JOURNAL OF APPLIED POLYMER SCIENCE VOL. VI, ISSUE NO. 21, PAGES 332-337 (1962)

Characterizing Impact Behavior of Thermoplastics*

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INTRODUCTION

Impact strength is a major criterion used in the specification of the mechanical usefulness of high polymer thermoplastics. At present there is very little known about the influence of the composition of these polymeric materials on the mechanical impact behavior. Increasing commercial use of thermoplastics in widely different fields has resulted in increasing demands for reliable experimental methods to evaluate both present and new materials in a manner that will provide some predictable comparison of a useful commercial life.

The various types of impact testing machines now used or being developed are essentially instruments that rapidly load the sample to yielding and subsequent failure. The loading is flexural in the Izod-type test,[1] unidirectional in the tensile impact instruments,[2] compressive in many drop weight machines, and there may be torsional impact-type test machines in common use. In all these instruments the total energy required for failure is the numeric criterion of the impact strength of the thermoplastic under test.

The work described in this paper illustrates that the numeric value of the energy required to break a rapidly loaded specimen is an incomplete representation of the impact behavior. Knowledge of how the impact energy is absorbed by the specimen while it is elastically and plastically deflecting under the impact loading and the behavior of the specimen after yielding are important in understanding the impact characteristics and differences in impact strengths of thermoplastics.

IMPACT STRENGTH AND FAILURE

In conventional types of impact tests the impact strength is reported in terms of the energy absorbed by the specimen when it is struck and fails under impact. The impact strength is assumed to be equivalent to the loss in kinetic energy resulting from the momentum exchange between a moving mass and the test specimen. When required, appropriate corrections are introduced to compensate for known errors as kinetic energy imparted to part of test specimen and holder and such other corrections that may be determinable for specific test methods.

The controversial element in this result is the assumption that the impact energy value is the energy required for failure. Properly, this conventional impact strength energy is the total energy absorbed in breaking the specimen. Actually, the energy for failure could be much less than the total energy. The reason for this discrepancy arises from the consideration that after the sample has reached the elastic limit and started to yield, an appreciable amount of energy can be absorbed in the process of plastic drawing and tearing that occurs after yielding. At the yield point, the sample has failed and the energy required to produce yielding would be more representative of a practical measure for impact strength than the total breaking energy.

The consequence of making no qualification between total energy for breaking (that is, the conventional impact strength) and the energy to yielding is that many materials are misleadingly considered to have superior impact properties while, in reality, these materials fail by yielding at relatively low energies, and the major part of the impact strength is used in plastic flow and tearing after yielding.

It was the consideration of this misconception of impact behavior that led to the development of impact testing equipment that would show the force-time behavior of the specimen during impact.

AUTOGRAPHIC IMPACT TESTER

Apparatus for depicting the force-time behavior of materials during impact has been in use for several decades.[3] Essentially, the equipment con-

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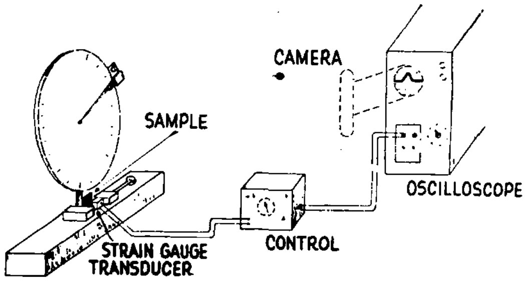

Fig. 1. Schematic autographic Izod impact test setup.

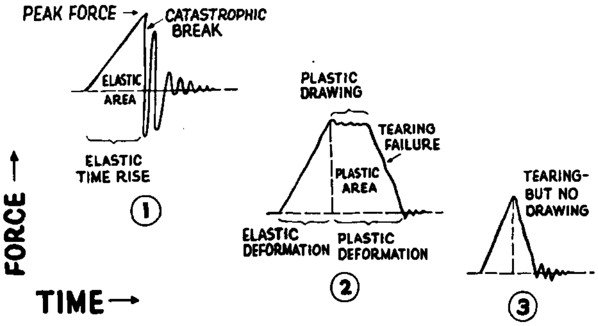

Fig. 2. Types of impulse curves.

sists of a transducer activated by the sample with an oscilloscope to display the transducer output and a camera to record the oscilloscope trace. Figure 1 is a schematic outline illustrating a conventional flexural Izod test unit modified for a transducer with a control box and oscilloscope. The sweep trigger mechanism and calibration equipment are not shown in order to reduce complexity. It can be readily seen that most types of impact testing equipment could be modified in a similar manner and some commercial high speed test equipment (Plas-Tech Equipment Corp., Natick, Mass.) provide experimental dynamic stress-time data.

The kinetic energy loss which is taken as the conventional impact strength of the sample is read from the circular dial plate in the usual manner. Standard notched samples $^1/_8$ x $^1/_2$ x $2^1/_2$ in. are used. Calibration is made using a standard size steel sample. The oscilloscope y-axis deflection is calibrated directly in force units and the calibrated x-axis sweep of the oscilloscope provides the time base. The trigger mechanism for a single sweep is a simple mechanical contact switch adjustable to 0.001 in. displacement with respect to the point at which the pendulum hammer contacts the sample. The force-time impact behavior has been found to vary from 10^{-4} to 10^{-1} sec. over a range of materials and this necessitates adjustment of the triggering in order to have the deflection appear on the oscilloscope.

CHARACTERIZATION OF IMPACT BEHAVIOR

All workers who have studied impact characteristics are aware that cases could occur wherein two materials that show equivalent impact strengths may differ in their breaking behavior. The force-time schematics of Figure 2 graphically portray the reasons for this behavior.

These line diagrams illustrate the three general types of impulse curves. The first type reveals that the sample deforms uniformly under the impacting blow until the peak force is reached, and then the sample yields and breaks catastrophically as indicated by the force falling to zero. The vibrations shown in this sketch after the peak arise from the mechanical vibrations of the transducer and are generally known as "ringing" of the transducer. The second type of impulse curve shows that the sample undergoes some plastic drawing at constant force after yielding, and then the sample shows tearing, otherwise the force would drop to zero within one-quarter period of the transducer mechanical ringing time. The third type of impulse curve shows tearing after yielding but no plastic drawing.

The several parts of each impulse diagram have been named for ease of reference, i.e., the base of the right triangle of the elastic area is called the elastic rise time, the hypothenuse is known as the force rate. The peak force or yield force is self-evident as is the elastic deformation time and plastic deformation time. At the present stage of development it is recognized that additional information may produce some changes in identification of these diagrams and the present definitions. The terms elastic area, plastic area, plastic drawing, tearing, and catastrophic break are descriptive of the mechanical processes associated with these portions of the impulse diagrams.

The total area under a force-time curve is a function of the impulse in pound-seconds that the sample has reacted to and transmitted to the transducer. It would be expected that the value of the impulse will correlate with the kinetic energy absorbed. The classical relation for two perfectly elastic bodies can be readily formulated,[4] but in this case the bodies are not perfectly elastic and the possibility of interactions in transmitting the force to the transducer must not be overlooked. With properly controlled conditions a linear correlation is found to exist between the impulse and total breaking energy as indicated under the experimental results.

EXPERIMENTAL

Calibration

Operation of the autographic impact tester involves calibration of the transducer and adjustment of the trigger mechanism to insure that the oscilloscope trace will show the force-time depicting the sample behavior during impact. Calibration in absolute units is made with a dummy steel sample with the same dimensions as a standard impact sample. The steel sample is clamped in the anvil with the transducer and a flexible line is attached to the dummy at the point at which the pendulum hammer normally strikes the sample. By use of either dead weights, a calibrated spring, or an air piston, a known force is applied to the dummy sample and the response of the transducer as shown by the movement of the oscilloscope trace is recorded. Check calibrations are made before each test and a fixed preloading due to clamping in the anvil is used. With different transducers the maximum force values and the preloading are standardized by preliminary calibration.

Results

In Table I the averaged experimental results are listed for five commercial thermoplastics. These data are average results obtained from measurements on five or more compression molded samples of each material. All samples were standard $^1/_8$-in. notched test pieces, the total energy for breaking in conventional terms of ft.-lb./inch notch was computed from the energy loss of the pendulum hammer which was obtained simultaneously with the force-time photograph. The data show very clearly that there are large differences in the peak forces, the elastic and plastic deformation times, and the elastic and plastic impulse values.

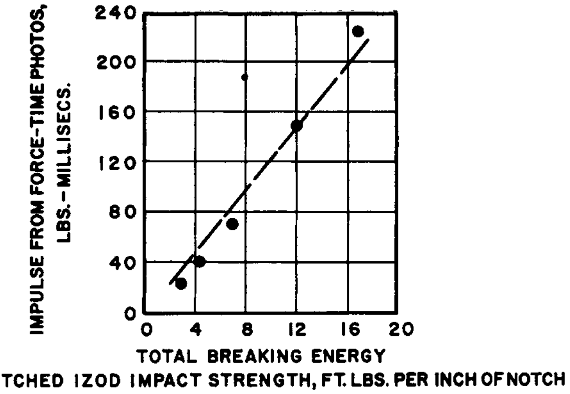

Fig. 3. Correlation between total impulse from force-time photos and notched Izod impact strength.

Figure 3 presents force-time photographs of the five thermoplastics listed in Table I. The characteristic breaking behavior of these materials is self-evident and the distinguishing features of the impulse curves illustrated in Figure 2 are clearly depicted in the photographs. The force-time coordinates are not directly comparable between photographs since the amplification in the x and y channels of the oscilloscope were varied to fit the impact pulse on the photograph.

For comparison it is of interest to determine whether the area under the impulse curves can be taken as representative of the energy absorbed during breaking. Figure 4 is a plot of the values of the total impulse computed from the force-time photographs and the conventional impact strength. These results exhibit the excellent linear correlation found in other experimental data of this type.

TABLE I
Comparison of Total Breaking Energy and Impulse Data from Force-Time Photographs

Thermoplastic	Total breaking energy, ft.-lb./in. notch	Breaking times, msec. Elastic	Plastic	Total	Peak force, lb.	Impulse, lb.-msec. Elastic	Plastic	Total
Kralastic[a]	4.2	1.06	0	1.06	75	40	0	40
Kralastic B[a]	11.9	1.30	2.60	3.90	72	45	93	138
Lexan[b]	16.8	1.67	3.00	4.67	97	81	146	227
Tenite butyrate[c]	6.8	1.21	.87	2.08	65	38	28	66
Styron 480[d]	2.9	0.92	0	0.92	52	24	0	24

[a] Naugatuck Chemical Co.

[b] Registered trademark, General Electric Co.

[c] Registered trademark, Tennessee Eastman.

[d] Registered trademark, Dow Chemical Co.

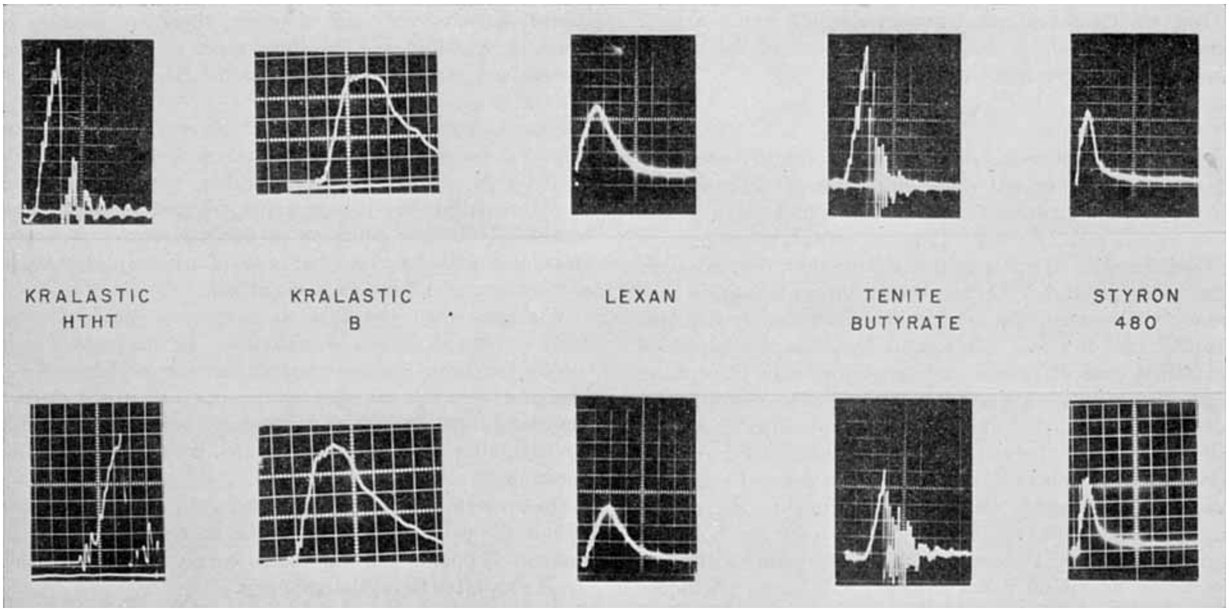

Fig. 4. Impact photographs.

DISCUSSION

The experimental results on impact behavior as recorded by the force-time photographs of the autographic impact tester corroborate previous intuitive concepts that thermoplastics exhibit large differences in breaking behavior under impact. The data of Table I show that the peak forces at which the samples begin to yield change by a factor of two. Also, there is no relation between the total impulse and the peak force when a material yields plastically. The correlation between total impulse and total breaking energy, or conventional impact, indicates that the area under the impulse curve may be taken as estimates of the energy absorbed elastically before yielding and the energy absorbed in plastic drawing and tearing. From the ratios of the respective impulse values it is easily determined that about 70% of the total breaking energy of the two thermoplastics of Table I with highest impact strengths is due to energy absorbed after the sample had yielded.

Consideration of this result raises serious doubt on the present general use of impact strength as a criterion for the impact characterization of thermoplastics. A more realistic measure would be the energy required to produce yielding or in terms of the present paper, the energy absorbed up to the peak force. The energy absorbed by the material in tearing or plastic drawing is not a factor in the mechanical strength. There are cases when plastic drawing or yielding would be highly desirable. In certain articles the type of break, as in football helmets, should not be a sharp fracture. The need for additional examination of the nature of energy absorption during impact is clearly a requirement necessary to characterize impact behavior for the most advantageous end use of thermoplastics.

References

1. ASTM Designation D-256-56, Am. Soc. Testing Materials, Philadelphia, Penn.

2. "Impact and Shock Resistance of Plastics," Final Report, PB151725, U. S. Department of Commerce, Office of Tech. Services, Dec. 1957.

3. U. S. Pat. 2,362,529 (1944).

4. Condon and Odishaw, in *Handbook of Physics*, McGraw-Hill, New York, pp. 2–11.

Synopsis

Conventional impact testing of thermoplastics gives a single numeric criterion of impact behavior in terms of total breaking energy. It is shown that impact behavior is characterized by an elastic phase and, after yielding, a plastic phase may occur. An autographic impact tester was built by modification of a standard pendulum hammer Izod impact unit. Force-time impulse curves show three characteristic categories in breaking; catastrophic, plastic drawing with tearing, and tearing. Photographs of impulse curves on five commercial thermoplastics clearly depict the three breaking categories. The impulse as measured by the area under the force-time curve shows a linear correlation with impact strength. The peak force at yielding exhibits over a 2 to 1 variation among the five commercial plastics. The three materials with highest impact strengths absorb approximately 70% of the total impulse after yielding.

These results indicate that impact strength is not a good single measure of the mechanical behavior of the impact properties of thermoplastics.

Résumé

Un essai conventionnel d'impact pour les matières thermoplastiques donne un critère numérique simple du comportement au choc en termes d'énergie de rupture totale. On montre que le comportement au choc est caractérisé par une phase élastique et, après qu'il se soit produit, on peut avoir une phase plastique. On a construit un contrôleur de choc autograph en modifiant le marteau d'un balancier standard Izod d'unité de choc. Les courbes force-temps d'impulsion montrent trois catégories caractéristiques dans la rupture: complète, passage à un état plastique avec déchirure, et déchirure. Des vues des courbes d'impulsion faites sur cinq substances thermoplastiques commerciales montrent clairement les trois sortes de cassure. On mesure l'impulsion par la surface située sous la courbe force-temps, ce qui montre une corrélation linéaire avec la force du choc. La force maximum au moment où celle-ci se produit montre une variation de moitié parmi les cinq substances plastiques commerciales. Les trois substances de forces de choc les plus élevées absorbent environ 70% de l'impulsion totale. Ces résultats indiquent que la force de choc n'est pas une mesure convenable et simple du comportement mécanique des propriétés de choc des thermoplastiques.

Zusammenfassung

Die konventionelle Schlagprüfung von thermoplastischen Substanzen gibt ein einziges numerisches Kriterium des Schlagverhaltens, nämlich die gesamte aufgewendete Bruchenergie. Es wird gezeigt, dass das Schlagverhalten durch eine elastische Phase charakterisiert ist, und dass nach Erreichen der Streckgrenze eine plastische Phase auftreten kann. Ein selbstschreibender Schlagzähigkeits-Tester wurde unter Modifizierung eines Standardpendelhammerschlaggeräts gebaut. Kraft-Zeitimpulskurven zeigen drei charakteristische Bruchkategorien; plötzlicher Bruch, plastische Verformung mit Reissen und Reissen allein. Photographische Aufnahme der Impulskurven von fünf handelsüblichen thermoplastischen Substanzen zeigen die drei Bruchkategorien klar. Der Impuls wird durch die Fläche unter der Kraft-Zeitkurve gemessen und zeigt eine lineare Beziehung zur Schlagzähigkeit. Der Höchstwert der Kraft bei der Streckgrenze zeigt bei den fünf handelsüblichen Kunststoffen eine Variation von mehr als 2 zu 1. Die drei Materialien mit der höchsten Schlagzähigkeit absorbieren nach der Streckgrenze ungefähr 70% des Totalimpulses. Die Ergebnisse sprechen dafür, dass die Schlagzähnigkeit als Einzelgrösse kein gutes Mass für das mechanische Verhalten in bezug auf die Schlageigenschaften von thermoplastischen Substanzen ist.

Discussion

Question: It is my opinion that the Izod test generally points out the notch sensitivity of the material. Are you finding a lot more notch sensitivity than anything else? Is it possible that this is all you are measuring?

Answer: Tests have been made on samples with variation in notch width and in depth, and on unnotched samples. Although no exhaustive study was made, the breaking behavior remains consistent for most materials; there are some exceptions, however, and of course there are changes in absolute magnitudes. The three types of characterization shown here can be used for a classification of all types of flexural impact breaks.

Some high speed tensile tests exhibit similar characterization. Metal samples, both notched and unnotched, have been tested and showed corresponding breaking behavior. Cylindrical tests samples of a few selected thermoplastics exhibited breaking behavior in flexural impact that corresponded with breaking behavior of rectangular samples with, of course, differences in magnitude.

We agree with you that there may be many unusual factors in the fracturing of materials. In this paper we are attempting to set down some characteristics or definitions of breaking behavior so that ambiguous or poorly defined numerical tests results, on breaking energies or tensile strength after a material has yielded, will be recognized as incomplete.

Question: It depends upon the use to which you intend to put the plastic. I should think that the fact that the material is ductile and can absorb energy beyond the yield could very often be capitalized upon.

Answer: I agree most heartily. This was commented on in the concluding remarks of my talk.

Question: Thus, specifying the energy-absorbing capacity of the material is quite important.

Answer: Specifying the manner in which it breaks is important.

Question: It is very easy to make a suggestion but, of course, very difficult to follow it. However, if you could test impaction in microcalorimeters for your test, it would be very interesting to see how much work done by your pendulum in breaking the sample is converted to heat, because in such case total plastic deformation would not be shown.

Answer: We have attempted to calculate the temperature rise from the breaking energy, but a major difficulty arises in deciding what order of magnitude should be used for the dimension of the mass perpendicular to the plane of the break, so that mass or volume involved in the actual breaking may be estimated.

Calculations made on the basis of so-called molecular dimensions for the break and actual total breaking energies give an excessive temperature rise, but when a supposedly more practical value of the dimension involved is taken—say to the order of 10^{-4} in.—the temperature becomes quite low compared with that of the melting properties of the thermoplastic.

Our attempts at measuring this temperature by thermocouples were hindered by the thermocouple response time, and the sensitivity was inadequate.

Question: I have measured some temperature rises in tensile specimens in a high speed stress-strain machine with a very thin thermocouple of wire diameter of about 0.001 in. On an oscilloscope that was able to respond to rapid transient voltages, I have obtained temperature increases of 135°C. The tests were made on a nylon specimen about $^1/_8$ in. in diameter and the thermocouple was threaded into a hole through one end. The sample was not notched and the hole along the sample axis through which the thermocouple was threaded was approximately 0.014 in. in diameter.

Answer: Was this a differential temperature rise?

Question: It was a differential temperature and represented an appreciable fraction of the rise to the melting point, but it is below the melting point. I made some calculations on a polyethylene and I am quite certain that in so-called high-density polyethylene the temperatures go up to the melting point. In low-density polyethylene the temperature rise may not get to the melting point, which I think has something to do with the manner in which these materials break. Breaking differences between these polyethylenes have been reported.

Some people have been disappointed because the high-density polyethylene had a higher tensile strength. It should have a greater toughness, and toughness is poorly defined, as we well know.

The differences appear to be that with the higher tensile strength the higher temperature may be localized and produce a line break, whence the energy is absorbed in the smaller amount of material. Consequently, the total energy absorption is smaller in a given test specimen of high-density polyethylene than that in a similar specimen of low-density polyethylene.

Question: May I offer the results of some measurements we made that would support your contentions? We were interested in two kinds of materials, one of which had a relatively high impact strength when tested in the Izod machine, and the other a low impact strength. These showed stress–strain curves that appeared to be identical under normal conditions of testing. The initial elastic deformation rose to a yield point and both materials showed plastic flow of 20–30%. As the speed of test was increased to velocities that were of the order of magnitude of striking velocities of the impact hammer in the Izod, we discovered that the two materials differed: they had the same initial elastic rise to the same yield point, but one material fractured at the yield point and the other had continued elongation at that velocity. And, of course, the work or energy under the stress–elongation curve of the material that had continued elo gation was considerably higher.

We came to the conclusion that high-impact materials are those having high elongation at high rates of elongation.

Answer: We have had some work done by Plas-Tech along this line and are quite familiar with your points and I am glad you brought it out.

Question: What sort of transducer did you use? How was it fastened to the work and what was actually measured?

Answer: It was a simple little strain gauge unit that anyone can make. We are now having trouble because we are measuring impulses with 1000-lb. peak forces on some materials. But you can take any kind of a mechanical system and mount some strain gauges on it, put the output into an oscilloscope with a convenient control, and calibrate. We have had four or five different mechanical arrangements in our initial work.

Question: In other words, your output was force on the impulse pictures?

Answer: Yes.

Question: I think it has been pretty clearly shown in the case of some thermoplastic materials that as you go to higher dimensions along the notch—i.e., a longer notch or a wider material—you can go from this ductile state to a brittle state.

In the case of some materials—for example, the polycarbonates—did you find such changes to be troublesome in your tests? What would have been shown as over against what you found in the ductile type if you had used a specimen having a notch width of 1/4 in., which I can almost guarantee would show a brittle break? This brittle breaking will not absorb a great amount of energy. It sounds anomalous, but the quarter-inch specimen absorbs probably an eighth of the energy that the eighth-inch specimen will absorb.

Answer: Well, now we are getting into the semantics of breaking.

Question: I don't think we are. I think there is a ready explanation for what is said. And I think that in this field you must watch the stresses in the thicker specimen, down near the center of the specimen, that are not uniaxial; these are multiaxial.

Answer: Right.

Question: Also, the elongations are not as great in much of the multiaxial testing—or biaxial, if we wish to confine ourselves to two dimensions—and energies to break will be considerably less. Many illustrations of that can be given.

Question: The question was whether you had tried the quarter-inch notch and found any information for comparison.

Answer: Yes, we have. Samples with eighth-inch and quarter-inch width have been tested; the quarter-inch one breaks at a much lower energy. Well, it can break in many different ways at a much lower energy. The quarter-inch sample could break catastrophically with a higher peak force, and this peak force, with the same force rate, would show lower total impulse area than when plastic drawing or tearing occurs. It may go up to just the same peak force and do a little tearing instead of the large plastic drawing exhibited by the thinner eighth-inch sample. This variation in breaking behavior can result in large differences in breaking energies.

It is not possible to state what one can do in every case because materials do not behave uniformly. We are trying to type most commercial plastics and have observed unusual breaking changes that are not readily understood. Some thermoplastics do not behave in a smooth and uniform manner. This is why we are making an effort to characterize impact behavior; we must become more knowledgeable. Although we have examined a large number of thermoplastic materials and can characterize the breaking behavior of most of those tested, there is insufficient data to state any generalizations. Our present tentative conclusion is that breaking behavior is not a simple uniform action for all materials.

Question: In working in a situation like this, one might also have difficulty in stipulating velocity conditions. Initially one is working, say, at about 8000 in./min. To get ductility, it is necessary to go far below that. Thus the entire test depends upon the behavior of the material being used, and its response to a variety of velocities and strain rates.

Answer: Yes, attention to experimental conditions must be exercised constantly. Our test conditions were arranged such that the amount of energy absorbed in breaking a sample was only a fractional part, much less than 50%, or the total energy in the impacting hammer.

Question: In working with polycarbonates, if you do get a good tough break you will pull quite a bit of energy out of the pendulum.

Answer: Yes. A similar test situation occurs when metal samples are broken.