Investigation of Instrumented Impact Test and Loading Rate Dependency of Fracture Toughness in Brittle Polymers

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In the present study, the effect of the specimen size on the vibrational wave superimposed on the load-deflection curve of polymers is first investigated. Next, in the instrumented Charpy test, a shock-absorbing material is used in order to prevent the generation of a vibrational wave superimposed on the load-deflection curve, and its validity is examined. Further, differences in the impact response curves obtained by the instrumented Charpy test and the one-point bend test are compared and discussed. The results of this study are summarized as follows. (1) The vibrational wave can be prevented by the use of a small specimen which shortens the period of the vibrational wave. (2) The load value is lowered by the use of shock-absorbing material. (3) The differences in the impact response curves and the fracture times obtained from the instrumented Charpy impact test and the one-point bend test are rather large at the lower impact velocity of 3.10 m/s; however, the obtained K_{Id} values are nearly coincident.

Key Words: Stress Intensity Factor, High-Polymer Materials, Brittle Fracture, Fracture Toughness, Instrumented Charpy Test, Impact Response Curve, One-Point Bend Test, Shock-Absorbing Material

1. Introduction

Since polymers are very light and have a good formability, they are used in various capacities from industrial components to daily necessities. Polymers, for which the specific strength is competitive with that of light metals, have been developed recently. These polymers are expected to be increasingly used as structural materials. In order to increase the use of polymers in this role, it is very important to be able to assure safety against fracture and to establish a method of evaluation for dynamic fracture toughness.

In general, many polymers are used below the glass transition temperature and their fracture behaviors are brittle. In the case of the dynamic loading test for brittle materials, a vibrational wave is superimposed on a load-deflection curve due to the inertial effect and a stress wave is generated at impact. Therefore, it is very difficult to measure the exact load-deflection curve and to evaluate the exact fracture toughness under the dynamic loading conditions.

Therefore, in this study, the vibrational wave superimposed on the load-deflection curve recorded by the instrumented Charpy impact test was analyzed and the effect of specimen dimension on the vibrational wave was investigated for four kinds of polymers. Moreover, the change in fracture toughness values with changing loading rate was studied. Furthermore, the validity of the use of shock-absorbing material, which can suppress the generation of the vibrational wave at impact, was examined. Lastly, the time history of the stress intensity factor measured by the one-point bend test[1],[2] was compared with the impact response curve measured by the instrumented Charpy impact test[3], and the differences in fracture behavior and fracture toughness values between the one-point bend test and the Charpy impact test were discussed.

2. Experimental

2.1 Materials and specimen dimensions

In this study, four kinds of polymers, PMMA, polyamide, nylon and silica-filled epoxy resin, and

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seven kinds of specimens were used. The dimensions of the specimens are summarized in Table 1. All specimens were machined from the plate in the direction of the edge-width. Of these specimens, (A), (B), (C), (D) and (E) were used to clarify the effect of specimen dimension on the vibrational wave superimposed on the load-deflection curve. In contrast, (F) and (G) were used to assess the fracture toughness values for the various loading rates. In addition, they were used to clarify the effect of shock-absorbing material and the difference in fracture behaviors between the one-point bend test and the Charpy impact test. Therefore, they were precracked to a crack length of $a_0/W=0.5$ (a_0 is the initial crack length and W is the specimen width) using the "dead-load" method, which applies a constant load to the specimen until a pop-in crack appears.

2.2 Dynamic and static three-point bending tests

In the dynamic bending test, the 14.7 J capacity instrumented Charpy impact testing machine was used for all materials. The instrumented Charpy impact test was conducted in atmosphere and the specimen was loaded under the recommended conditions of $E_0>3E_t$ (E_0 is the applied energy and E_t is the total absorbed energy)[4]. Incidentally, in the dynamic bending test, a shock-absorbing material was used in order to suppress the vibrational wave generated at impact and its effectiveness was examined. The shock-absorbing material (GELNAC N-30 (thickness: 2 mm), Japan Automation Co.) was applied to both impact points of the specimen and anvil portions of the 14.7 J capacity instrumented Charpy impact testing machine.

Table 1 Specimen dimensions

Specimen	Thickness (mm)	Width (mm)	Span length (mm)	Length (mm)	Notch geometry
(A)	15	15	60	90	U
(B)	10	10	40	55	U
(C)	4	6	40	50	slit
(D)	4	10	60	80	V
(E)	10	10	40	55	V
(F)	15	15	60	90	crack
(G)	10	10	40	55	crack

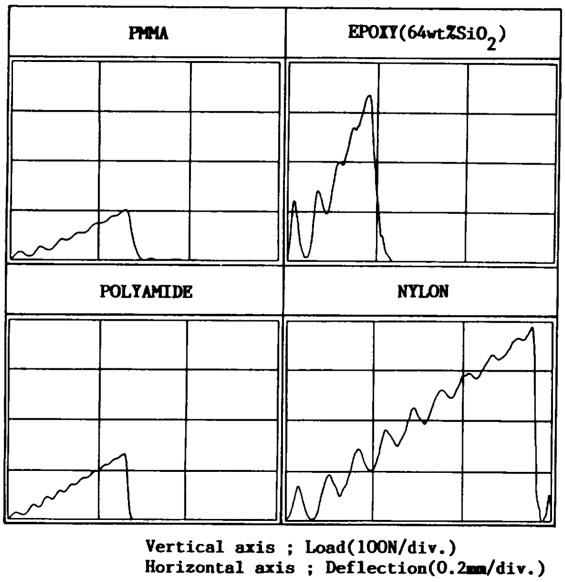


Fig. 1 Typical load-deflection curves obtained by instrumented Charpy impact test (specimen (G))

The static bending test was carried out using an Instron-type universal testing machine.

2.3 Evaluation method of dynamic fracture toughness and static fracture toughness

Dynamic fracture toughness was evaluated by the impact response curve method presented by Kalthoff[5] using the 14.7 J capacity instrumented Charpy impact testing machine. Fracture time (t_f) is obtained from the change in strain gauge output attached to the specimen[5]. That is, the rapid changing point of the strain gauge output is defined as the crack initiation point in this study. Moreover, the one-point bend test was conducted by modifying the anvil portion of the 14.7 J capacity instrumented Charpy impact testing machine. In the one-point bend test, the time history of the stress intensity factor and the fracture time were measured in the same way as that used in the impact response curve method.

The static fracture toughness was evaluated according to the ASTM E399 method.

3. Results and Discussion

3.1 Effect of specimen dimensions on the vibrational wave superimposed on the load-deflection curve

Figure 1 shows the typical load-deflection curves recorded by the instrumented Charpy impact test for specimen (G). It is found that all load-deflection curves are of the elastic-brittle fracture type and the vibrational waves are superimposed on the load-deflection curves.

Incidentally, the Charpy impact test can be modeled as in the vibrational system shown in Fig. 2 (a)[6],[7]. In this system and when brittle fracture is considered, the superimposed vibrational wave can be thought to converge with linearly increasing load with time[6],[7]. Then, when the initial amplitude (a_1/P_f) and the logarithmic decrement (δ) in the vibrational wave are defined as in Fig. 2(b), the relationships between initial amplitude or logarithmic decrement and time period of the vibrational wave (τ) for the load-time curve satisfying the recommended condition of $t_f>3\tau$[8] were investigated. The results are shown in Fig. 3. It is found that the specimen shortened the time period of the vibrational wave, producing a small initial amplitude and large logarithmic decrement.

That is, the vibrational wave superimposed on the load-deflection curve can be suppressed by means of the specimen which shortens the time period of the vibrational wave.

Server experimentally presented the time period of the vibrational wave as Eq. (1)[8].

$$\tau=\frac{1.68(SWEBC_s)^{1/2}}{C_0} \qquad (1)$$

where B is the specimen thickness, E is Young's modulus, C_s is elastic compliance of the specimen and C_0 is sound speed in the specimen. Equation (1) shows that the time period of the vibrational wave is proportional to the specimen dimensions; therefore, the time period of the vibrational wave can be shortened by the use of a small-size specimen.

It has already been confirmed for used materials that τ calculated from Eq. (1) shows good agreement with that obtained from the load-time curve measured by the instrumented Charpy impact test. Therefore, Eq. (1) can be applied for calculating the time period of the vibrational wave. Accordingly, it is clear from the results of Fig. 3(a) and Eq. (1) that the small-size specimen produces small initial amplitude and large logarithmic decrement. That is, it can be considered in the specimen geometry which shortens the time period of the vibrational wave that the inertial effect is reduced and the load-deflection curve reflects the deformation and fracture behaviors of the specimen itself. Such a specimen is considered to be suitable for a dynamic loading test such as the instrumented Charpy impact test. However, the variation in toughness may be increased by the use of a small-size specimen. Therefore, from this viewpoint the specimen size must be further investigated.

3.2 Effect of loading rate on fracture toughness of silica-filled epoxy resin

Figure 4 shows the change in fracture toughness of a silica-filled epoxy resin with stress intensity rate, which is defined as the stress intensity factor (K_I) divided by fracture time (t_f)[8]. In Fig. 4, at a low stress intensity rate, an Instron-type universal testing machine was used and the stress intensity rate was controlled by changing the cross-head speed. On the

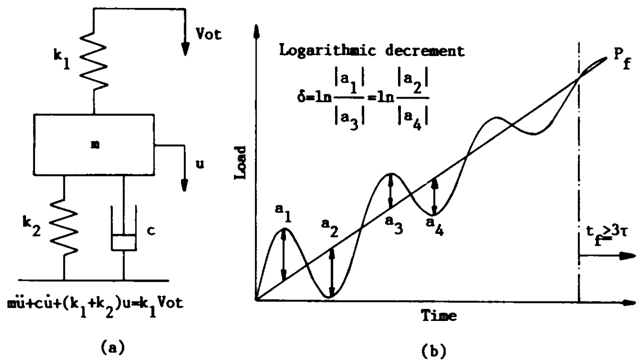
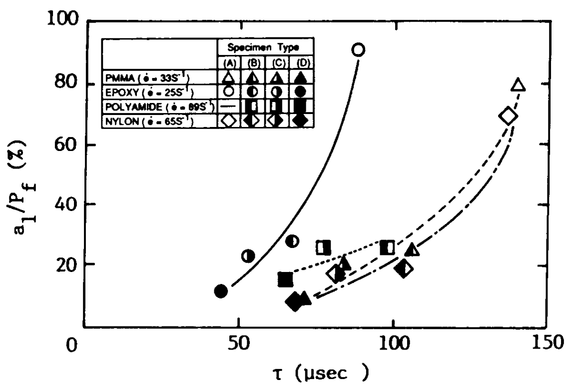
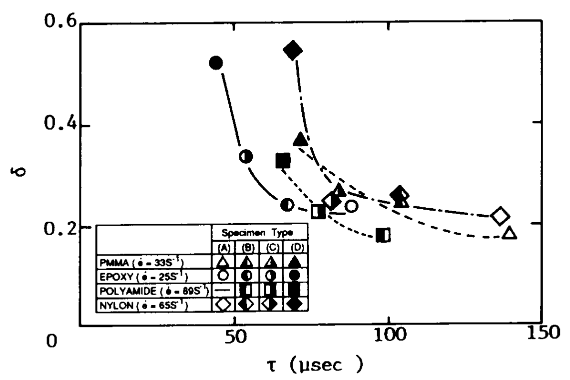


Fig. 2 Vibrational model in Charpy impact test and quantification of vibrational wave superimposed on load-deflection curve
(a) Vibrational model in Charpy impact test
(b) Quantification of vibrational wave superimposed on load-deflection curve



(a) Relationships between initial amplitude and time period



(b) Relationships between logarithmic decrement and time period

Fig. 3 Evaluation of behaviors of vibrational wave superimposed on load-deflection curve ($\dot{e}$ is nominal strain rate)

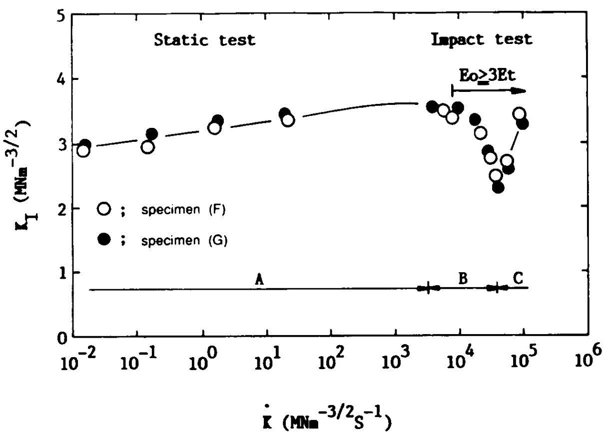


Fig. 4 Change in fracture toughness values of silica-filled epoxy resin with stress intensity rate

other hand, at a high stress intensity rate, the 14.7 J capacity instrumented Charpy impact testing machine was used and the test was carried out at 10°, 30°, 50°, 70°, 90°, 110° and 140° impact angles of the hammer. As mentioned previously, the static fracture toughness was evaluated according to the ASTM E399 method and the dynamic fracture toughness was evaluated by the impact response curve method. In these tests, specimens (F) and (G) were used because specimen (F) the most easily generates the vibrational wave and specimen (G) was the same dimensions as the standard Charpy specimen for metallic materials. From the results of the test, the fracture toughness values of both specimens (F) and (G) showed a loading rate dependency. Also, the fracture toughness values changed in three phases with the loading rate[9]. That is, the fracture toughness increases monotonously (A area), then decreases rapidly (B area), and increases again (C area). These behaviors were not dependent on the specimen dimensions.

Figure 5 shows the schematic explanation of the change in crack propagation mode near the precrack tip with changing stress intensity rate. In the A area, where the stress intensity rate is low, crack propagation behaviors can be assumed to occur as follows: (a) the crack propagates in the matrix deflecting at the large-size silica particles, and when the stress intensity rate increases, (b) the crack propagates with fracturing of the large-size silica particles. In the B area, the crack propagates mostly with fracturing of the large-size silica particles, however, (c) debonding of the interface between silica particles and the matrix can also be observed. In the C area, the crack propagates in the matrix deflecting at the large-size silica particles or debonding the interface between silica particles and the matrix. It is found from these observations that the fracture toughness changes in silica-filled epoxy resin with changing stress intensity rate are strongly affected by the existence of coarse silica particles[9].

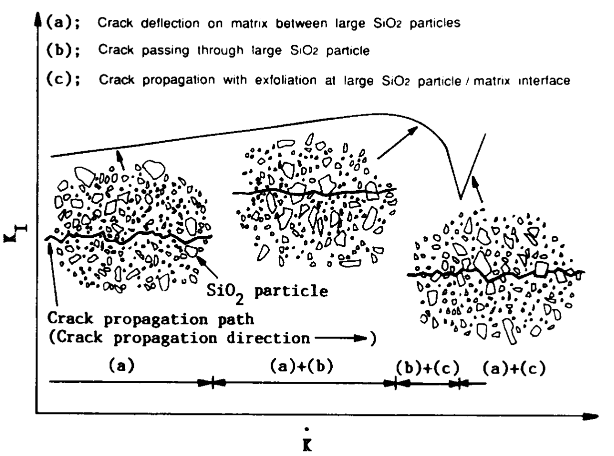
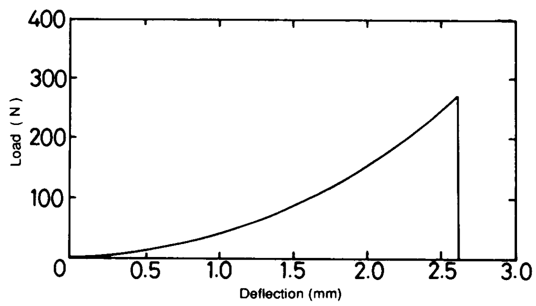


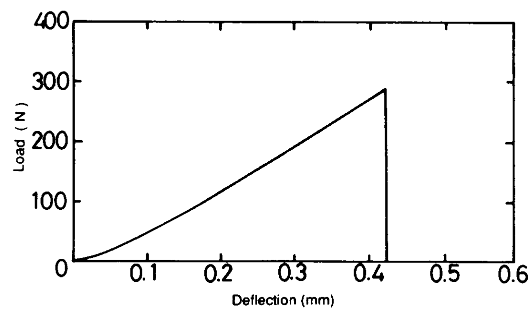
Fig. 5 Change in fracture surface of silica-filled epoxy resin with stress intensity rate

3.3 Effect of shock-absorbing material

Figure 6 shows the typical load-deflection curves which were tested statically using an Instron-type universal testing machine (cross-head speed: 0.5 mm/min). Figure 6(a) is the load-deflection curve with shock-absorbing material and Fig. 6(b) is without shock-absorbing material. In the case of brittle materials, measurement of the exact maximum load is very important because the crack propagates unstably from the maximum load. Hence, the values of maximum load and maximum load deflection were measured under the static loading conditions in order to examine the effect of shock-absorbing material. Table 2 shows the comparisons of the maximum load and maximum load deflection with and without shock-absorbing materials. It is found that the use of shock-absorbing material produces both small maximum load and large maximum load deflection. That is, the maximum load with shock-absorbing material is 10% smaller than that without shock-absorbing material and the maximum load deflection with shock-absorbing material is about 7 times larger than that without shock-absorbing material. As an aside, one of the functions of the shock-absorbing material is to decrease both load and deformation generated at impact. However, the shock-absorbing material cannot decrease both load and deformation simultaneous-



(a) With shock-absorbing material

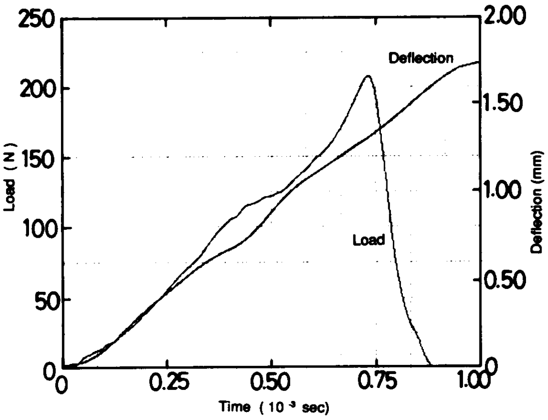


(b) Without shock-absorbing material

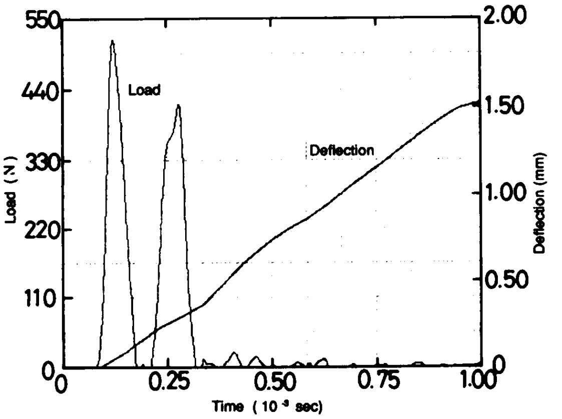
Fig. 6 Load-deflection curves of PMMA measured by static three-point bending test (specimen (F))

Table 2 Maximum load and maximum load deflection measured by static bending test (comparisons of tests with and without shock-absorbing material)

Test number	With shock-absorbing material		Without shock-absorbing material	
	Maximum load (N)	Maximum load deflection (mm)	Maximum load (N)	Maximum load deflection (mm)
1	264.8	2.62	279.5	0.422
2	264.8	2.82	289.3	0.410
3	250.1	2.82	287.3	0.388
Average	259.9	2.75	285.4	0.407



(a) With shock-absorbing material



(b) Without shock-absorbing material

Fig. 7 Curves of load-time and deflection-time of PMMA measured by instrumented Charpy impact test (specimen (F))

ly under constant impact energy ; therefore, the structure of shock-absorbing material is generally designed to decrease the load at the expense of deformation[10]. Accordingly, the results of Table 2 are explained.

As specimen (F) is the most vibratory according to the results of 3.1, it was used to clarify the effect of shock-absorbing material under the dynamic loading conditions. Figure 7 shows the typical curves of load-time and deflection-time of PMMA recorded by the instrumented Charpy impact test (impact velocity : 1.98 m/s). Figure 7(a) shows the curves of load-time and deflection-time with shock-absorbing material, and Fig. 7(b) shows those without shock-absorbing material. It is observed that the shape of the load-time curve is changed drastically and the vibrational wave

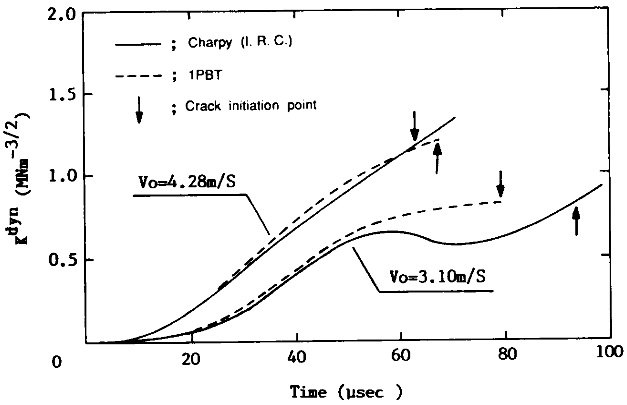


Fig. 8 Comparison between impact response curve measured by instrumented Charpy impact test and time history of stress intensity factor measured by one-point bend test (PMMA, specimen (G))

superimposed on the load-time curve disappears completely by the use of the shock-absorbing material. On the other hand, it can be found from the shape of the load-time curve shown in Fig. 7(b) that the specimen without shock-absorbing material is fractured by the inertial load. Therefore, the maximum load is not a substantial fracture load and the difference in maximum load or maximum load deflection between the tests with and without shock-absorbing material cannot be clarified quantitatively as the static bending test. However, it is presumed from the results of the static bending test that the maximum load may be decreased by the use of the shock-absorbing material. However, it is very effective to use the shock-absorbing material for decreasing the initial oscillations in the impact test of brittle materials. Therefore, it is necessary to study the usefulness of the shock-absorbing material from various viewpoints.

3.4 Result of one-point bend test

Figure 8 shows the impact response curve, the crack initiation point measured by the instrumented Charpy impact test, the time history of the stress intensity factor and the crack initiation point measured by the one-point bend test for specimen (G) of PMMA. Figure 9 shows those for specimen (G) of silica-filled epoxy resin. It can be observed from Figs. 8(a) and (b) that the vibrational wave is superimposed on the impact response curve at an impact speed of 3.10 m/s. However, in the case of a test at the impact speed of 4.28 m/s, the vibrational behavior

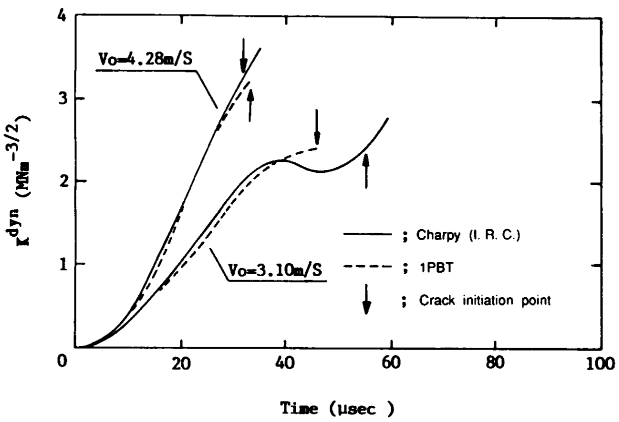


Fig. 9 Comparison between impact response curve measured by instrumented Charpy impact test and time history of stress intensity factor measured by one-point bend test (silica-filled epoxy resin, specimen (G))

cannot be observed in the impact response curve, and moreover, the shape of the impact response curve agrees with that of the time history of the stress intensity factor in the one-point bend test for both materials. In addition, in both materials, the difference in fracture time between the one-point bend test and the Charpy impact test increases with decreasing impact velocity. That is, the fracture time obtained using the instrumented Charpy impact test is longer than that of the one-point bend test. The reason for this can be explained as follows. (1) The specimen tested at the impact velocity of 3.10 m/s does not fracture within the natural frequency of the specimen. (2) In a such case, the fracture time is affected by the loading mode of the specimen. (3) Moreover, the loading mode in the one-point bend test is different from that in the Charpy impact test.

However, it can be clarified that K_{Id} measured by the one-point bend test is almost the same as that obtained by the instrumented Charpy impact test.

4. Conclusions

The test method for dynamic fracture toughness of brittle polymers was studied from various viewpoints. The results of this study can be summarized as follows.

(1) The vibrational wave generated at impact in the load-deflection curve can be suppressed by using a specimen geometry which shortens the time period of the vibrational wave.

(2) The fracture toughness values of silica-filled epoxy resin are dependent on the loading rate and are affected strongly by the existence of coarse silica particles.

(3) In the static bending test, the maximum load with shock-absorbing material appears to be 10% smaller than that without shock-absorbing material and the maximum load deflection with shock-absorbing material is about 7 times larger than that without shock-absorbing material. In the dynamic bending test, the maximum load may also be reduced by the use of shock-absorbing material.

(4) In PMMA and silica-filled epoxy resin, the vibrational behavior can be observed by means of the impact response curve measured at the impact speed of 3.10 m/s using the instrumented Charpy impact test. However, at the impact speed of 4.28 m/s, the vibrational behavior cannot be observed. Moreover, the fracture time in the instrumented Charpy impact test is longer than that in the one-point bend test. It is possible that the fracture time is affected by the loading mode in the specimen. However, K_{Id} measured by the one-point bend test is nearly coincident with that obtained by the instrumented Charpy impact test.

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