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Instrumented Pendulum Impact Testing of Plastics

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Abstract: Conventional impact tests (without instrumentation) are performed to measure the energy required to break a notched specimen under dynamic loading. Instrumented impact tests not only measure the notched specimen breaking energy but also quantify the energy required to form a crack at the root of the notch and the energy required to propagate the crack through the material. Instrumented test systems use strikers which have strain gages so that the load-deflection curve during the impact event can be derived. These data provide load, deflection, and energy data which can be correlated with engineering parameters such as fracture toughness, ductility, and fracture resistance.

This paper compares instrumented impact results obtained using both the Charpy and Izod test procedures. Several possible limitations of the instrumented test procedure have been identified and test procedures to overcome these limitations have been proposed. In addition, an important potential limitation of the Izod test, specimen clamping pressure, has been studied.

Keywords: instrumented impact test, Charpy test, Izod test, fracture resistance, striker, strain gages, dynamic testing

Introduction

The most common laboratory impact test configurations are the pendulum

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machine and the drop tower. However, other test geometries and loading configurations have been used in the past. Pendulum tests are most commonly performed using either the Charpy or Izod test configuration. The focus of this paper is on the use of an instrumented striker system with pendulum impact machines for characterizing the dynamic response of a variety of plastics.

The instrumented impact test involves the attachment of strain gages to the striker so that the force applied during impact can be measured. The advantage of instrumented testing is that load-time data, in addition to absorbed energy, can be measured during the test. For plastics, additional data include the peak load, brittle fracture load, crack arrest load, and their corresponding energies. These parameters give insight into the fracture mechanisms and the temperature dependence of the fracture process. Provided accurate loads are measured, fracture toughness estimates can be calculated for many materials using the instrumented data. This paper reports results of instrumented impact tests on plastics which cover a wide range of ductilities and provides examples related to the interpretation of instrumented data as well as on the limitations of the test approach.

The majority of instrumented tests performed in the past have used signal filtering, and occasionally interfacial damping material, to smooth the dynamic response of the specimen to impact loading. Modern strain gages, amplifiers, and data acquisition boards do not require signal smoothing techniques. In fact, filtering is not desirable for most applications because it results in attenuation of the load signal and in skewing of the load-time curve which results in inaccurate absorbed energy measurement. Instrumented testing without filtering is shown to be superior for accurate load and energy measurement in instrumented tests.

The paper also focuses on the comparison of the Charpy and Izod test geometries. The Izod test has a potential disadvantage in that the test piece is clamped which can result in a stress field in the vicinity of the notch prior to impact. On the other hand, the Charpy test consists of a simply supported beam which is not stressed prior to impact. Test data are presented which compare impact results obtained as a function of clamping pressure for both hard, brittle plastics and for ductile materials.

Materials

The plastic materials chosen for this study cover a wide range of properties and applications. Commercially available bisphenol-A polycarbonate (PC), Tuffak®, and poly(methyl methacrylate) (PMMA), Plexiglas G®, samples, neither of them modified with toughening agents, were used. A poly(vinyl chloride) (PVC) grade was chosen so it would meet the requirements for a standard testing formulation for so-called vinyl siding. Three types of samples, each containing a different proprietary additive were prepared from the starting PVC to produce specimens with various degrees of impact resistance. The additive in each case was loaded at the level of 5 parts per hundred parts of resin. Other suitable formulation ingredients, such as processing aids, lubricants and stabilizers were added. Poly(butylene terephthalate) (PBT), a polymer that is seeing increased use in automotive applications, was used in neat and modified version. The latter, referred to *as Mod-PBT in this work, contains 20 weight % of a proprietary core/shell additive.*

Specimen Preparation

Except for the two commercial-grade polymers, the other formulations were first melt-blended and shaped into specimens with adequate dimensions. The PVC formulations were milled on a two-roll mill at 170°C and pressed into 3.18 mm-thick plaques. The PBT materials were first extruded and pelletized in a twin-screw extruder using a 240°C melt temperature. These materials were further injection molded into plaques of 3.18 mm thickness and 5 cm by 7.6 cm dimensions.

Notched Izod specimens were cut and notched from the above materials using a diamond-head cutter, following the ASTM D 256 standard (0.254 mm radius, 2.0 mm notch depth). The specimens for Charpy instrumented testing were also diamond cut from the same materials, using the same type of notch. Every sample was run at an ambient temperature of 23°C with no pre-conditioning, except for letting the samples equilibrate with the humidity of the room (50% relative humidity) for at least one day prior to testing.

Test Procedure

Charpy Test

Measurements were made using a state-of-the art instrumented striker system which was installed on a Tinius Olsen Model 92 T plastics impact tester. The instrument was configured for testing in accordance with ISO 179. The test machine was equipped with an optical encoder and digital readout for independent measurement of the total absorbed energy. As shown in Figure 1, the pendulum is a bifurcated (compound) design

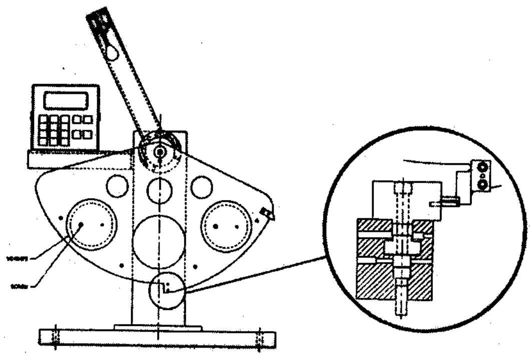


Figure 1 *Bifurcated Pendulum Geometry Used for Charpy Impact Tests*

which reduces windage and frictional losses. The test machine was leveled and securely bolted to a massive laboratory bench to prevent errors in total energy measurement. The drop height was set at 61 cm so that a 3.5 m/s impact velocity could be achieved.

The striker was fabricated in accordance with ISO 179 and contains strain gages located near the point of impact. The instrumented system is a Tinius Olsen system v2.1 which is capable of measuring any number of data points up to 19,000 per test. The time scale can be set at any range from 20 microseconds to 20 seconds, however, most impact tests have a duration ranging from about 0.5 milliseconds to 20 milliseconds. Experience in metals testing [1] has shown that at least 500 data points per millisecond are needed to accurately characterize the dynamic portions of the load-time curve. It is recommend that instrumented impact tests be conducted using 500 to 1000 data points per millisecond. The tests reported here were run with 10,000 data points acquired over 15 milliseconds.

Izod Test

Izod tests were performed in accordance with ASTM D256. The Izod tests were performed on a Tinius Olsen Model 66 equipped with an Instron Dynatup instrumented Izod striker. The test machine design is a conventional U-type hammer. The instrumented system used with the Izod tests is an older system with limited capability. First, the system has a 2048 data point limitation. Second, the system can only be set to acquire over discrete time intervals (ex., 2 milliseconds, 5 milliseconds, etc.). This approach has the disadvantage of spreading an already limited number of points over a broad time scale or forcing truncation of data. In particular, a 3 millisecond test would have to either be conducted over the 2 millisecond time range (1000 data points per millisecond) with unacceptable data loss, or it would have to be conducted over 5 milliseconds (400 data points per millisecond) with poor characterization of dynamic events. The system also uses electronic signal filtering which causes reduction of the magnitude of the measured forces and distortion of the load-time curve. The integrated energy in this system is obtained by scaling the loads so that the integrated energy matches the optical encoder energy. While this approach can produce a total absorbed energy which matches the encoder, the loads, deflections, and partitioned energies are not valid because of the effects of filtering. It is important to note that the Model 66 test machine could have been instrumented with the advanced instrumented striker system such as the one used with the Charpy test machine, however, since there are many Izod test machines with limited capability as described here the limited test machine was used to quantify the limits of such a system and to compare with the more advanced system.

Results and Discussion

Figures 2 through 4 show typical results from the instrumented Charpy tests. Figure 2 is a plot of the raw voltage-time data. Figure 3 shows the steps involved in the integration of the instrumented data to determine the total absorbed energy. First, the voltage-time signal is converted to a force-time curve using the static calibration data. Next, the force-time curve is integrated to yield the velocity-time curve. Then the velocity-time curve is integrated to give the striker displacement-time curve. Finally, the force-displacement curve is integrated to give the total absorbed energy. Figure 4 shows the final step in the data analysis. The characteristic load points are determined by fitting portions of the load-displacement curve. For ductile plastics, the important parameter is the peak load which is determined by fitting the data near the peak to give the average of the peak data. In many materials, the formation of the crack at the root of the notch along the notch front occurs just prior to or at peak load. Therefore, it is a reasonable approximation to define the energy to peak load as the "crack formation energy". Similarly, the post-peak load energy can be defined as the "crack propagation resistance" energy. These data are shown in the table given in Figure 4.

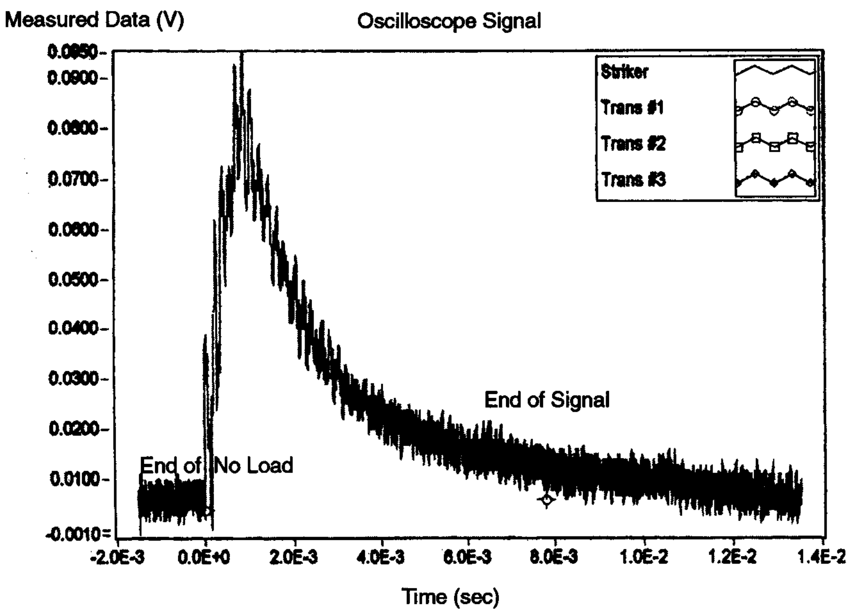


Figure 2 *Instrumented Charpy V-Notch Voltage-Time Curve for Toughened PVC*

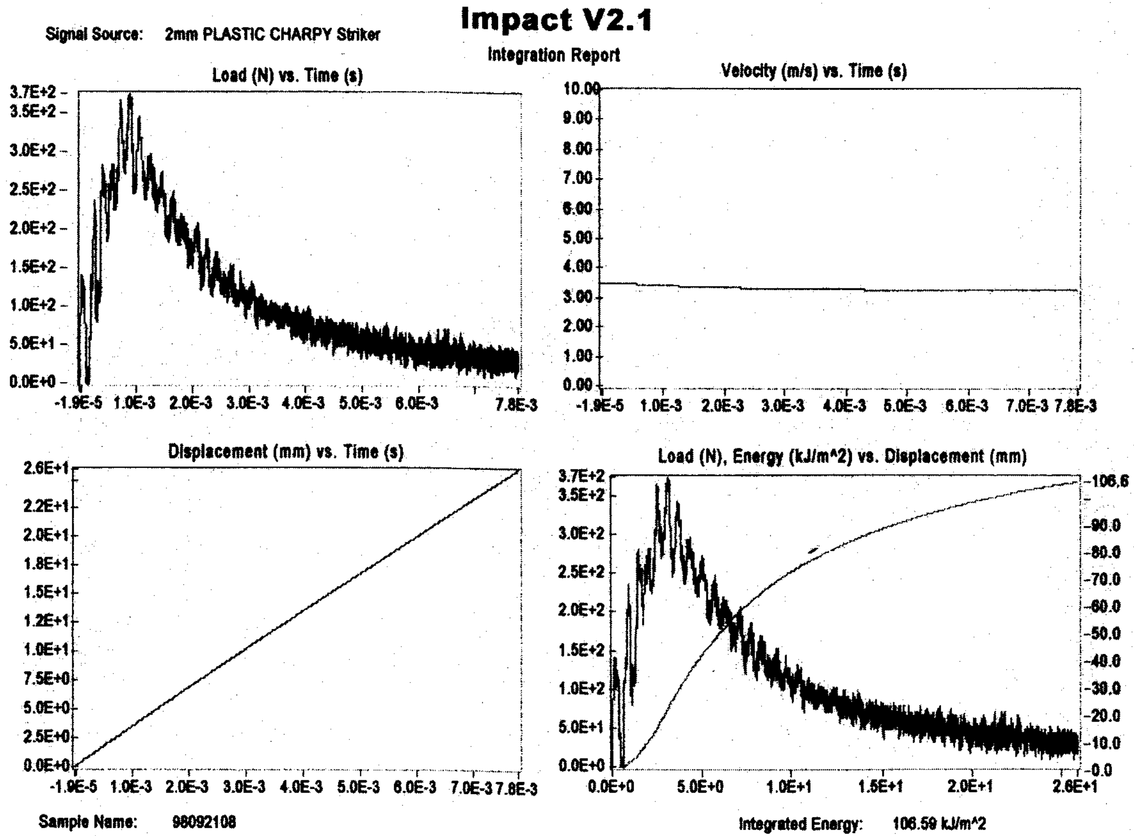
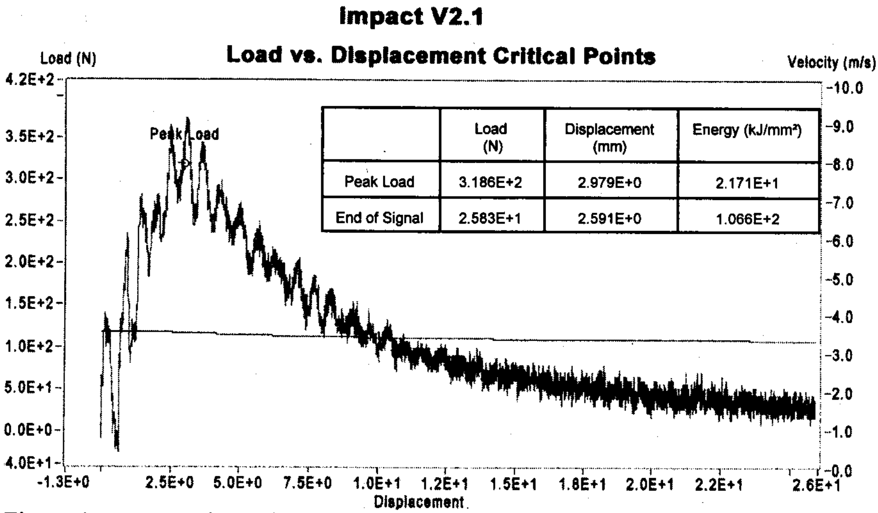


Figure 3 *Integration Steps to Obtain Total Absorbed Energy a) upper left - force-time curve from striker calibration b) upper right - velocity-time curve obtained by integration of force-time curve c) lower left - striker displacement-time curve from integration of velocity-time curve d) lower right - force-displacement curve and integration to yield total absorbed energy*



	Load (N)	Displacement (mm)	Energy (kJ/mm²)
Peak Load	3.186E+2	2.979E+0	2.171E+1
End of Signal	2.583E+1	2.591E+0	1.066E+2

Figure 4 *Load-Displacement Critical Points for Toughened PVC. The Integrated Energy is Partitioned into Pre-Maximum Load Energy and Post-Maximum Load Energy*

Figure 5 shows the voltage-time curve with the data points indicated. This plot is used to check the settings on the time interval and number of acquired points. Also note that the time scale has been set long enough to ensure that the signal is not truncated until the fracture process is completed. Plastic tests often involve low load levels. As shown

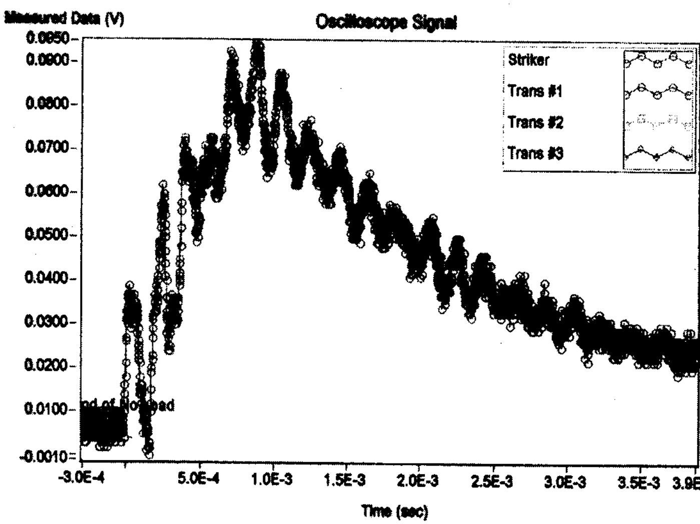


Figure 5 *Amplified View of Voltage-Time Curve Showing Individual Data Points for Test Performed on Toughened PVC*

in Figures 2 and 5, the baseline signal has ~ 15 mV of electronic noise. However, this noise is not significant, even in low applied force tests such as with plastics, because there are sufficient data acquired to fully characterize each peak and to thus obtain a robust average baseline signal. Figure 5 also shows the dynamic load oscillations which occur during load rise. There are more than enough data points to fully characterize these oscillations. Figure 6 shows a typical Dynatup load-deflection curve. It is important to note that the setup used for the instrumented notched Izod tests filters the electronic signal. The instrument also cuts off the tail of the signal and the final portion of the fracture process cannot always be properly accounted for, particularly in ductile samples. Even though it appears to contain a higher degree of noise, the instrumented Charpy signal registers substantially more data points (up to 19,000 points can be acquired) to obtain the true average signal and follows the energy absorption path from beginning to end, without any cut-offs.

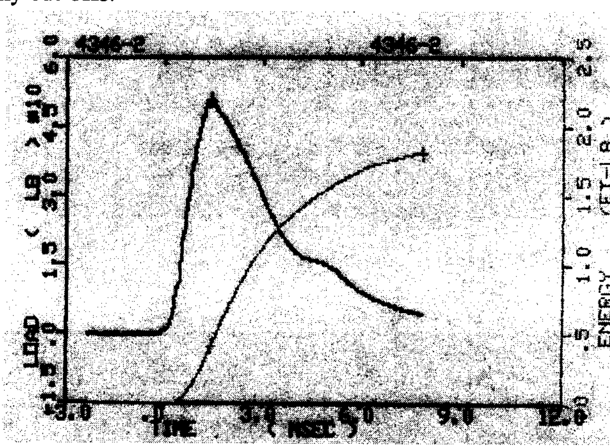


Figure 6 *Typical Dynatup Filtered Izod Load-Time Curve. As a Result of Limited Data Points the Curve is Cut Off Prior to Completion of the Test*

Table 1 provides a summary of the results obtained with the instrumented Charpy tester along with notched Izod test results. In one case (PBT and modified PBT), data were also obtained on an instrumented Izod-type setup. The mean, standard deviation and number of samples used to make the measurements are reported in the table. A signal to noise ratio (S/N), calculated as the mean divided by the standard deviation, is also reported for each material. Figure 7 compares the S/N ratios graphically. The instrumented Charpy has an S/N ratio which is about constant at all energy levels. The Dynatup system has a poor S/N for the low energy tests and a better S/N for high energy measurements. This is believed to be a result of load-time distortion due to filtering and to limited data points which has a more significant effect on low energy measurements. Overall, the Charpy and Izod tests show comparable S/N ratios for intermediate and high energy tests.

Figure 8 shows that the energy measured according to the instrumented Charpy test has a high degree of correlation with the fracture energy as measured by the 3.17 mm notched Izod, which validates the use of the more informative instrumented Charpy test.

Table 1 *Comparison of Charpy and Izod Data*

Sample ID	Material	Instrumented Charpy V-Notch				Notched Izod (3.17 mm)				Instrumented Izod (3.17 mm)			
		Mean (S) (kJ/m²)	Std. Dev. (N) (kJ/m²)	# Tests	S/N Ratio	Mean (S) (J/cm)	Std. Dev. (N) (J/cm)	# Tests	S/N Ratio	Mean (S) (J/cm)	Std. Dev. (N) (J/cm)	# Tests	S/N Ratio
Plexiglas G	PMMA	1.31	0.039	10	33.8	0.19	0.032	5	12.0	-	-	-	--
Tuffak	PC	84.38	3.01	10	28.0	9.75	0.21	5	46.3	-	-	-	--
1937-C1	Toughened PVC	106.28	5.83	5	18.2	12.07	0.23	5	53.3	-	-	-	--
1937-C2	Toughened PVC	16.51	1.87	5	8.8	1.34	0.07	5	19.2	-	-	-	--
1937-B5	Toughened PVC	1.48	0.05	5	27.8	0.15	0.02	5	7.0	-	-	-	--
PBT	PBT	4.55	0.22	9	21.0	0.51	0.04	5	11.9	0.14	0.01	10	10.0
Modified PBT	Toughened PBT	82.12	2.46	10	33.4	8.52	0.65	5	13.1	2.54	0.04	10	62.0

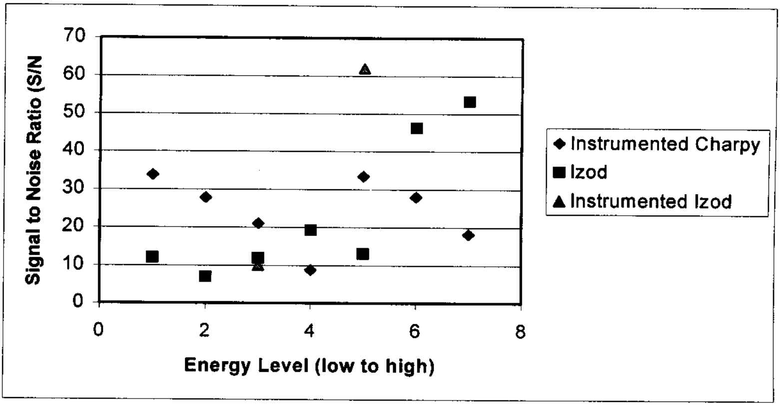


Figure 7 *Comparison of Signal to Noise Ratio for Charpy and Izod Tests*

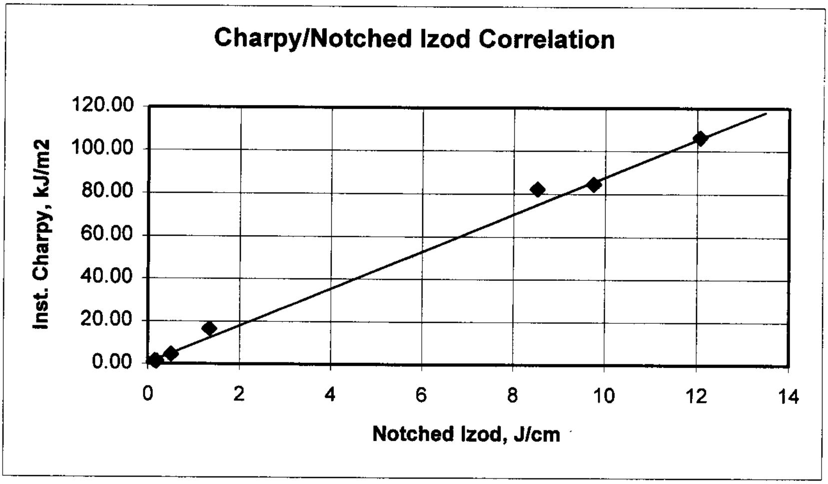


Figure 8 *Correlation Between 3.17 mm Notched Izod and Instrumented Charpy Data*

The amount of detail and number of data points gathered provide far more information than the single energy value from the Izod. Table 2 illustrates additional information which can be obtained. For materials which initiate a crack near peak load, the "Energy to Peak Load" represents the material resistance to crack formation. The "Post-Peak Load Energy" represents the material resistance to crack extension for ductile materials. For example, Tuffak and modified PBT both have about the same total energy, but Tuffak has a higher crack formation energy and higher peak load. The 1937-C1, with a significantly higher total energy, has a lower crack formation energy than Tuffak. Thus, total energy alone is not a good parameter for assessing the suitability of a particular material for a given application.

Table 2 *Summary of Instrumented Charpy Test Parameters*

MATERIAL	TOTAL ENERGY (kJ/m^2)	PEAK LOAD (N)	ENERGY TO PEAK LOAD (kJ/m^2)	POST-PEAK LOAD ENERGY (kJ/m^2)	TOTAL STRIKER DISPLACEMENT (mm)
Plexiglass G	1.31	109.89	0.44	0.88	0.42
Tuffak	79.46	291.92	34.95	44.52	13.13
1937-C1	106.28	326.52	24.46	81.82	26.53
1937-C2	16.51	305.12	15.80	0.71	2.70
1937-B5	1.48	117.96	0.58	0.90	0.51
PBT	4.55	191.8	1.66	2.89	1.19
Mod PBT	82.12	220.20	24.47	57.64	20.97

Izod Clamping Pressure

Another test limitation examined was the role of the clamping pressure on the outcome of the notched Izod test. Table 3 shows the results obtained when Izod specimens were clamped using a pneumatic system. The clamping pressures on the table indicate the air pressure used to clamp in the samples. The data in the table shows that clamping pressure can have an effect (perhaps ~ 5%) on ductile materials. The effect on brittle (hard) materials such as Plexiglas G is not statistically significant. The clamping pressure effect is believed to be caused by deformation in the vicinity of the notch prior to impact.

Table 3 *Effect of Clamping Pressure on Izod Test Specimens*

Clamping Pressure (psig)	Tuffak		Plexiglas G	
	Mean (J/cm)	Std. Dev. (J/cm)	Mean (J/cm)	Std. Dev. (J/cm)
18	9.75	0.21	0.19	0.02
36	9.25	0.27	0.21	0.01
54	9.43	0.13	0.20	0.01

Summary and Conclusions

It has been demonstrated that the Charpy and Izod fracture energies correlate well. There does not appear to be any practical limit to the energy level which can be measured using instrumented strikers because the strain gages can be calibrated over a wide energy range. However, it has been observed that instrumented tests should be performed without filtering because electronic filtering causes attenuation of the measured loads and time distortion of the signal. The net effect is that the load-time response cannot be accurately measured when filtering is done. Filtering in not advised because it leads to inaccurate test results which negates the many benefits of instrumented testing.

Instrumented test systems should provide continuous control over the time range for data acquisition and the total number of data points acquired over that range. Older instrumented test systems which are limited to 2000 data points are considered to not fulfill the needs of accurate instrumented testing. A minimum of 500 test points per millisecond is recommended for accurate results. Also, the instrumented data acquisition must be run long enough to ensure that the load-time signal is not truncated prior to complete unloading. This is a problem which can occur in older test systems which do not provide continuous control over the acquisition time range and number of data points.

Finally, the Izod test has been shown to be affected by clamping pressure, and this effect will be larger for more ductile materials. Additional work should be conducted in the future to address this through revision to existing standards. The reader is referred to ASTM D256 for further guidance on clamping pressure. Our overall conclusion is that the Charpy test is a superior test geometry for plastics and should replace the Izod test.

Reference

[1] Proposed ASTM Standard Method for Instrumented Impact Tests of Metallic Materials, Draft 7, December, 1998, Prepared by ASTM Sub-Committee E28.07.08 on Miniaturized Charpy/Instrumented Testing