Instrumented Izod Impact Testing

S. E. SLAVIN* and G. T. BESWICK

Research Division, Rohm and Haas Co., Bristol Research Park, Bristol, Pennsylvania 19007

SYNOPSIS

The notched Izod impact test is the most prevalent technique used to characterize the effects of high-impulse loads on polymeric materials. In order to extract ancillary information concerning fracture properties in addition to the total fracture energy, an instrumented version of this test is examined. Oscillations in the load signal, which severely degraded the utility of the data for materials fracturing in a brittle manner, are determined to be the result of specimen vibration caused by the impact of the hammer. Placement of a felt cushion on the face of the hammer is shown to eliminate these oscillations and the effects of the felt on the load-time information are shown to be minimal. Finally, peak load data extracted from instrumented Izod tests employing felt padding, is used to determine the stress-intensity factor for several plastics of commercial interest. © 1993 John Wiley & Sons, Inc.

INTRODUCTION

As the trend toward the use of engineering plastics in structural applications accelerates, a heightened interest in the impact properties of these materials has developed. The Izod and Charpy impact tests are among the methods most commonly employed to evaluate impact performance because of their simplicity, speed, and cost effectiveness. The tradeoff for these positive attributes is that the standard test characterizes only the total fracture energy. Although this parameter is comprised of both crack initiation and propagation components, the relative magnitudes of these constituents is not discernible via these techniques. Additionally, load bearing capabilities, relative stiffness, and basic fracture properties such as the stress-intensity factor cannot be determined.

A relatively simple technique that potentially addresses these shortcomings without compromising the positive characteristics of these tests involves the addition of a load transducer to the tester's hammer. The resulting load versus time curve contains within it a wealth of information about the basic fracture properties of the specimen. The major drawback is the existence of oscillations in the load signal that in the past have restricted this methodology to the examination of ductile materials. With brittle materials in general, the magnitude and frequency of these fluctuations are such that they dominate the results at standard strain rates, thus effectively depriving them of any real value. In this paper, we report the results of experiments to isolate the source of these oscillations and demonstrate a simple technique that effectively eliminates them. Additionally, the stress-intensity factors of several plastics are determined from the peak-fracture loads of razor-notched Izod specimens in plane strain.

The concept of instrumented impact testing is not a new one.[1-10] Many prior attempts tended to involve either servo-hydraulic or gravity-driven darts containing a load transducer. Typically, the specimens are supported by annular clamps. This test geometry generates a biaxial stress field in the material. As the strain rates associated with this geometry are not excessive, load fluctuations tend not to be a major problem. Extremely high strain-rate tests such as the notched Charpy have been instrumented with some success in attempts to examine the stress-intensity factor of various materials.[6] The ease of obtaining plane-strain conditions makes this geometry attractive for the determination of this crack-propagation parameter.

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* To whom correspondence should be addressed.

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EXPERIMENTAL

Our main interest is in the instrumentation of the Izod impact test because it is in the greatest demand in our laboratory. The cantilever geometry generates stress fields similar to those induced in the flexural-impact test. Toward this aim, a hammer modified by the inclusion of a force transducer was adapted to a Tinius Olsen Model 66 pendulum impact tester. The load versus time information is acquired via an 830-i data acquisition system manufactured by Dynatup Inc. The associated software integrates the load-time data to generate the velocity and displacement as functions of time, thus enabling energies to be calculated.

Initial experimentation with the system quickly confirmed that oscillations were present in the load signal. With tough ductile materials such as Tuffak® (polycarbonate) sheet (Fig. 1), the frequency of the load fluctuations is an order of magnitude higher than the characteristic frequency of the failure event. Although their magnitude is large at the outset, the oscillations are generally almost fully damped by the time the peak load is reached. Under these circumstances, mathematical smoothing yields reasonable results (Fig. 2) with little degradation in the value of the data.[11] With brittle materials such as Plexiglas® poly(methyl methacrylate) sheet (Fig. 3), the oscillatory behavior clearly dominates the results, rendering them nearly useless. Given that plane-strain conditions result in brittle behavior, elimination of these load oscillations is essential if this test is to be used for the determination of stress-intensity factors.

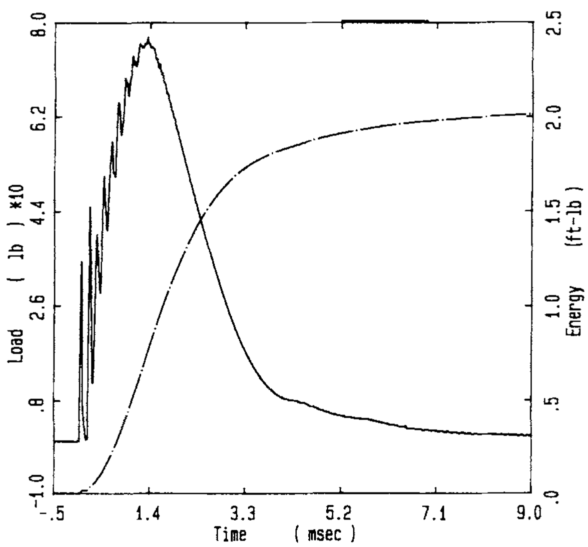

Figure 1 The load vs. time and energy vs. time curves of $\frac{1}{8}''$ Tuffak® polycarbonate obtained from an instrumented pendulum impact tester. The solid curve represents the load and the broken curve, the total energy.

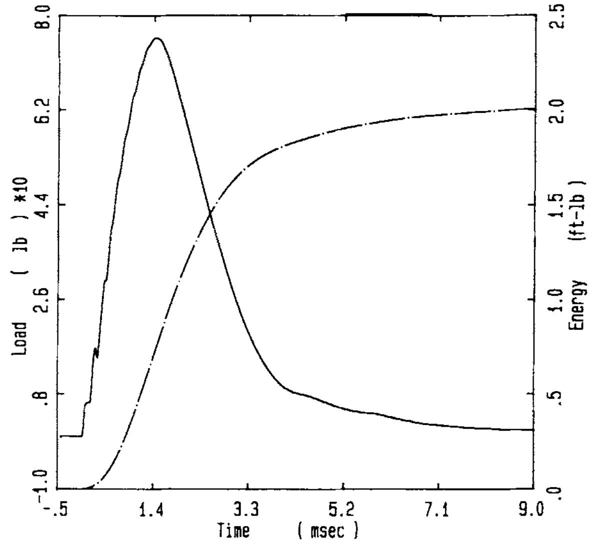

Figure 2 A mathematically smoothed version of the load vs. time curve for the $\frac{1}{8}''$ Tuffak® polycarbonate specimen shown in Figure 1. A 50 point running average was employed.

In order to isolate the source of the oscillations,[11] instrumented Izod impact tests were performed on several materials using both dart and pendulum impact testers. Two different specimen geometries were employed, the standard nominal $\frac{1}{8}''$ Izod bar[12] and a version modified by the removal of 0.3125″ of ma-

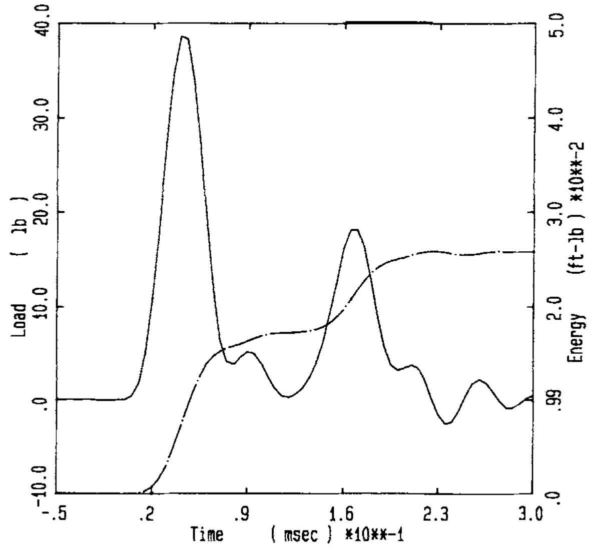

Figure 3 The load vs. time and energy vs. time curves of $\frac{1}{8}''$ Plexiglas® poly(methyl methacrylate).

terial from the test end. The resulting load versus time curves were analyzed to determine the oscillation frequency of the load signal. Table I contains a summary of the results, each of which were compiled from a minimum of five samples. For Tuffak® sheet and Aluminum (2024) specimens, five cycles were used to determine the oscillation frequency. In the case of the Plexiglas® sheet, the peak separation was employed, because only two complete cycles are present. Additionally, the natural resonance frequencies of the two testing machines were determined from the load curves generated via manually tapping each tup. As can be seen by comparison of the last two entries in Table I, the resonance frequencies of the two instruments are quite different.

DISCUSSION

Examination of Table I reveals the following: (a) For a given material, the load oscillation frequency changes with the specimen geometry. Appropriately, smaller samples oscillate at higher frequencies. (b) Comparing materials, the frequency varies with the mechanical properties in the expected manner, that is, increasing for higher modulus materials. (c) Finally, despite the differences in the instrumental resonance frequencies, there is no apparent correlation between the load-oscillation frequency and the test instrument employed. Given these facts, it seems reasonable to conclude that the load fluctuations represent mechanical vibration of the specimen, caused by the impact of the hammer.

Two potential techniques for eliminating these oscillations were examined. As suggested in the literature,[6] the magnitude of the vibrations can be minimized via reduction of the impact velocity of the hammer. Although this concept has some utility, complete damping is not achieved. Additionally, by altering the strain rate, we are no longer performing the Izod impact test as defined by the ASTM.[12]

A second approach involves the use of padding attached to the face of the hammer itself to cushion the initial blow that precipitates the oscillations. The padding was not attached to the specimen in order to avoid alteration of the toss factor, which represents the kinetic energy imparted to the broken portion of the sample subsequent to fracture.[12] Through a trial and error approach, the material of choice was determined to be $\frac{1}{8}''$ felt pipe insulation. This material proved capable of eliminating nearly all of the load oscillations for the most brittle plastics examined. Although there is obviously some energy lost to deformation of the felt, examination of its compressional properties (Fig. 4) suggest this loss is minimal, as demonstrated by the small area under the load-displacement curve. This energy loss should also be systematic in nature, and could, in principle, be taken into account.

Figure 5 shows the load-time curve resulting from the use of a felt cushion with an $\frac{1}{8}''$ Plexiglas® sheet specimen. Because this material is representative of a typical brittle amorphous polymer, we see that useful information can be obtained via this methodology, under conditions where little was available previously. The initial curvature at short times, presumably related to the initial loading and deformation of the felt, quickly gives way to the expected linear stress–strain behavior. If desired, a relative stiffness or pseudo modulus can be determined from the slope of the linear region. Accurate maximum loads, untainted by inertial effects[11] and vibrations can also be determined. Figure 6 displays the results for a sample of Tuffak® sheet. As expected, monotonic vibration-free ductile behavior is observed subsequent to the initial linear-elastic loading.

Table II contains a summary of instrumented Izod impact results for both $\frac{1}{8}''$ Tuffak® and Plexiglas®

Table I Specimen and Instrument Oscillation Frequencies

Material	Machine Type	Specimen Type	Oscillation Frequency (Hz)	Standard Deviation
Tuffak®	Pendulum	Standard	6,536	75
Tuffak®	Pendulum	Short	9,852	97
Tuffak®	Dart	Short	9,950	99
Plexiglas®	Pendulum	Standard	8,475	287
Plexiglas®	Pendulum	Short	13,158	866
Plexiglas®	Dart	Short	12,820	657
Aluminum	Pendulum	Standard	20,513	526
None	Pendulum	Resonance frequency	4,098	59
None	Dart	Resonance frequency	11,364	226

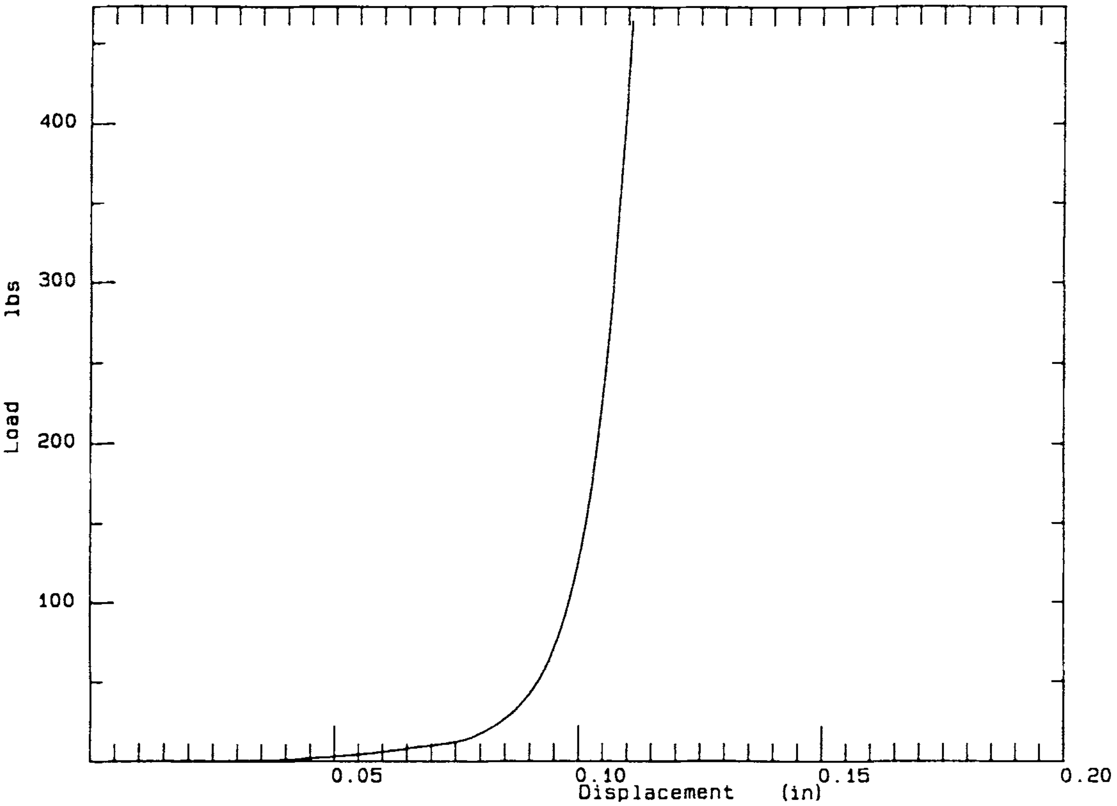

Figure 4 The compressional load vs. displacement curve for a 1 in.^{2} sample of $\frac{1}{8}''$ thick felt.

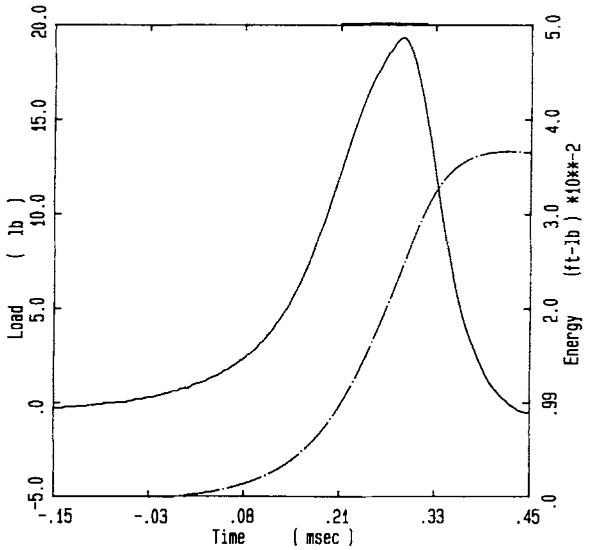

Figure 5 The load vs. time and energy vs. time curves of $\frac{1}{8}''$ Plexiglas® poly(methyl methacrylate) obtained using a felt cushion on the hammer of an instrumented pendulum impact tester.

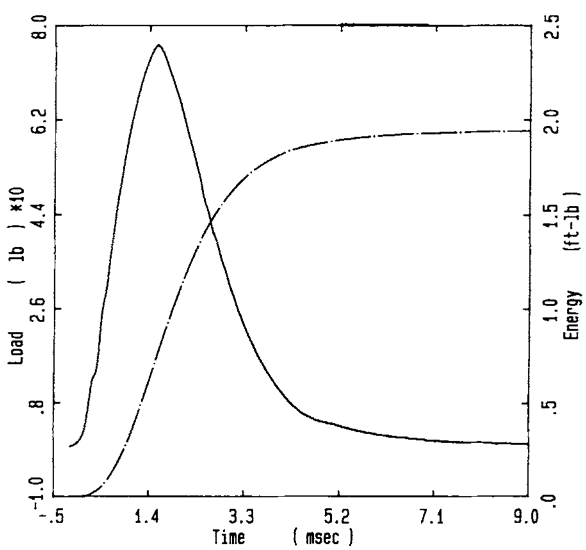

Figure 6 The load vs. time and energy vs. time curves of $\frac{1}{8}''$ Tuffak® polycarbonate obtained using a felt cushion on the hammer of an instrumented pendulum impact tester.

Table II Instrumented Izod Impact Test Parameters

Material	Time to Max. Load (ms)	Total Time (ms)	Max. Load (lbs)	Energy to Max. Load (ft-lbs)	Total Energy (ft-lbs)
Tuffak® (N)	1.27 ± 0.08	9.24 ± 0.31	76.15 ± 1.62	0.68 ± 0.07	1.97 ± 0.05
Tuffak® (F)	1.51 ± 0.04	9.07 ± 0.11	74.94 ± 0.86	0.70 ± 0.04	1.88 ± 0.05
Plexiglas® (N)	0.044 ± 0.005	0.20 ± 0.05	39.52 ± 1.82	0.01 ± 0.0	0.026 ± 0.005
Plexiglas® (F)	0.33 ± 0.03	0.47 ± 0.03	18.80 ± 1.31	0.028 ± 0.004	0.04 ± 0.0

Mean ± SD. (F), Felt on hammer; (N), unpadded hammer.

sheet with and without the presence of the felt cushion. Groups of five samples were analyzed in each case. The effects of the felt are best estimated by examination of the Tuffak® sheet data, as that from the Plexiglas® sheet without the cushion are of questionable value. Inertial effects result in severe specimen bounce that generates artificially high loads and short event times. In the case of the Tuffak® sheet, the only statistically significant difference caused by the presence of the felt is in an increase in the time to achieve the maximum load. Because this increase presumably represents the time to deform the felt and occurs at low loads, the effects of this phenomena on the energy values are minimal.

Having circumvented the load-oscillation problem, the final phase of experimentation involved attempting to determine the stress intensity factor ($K1$) for several polymeric materials of commercial interest from instrumented Izod data. Materials chosen include Tuffak®, DR® [rubber modified poly(methyl methacrylate)], and Plexiglas® sheet, because they cover the range from ductile to brittle performance in the standard notched Izod impact test. Samples consisted of standard $\frac{1}{8}''$ and $\frac{1}{4}''$ Izod specimens that were razor notched at the base of the normal 10-mill notch. Maximum load values obtained from felt cushioned instrumented impact tests, were converted to $K1$ values via the following relationship appropriate for the notched cantilever geometry:[13]

$$K1 = \frac{6M\{.38 + 1.3c/t - 1.2c^2/t^2\}}{w(\pi)^{0.5}(t-c)^{1.5}} \tag{1}$$

where: M = the bending moment = (0.866) max. load; c = the total notch depth; t = the specimen thickness; w = the specimen width. Table III contains a summary of the stress-intensity factors for two different thicknesses of several polymeric materials. Additionally, estimates of the plastic zone radius at the crack tip have been calculated via the following relationship:[14]

$$Rp \approx 0.5(K1)^2/(\sigma_y)^2 \tag{2}$$

where σ_y = the yield stress and $K1$ = the stress-intensity factor.

The validity of the stress-intensity factor measurements can be examined in several ways. Thin specimens are known to produce artificially high values for this parameter because plane-strain conditions do not exist during the test. Under these circumstances, material flow parallel to the crack

Table III Stress Intensity Factors and Plastic Zone Radii Estimates

Material	Width (in.)	Maximum Load (lbs)	$K1$ (psi-in.$^{0.5}$)	Rp (10^{-3} in.)
Tuffak®	0.117	23.46 ± 1.23	1394 ± 73	13.8
Tuffak®	0.240	49.80 ± 0.29	1443 ± 8.0	14.7
Plexiglas®	0.113	14.48 ± 0.85	891 ± 61	3.6
Plexiglas®	0.235	31.06 ± 0.84	919 ± 25	3.8
DR®	0.128	32.18 ± 0.85	1748 ± 46	33.0
DR®	0.238	58.71 ± 0.67	1715 ± 20	31.8

Mean ± SD.

tip dissipates energy. The increased maximum loads that power this process produce falsely high values for the stress-intensity factor. The strongest argument for validity in this case is the observation that the values presented in Table III are essentially independent of the specimen width. Additional support for this conclusion comes from visual inspection of the fractured samples that show no evidence of a reduction in width along the fracture surface.

The ASTM has estimated the validity of such measurements in terms of the relationship between the radius of the plastic zone at the crack tip and the specimen geometry. In what is considered to be a very conservative set of criteria, they suggest that specimen width, crack length, and the distance between the crack tip and free surface be at least 15 times larger than the plastic-zone radius. Clearly, we do not meet these criteria in all cases. However, according to Suh and Turner[15] "The fracture criterion gives reasonable results in most materials when the pertinent dimensions of the part are ten times greater than the plastic zone radius, and ratios as small as three have been found to be adequate in some instances." In this case, the extremely high strain rates associated with the Izod impact test appear to induce the necessary plane-strain conditions and associated brittle behavior at ratios as low as four.

CONCLUSION

Through careful examination of the changes in the load oscillation frequency of various materials, specimen geometries, and test instruments, we postulate that the cause of these fluctuations is mechanical vibration of the specimen itself. Furthermore, the concept of employing an essentially nonabsorbing cushion on the hammer face to eliminate these vibrations has been demonstrated to be feasible. Finally, having developed a technique to acquire accurate peak-load data under high-rate plane-strain conditions, we demonstrated the methodology necessary to acquire stress-intensity factor data from an instrumented pendulum impact tester employing the notched Izod geometry.

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