals. (3) Testing speed has been made variable continuously in order to prevent unusual heat generation in plastics. Dynamic durability was evaluated by comparing the number of cycles to failure in ±5.8 kg/mm^2 (bending stress amplitude of force) by a testing speed of 1500 rpm. Experimental results are shown in Table III, including temperature rises on specimen surface during fatigue testing.

TABLE III
Number of Cycles to Failure and Temperature Rise Under Rotational Bending[a]

Factor	Symbol	Initial deflection mm	Temperature on specimen surface, °C	Number of cycles to failure, ×10⁴
Low MW	①	35.4	61 60	2.8 4.7
Medium MW	②	35.2	84 96 70 82	4.8 5.9 3.5 2.4
Standard	Ⓢ	41.0	108 97 89 96 103	3.8 1.5 3.8 1.9 1.0
Lower temp. of mold	③	41.1	76 77 74	1.1 1.1 0.8
Imperfect drying of pellets	④	42.1	82 82 87	3.8 1.2 2.3
By extrusion and machining	⑤	39.5	36 35 38	0.9 1.1 1.1
PE blended	⑦	42.4	94 101 90 85	0.6 0.8 0.6 0.6
Glass fiber filled	⑧	14.6	30	35[b] 34[b] 41[b]

[a] Ambient temp., 20° ± 5° C.
[b] Broke down at clamp.

TORSIONAL STRENGTH AND FATIGUE

Torsional properties of engineering plastics are important in practice, but few studies have been reported because there is no proper testing machine for plastics. So we developed a new testing apparatus called "MO-U machine." By making use of this apparatus, torsional fatigue strength under repeated constant amplitude of deformation can be measured in addition to static torsional properties. A schematic view of this apparatus is shown in Figure 4. The test was carried out with a testing speed of 5°/sec in static torsion and with alternating speed of 600 cpm at 17° ± 17° in dynamic torsion.

Experimental results are shown in Table IV. As for static torsional properties, there were no remarkable differences among samples except for "glass fiber filled," which had higher strength but much smaller angle to failure.

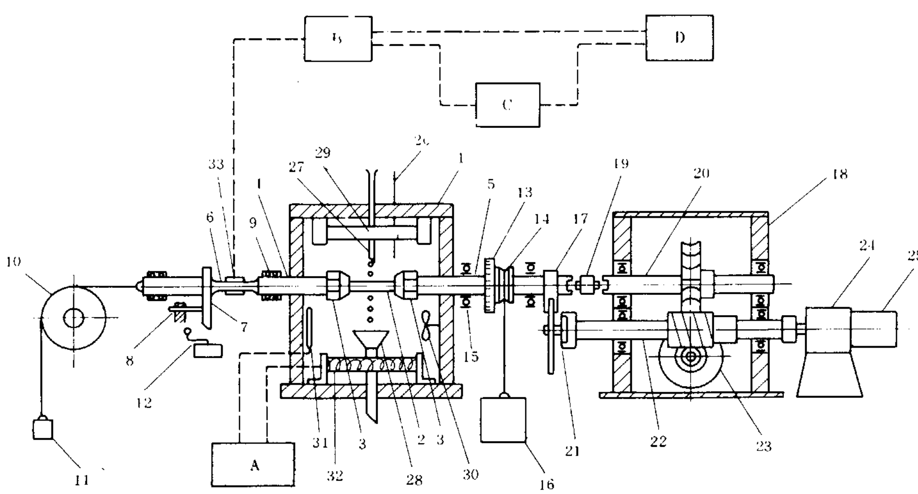

Fig. 4. Schematic view of testing machine "MO-U": (A) temperature controller; (B) strain gauge amplifier; (C) rectifier; (D) pen recorder; (1) chamber; (2) specimen; (11) dead weight for sliding automatic stopper; (18) gear box; (21) eccentric shaft; (24) motor; (33) strain gauge for measuring torque.

TABLE IV
Number of Cycles to Failure in Torsional Fatigue Testing

Factor	Low MW	Medium MW	Standard	Lower temp. of mold	Lower temp. of cylinder	Imperfect drying of pellets	By extrusion and machining	PE blended	Glass fiber filled
	①	②	Ⓢ	③	③'	④	⑤	⑦	⑧
Initial shear stress, kg/mm²	4.3	4.3	4.3	4.3	4.2	4.2	4.1	4.1	8.4
Number of cycles to failure × 10^4	30	37	48	34	29	22	9	10	0.06
	31	39	57	39	32	25	10	14	0.06
	38	41	60	46	38	38	21	18	0.06

Table IV shows that the standard sample was best in torsional fatigue strength.

IMPACTING STRENGTH AND FATIGUE

An Izod-type impact tester was used for evaluating impact strength of samples, and a revised impact fatigue tester which applies impulsive force to a specimen by dropping weight repeatedly was adopted here for evaluating impact fatigue strength. The mechanical structure of this machine is given in Figure 5.

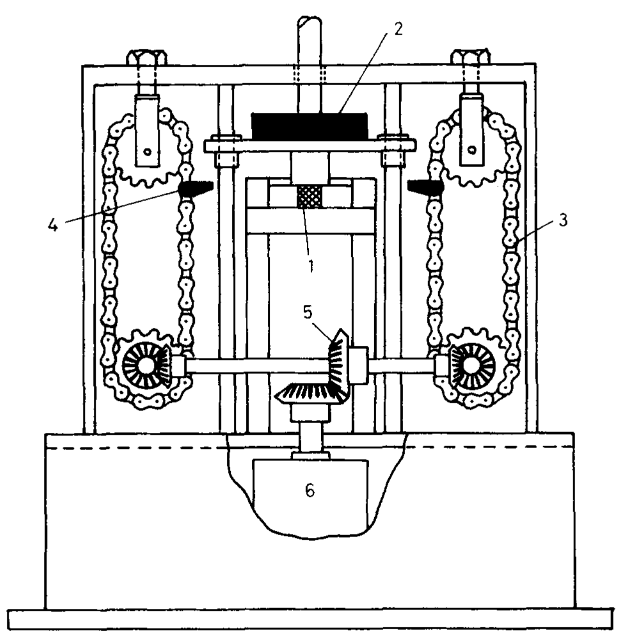

Fig. 5. Mechanism of impact fatigue tester: (1) specimen; (2) dropping weight; (3) chain; (4) hanger; (5) gear; (6) motor.

TABLE V
Izod Impact Strength

Factor	Symbol	Number of specimens	Average value, kg·cm/cm of notch
Low MW	①	10	13.1
Standard	Ⓢ	10	18.2
Lower temp. of mold	③	10	22.1
Imperfect drying of pellets	④	10	16.5
By extrusion and machining	⑤	7	11.9
PE blended	⑦	10	23.9
Glass fiber filled	⑧	10	12.7

The fatigue test conditions were chosen as follows: dropping weight, 140, 240, 440, 640, 840, and 1040 g; falling distance, 10 mm; speed of testing, 30 cpm. Evaluation of impact strength is carried out using absorbed energy of a specimen at impact failure per unit notch length; and impact fatigue strength is evaluated by comparing the total number of cycles to failure of a specimen by repeated impulsive force. V-Notched Izod impact strength was measured and is shown in Table V. "Glass fiber filled" and "by extrusion and machining" had considerably lower impact strength than the standard sample. Figure 6 shows the results of impact fatigue testing. "Glass fiber filled" had longer endurance limit under lower load conditions, but considerably shorter under higher load conditions than the standard sample.

CAVITATION EROSION

Resistance of polycarbonate to cavitation was evaluated here through experiments on degradation of polymer due to high cycle sound wave irradiation in solution and through another type of experiments on cavitation ero-

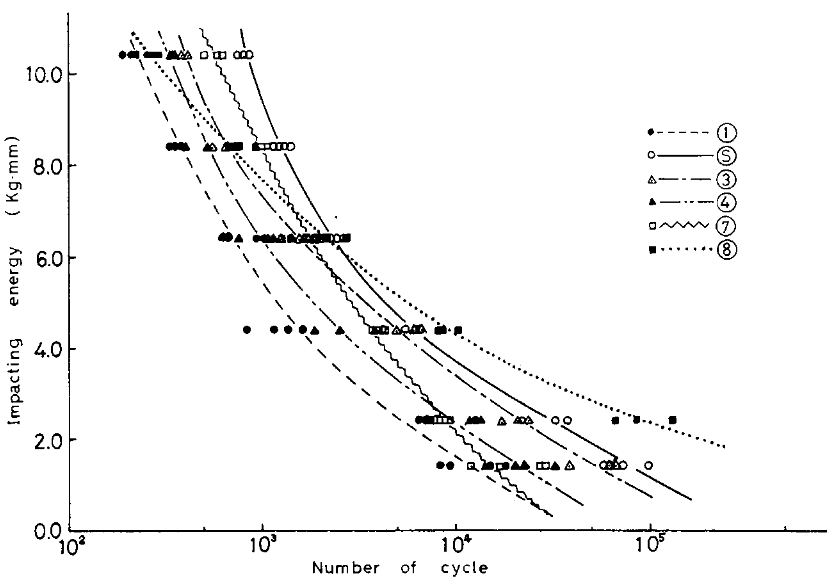

Fig. 6. Impacting fatigue diagrams.

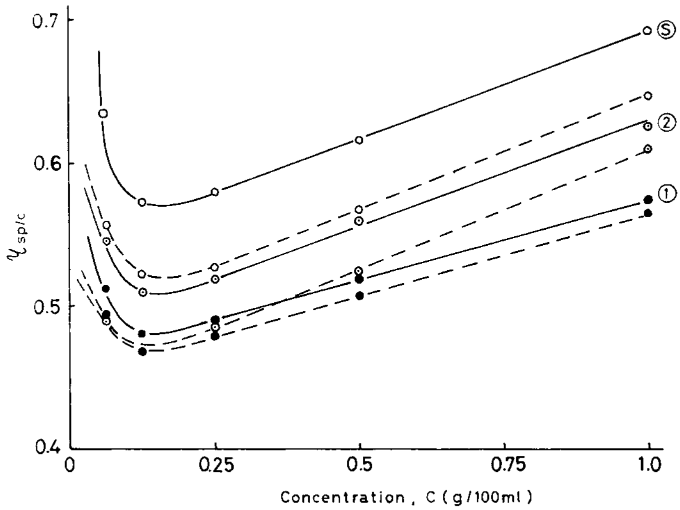

Fig. 7. Viscosity changes caused by sonic irradiation.

sion of plastics by applying high-cycle sound wave irradiation to plate specimens in water. Experiments on cavitation degradation were carried out using a sonic shear stability tester for lubricants (ASTM-D2603), and experiments on cavitation erosion were carried out using a sonic vibratory cavitation tester. In the former test, 12 KHz sonic irradiation was applied to a specimen in dioxane solution under cooling with running water. Degradation was compared by measuring a viscometric average molecular weight before and after irradiation. In the latter test, 6.7 KHz sonic irradiation was ap-

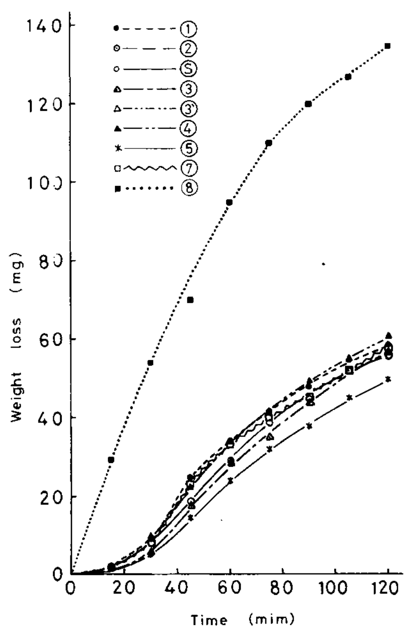

Fig. 8. Weight losses caused by cavitation erosion.

plied to a plate specimen in water at 25° ± 2°C, and cavitation erosion was compared by the weight change of the specimen.

On degradation of polymer by irradiation of sonic wave, Figure 7 shows the experimental results. Decrease in solution viscosity was observed in all cases, because molecular weight was decreased by polymer chain scission. Besides, the results indicate that higher initial molecular weight showed more decrease in viscosity.

Experimental results of cavitation erosion are shown in Figure 8. No significant differences were observed among the test samples, excepting "glass fiber filled" which was subjected to considerable damage.

SOLVENT CRACKING

With polycarbonate, a solvent cracking phenomenon is sometimes an obstacle for development of practical applications. Solvent cracking was studied here by immersing test specimens in the solvent under nonload, static load, and vibrating load conditions. As testing solvent, 70% acetone aqueous solution was chosen, because the growth speed of cracks can be controlled by changing the concentration.

For nonload conditions, the changes in appearance were observed and the changes in weight of test specimens were measured after immersing them in the solvent without loading. The experiment under static load conditions was carried out by means of the testing apparatus called "LPN apparatus." A C-shaped specimen was immersed in the solvent, stretched in constant distance, and then the decay of recovery force in the specimen was recorded continuously. The experiment in vibrating conditions was carried out by using a "dynamic LPN apparatus" which was constructed by modifying the "LPN apparatus." A C-shaped specimen was immersed in solvent while applying vibration at constant frequency (25 Hz), and then the reduction of acceleration of vibration was traced; here, the initial acceleration was 3 G.

Figure 9 shows time–weight change relations by immersion without load. No significant differences were observed among the samples excepting "glass fiber filled," whose weight was increased by swelling, corresponding to the

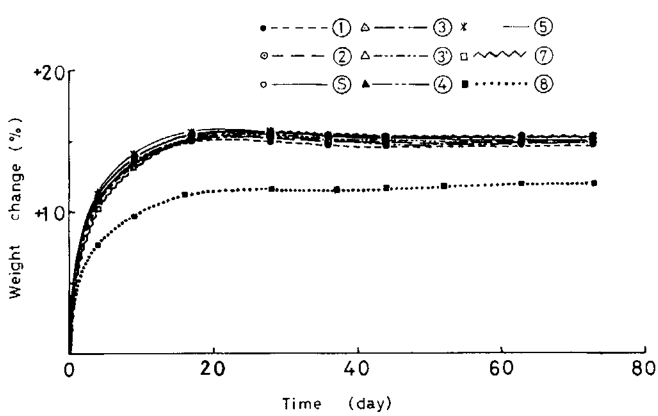

Fig. 9. Weight changes caused by immersion without load.

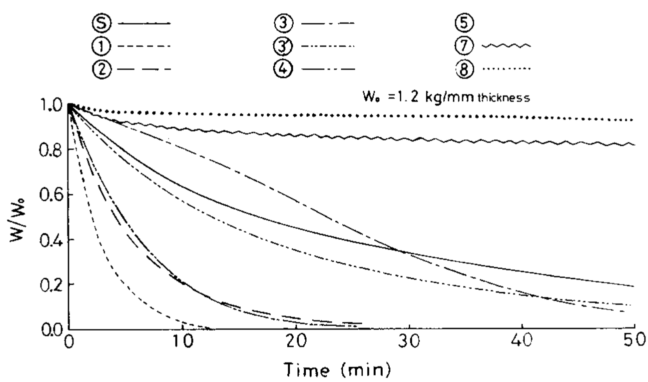

Fig. 10. Stress relaxation curves in 70% acetone aqueous solution under constant force conditions.

resin content. Figure 10 shows apparent stress relaxation curves in the solvent under static load conditions. "Low MW," "medium MW," "imperfect drying of pellets," and "by extrusion and machining" had considerably shorter endurance limits than the standard sample. On the other hand, "PE blended" and "glass fiber filled" had excellent durability, showing no solvent cracking. In the case of stress relaxation in air, stress decreases after 50 min were within 5%, and no crack was appeared in any sample. Figure 11 shows the decay of acceleration under vibrating conditions in the solvent. "Lower MW," "imperfect drying of pellets," and "by extrusion and machining" had much shorter endurance limits than the standard sample. Besides, "glass fiber filled" did not have excellent durability, in contrast to solvent cracking under nonload and static load conditions.

CONCLUSIONS

Dynamic durabilities under plane bending, rotational bending, torsional and impacting fatigue, and in cavitation and dynamic solvent cracking were studied in addition to static mechanical properties. Experimental results are summarized in Table VI. From this table it is clear that the influence of

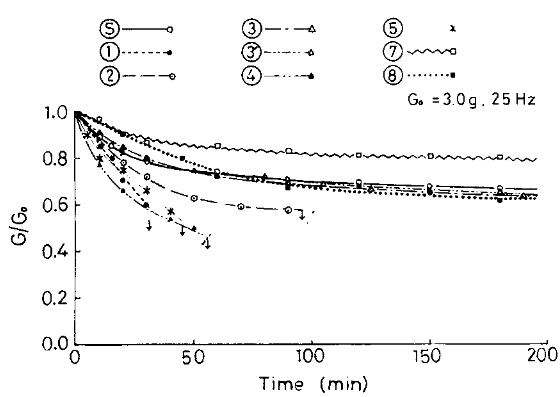

Fig. 11. Dynamic stress relaxation curves in 70% acetone aqueous solution under vibrating conditions.

TABLE VI
Summary of Experimental Results[a]

Factor	Average molecular weight			Molding variables				Specimen preparation method		Filler		
	Low MW ①	Medium MW ②	High MW Ⓢ	Optimum condition Ⓢ	Lower temp. of mold ③	Lower temp. of cylinder ③'	Imperfect drying of pellets ④	By injection Ⓢ	By extrusion and machining ⑤	Unfilled Ⓢ	PE blended ⑦	Glass fiber filled ⑧
Tensile												
Strength	—		0	0	+		—	0	+	0	0	+
Elongation	—		0	0	+		+	0	0	0	0	— —
Plane bending fatigue												
Const. dynamic load	— —	—	0	0	—	—	— —	0	— —	0	— —	+
Const. dynamic deflection	±	—	0	0	—	0	— —	0	— —	0	— —	— —
Rotational bending fatigue	+	+	0	0	— —		±	0	—	0	— —	+
Torsional												
Strength	0	0	0	0	+	0	0	0	0	0	—	+
Fatigue	—	—	0	0	—	—	— —	0	— —	0	—	— —
Impacting												
Strength	—		0	0	+		—	0	— —	0	+	— —
Fatigue												
Low load	—		0	0	0		— —	0	—	0	—	+
Med. load	—		0	0	—		— —	0	—	0	—	+
High load	—		0	0	—		—	0	— —	0	—	— —
Cavitation												
Degradation	++	+	0									
Erosion	—		0	0	0		—	0	+	0	0	— —
Solvent cracking												
Under nonload	0	0	0	0	0	0	0	0	0	0	0	++
Under static load	— —	—	0	0	0	—	— —	0	— —	0	+	++
Under vibration	— —	—	0	0	0	0	— —	0	— —	0	+	0

[a] Evaluation: 0 :equivalent to the standard sample:+:longer endurance life; ++:much longer; —:shorter endurance life, — —:much shorter; ±:endurance life varies widely.

each factor on dynamic durabilities of polycarbonate is not uniform and depends on the type of test.

Typical influences of factor upon dynamic durability of polycarbonate are summarized as follows;

Tensile Properties. A sample with a lower molecular weight has poor performance with respect to tensile strength, Young's modulus, and elongation. Filling of glass fiber increases strength and rigidity of specimens, but decreases their elongation. In the case of a sample molded at lower temperature and with imperfect drying of pellets, Young's modulus is lower than for a sample molded normally under optimum conditions.

Bending Fatigue. Effect of molecular weight is irregular. Polyethylene blending decreases normal bending fatigue strength. Filling of glass fiber is advantageous for testing under constant force, but disadvantageous for testing under constant deformation. Influence of molding conditions is apparent: a sample molded under optimum conditions is best with respect to bending fatigue strength. Specimens prepared by injection molding are superior to those prepared by machining from extruded sheet.

Torsional Fatigue. Samples with high molecular weight with nonfiller and molded under optimum conditions are excellent with respect to torsional fatigue strength. Specimens prepared by machining are remarkably inferior to those prepared by injection molding. Such effects are not observed on static torsional properties.

Impacting Fatigue. Samples with lower molecular weight have lower impacting fatigue strength. Polyethylene blending and imperfect drying of pellets have negative effects on impacting fatigue resistance. Filling with glass fiber is disadvantageous under higher load impacting. A specimen prepared by injection is superior to that prepared by machining.

Cavitation Erosion. Samples with lower molecular weight have better resistance to sonic scission but have poor resistance to sonic erosion. Filling with glass fiber causes considerable damage by cavitation erosion.

Solvent Cracking. In the case of nonloading, differences in various samples are not remarkable, except for samples with glass fiber filling. Under static and dynamic loading conditions, samples with lower molecular weight molded under imperfect drying conditions and prepared by machining are inferior to standard samples. Filling with glass fiber and blending polyethylene are advantageous for resistance to solvent cracking.

By observing the influence of each factor mentioned above on durability of polycarbonate, the following conclusions can be reached. In regard to the effect of average molecular weight, samples of higher MW are generally excellent in dynamic durability except for rotational bending fatigue and sonic degradation. In regard to the effect of fillers, blending polyethylene gives a lower brittleness and decreases dynamic durability except for impacting fatigue and solvent cracking. And filling of glass fiber is effective for increasing static strength and fatigue strength in test under constant force, but is disadvantageous for fatigue strength under constant deformation conditions because of higher brittleness. In regard to the effect of molding conditions, imperfect drying of pellets results in considerable lowering of durability, and molding at lower temperature is disadvantageous for dynamic durability though advantageous for some static properties. In regard to the effect of methods of preparing specimens, specimens prepared by injection molding are generally superior in dynamic durability to those prepared by machining of extruded sheet, except for tensile strength and cavitation erosion in the case of polycarbonate.

Conclusions derived from this study are applicable to selection of variable factors in engineering plastics, polycarbonate, and so on, for the purpose of dynamic uses.

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References

1. S. Shimamura and H. Maki, Proc. 5th Japan Congress Mater. Research, 1962, p. 136.
2. M. N. Riddell, G. P. Koo, and J. L. O'Toole, *Polym. Eng. Sci.*, **6**, 363 (1966).
3. K. H. Boller, *Mod. Plast.*, **34**, 163 (1957).
4. L. C. Cessna, J. A. Levens, and J. B. Thomson, *Polym. Eng. Sci.*, **9**, 339 (1969).
5. T. Fujii, S. Otsuki, K. Mizukawa, and Y. Masuda, Proc. 7th Japan Congress Mater. Research, 1964, p. 133.
6. M. Sato, *Electr. Comm. Lab. Technol. J.*, **15**, 357 (1966).
7. F. Ohishi, *J. Soc. Mater. Sci. Japan*, **17**, 826 (1968).
8. F. Ohishi, *J. Soc. Mater. Sci. Japan*, **20**, 462 (1971).
9. F. Ohishi, Y. Tsuruga, and T. Ogawa, *J. Soc. Rubber Ind. Japan*, **47**, 754 (1974).
10. F. Ohishi, H. Matsushita, and K. Minabe, *J. Soc. Rubber Ind. Japan*, **44**, 937 (1971).
11. F. Ohishi, *J. Appl. Polym. Sci.*, **15**, 381 (1971).
12. F. Ohishi and T. Segawa, *J. Soc. Rubber Ind. Japan*, **44**, 531 (1971).

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