JOURNAL OF APPLIED POLYMER SCIENCE VOL. 8, PP. 101-110 (1964)

High Speed Puncture Testing of Thermoplastics

F. J. FURNO R. S. WEBB and N. P. COOK, *Marbon Chemical Division, Borg-Warner Corporation, Washington, West Virginia*

Synopsis

An extensive study has been made of a broad range of polymeric materials, by the instrumented high speed puncture method. The range of strain rates prevalent in these tests has been related to the strain rates in parts subjected to normal abuse. It has been further demonstrated that at some critical test speed each material exhibited a load maximum which is accompanied by a change in the mode of failure and loss of ductility. This "critical speed" has been shown to be characteristic of the material under test.

Introduction

It has long been recognized that the various tests for measuring impact strength of plastics are not adequate for characterizing the "toughness" of materials.[1-3] These tests are limited by virtue of inadequate and/or unrealistic range of strain-rates, unnatural failure modes, and/or insufficient stress-strain measurement capabilities. These test deficiencies have been found to result in gross differences between the actual abuse resistance of end products and that which would be predicted from standard impact data. In an effort to better relate part performance to material properties, the industry has turned more and more to simulated abuse tests such as the falling dart. As may be seen (Table I) materials having equivalent notched izod energy do not necessarily behave the same in a simulated abuse test. This information can be most useful in selecting materials for specific designs. Several plastics processors have incorporated such abuse tests as the dart drop in their quality control programs.

Although the dart drop is a step forward from the izod test, there are still limitations: narrow range of test speeds, lack of sensitivity, large material and manpower requirements, and inability to measure stress and strain. As an outgrowth of our dart drop and part performance experience, Marbon decided to characterize a wide range of thermoplastics with an instrumented puncture test which overcomes most of the disadvantages referred to above.

A study of the test speed and strain rate characteristics of several common tests shows the puncture test to be pertinent to design. Figure 1 shows graphically the relative test speeds employed in various laboratory mechanical tests. The rate of strain estimated to result from each of these

TABLE I

Material	Notched izod ft.-lb./in. of notch	Falling dart-ft. lb. to rupture	
		Tray	Box
Cycolac T	3.0–5.0	15–23	24–25
Cycolac GSM	5.0–8.0	33–34	25–30
Cycolon AM	2.0–3.0	12–13	24–30
Comp. ABS A	4.7	15–17	20–25
Comp. ABS B	4.0–6.0	8–15	17–20
Comp. ABS D	2.5–5.5	1–2	3–10
Comp. ABS E	1.3–4.0	1	1.5–4.5
HIPS A	2.8–4.1	1	1

tests is also shown. In estimating the strain rates resulting from the dart drop, the average velocity of the dart was used. Particular attention is called to the strain rate of the notched izod. It is over 200 × as great as the strain rate of most dart drop tests.

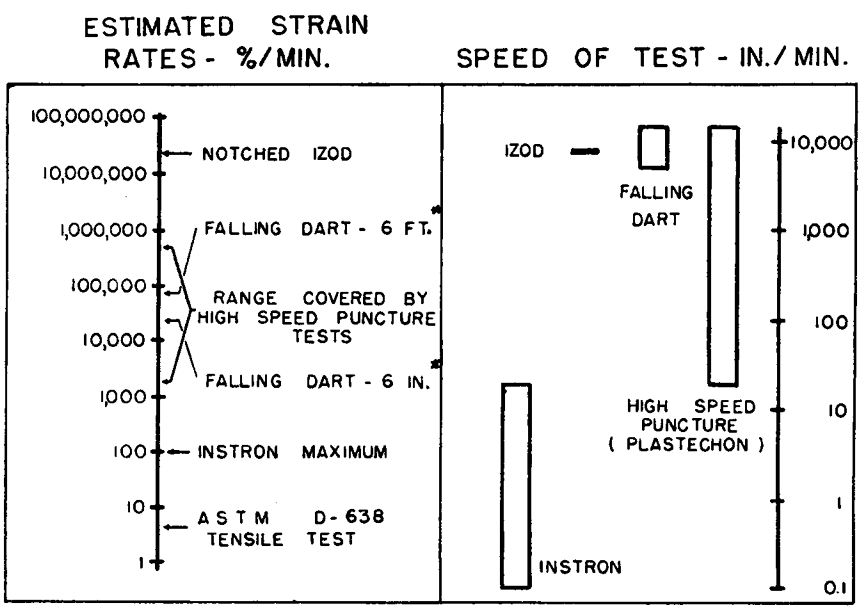

Fig. 1. Relative test speeds employed in various laboratory mechanical tests. Asterisks in graph indicate average strain rate.

Rough approximations were made of the strain rate imposed on various small, well designed ABS parts during normal abuse. The range of maximum (average rate at point of maximum) strain rate in such parts is from 10^4 to 10^6%/min. It was therefore concluded that the strain rates imposed upon the specimens during puncture over the test speed range of this series are representative of service abuse.

Experimental

Tests were conducted using a puncture tool as shown in Figure 2. The specimen is clamped between two plates with a one-inch diameter test surface exposed. The plunger, a $^1/_4$-in. steel rod with a spherical end is forced through the center of the exposed test area at the desired speed.

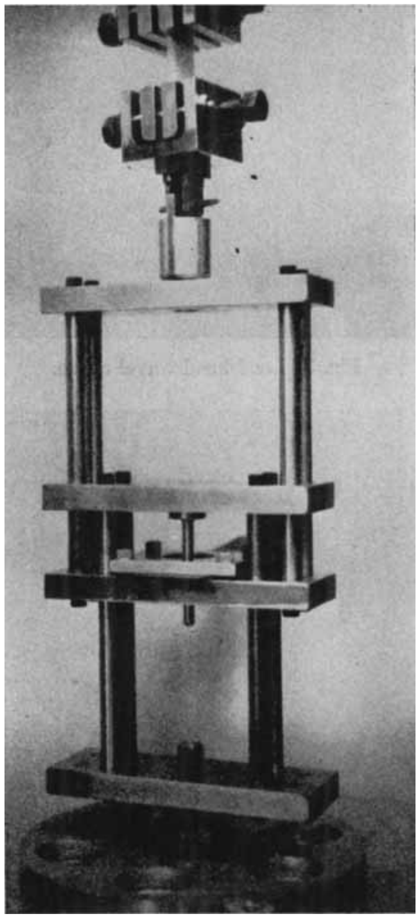

Fig. 2. Puncture tool.

Low speed tests were conducted on Model TT Instron Tensile Machine while tests at speeds above 20 in./min. were made on a Model 581 Plastechon. The load-head travel curve was obtained photographically from the Plastechon oscilloscope. See Figure 3 as an example. The exact speed of each test was calculated from a reference pulse of known frequency supplied to the oscilloscope trace. Specimen fracture was recorded with a Fastax Model WF-3 high speed camera. The maximum camera speed was approximately 7500 frames/sec. The puncture speed range employed was 1–11,000 ipm. The equipment setup is shown in Figure 4.

Specimens were prepared from compression molded slabs 0.085 ± 0.005 in. thick. The molded slabs were cut into $1^1/_2$ in. wide strips and conditioned according to ASTM D618-61 procedure A prior to testing. Materials

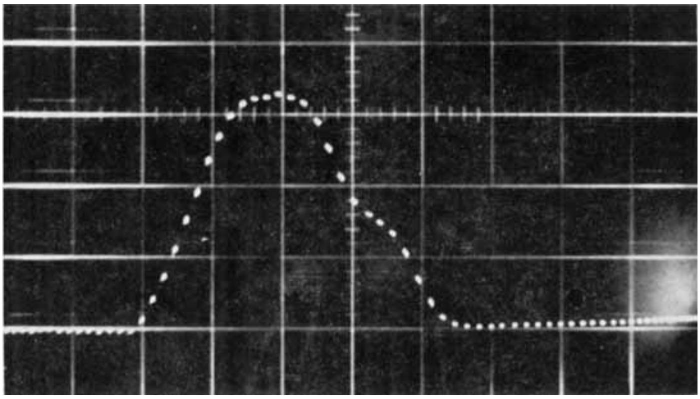

Fig. 3. Load-head travel curve.

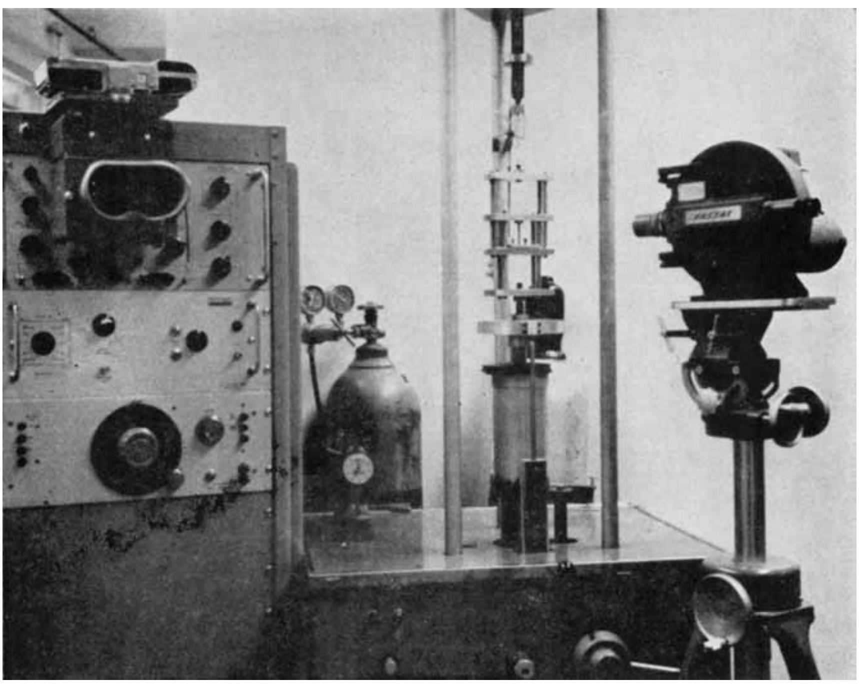

Fig. 4. Equipment setup for low speed tests.

thus far evaluated by this method include 25 commercially available grades of five generic families: acrylonitrile–butadiene–styrene (ABS), polystyrene (GP and HIPS), acetal, polypropylene, and polyethylene.

Specimens of each material were punctured at a variety of speeds. The maximum load per unit thickness during puncture was plotted versus log test speed.

Discussion

From the load-test speed plots a distinct pattern emerged (see Fig. 5). There appeared a region at low speed through which the load to rupture was relatively independent of speed, followed by an increase in load with increasing speed to a maximum. Increases in test speed beyond the speed of this peak resulted in a rapid decline in the load to puncture. The test speed at which this maximum load to puncture occurs was found to be a characteristic of the particular plastic product tested. This "critical speed" was found to range from 10 in./min. to 8000 in./min. for the formulations thus far tested. Within generic families considerable variation was encountered.

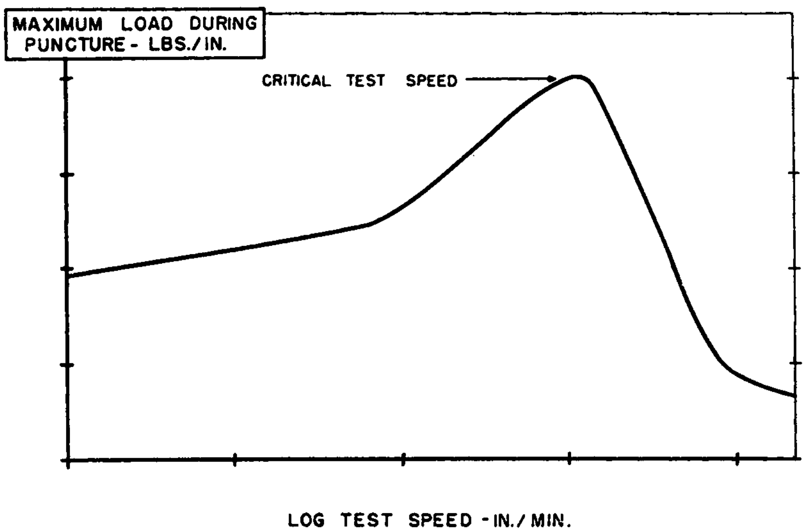

Fig. 5. Characteristic load speed curve.

Load-test speed curves for two ABS plastics, Cycolac Brand Polymer Grade T and Cycolon Brand Polymer Grade AM, are shown in Figure 6. The pattern of behavior of these materials is very similar. Both rise to a peak load at very high test speeds. The "critical speed" of Cycolac Brand Polymer, Grade T is approximately 7500 ipm while Cycolon Brand Polymer Grade AM reaches its load maximum at approximately 5000 ipm. Each falls to the load level of low speed puncture at test speeds of 11,000 ipm.

Figure 7 illustrates two materials with widely separated "critical speeds." The acetal reaches its peak load at only 10 ipm and falls steadily but not

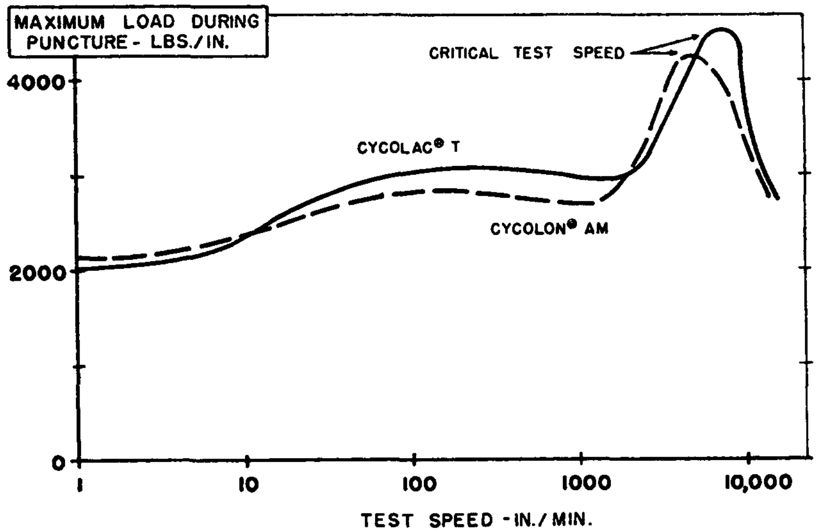

Fig. 6. Load test speed curves for two ABS plastics, Cycolac Brand Polymer Grade T and Cycolon Brand Polymer Grade AM.

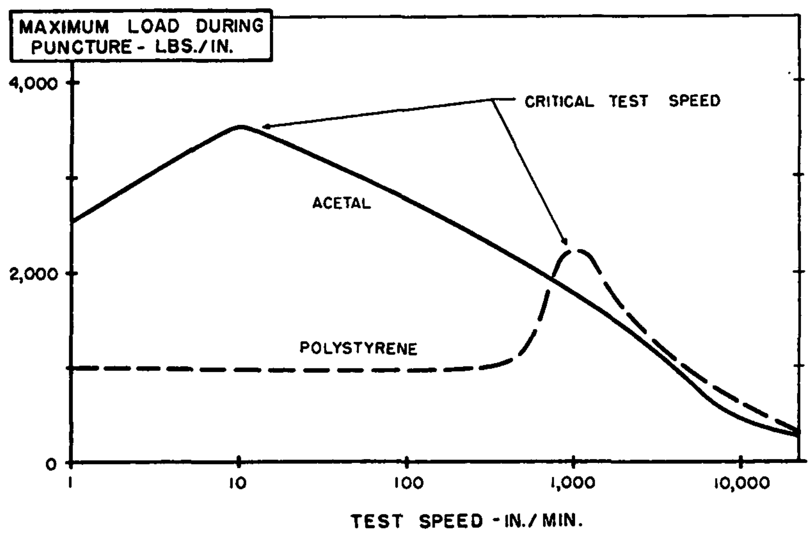

Fig. 7. Critical speeds of acetal and polystyrene.

drastically with increasing speed of test up to the maximum speed of our equipment. The high impact polystyrene reaches its peak at 1000 ipm, then falls rapidly to approximately the level of the acetal at 2000 ipm.

Visual examination of the punctured specimens and study of the high speed photographs of the specimens during test revealed certain patterns in failure geometry. Figure 8 illustrates five such geometries. The failure types depicted generally represent tests of increasing speed from A to E.

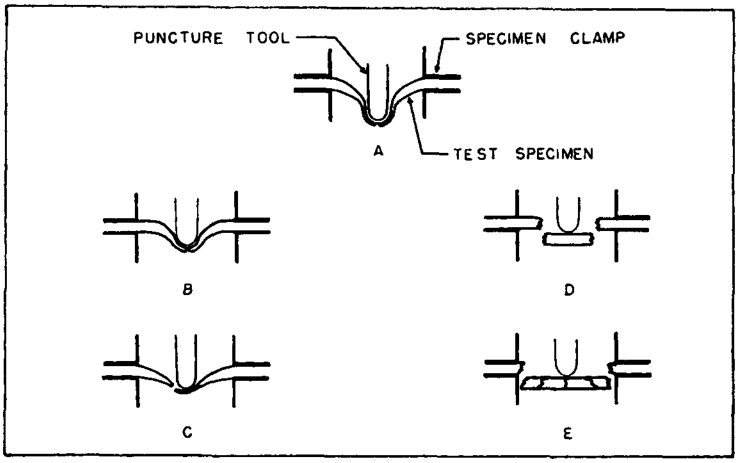

Fig. 8. Observed fracture geometries.

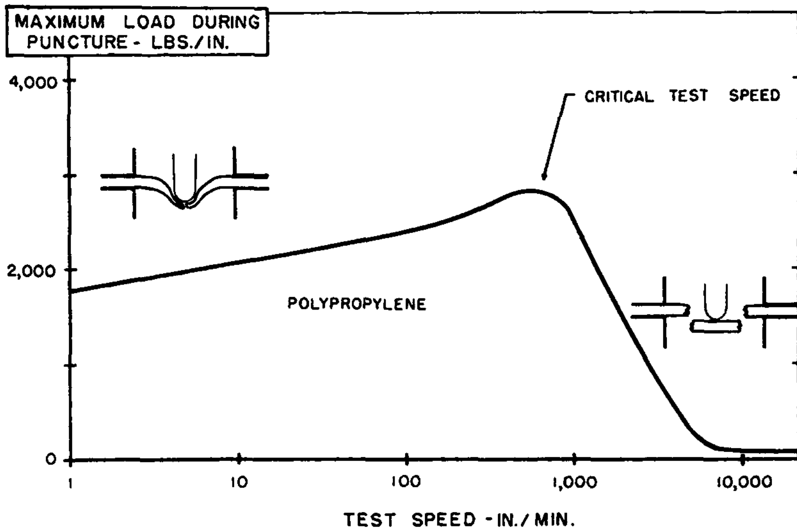

Fig. 9. Relationship between fracture geometry and load-speed characteristics for a general purpose polypropylene.

Not all materials were found to exhibit each of these patterns. Failures as illustrated by D and E were in a few instances found to occur with very slight deflection (<030) and with no detectable load transmitted to the load cell. For other materials, even D and E type failure required substantial load.

For each of the materials studied the nature of the puncture above the "critical speed" was different from that at lower speeds. It was further noted that the change in behavior tended to be from ductile to brittle. In some cases, notably the "tougher" ABS grades, this change was only

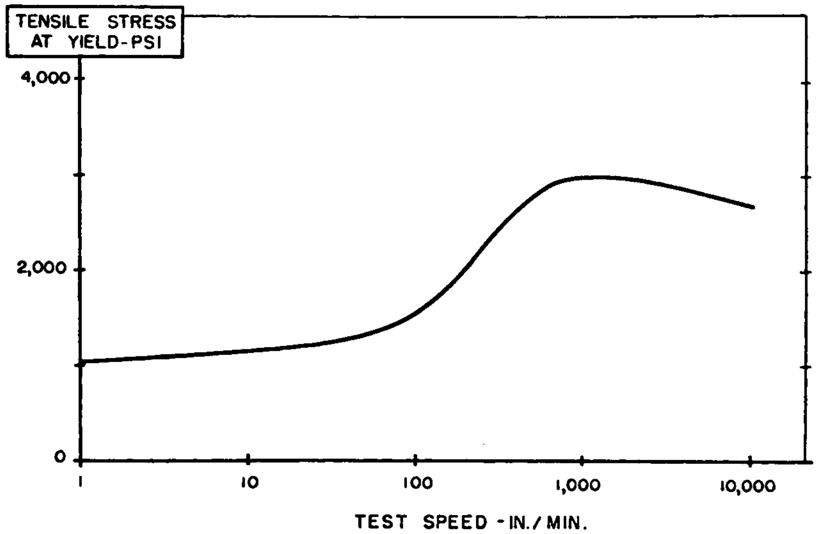

Fig. 10. Yield stress versus test speed for polypropylene.

a loss in the extent of permanent deformation. In others it was from a small puncture with slight permanent deformation to the almost explosive shattering of the entire exposed test surface.

Figure 9 shows the relationship between fracture geometry and load-speed characteristics for a general purpose polypropylene. The type of fracture is shown above the load-speed curve. Below the critical speed, ductile Type A fractures were observed, while above the critical speed, brittle Type D and E fractures occurred.

The existence of a critical puncture velocity is not unexpected. Many workers have reported the existence of critical strain rates for a variety of polymeric materials. Firstly, the critical strain rate for polymer films in tension have been shown[4–6] to be accompanied by a substantial loss of ductility. Secondly, Meltzer and Supnik[7] have reported tensile yield stress for polyethylene over a range of test speeds which show a test speed dependence similar to that found in the puncture test. Their data is plotted in Figure 10. Similar phenomena were observed for some of the materials included in this study.

Thirdly, dynamic mechanical measurements of modulus and damping such as reported by Maxwell[8] show critical test frequencies. These dynamic measurements, when made in bending, do not show the same sharp peaks because the total strain at a point in the specimen is proportional to its distance from the neutral axis. Therefore, only a small portion of the material is at the "critical strain rate" at a given frequency. This tends to smooth the peaks and minimize the effect of critical frequency. Where elastomers have been tested in compression or tension, response characteristics have been similar to those found in the puncture test.[9]

It cannot be said that each of these "critical" test speeds is a manifestation of the same basic mechanism of material response. To rationalize each of these behavior patterns, one must turn to the classic argument that response of a material to any forcing function is governed by one or more storage and/or relaxation mechanisms. Thus each "critical speed" results in a rate of deformation where one mechanism is yielding its place of prime importance to another.

The distribution of strain and therefore strain rates is complex in any mechanical test. This is particularly true in puncture where there is little possibility of analyzing behavior as a uni-axial system. Most strain rates calculated are, therefore, only gross deformation rates and not directly usable in a study of molecular response times.

The exact location of a "critical" point on the test speed scale must necessarily depend upon such material characteristics as Poisson's Ratio, Young's Modulus, and yield strain as well as strain rate. In all probability, there is no simple relationship between the test speeds, which result in "critical" behavior for different tests.

It is not likely that a single test procedure can ever adequately reproduce the full spectrum of strain rates, stress wave distributions or three dimensional strains associated with part usage. The puncture test does, however, contain many of the elements of complex bending encountered by plastic parts during normal service. It is a healthy trend that conventional "Metal" tests are being supplemented by new procedures which consider the viscoelastic nature of high polymers.

While the full value of this test has not yet been determined, it has been used for the following practical problems: (*A*) Screening of new polymers where laboratory quantities are limited; (*B*) quantitative evaluation of the effects of pigment loading on abuse resistance; (*C*) study of the effects of natural and accelerated aging of polymers; (*D*) effects of extrusion vacuum forming and injection molding on impact resistance; (*E*) evaluation of competitive products.

References

1. Maxwell, B., and J. P. Harrington, *Trans. ASME*, **74**, 579 (1952).
2. Maxwell, B., J. P. Harrington and R. E. Monica, "The Tensile Impact Properties of Some Plastics," *Tech. Reports*, **24A**, Plastics Laboratory, Princeton, New Jersey, 1952.
3. Ely, R. E., *Plastics Technol.*, **3**, 900 (1957).
4. Sandek, L., *Plastics Technol.*, **8**, 26 (1962).
5. Patterson, G. D., Jr., and W. H. Miller, Jr., *J. Appl. Polymer Sci.*, **4**, 291 (1960).
6. Amborski, L. E., and T. D. Mecca, *J. Appl. Polymer Sci.*, **4**, 332 (1960).
7. Meltzer, T. H., and R. H. Supnik, *SPE Tech. Papers*, **9**, 1–4 (1963).
8. Maxwell, B., *J. Polymer Sci.*, **20**, 551 (1956).
9. Berger, M., *J. Appl. Polymer Sci.*, **4**, 269 (1960).

Résumé

Une étude approfondie a été effectuée sur un grand nombre de matériaux polymériques par une méthode instrumentale à pointe à vitesse rapide. Le domaine de vitesses de tension prépondérante dans ces tests a été mis en relation avec les vitesses d'élongation dans les parties soumises au traitement normal. On a démontré de plus qu'à une certaine vitesse du test critique, chaque matériel présente un maximum de charge accompagné d'un changement dans le mode de diminution et de perte de ductibilité. On montre que cette "vitesse critique" est une caractéristique du matériel étudié.

Zusammenfassung

Eine ausgedehnte Untersuchung wurde an einer grossen Zahl von polymeren Materialien mit einer Hochgeschwindigkeitslochungsmethode durchgeführt. Der bei diesen Tests vorherrschende Bereich der Verformungsgeschwindigkeit wurde mit der Verformungsgeschwindigkeit von normaler Abnützung unterworfenen Teilen in Beziehung gesetzt. Weiters wurde gezeigt, dass bei einer bestimmten kritischen Testgeschwindigkeit jedes Material eine Maximalbelastung aufweist, bei welcher eine Änderung des Bruchvorganges und ein Dehnbarkeitsverlust auftritt. Diese "kritische Geschwindigkeit" bildet eine charakteristische Grösse für das getestete Material.