JOURNAL OF APPLIED POLYMER SCIENCE VOL. II, ISSUE NO. 6, PAGES 289-296 (1959)

Anisotropy in Thermoplastic Moldings and Their Impact Strength

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I. INTRODUCTION

It has been pointed out by several researchers[1-5] in the past that injection moldings of such vinyl polymers as polystyrene possess considerable mechanical anisotropy. Special fabrication methods, such as valve gating,[6] along with special molding conditions,[2] have been suggested to produce more nearly isotropic parts. In spite of the growing concern about the anisotropic character of injection-molded thermoplastic materials, an appreciable amount of mechanical property testing is still done on injection-molded specimens, where the polymer is oriented along the main axis of the specimen. Therefore, the enhanced strength of the specimen is measured, and no information on the inherently weak perpendicular direction is obtained. As pointed out by Lee, Horsley, and Wright,[3] this orientation is particularly serious in case of thin moldings. In the work described below, we have attempted to differentiate the anisotropic behavior of polystyrene, its copolymers, and the rubber reinforced polystyrenes. Stress-strain and impact properties have been determined on specimens cut from large flat moldings, essentially parallel and perpendicular to the flow. Then we have attempted to correlate these data with the more practical dart-drop impact data, which gives multiaxial stressing. Injection-molded, as well as extruded and compression-molded specimens, have been investigated.

A dart-drop test method has been developed, and test variables such as drop height, dart-tip radius and specimen size have been investigated. In these experiments, the specimens were always stressed multiaxially by dropping the dart on a large supported flat surface. This method differs, then, from the majority of ball- and dart-drop methods[7-13] since they generally involve the use of oriented rectangular specimens which are broken along the axis of orientation and do not permit description of the anisotropic character of such moldings.

II. EXPERIMENTAL

Materials and Heat Fabrication

A series of commercial thermoplastic molding and extrusion grade polymers were used in this study. All polymers were used as received, and care was taken not to allow any contamination or appreciable moisture absorption to occur before the heat fabrication.

Compression molding was carried out in a steam-heated P.H.I. model PA7 hydraulic press, predetermined weighed loads of polymer granules being used for each specimen. A four-cavity mold (5 in. × 0.1 in.) was used. The polymer was generally melted at an appropriate temperature, before the full 15-ton pressure was applied. To avoid sink marks heavy-duty aluminum foil was placed above and below the mold. The specimens were allowed to cool slowly before removal from the mold. The resulting moldings were of fairly uniform thickness (±0.005 in.).

Injection moldings were carried out on several different molding machines, utilizing optimum conditions as far as cycle time, ram pressure and mold temperature were concerned. Cylinder temperature, however, was varied over a wide range for the purpose of this study.

Molding machine	Specimen
Lester, 12 oz.	Dinner plate cover 8 in. × 8 in. × 1.25 in. (0.092 in. thick)
Reed-Prentice, 4 oz.	Box, 4 in. × 4 in. × 2.5 in. (0.110 in. thick)
Fellows, 3 oz.	Wafer, 4 in. × 6 in. × 0.150 in.
Watson-Stillman, 1 oz.	Test specimen, $6^3/_8$ in. × $^1/_2$ in. × $^1/_8$ in.

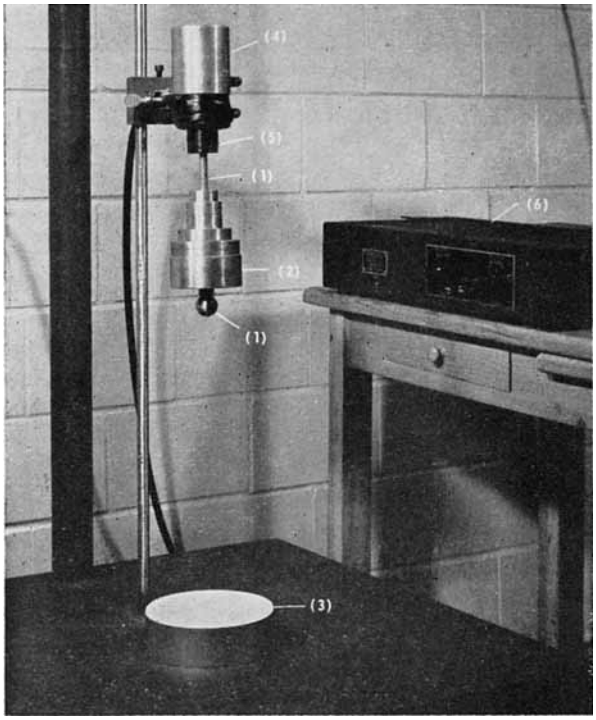


Fig. 1. Dart drop test assembly: (1) dart; (2) removable weights; (3) supported 5-in. disk specimen; (4) electromagnet; (5) guiding sleeve; (6) selenium rectifier.

Extrusion of the impact grade polystyrene sheet was carried out on a National Rubber Machinery $2^1/_2$ inch extruder at a rate of 86 lb./hr. The 5-in. disks were stamped out of the resulting 0.100-in. sheet with a punch press fitted with an appropriate die.

Dart Drop Apparatus

The dart drop apparatus is shown in Figure 1. It consists of a massive steel plate, 1 in. × 24 in. × 24 in., fitted with leveling bolts. A 6-ft. section of 2-in. diameter steel pipe is welded vertically to the base, and a 0.25-in. steel rod runs parallel to this pipe. A specially constructed electromagnet is held by an adjustable condenser clamp which is attached to the steel rod. In this manner, the electromagnet can be adjusted to a given drop height. The magnet is powered by a 3-amp. selenium rectifier which is sufficient to support a dart load of approximately 4000 g. The magnet coil surrounds a wooden cylindrical sleeve. The shaft of the dart fits into the sleeve so that the dart is "aimed" at the point of impact.

The dart was made by silver soldering a 0.875-in. steel ball bearing to a 10-in. steel shaft. Cylindrical steel weights varying from 10 to 1000 g. can be loaded onto the shaft, and each weight is locked to the shaft by means of set screws. In this manner, the dart and weight become one rigid unit. An Ethocel sheet was rolled into a tube 18 in. in length and 6 in. in diameter. The tube was held in a vertical position surrounding the disk specimen and its support in order to preclude the hazard of flying specimen fragments.

Dart Drop Testing Procedure

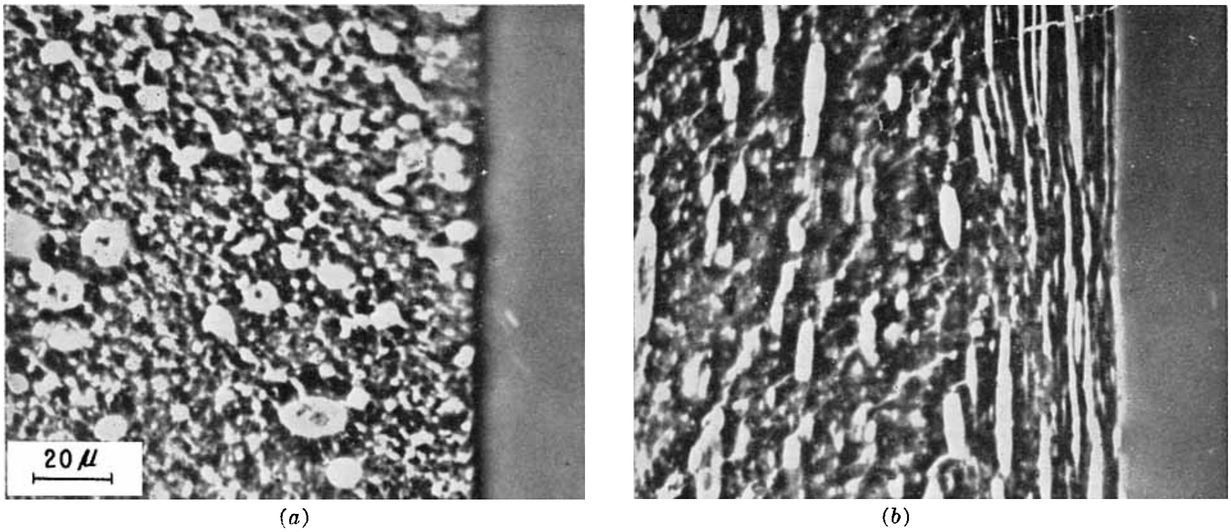
Hollow container test specimens were placed in an inverted position on the massive steel plate for testing. The disk or wafer specimens were placed on a base designed to support the specimen uniformly. In order to keep the amount of energy absorbed by the apparatus at a minimum, the specimens were placed on the base without clamping. This also allowed the specimens to deform naturally, thus eliminating the measurement of energy in excess of the breaking strength. In our experiments, a method was used to determine the energy required to initiate fracture in 50% of the specimens. With this method, each specimen, excluding the first trial specimen used to locate the approximate energy level, is subjected to only one drop. This method was chosen to eliminate fatigue or work hardening of the specimens as found in the repeated-blow method. In this method the dart weight is either decreased or increased by a given increment depending upon whether fracture is experienced or not. After testing the usual 20 specimens in this fashion, the 50% failure energy or the mean breaking energy is obtained. Normal statistical treatment of the data is carried out.

III. RESULTS AND DISCUSSION

Anisotropy in Heat-Fabricated Polymers

The fact that mechanical properties vary considerably from one location and direction to another in a molding has been reported by R. S. Spencer[1] for the flexural properties of polystyrene, by R. Nitsche,[4] and more recently by Adams, Jackson, and McCarthy,[14] and Chatain.[5]

By using test specimens cut parallel and perpendicular to the flow orientation, stress-strain and Izod impact properties of a series of different commercial polymers were measured; the results are summarized in Table I. These properties cover the range from short-shot moldings having the most anisotropy to those probably having the best uniformity possible. It can be seen that, while the parallel property is in the range of values reported



(a) (b)

Fig. 2. Dark-phase contrast micrographs of rubber-modified polystyrene A: (a) compression-molded specimen with tensile strength = 4590 lb./in.^{2}, elongation = 22.1%, Izod notched impact strength = 0.99 ft.-lb./in.; (b) injection-molded specimen with tensile strength = 4430 lb./in.^{2}, elongation = 30.9%, Izod notched impact strength = 2.54 ft.-lb./in.

for commercial materials, the corresponding perpendicular tensile strength is lower than that obtained by use of A.S.T.M. procedures. For instance, in the case of polystyrene, the perpendicular tensile strength is only one third of the tensile strength in the parallel direction.

Upon qualitative examination, it appears that the polymers associated with improved practical toughness possess considerable strength in the weaker perpendicular direction. For example, even though the maximum Izod notched impact strength of the nylon used in our study is about 2.5 ft.-lb./in., the minimum strength in the perpendicular direction is more than 1.7 ft.-lb./in. These nylon dinner-plate covers did not fracture, even when a most severe blow was dealt with a hammer. A uniformly molded ABS polymer also showed unusual impact resistance. It appears that the high perpendicular strength of a polymer is of prime importance in determining its practical impact resistance. Similarly, one could speculate on the superior practical strength of styrene copolymers and polymethyl methacrylate as compared to that of polystyrene.

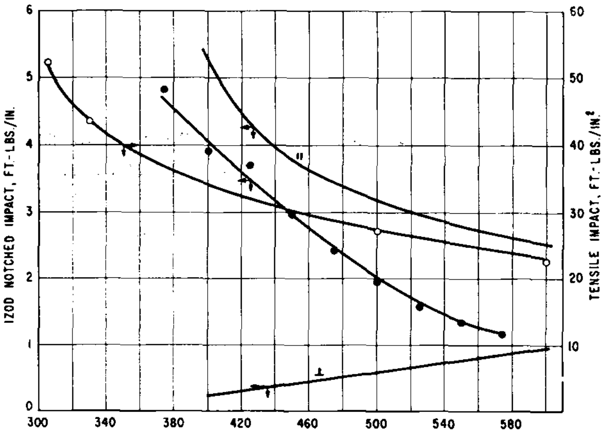


Fig. 3. Effect of orientation and molding temperature on impact strength of rubber-reinforced polystyrene: (∥) specimens parallel to flow orientation; (⊥) specimens perpendicular to flow orientation; (●) A.S.T.M. Izod notched impact strength; (○) Tensile impact strength.

Rubber-modified polystyrene shows considerable anisotropy, and yet it has found considerable application in uses where toughness is of prime importance. It appears that it is of considerable importance that heat-fabricated pieces made from rubber-modified polystyrene should be as isotropic as possible to take advantage of the reinforcing character of the rubber. In Figure 2, dark-phase contrast micrographs show the relative orientation of rubber particles in compression- and injection-molded test specimens.[15] In Figure 3, a sketch is presented which shows the variation of notched impact strength in specimens cut parallel and perpendicular to flow orientation as a function of molding temperature. The dinner-plate cover moldings were used to obtain the specimens normal to each other. Also included in this graph are some A.S.T.M. notched impact strength[1f] and some tensile impact strength data. The latter two curves are quite similar to the curve of impact strength parallel to flow orientation. As in all these cases, the orientation is the highest at low molding temperatures, thus giving enhanced mechanical strength. When a specimen is cut normal to flow orientation, the strength actually increases with increased molding temperature. At high molding temperatures, more nearly isotropic moldings will result.

Anisotropy in Moldings and Dart Drop Test

By measuring conventional stress-strain and impact properties for specimens cut normal to each other from a large injection-molded piece, it has been demonstrated that vinyl polymers like polystyrene possess considerable mechanical anisotropy. If one takes advantage of the dart drop impact measurement described in the experimental section, the results seem to indicate that the properties of the weaker perpendicular-to-flow specimen may be correlated to some extent with this dart drop impact strength. In Figure 4, box moldings of several rubber reinforced polystyrenes show that increased molding temperatures produce from slightly tougher to dramatically tougher moldings. Although these results are contrary to the data provided by the A.S.T.M. Izod impact test, they appear to be more consistent with the perpendicular-to-flow impact properties. In fact, the unnotched Izod impact strength of the perpendicular specimens seems to provide a reasonably good correlation when the logarithm of the dart drop energy is plotted against the impact strength. Such a plot is shown in Figure 5 for the dinner-plate cover specimens prepared from a series of commercial thermoplastic materials. Because the data are somewhat sketchy for the higher impact values, no statistical analysis of the data was undertaken.

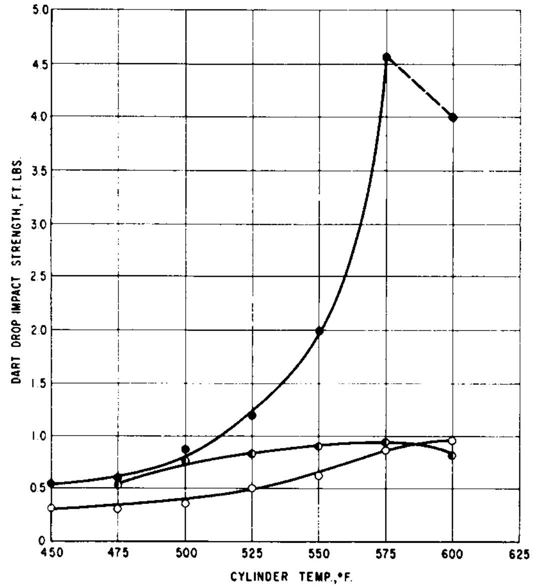


Fig. 4. Effect of cylinder temperature on impact strength of rubber-modified polystyrene boxes: (●) rubber-modified polystyrene A; (◐) rubber-modified polystyrene C; (○) rubber-modified polystyrene D. Each point represents 20 drops.

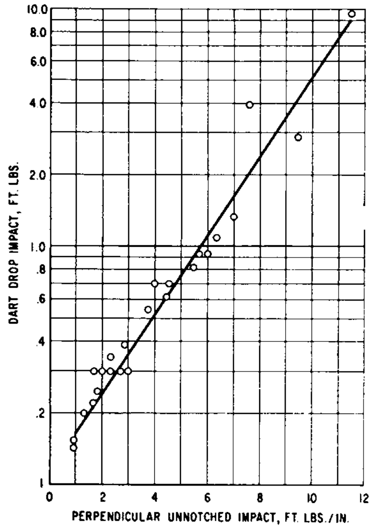


Fig. 5. Correlation between dart drop impact strength and unnotched Izod impact strength of dinner-plate cover specimens oriented perpendicular to flow.

Investigation of Dart Drop Test Variables

A number of researchers[7-13] have published information on the dart or ball drop impact test for high polymers. However, since in most of the previous work the possibility of specimen anisotropy was not considered, it is of some importance to investigate the test variables for this particular test. Further, several test variables were studied in order to learn whether a dart drop test could be considered equivalent to a ball drop test, where the drop height, ball size, or both are varied.

Effect of Drop Height. Two different types of impact grade polymers were used to illustrate the effect of drop height. In both cases, when the drop height was varied between 1 and 5 ft., yielding impact speeds of 96–214 in./sec., the corresponding rate of straining did not have any significant effect on the impact strength. The 95% confidence limits for each impact speed measurement covered the same impact strength band for the whole range.

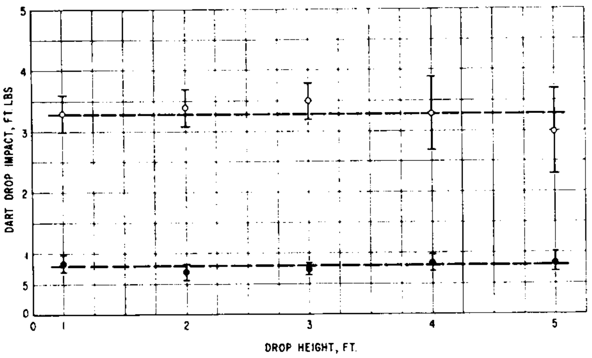


Fig. 6. Effect of drop height on dart drop impact strength: (●) rubber-modified polystyrene A, dinner-plate cover moldings; (O) ABS polymer, wafer moldings. Each point represents 20 drops; brackets indicate 95% confidence limits.

Data for the rubber-modified polystyrene dinner-plate cover specimens and for the injection-molded flat wafer specimens of an ABS plastic are given in Figure 6. From these results, it appears that, within a limited range, a ball drop impact test may give rather similar results to the dart drop test, as the latter is not affected by varying the drop height over the range of 1–5 ft.

Effect of Dart Tip Radius. A series of darts whose ball-bearing striking surfaces had different radii were used in this study. These radii varied from 0.220 to 0.625 in. As shown in Figure 7, the rigid styrene/acrylonitrile copolymer showed no variation in dart drop impact strength as a function of the striking-head radius, while the rubber-modified polystyrene specimens showed a considerable increase in impact strength as the dart tip radius was increased. The results are not particularly surprising, since, in the case of a rigid material with a high modulus, essentially a point contact between the specimen and the striking surface can be visualized. For ductile materials with lower moduli, on the other hand, a considerably larger contact area prevails with increasing dart tip radius; as a result, the energy is distributed over a wider area than for rigid materials. Again, when considering a corresponding ball drop impact measurement, these data seem to suggest that, with rigid polymers, the ball size can be varied without seriously affecting the measured impact strength. With the more ductile, rubber-reinforced polystyrenes, however, changing the ball size to cover a broader impact energy range may introduce errors.

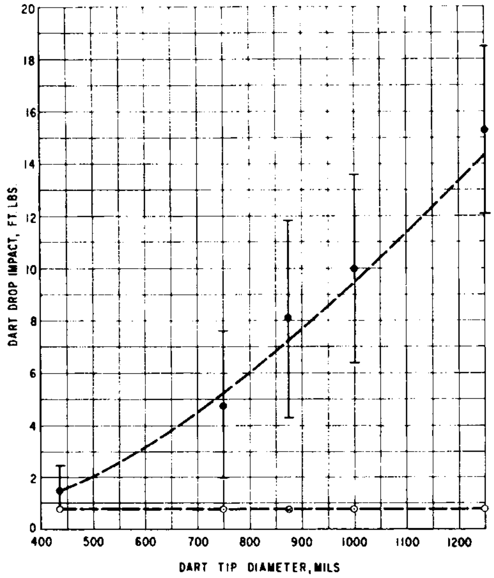


Fig. 7. Effect of dart tip radius: (●) rubber-reinforced polystyrene A, disk specimens stamped from extruded sheet; (O) styrene/acrylonitrile copolymer, wafer specimens, injection-molded.

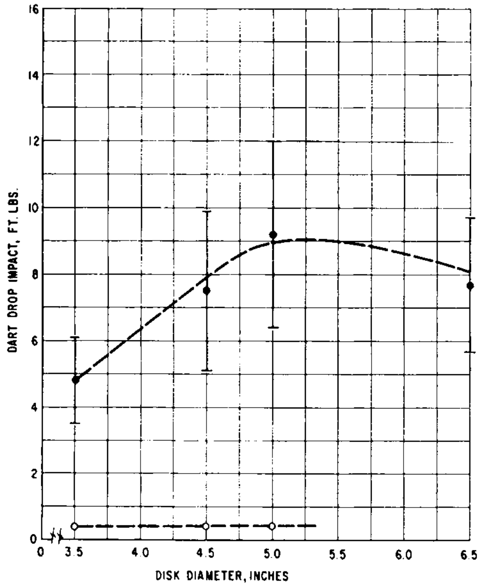


Fig. 8. Effect of specimen size: (●) rubber-reinforced polystyrene A, disk specimens stamped from extruded sheet; (O) styrene/acrylonitrile copolymer, wafer specimens, injection-molded.

Effect of Specimen Size. The size of a dart or a ball drop test specimen is often determined by an arbitrary choice. It was, therefore, important to investigate the effect of the disk diameter on the impact strength when the thickness is kept constant. Another reason for investigating the specimen size is associated with the observation of unusual breaking patterns found for some polymers. These breaking patterns are associated with the many different wave forms which can be established in a specimen at the moment of impact. It is thought that the effects due to these waves are greatly influenced by specimen geometry. This interesting aspect of impact testing would require a separate investigation before any conclusions concerning it could be drawn. The results, as shown in Figure 8, indicate that the rigid styrene copolymer again is insensitive to variations in disk diameter between 3.5 and 5 in. With the ductile material, specimens of 4.5–6.5 in. diameter seem to give rather uniform data. The 3.5-in. specimen, however, requires less energy to break.

Some Dart Drop Impact Results

The dart drop impact data given in the previous sections were obtained for specimens prepared by different methods; no discussion on the effect of the particular method used was undertaken, however. It is the purpose of this section to review briefly the dart drop impact strength of several classes of polymers and to illustrate the effect of the heat-fabrication method on the specimen strength. These data would then be of further use in presenting the idea of the anisotropy of the polymers investigated.

TABLE I
Anisotropy of Commercial Injection-Molded Polymers[a]

Polymer	Maximum tensile strength $(\parallel)$, lb./in.^{2}	Tensile strength ratio $(\parallel/\perp)$	Maximum notched Izod impact strength $(\parallel)$; ft.-lb./in.	Notched impact strength ratio $(\parallel/\perp)$
Polystyrene	7,300	1.3–2.9	1.2	1.0–10.0
Polymethyl methacrylate	8,200	1.1–1.6	0.26	1.0–1.1
Styrene/acrylonitrile copolymer	10,200	1.1–1.9	0.43	1.2–2.2
Methyl methacrylate styrene copolymer	10,100	1.2–1.4	0.39	1.0–1.6
Rubber-modified polystyrene	5,600	1.0–1.6	5.3	3–23
Nylon	9,000	1.0	2.5	1.2–1.4
ABS polymer	5,300	1.0–1.1	6.6	1.2–4.4

[a] Dinner plate cover (8 in. × 8 in. × 1.25 in. × 0.1 in.) molded on a 12 oz. Lester injection machine covering the extremes in molding conditions.

TABLE II
Typical Dart Drop Impact Data on Commercial Molding Grade Polymers

Polymer	Method of specimen preparation[a]	Dart drop impact strength, ft.-lb.	Standard deviation ft.-lb.
Polystyrene	Injection-molded	0.22	0.027
	Compression-molded	0.41	0.030
Poly methyl methacrylate	Injection-molded	0.49	0.035
	Compression-molded	0.53	0.040
Styrene/acrylonitrile copolymer	Injection-molded	0.48	0.032
	Compression-molded	0.45	0.030
Methyl methacrylate/styrene copolymer	Injection-molded	0.49	0.035
Rubber modified polystyrene A	Compression-molded	0.48	0.020
	Injection-molded (short shot temperature)	0.20	0.014
	Injection-molded (maximum temperature)	6.0	—
	Compression-molded	10.4	1.4
	Extruded sheet	12.1	1.8
Rubber-modified polystyrene B	Extruded sheet	22.6	2.3
Rubber-modified-polystyrene C	Extruded sheet	6.4	1.0
Nylon	Injection-molded	>40	—

[a] All injection molded specimens were 8 in. × 8 in. × 1.25 in. × 0.1 in. dinner plate covers. Extruded and compression molded specimens were 5 in. diameter disks of 0.1 in. thickness.

Table II summarizes the dart drop impact data of several commercial polymers. First, it shows that injection-molded polystyrene has only about half the strength of a compression-molded polystyrene specimen. Polystyrene, its copolymers and polymethyl methacrylate show no change in impact strength when vastly different molding conditions are used in both injection and compression techniques. This observation is in accord with the directional property information, as there is no appreciable difference due to molding conditions in the Izod impact strength of specimens cut perpendicular to the flow orientation. These data agree with the finding of Chatain.[5] The parallel property increases with decreased molding temperature as well as the ratio of parallel to perpendicular strengths ($\|/\perp$) shown in Table I. In the case of rigid polymers, no change occurs in the perpendicular-to-flow properties, and injection-molding conditions have very little effect on the dart drop impact strength.

Rubber-modified polystyrenes, on the other hand, show a uniquely different pattern. For one of the commercial, impact-grade polystyrenes it is shown that, when prepared under short-shot injection molding conditions, the molding has little or no practical impact advantage over the general-purpose polystyrene. However, when higher molding temperatures are employed, a manyfold improvement may result. In the case of the rubber-modified polystyrene A, the dart drop impact increases, due to higher molding temperatures, from 0.2 to 6 ft.-lb./in. Similar changes were found with other impact materials but not in such dramatic fashion (Fig. 4). When the same material was compression-molded, impact strengths of 10 ft. lb./in. were found, and, in the case of a carefully extruded sheet, an impact strength of 12 ft.-lb. was recorded. This latter value may be considered to be approaching the inherent or fundamental impact strength of the material. Impact strength of an extruded specimen may be above that of the compression-molded sample, since uniform packing and a very low degree of orientation prevail in this case.

And finally, in the case of nylon moldings, due to their essentially isotropic character and to their relatively high Izod impact strength in the direction of orientation perpendicular to flow (1.7 ft.-lb./in. for notched Izod impact strength and in excess of 15 ft.-lb./in. for the unnotched Izod impact strength), the specimens did not fail in the dart drop impact test, even with maximum loading.

The authors wish to thank A. A. Pettis and F. L. Dicken, who carried out much of the experimental work, and J. A. Schmitt, S. G. Turley and numerous other colleagues in the Styrene Polymerization Laboratory for their helpful suggestions and discussions. We would also like to thank The Dow Chemical Company for permission to publish this work.

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Synopsis

The mechanical anisotropy of several thermoplastic polymers has been investigated, and the relationship with a practical dart drop impact measurement has been explored. It has been shown that the unnotched Izod impact strength of a specimen taken perpendicular to flow orientation can be correlated with the dart drop impact strength. Further, the effect of several dart drop test variables, such as drop height, dart tip radius, and specimen size, have been investigated and reported. It has been concluded that the conventional strength measurement of injection-molded specimens may lead to erroneous appraisal of the practical strength of a material. Testing at an orientation normal to flow or by multiaxial stressing as in a dart drop test is suggested.

Résumé

L'anisotropie mécanique de plusieurs polymères thermoplastiques a été étudiée et on a examiné la rapport qu'elle présente avec une mesure pratique de l'impact d'une goutte. On a montré que la force d'impact Izod d'un échantillon perpendiculairement à l'orientation d'écoulement peut être reliée à la force d'impact de la goutte. En outre on a examiné et rapporté l'effet des nombreuses variables qui se présentent dans les tests à la goutte, tels qua sa hauteur, le rayon du bout, et la grandeur de l'échantillon. On en conclut que la mesure habituelle de la force d'échantillon moulus par injection peut mener à une appréciation erronnée de la force pratique du matériau. Un essai normal par rapport à l'orientation d'écoulement ou un étirement multiaxial comme dans l'essai à la goutte est suggéré.

Zusammenfassung

Die mechanische Anisotropie mehrerer thermoplastischer Polymerer und ihr Einfluss auf die Ergebnisse einer praktischen Fallkörper-Schlagmessung wurden untersucht. Es wurde gezeigt, dass die Schlagfestigkeit einer Probe nach Izod (ohne Kerbe) in der Richtung senkrecht zur Fliessorientierung zur Fallkörper-Schlagfestigkeit in Beziehung gebracht werden kann. Weiters wurde der Einfluss einiger Variabler beim Fallkörpertest, wie Fallhöhe, Radius des Fallkörpers und Probengrösse untersucht und beschrieben. Man kommt zu dem Schluss, dass die konventionelle Festigkeitsmessung bei Spritzgussmassen zu einer falschen Einschätzung ihrer praktischen Festigkeit führen kann. Es wird eine Prüfung normal zur Fliessorientierung oder eine multiaxiale Beanspruchung wie beim Fallkörpertest vorgeschlagen.

Received May 4, 1959