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Factors Influencing Izod Impact Properties of Thermoplastics Measured with the Autographic Impact Test

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Synopsis

The standardization of notched Izod impact test data to normalized values of foot pounds per inch of notch is based on the assumption of a 1:1 increase in breaking strength with increasing notch width. This assumed relation is not supported by experimental tests on commercial thermoplastics. As notch width was increased from 1/8 to 1/4 to 3/8 to 1/2 in., nine of ten thermoplastics tested showed a decrease in normalized impact strength. Each material appears to show a characteristic loss in breaking strengths as the notch width increases. A technique developed for calibration of pendulum impact testers has been used to examine the variation of impact breaking strength in relation to the total kinetic energy of the hammer. Experimental tests show practically no change in impact strengths up to values that take 2/3 of the available hammer energy. Experimental work on the comparison of the impulse transferred by the hammer during breaking with impulse curves photographed by the Autographic Impact test show very good agreement for catastrophic breaks and fair agreement for plastic type breaks. The reduction in recorded impulse is attributed to the degrading of the sample during the plastic portion of the breaking cycle. The peak force of thermoplastics as measured by the Autographic Impact test increases as the temperature decreases from 100°C. or above to 0°C. Over the same temperature range flexural tests on small cantilever samples of these thermoplastics show the same thermal dependence for the flexural yield or permanent distortion stress. Plots of the impact peak forces and flexural yield stress at corresponding temperatures give a linear correlation. Each thermoplastic material exhibits a unique relation for this correlation between impact yielding and flexural yielding. This correlation between the impact and flexural tests over the range of temperatures is the first known experimental indication of a direct relation between impact properties and standard physical tests.

INTRODUCTION

The performance of a material as a commercially useful article is the criterion for determining the required physical properties of the material. For rapid evaluation of materials there are many types of empirical and scientific tests that are used to measure the properties of materials. The empirical tests are supposed to simulate the use conditions and give some indication of the behavior of the material as a commercial product. The scientific tests are designed to measure a mechanical or physical property and the numerical value of the property measured is interpreted as an indication of the commercial usefulness.

When the measurements from either or both empirical or scientific tests are reasonably understood in terms of the useful life of the material, then an evaluation of the material can be made by these tests with confidence. However, there are many tests that are used for the evaluation of physical properties on the assumption that the test method should give a measure of the behavior of the material. These test results can give misleading information due to type of test method, effect of sample dimensions, inadequate understanding of the test, and lack of relation between the physical factors measured with respect to other properties of the material.

Impact testing of thermoplastics and other materials is a well known test method used to evaluate a physical property called the impact strength of the material. Although there are various types of impact tests in common use such as the tensile impact and the flexural impact tests of notched Izod, the Charpy, and the Drop Weight, which give a numerical value that supposedly measures the impact behavior, these tests can give disconcordant results on many materials. Care must be exercised in evaluating impact properties as shown in a series of articles by Vincent[1] and Horsley.[2]

Because of the extensive use of the notched Izod method[3] for testing thermoplastics, the Izod impact test method has been examined in our work to assess its usefulness in evaluation of impact properties. In an earlier paper[4] a transducer-recording system for the Izod impact test was described which gave a photographic record of the force-time or impulse curve of the specimen during the impact. The method, called Autographic Impact, provides a calibrated photographic record of the impact behavior during breaking. This paper presents additional information on three phases of the notched Izod impact test, namely, the effect of notch width on impact strength, the influence of the amount of kinetic energy lost by the hammer and a correlation between impact and flexural properties over a range of temperatures. Essentially all the work reported will be in reference to the notched Izod impact test.

PART I

Normalized Test Data

The impact strength is conventionally reported in terms of energy per unit thickness of the specimen, that is, as foot pounds per inch of notch for notched specimens. This method of reporting the test results is based on the standardization or normalizing of the energy lost by the impacting mass. Presumably, due to limitations in capacities of impact testing machines, the conventional practice is to test samples of some convenient width less than one inch and then normalize the breaking energy to impact strength in terms of a sample one inch wide.

For conventional mechanical tests such as a tensile, compression or torsional, the concepts of classical mechanics show that the elastic properties and the energy for elastic deformation are related to the sample dimensions in accordance with specific laws. As is well known, experimental data on elastic properties from test pieces of different dimensions show acceptable agreement with theory as shown by the correspondence of the stress-strain plots which are plots of standardized load and deflection. Although there appears to be little observable effect of test piece dimensions on stress-strain plots, exceptions are known as in the case of thin filaments of metal and glass.

The standardization of impact data assumes that the breaking energy increases linearly with the width of the test specimen. The basis for this assumption can be found in the analysis of cantilever beams.[5] The loading under impact of the cantilever test specimen in the Izod impact test is identically the same as a concentrated load on a cantilever beam. In the analysis for this system of loading the energy required to deflect the beam within its elastic limits should increase linearly as the beam width increases, if all other factors remain constant. In experimental work[6] reported on the effect of dimensional changes of test specimens on the impact properties of metals, the impact results are strongly dependent on specimen dimensions. For thermoplastic materials the effect of notch variations,[7] and other physical properties[8] have been reported but there appears to be practically no work published that was specifically directed towards the effect of notch width on impact strength of thermoplastics.

Effect of Notch Width on Impact

The impact strength computed from test data on a standard notched Izod test specimen is obtained from the relation

$$E = B/12\,w \tag{1}$$

where E is the calculated impact strength in ft. lb. for a hypothetical specimen with a notch width of one inch, B is the breaking energy in inch pounds that is read from the indicator of the test machine, w is the measured width of the notch specimen and the number 12 is the proportionality factor for conversion of in. lb. to ft. lb. With test specimens of different notch widths but of the same material, eq. (1) gives the following equalities:

$$E = B_1/12\,w_1 = B_2/12\,w_2 = B_3/12\,w_3 \ldots \tag{2}$$

where B_1, B_2, B_3 are the respective breaking strengths for samples with notch widths w_1, w_2, w_3. The assumption of a linear increase in breaking strength proportional to the notch width means that each of the equivalent fractions of eq. (2) should give the same value for E, the impact strength of the material.

TABLE I
Variation of Impact Behavior as Notch Width Increases Averaged Values of Impact

Material	Notch width, in.	Breaking times			Peak force, lb.	Impulse		Total breaking energy, in. lb.	Impact strength, ft. lb. in. notch
		Elastic, msec.	Plastic, msec.	Total, msec.		Elastic, #/lb. msec.	Total, #/lb. msec.		
Polymethyl methacrylate	$^{1}/_{8}$	0.20	0	0.20	34	3.3	3.3	0.6	0.40
	$^{1}/_{4}$	0.23	0	0.23	65	7.9	7.9	1.5	0.50
	$^{3}/_{8}$	0.22	0	0.22	93	13.7	13.7	2.0	0.44
	$^{1}/_{2}$	0.21	0	0.21	110	16.0	16.0	2.5	0.42
Polystyrene	$^{1}/_{8}$	0.17	0	0.17	24	2.1	2.1	0.5	0.34
	$^{1}/_{2}$	0.15	0	0.15	32	3.5	3.5	0.65	0.21
	$^{3}/_{8}$	0.17	0	0.17	55	5.2	5.2	1.12	0.25
	$^{1}/_{2}$	0.21	0	0.21	74	9.8	9.8	1.80	0.28
Cellulose acetate butyrate	$^{1}/_{8}$	1.35	0	1.35	49	33.1	33.1	7.5	4.95
	$^{1}/_{4}$	1.40	0	1.40	85	65.0	65.0	10.3	3.40
	$^{1}/_{2}$	1.21	0	1.21	153	100.0	100.0	15.2	2.52
Rubber modified polystyrene	$^{1}/_{8}$	0.92	0.91	1.83	36	16.5	33.3	8.0	5.28
	$^{1}/_{4}$	0.93	0.93	1.96	60	30.2	58.1	11.3	3.73
	$^{1}/_{2}$	0.97	0.69	1.66	101	49.7	85.2	19.0	3.16
Polycarbonate	$^{1}/_{8}$	1.66	2.98	4.65	98	81	228.0	25.0	16.50
	$^{1}/_{4}$	1.88	2.04	3.92	178	167	339.0	40.6	13.40
	$^{3}/_{8}$	1.30	0	1.30	223	144	144.0	14.5	3.21
	$^{1}/_{2}$	1.25	0	1.25	295	186	186.0	18.4	3.06

ABS type II	1/8	0.68	0.32	1.00	75	25.5	38.0	6.1	4.0
	1/4	0.75	0.31	1.06	103	38.2	54.6	8.0	2.7
	1/2	0.75	0.39	1.14	183	69.0	105.3	16.1	2.7
ABS type I grade I manufacturer A	1/8	1.20	2.70	3.90	73	44.5	144.0	16.5	11.0
	1/4	1.34	3.12	4.46	118	78.4	259.0	28.0	9.2
	3/8	1.60	3.34	4.94	167	130.0	400.0	41.0	9.1
	1/2	1.30	2.97	3.90	186	121.0	383.0	55.0	9.1
ABS type II manufacturer B	1/8	0.74	0.60	1.35	87	32.3	58.4	8.3	5.5
	1/4	0.87	0.40	1.27	122	53.0	78.0	11.2	3.7
	3/8	0.84	0.13	1.01	161	79.0	87.0	13.7	3.2
	1/2	0.85	0.26	1.11	215	95.0	125.0	19.3	3.2
PVC type II	1/8	1.10	2.6	3.7	88	43.8	161.0	18.4	12.4
	1/4	1.0	0	1.0	125	62.5	62.5	10.0	3.3
	3/8	1.1	0	1.1	175	98.0	98.0	13.2	2.9
	1/2	1.5	0	1.5	258	193.0	193.0	24.3	4.0
PVC type I grade 2	1/8	0.54	0	0.54	60	30.0	30.0	2.8	1.9
	1/4	0.59	0	0.67	112	44.5	44.5	4.3	1.4
	3/8	0.67	0	0.67	135	67.5	67.5	5.2	1.1

Another manner of stating this proportionality is to rearrange the quantities of eq. (2) as:

$$
\begin{aligned}
B_2/B_1 &= w_2/w_1 \\
B_3/B_1 &= w_3/w_1 \\
B_4/B_1 &= w_4/w_1 \qquad (3)
\end{aligned}
$$

then, by plotting the ratios of the breaking strengths as a function of the ratios of the sample notch widths in terms of eq. (3), the plots should follow a line with a positive slope of 45° on equal x and y coordinates. Plots of this type, as shown below, clearly reveal the influence of notch width on impact strength.

Experimental Equipment and Materials

Standard impact test methods[3] were used in all test work. The impact tests were made on two pendulum hammer Izod type impact testing machines with maximum capacities of 50–200 in. lb. Each testing machine was equipped with a transducer and accessory apparatus for Autographic recording[4] of the force acting on the sample at the point of impact as a function of time. The total breaking energy in inch pounds required to break each sample was read from the indicator scale on the test stand. The transducers and oscilloscope used for photographic records of the force-time curve were calibrated for each group of tests.

Commercial thermoplastics were used for all impact test work. Compression molded slabs of several thicknesses, namely $^1/_8$ in., $^1/_4$ in., $^3/_8$ in., $^1/_2$ in. were prepared according to the manufacturer's recommended molding temperatures. From these molded slabs the test samples of standard size, $2^1/_2$ in. length × $^1/_2$ in. depth were cut and notched to give samples with notch widths of $^1/_8$ in., $^1/_4$ in., $^3/_8$ in., and $^1/_2$ in. All tests on effect of notch width were made at room temperature.

Notch Width Test Results

The averaged impact test data for samples with notch widths from $^1/_8$ in. to $^1/_2$ in. of ten commercial thermoplastics are listed in Table I. The averaged values listed are from a minimum of five tests at each notch width. In cases where test data showed appreciable scattering, additional tests were made, usually to a total of ten, in order to improve the certainty of a representative average for that material. Test data in the columns titled Breaking Times, Peak Force and Impulse are from the Autographic Impact photos. The column titled Breaking Energy is the indicator dial reading of the test instrument and the last column on the right is the computed impact strength. The thermoplastics are not listed in any special sequence in this table.

Figures 1 and 2 are plots of these data in terms of the breaking strength ratios and the notch width ratios given by eq. (3). The solid line is the expected relation for the proportional increase of breaking strength with increasing notch width. These plots demonstrate that thermoplastic materials do not show good agreement with the assumption that breaking

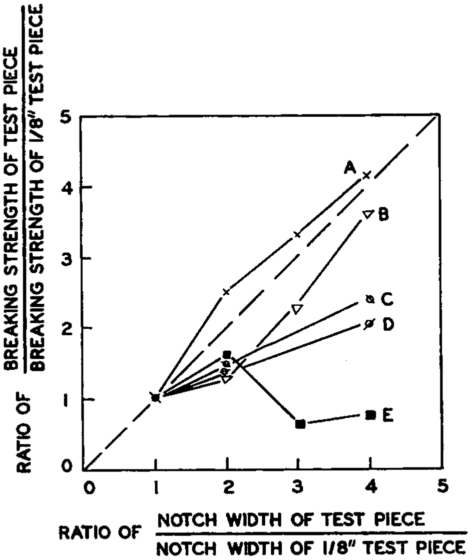

Fig. 1. The proportional increase of breaking strength as related to the proportional increase of notch width in Izod impact tests. Material *A*, polymethyl methacrylate; *B*, polystyrene; *C*, rubber modified polystyrene; *D*, cellulose butyrate; *E*, polycarbonate.

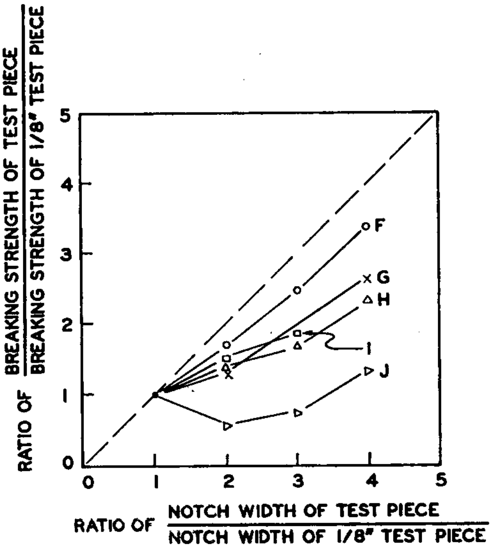

Fig. 2. The proportional increase of breaking strength as related to the proportional increase of notch width in Izod impact tests. Material *F*, ABS Type I; *G*, ABS Type II; *H*, ABS Type II (different manufacturer); *I*, PVC Type I; *J*, PVC Type II.

strength increases uniformly with increasing notch width. Each of the ten thermoplastics that were tested appears to exhibit a specific variation in breaking strength as the notch width increases from $^1/_8$ in. to $^1/_2$ in. An important consequence of these results is that engineering design specifications for impact properties of thermoplastic articles may be in serious error when based on impact test data from samples with a smaller notch width than the designed article.

The Autographic Impact data on these ten thermoplastics was included to show that as notch width increases, the peak force at which the test specimen begins to yield under the impacting blow, also increases. However, neither the elastic nor plastic breaking times show any significant changes with increasing notch width.

PART II

Breaking Strength and Total Energy

During the work on evaluation of the notched Izod impact test, the question arose about the dependence of the breaking strength on the kinetic energy available in the impacting hammer. The trend in development of multi-range impact machines can produce situations such that impact tests on low capacity scales where the breaking energy is around 90% of the total hammer energy may give impact results that are not consistent with tests of the same material on the higher capacity scales of the impact test machine. While the practical problem, just cited, is of importance, the fundamental problem is whether the material under test is sensitive to rate of loading in the ranges of the impact testing machine. The term "rate of loading" is used here to mean the velocity of the impacting mass during the entire time of contact with the test specimen. Interest in the physical behavior of materials as influenced by the rate of application of stress or loading is, of course, a primary feature of this and the previous three *High Speed Testing Symposia.*

The rate of loading is not constant in pendulum type impact testing machines during the time of contact between the impacting mass and the test specimen. This is readily shown in the two cases given below for illustration.

Case I

Consider a multi-range impact machine set on a low range with M_s lb. hammer and a standard notched test piece with a breaking strength B that is 90% of the capacity for this range, then

$$B = .9M_sV_i^2 \tag{4}$$

Denoting the final velocity of the impacting mass by V_f and equating the kinetic energy change gives

$$.9M_sV_i^2 = M_s\,(V_i^2 - V_f^2) \tag{5}$$

The final velocity is

$$V_f = (.1)^{1/2} V_i \tag{6}$$

The average velocity during impact when taken as the arithmetical mean is

$$V_{\text{avg}} = (V_i + V_f)/2 \tag{7}$$

Whence for the conditions of this case the average velocity during impact is

$$V_{\text{avg}} = .525 V_i \tag{8}$$

Case II

Consider a larger capacity scale on the same testing machine such that the capacity of the larger scale is five times as great as the capacity on the smaller scale or

$$M_h = 5M_s.$$

Assume that the breaking strength remains unchanged, then on this scale of the machine, the breaking energy will be

$$B = .18 M_h V_i^2 \tag{9}$$

Equating the kinetic energy change gives

$$.18 M_h V_i^2 = M_h (V_i^2 - V_f^2) \tag{10}$$

and solving for V_f

$$V_f = .905 V_i \tag{11}$$

The arithmetical average velocity during impact is

$$V_{\text{avg}} = .952 V_i \tag{12}$$

The initial velocity is identical for all ranges of this type of machine, whence the average velocity for the higher impact range is, in this case, about 73% greater than for *Case I* with the lower range capacity. This spread in loading velocity is not very large but since our knowledge of the behavior of materials with respect to loading rates is not well documented, some exploratory experimental work was undertaken in this field.

Pendulum Machine Calibration

Limitations of materials and test equipment prevented experimental work as outlined above. In order to obtain data of the type desired, the kinetic energy of the impacting mass was varied by changing the height of fall. A preliminary study showed that this variation in height could be used to check the scale calibration of the impact tester, the weight of the impacting mass, the fixed maximum height of the pendulum and any non-uniformities between or within any scale.

The calibration method is to cut four meter sticks at lengths that will give kinetic energy values equal to say 80, 60, 40, and 20% of the total energy of the indicator scale. From a convenient reference surface such as the bench top on which the impact machine rests, the maximum height of the striking edge of the impact mass is measured. Then the pendulum is lowered to the minimum point of the swing and the height of the striking edge from the reference surface is measured. The difference in these heights equals the height of the swing of the pendulum. Now, the potential energy required to raise the pendulum to some height h is equal to the kinetic energy of impacting mass, whence

$$mgh = mv^2/2 \tag{13}$$

with m the weight of the mass in g., g is the gravitational constant and v is the velocity. Since the indicator is marked in terms of energy E then

$$E = mgh \tag{14}$$

and a plot of E as a function of h should be a straight line of slope mg. Since g is a constant, the slope of the line determines the mass of the impacting mass.

Figure 3 is a typical plot of eq. (14) for a commercial multi-range impact tester. In this case the four lengths of 80%, 60%, 40%, and 20% of h were all increased by the constant value of 23.8 cm. which was the distance from the bench top to the impact point on a sample mounted in the anvil of the impact machine. In using the calibrating sticks either for calibration or for changing the energy of the hammer, the pendulum is supported by resting the striking edge on the top of a stick of the desired height. The stick is struck a sharp blow directed away from the impact machine. There should be no undue influence on the fall of the pendulum when the blow removes the stick from the pendulum. If the stick is not properly

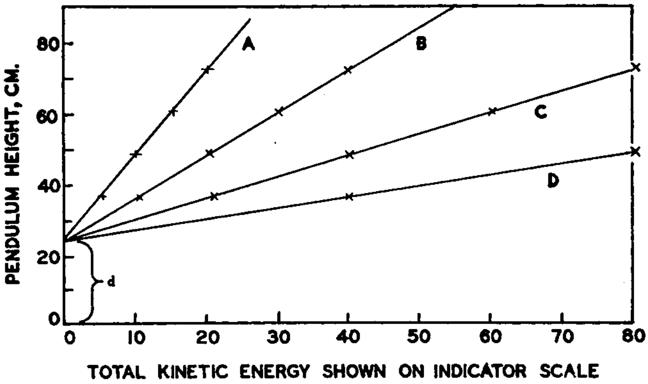

Fig. 3. Energy readings of indicator scale when pendulum hammer falls from different heights. The distance d is the height from the bench top to the impact point on the test piece. Capacities of multiple scales A, B, C, D are 25, 50, 100, 200 in. lb., respectively.

hit, a small but measurable error will be introduced by a slight raising of the pendulum or a small rubbing frictional contact as the pendulum falls due to improper or slow removal of the supporting stick. With slight practice and perhaps a few minor adjustments of the order of 1 or 2 mm. in lengths, consistent repeat scale indications can be obtained with no difficulty.

Experimental Results

Figure 4 is a plot of breaking energy read from the scale indicator of the impact tester as a function of the fractional total kinetic energy used to break the test piece. These data were obtained by breaking standard notched Izod test pieces over a range of hammer energies when the available kinetic energy was altered by lowering the height of fall. Each point is the average of three to five tests.

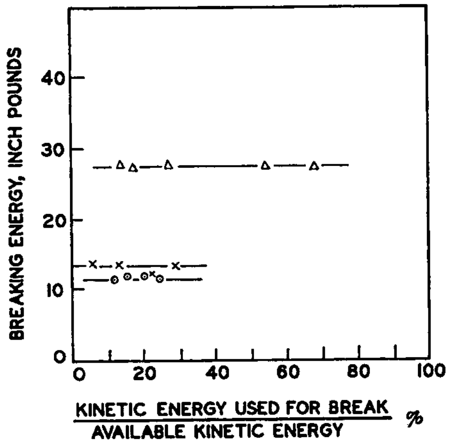

Fig. 4. Impact breaking energy as a function of the percentage of kinetic energy used for breaking the test piece. Material $^1/_8$ in. notched Izod test pieces; (△), polycarbonate; (×), ABS Type I; (⊙), cellulose butyrate modified. All tests at room temperature.

The results illustrate that for breaking energies up to 67% of the available kinetic energy of the pendulum hammer, there is little change in the breaking strength.

Autographic Impulse Comparison

The impulse photographs of the Autographic Impact test show the test piece reaction during the time of impact as the test piece is being deformed and broken. The coordinates for these photographs are calibrated independently in terms of force or loading (lb.) and time (msec.). From the Newtonian relation

$$f = ma \qquad (15)$$

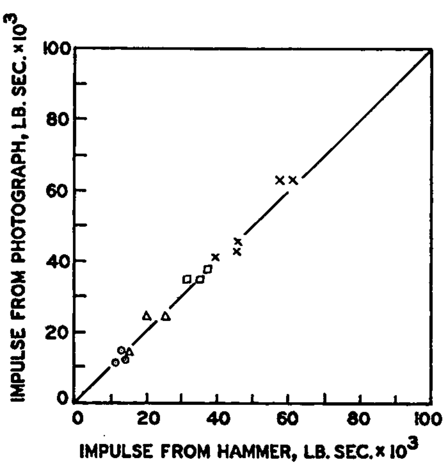

Fig. 5. Comparison of the impulse delivered by the hammer to break Izod notched test piece and the impulse recorded photographically from the test piece reaction to the transducer clamped with the test piece in the anvil. All samples showed brittle type or catastrophic breaks. Material identification: (⊙), ABS Type IV, $^1/_8$ in. notch, 25°C; (△), ABS Type II, $^1/_4$ in. notch, −20°C.; squares, same but at 5°C.; (×), polycarbonate, $^1/_4$ in. notch 25°C.

where f is the force acting on a mass m to produce an acceleration a, substitution of the derivative of the velocity v with respect to time t for acceleration in eq. (15) gives

$$f = m(dv/dt) \tag{16}$$

Integration of (16) yields

$$ft = mv \tag{17}$$

for initial conditions of $v = 0$ at $t = 0$. The conditions of eq. (17) state that the area under the impulse curve of the photographs with coordinates f, t should be equivalent in absolute units to the impulse lost by the hammer after breaking the sample. A comparison between the impulse recorded from the transducer in the Autographic Impact test and the impulse delivered by the hammer on breaking the sample was desired to confirm that the sample reaction on the transducer was equivalent to the hammer reaction on the sample.

Although the computation of impulse results is a relatively elementary matter in terms of the kinetic energy lost by the hammer, an uncertainty existed since there was no check on the uniformity of the scale indicators on the impact test machines. However, the calibration method described above removed this uncertainty and also, provided an accurate value for the mass of the impacting pendulum hammer. From a set of curves relating breaking energy to impulse lost by the hammer, a comparison was made between impulse values from the photographs and the impulse lost by the hammer.

Figure 5 is the comparison plot of the hammer impulse and the impulse from the photographs for a randomly selected group of samples, all of which exhibited a catastrophic type break. Figure 6 is a similar plot but these samples exhibited various types of plastic and tearing deformation after yielding. It is readily evident that the catastrophic type breaks show excellent agreement between the impulse lost by the hammer in breaking the sample and the impulse recorded photographically from the sample reaction on the transducer. For these type of breaks this agreement confirms that Autographic Impact data is an absolute indication of the sample behavior during impact. For samples with the plastic type of break, the photographic impulse recorded from the transducer is always lower than the impulse lost by the hammer. The reason for the consistent lower impulse shown on the photographs is attributed to the plastic phase of breaking. When the sample is tearing, the reaction transmitted to the transducer during this phase of breaking is not a 1:1 correspondence as when the sample is mechanically deforming before starting to yield. The reduced sample cross section during tearing will not produce the same reaction on the transducer as given by the original sample cross section and this reduction in transducer response will result in the lower impulse shown by impacted samples with plastic breaks. The initial portion of the impulse photographs to the yielding point of plastic type breaks is considered to be a 1:1 representation of the sample behavior under impact and any misrepresentation of the impulse will occur in the plastic region of the impulse curve.

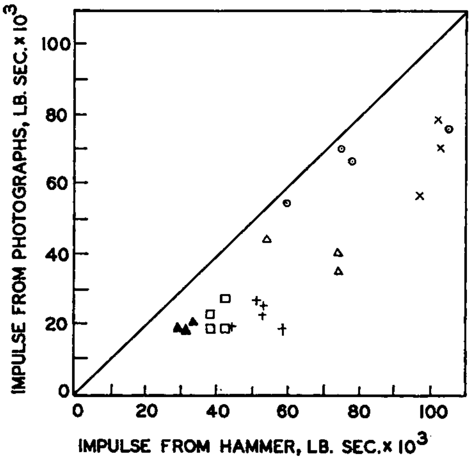

Fig. 6. Comparison of the hammer impulse and the photographically recorded impulse for samples with plastic tearing breaks. Material identification; (⊙), ABS Type II, 1/4 in. notch; (□), ABS Type II, 1/8 in. notch; (×), ABS Type IV, 1/4 in. notch; (+), ABS Type IV, 1/8 in. notch; (△), ABS Type IV, 1/4 in. notch; (▲), ABS grade, not designated, 1/8 in. notch. All tests at room temperature.

PART III

Temperature Dependence of Impact

The impact strength of all thermoplastics changes with temperature. The commercial importance of this thermal dependence of impact strength limits the usefulness of thermoplastics and there is increasing demand for improved performance over a wider range of temperatures. Although it is commonly agreed that the strength properties of materials arise from the composition of the material, at present very little is known about the influence of composition on physical properties. Experimental work on the variation of impact strength with temperature has revealed some interesting features of the impact properties through the use of the Autographic Impact technique.

All commercial thermoplastics show a decrease in impact strength as the testing temperature is lowered from room temperature. Impact strength of metals also decreases as the test temperature is lowered. The general trend of decreasing impact strength with decreasing temperature indicates that a common physical property must be varying with temperature. However, the wide differences in the magnitude of the decrease exhibited by materials tested in the same temperature range reveal that the impact strength variations are strongly influenced by the compositions of the materials.

The tensile strength of most commercial thermoplastics generally exhibits a slight increase as the temperature is lowered but this change is relatively minor and opposite to the reduction in impact strength in the same temperature range. These changes are considered to mean that tensile strength is not a primary factor in the thermal variation of impact strength of thermoplastics.

In addition to the work on thermal dependence of impact, other work on the thermal dependence of flexural properties of thermoplastics was undertaken. The flexural work was for evaluation of the effect of stress and temperature on the distortion of thermoplastics. The experimental results on the thermal dependence of impact and flexural properties has led to a very interesting correlation.

Experimental Results

Standard notched Izod test pieces of $^1/_4$ in. notch width were used for Autographic Impact tests on ten commercial thermoplastics over a temperature range from 0 to 100°C. and higher. All samples were heated or chilled in air at the desired temperature for 30 min. before testing. The experimental data are listed in Table II.

The flexural tests were load-deflection data on thermoplastic rods, $^1/_4$ in. diameter × 3 in. long, that were tested as cantilever beams with concentrated loads on a 3 in. span with deflection measured at the loading point. All samples were prepared by extrusion. The flexural load-

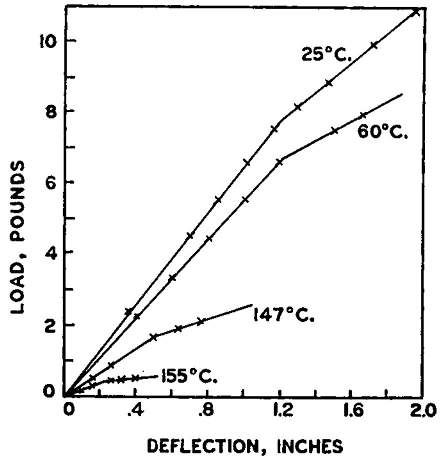

Fig. 7. Load-deflection plots at selected temperatures for flexurally loaded $^1/_4$ in. diameter ×3 in. length rods of polycarbonate. Flexural distortion load is taken at point of departure from Hooke's law. Cantilever beam with concentrated loading on a 3 in. span with deflection measured at loading point.

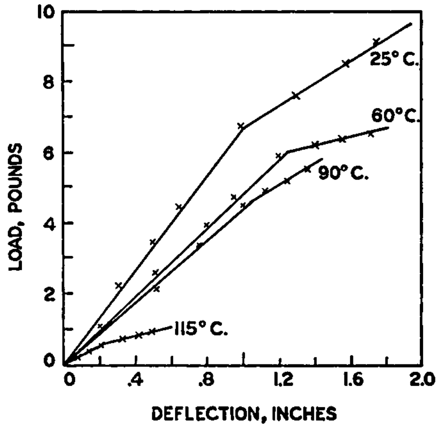

Fig. 8. Load-deflection plots at selected temperatures for flexurally loaded $^1/_4$ in. diameter ×3 in. length rods of ABS Type II thermoplastic. Flexural distortion load is taken at point of departure from Hooke's law. Cantilever beam with concentrated loading on a 3 in. span with deflection measured at loading point.

deflection tests for loads less than two pounds were run in a Maxwell Dynamic Tester[9] with the rod rotating at a slow speed of approximately one rpm and the loading was automatically recorded. When the flexural field load became greater than 800 g., the load-deflection tests were manually loaded with deflection recorded by an assistant operator.

The reason for these different techniques was that the Maxwell Tester provided a rapid and sensitive method for recording the loading at elevated temperatures. Several check tests between the two methods used for load-

TABLE II. Comparison of Notched Izod Impact Peak Load and Flexural Yield Load For a Range of Temperatures

Material	Test temp., °C.	Impact (notched samples) Peak load, lb.	Impact (notched samples) Breaking strength, in. lb.	Flexural yield load, lb.
Polymethyl methacrylate	25	75	1.25	11.2
	60	53	1.35	6.6
	90	50	1.46	1.39
	100	44	1.65	1.03
	111	35	1.9	0.176
Polystyrene	25	35	1.0	7.9
	60	33	1.0	5.9
	95	19	1.25	1.74
Cellulose acetate butyrate	25	72	21.0	2.86
	50	53	25.0	2.10
	65	42	27.0	0.73
	75	35	26.0	0.57
Polycarbonate	0	137	7.1	10.6
	25	144	6.5	9.9
	60	110	5.2	7.3
	75	112	5.3	6.6
	125	80	11.4	4.2
	150	62	80.0	1.72
	155	50	72.0	0.32
ABS type I-grade I	25	98	20.0	3.3
	50	82	22.0	2.1
	75	53	16.0	1.76
	100	44	15.0	0.44

(continued)

deflection data indicated no differences other than expected from experimental variations due to sampling.

The primary objective of these flexural tests was the determination of the load at which the material became plastically distorted. Figures 7 and 8 are typical plots of load-deflection curves for a range of temperatures which show linear elastic deflection to the yield load beyond which the sample yields plastically and is deformed permanently. Since all deflection tests were made with samples of identical dimensions, the loading at any point on the elastic portion of the load-deflection plot can be converted to maximum fiber stress by the appropriate beam equation. Beyond the yield point where the load-deflection plot departs from the straight line of Hooke's law, the equations of classical elasticity are not valid and computing the stress for loads beyond the yield point of flexural distortion is meaningless for such computations are based on the fallacious assumption that the material has not changed after yielding.

TABLE II (*continued*)

Material	Test temp., °C.	Impact (notched samples) Peak load, lb.	Impact (notched samples) Breaking strength, in. lb.	Flexural yield load, lb.
ABS type II	0	104	4.7	7.9
	25	110	10.5	6.4
	60	94	14.1	5.7
	90	92	19.0	4.6
	115	72	29.6	0.54
ABS type I	25	93	20.6	5.5
	60	81	19.1	3.5
	90	70	12.0	2.6
	100	56	9.0	0.55
ABS type IV	0	92	3.6	7.2
	25	78	7.2	6.0
	60	68	6.0	4.6
	97	49	3.0	1.1
	100	50	3.5	0.81
ABS type IV	0	100	2.6	6.2
	25	89	3.5	6.8
	75	65	3.7	2.6
	90	60	3.8	1.32
	100	40	3.9	0.57
ABS type intermediate not classified	25	62	20.0	4.6
	80	50	21.0	2.2
	100	33	12.7	0.48

The change in slope of the elastic or Hookean portion of the load-deflection plots shown in Figures 5 and 6 illustrates the well-known effect of temperature on modulus. The modulus change over the temperature range of the flexural distortion tests was as great as 50% for some materials and this produces an appreciable effect on the computed maximum fiber stress at the yield load. In Table II the loads for flexural distortion are listed for the materials at the respective test temperatures.

Impact and Flexural Correlation

The impact received by a sample is essentially a rapid loading of the sample when the hammer strikes and begins to bend the sample. Since the impacting velocity of 11 ft./sec. for conventional Izod impact machine is very much below the sonic velocity in thermoplastics, the impacted sample is considered to react elastically in the initial phase of the impact. Continued application of the load during the impact blow by the hammer

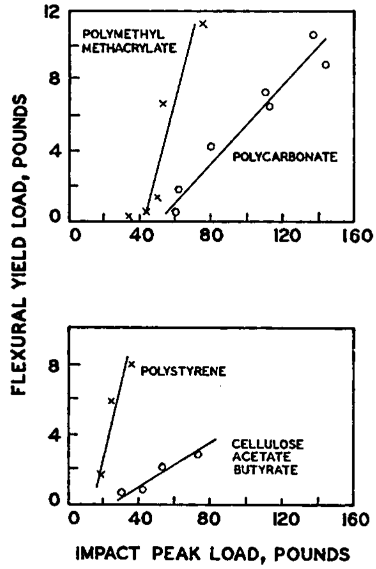

Fig. 9. Correlation of impact peak load for $^1/_4$ in. notched Izod samples and flexural yield load over a range of temperatures on four commercial thermoplastics.

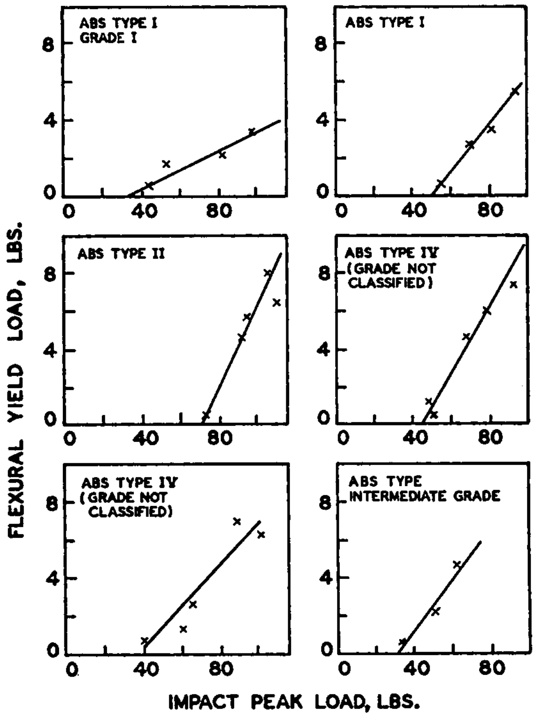

Fig. 10. Correlation of impact peak load for $^1/_4$ in. notched Izod samples and flexural yield load over a range of temperatures for six commercial thermoplastics.

increases the deflection to the yield point of the material which on the Autographic Impact photos is termed the peak force or peak load.

Inspection of the effects of temperature on impact behavior revealed that the peak loading from the impulse photos decreased with increasing temperature. The flexural yield load also decreased with increasing temperature. To determine whether the same physical properties of the material were influencing the yielding in the impact and the flexural tests, plots were made of the impact peak load and the flexural distortion load at corresponding temperatures over the range of test temperatures. Figures 9 and 10 show an essentially linear correlation between the peak load of impact loading and the distortion load for flexural loading for the ten commercial thermoplastics tested.

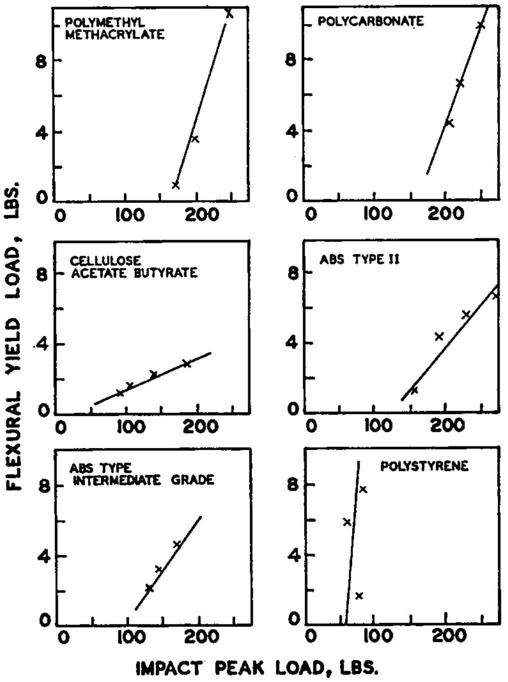

Fig. 11. Correlation of impact peak load for 1/4 in. *unnotched* Izod impact samples and flexural yield load over a range of temperatures.

The correlation between the peak load of 1/4 in. notch width Izod impact samples and the flexural yield load for 1/4 in. diameter rods at corresponding temperatures indicates that the same physical properties of the materials are primary factors in the yield of thermoplastics for impact and flexural tests. The changes in slope of the correlation lines is very likely the influence of the thermal dependence of these properties as determined by the composition of the material. Although sample dimensions were held constant to minimize dimensional effects, no general conclusions on the influence of composition have been made from this work. These results do not give any information on the plastic region of impact testing.

The correlation shown in these tests is expected to change with variations in sample dimensions. For example, the stress concentration developed in a notched impact test piece will cause yielding at a smaller peak load than measured for an unnotched test piece. Some preliminary work was done to determine the magnitude of the change expected for peak loads of notched and unnotched impact tests. Figure 11 is a group of plots for five thermoplastics that were tested as unnotched Izod impact samples. Results are listed in Table III. The peak loads are plotted against the flexural distortion load for corresponding temperatures as done previously. The correlation between these results is self-evident. As anticipated the change in experimental conditions (from notched to unnotched samples)

TABLE III
Comparison of Unnotched Izod Impact Peak Load and Flexural Yield Load For a Range of Temperatures

Material	Test temp., °C.	Impact (unnotched sample) Peak load, lb.	Impact (unnotched sample) Breaking strength, in. lb.	Flexural yield load, lb.
Polymethyl methacrylate	25	250	14.0	11.2
	80	200	15.0	3.5
	100	170	10.0	1.03
Polycarbonate	25	250	140.0	9.9
	75	222	150.0	6.6
	100	210	145.0	4.4
Cellulose acetate butyrate	25	186	112.0	2.86
	50	138	99.0	2.10
	65	110	88.0	0.73
	70	94	80.0	0.57
ABS type II	25	275	67.0	6.4
	60	232	109.0	5.7
	90	188	128.0	4.3
	115	156	118.0	0.54
ABS type intermediate not classified	25	245	170.0	4.6
	50	215	145.0	3.2
	80	158	132.0	2.2
Polystyrene	25	82	2.5	7.9
	60	59	1.75	5.9
	90	77	3.2	1.74

has produced some shifts in the correlation lines. Other factors can produce changes in these correlations such as crystallinity at low temperature, stress-relaxation at elevated temperatures and orientation introduced in preparation of samples.

DISCUSSION

Relations between impact properties and other physical properties of thermoplastics have been reported.[10] However, these results appear to be the first experimental data which show that the thermal dependence of the physical strength properties of importance in the impact yielding of thermoplastics is essentially the same as the thermal dependence of the physical strength factors that influence the flexural yielding in conventional slow speed mechanical tests. A corollary conclusion is that for the materials tested at the speed of loading in the standard Izod impact test no new factors are introduced in the yielding of thermoplastics. Examination of the trends shown in this work indicates that the rise of breaking energy with rising temperature can be attributed mainly to the increase in energy required for plastic tearing of the thermoplastic after yielding. Although the peak force decreases for all materials as the temperature rises, the effect of this change on the breaking energy is compensated by the additional energy required for the plastic region of the impact failure. The net change of this variation in the elastic and plastic phases of the impact failure is the primary contribution to the change in breaking energy as a function of temperatures.

The peak load at which the impacted sample begins to yield can be considered as a measure of the yield stress. For catastrophic or brittle type of breaks, the breaking energy may be considered as the product of a yield stress and a yield elongation when other variables such as sample dimensions and test machine methods are held constant. Since the yield stress for impact as indicated by the peak load decreases with increasing temperature and the breaking strength shows the opposite trend of increasing with decreasing temperature, the only tenable conclusion is that the yield elongation must increase at a greater rate with a rise in temperature in order to offset the lowering of the yield load. This conclusion is in accord with the increase of plastic energy of impacted samples as the temperature rises. The increase of plastic tearing is essentially an increase of elongation properties. The converse effect of a reduction in breaking strength with a drop in temperature appears to be primarily associated with a reduction in elongation properties. The well-known modulus increase of high polymers as the temperature decreases through and below the glass transition temperature of polymeric materials is one of the fundamental factors producing the higher impact yielding load as the temperature decreases. For improvement in low temperature impact properties, the results indicate that factors which will increase low temperature elongation of thermoplastics are of primary importance.

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Résumé

La standardisation des résultats du test d'impact d'entaille Izod à des valeurs normalisées en livres par pouce d'entaille est basée sur l'hypothèse d'une augmentation 1:1 dans la force de rupture avec l'augmentation de la largeur d'entaille. Cette relation n'est pas confirmée par les tests expérimentaux effectués sur les thermoplastiques commerciaux. Lorsqu'on augmente la largeur d'entaille de $^1/_8$ à $^1/_4$, $^3/_8$, $^1/_2$ in, neuf dizièmes des thermoplastiques étudiées présentent une diminution de la force d'impact normalisée. Chaque matériel semble montrer une perte caractéristique dans les forces de rupture lorsque la largeur d'entaille augmente. Une technique développée pour le calibrage des appareils de test à impact pendulaire a été employée pour examiner la variation de la force de l'impact de rupture en relation avec l'énergie cinétique totale du percuteur. Les tests expérimentaux ne montrent pratiquement aucun changement dans les forces d'impact jusqu'à des valeurs qui prennent $^2/_3$ de l'énergie disponible du percuteur. Le travail expérimental relatif à la comparaison de l'impulsion transmise par le percuteur pendant la rupture avec les courbes de l'impulsion photographiée par le test d'Impact Autographique montre un très bon accord pour les ruptures catastrophiques et un bon accord pour les ruptures du type plastique. La diminution dans l'impulsion enrégistrée est attribuée à la dégradation de l'échantillon pendant la partie plastique du cycle de rupture.

Zusammenfassung

Die Standardisierung von Izod-Kerbschlagtestdaten auf Normalwerte von Pfund-Fuss/Zoll Kerbe beruht auf der Annahme einer 1:1-Zunahme der Bruchfestigkeit mit wachsender Kerbbreite. Diese angenommene Beziehung wird durch Versuchstests an handelsüblichen Thermoplasten nicht gerechtfertigt. Bei Zunahme der Kerbbreite von $^1/_8''$ bis $^1/_4''$ auf $^3/_8''$ bis $^1/_2''$ zeigten 9 von 10 untersuchten Thermoplasten eine Abnahme der normalisierten Stossfestigkeit. Jedes Material scheint einen charakteristischen Verlust an Bruchfestigkeit mit zunehmender Kerbbreite zu zeigen. Ein zur Kalibrierung von Pendel-Stosstestern entwickeltes Verfahren wurde zur Überprüfung der Abhängigkeit der Stossbruchfestigkeit von der gesamten kinetischen Energie des Hammers benützt. Versuchstests zeigen bis zu Werten von $^2/_3$ der verfügbaren Hammerenergie praktisch keine Änderung der Stossfestigkeit. Versuche über die Impulsübertragung durch den Hammer während des Bruches im Vergleich zu Impulskurven, die mit dem Autograph-Stosstest aufgenommen wurden, zeigen gute Übereinstimmung bei Bruchkatastrophen und brauchbare Übereinstimmung bei Brüchen von plastischem Typus. Die Abnahme des aufgezeichneten Impulses wird auf einen Abbau während des plastischen Teils des Bruchzyklus zurückgeführt.