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Tensile Testing of Elastomers at Ultra-High Strain Rates

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INTRODUCTION

Efficient utilization of a rate-dependent material can only be assured if one knows its response to stress throughout the anticipated load, distortion, rate, and temperature spectra of its application. The determination of significant properties of matter subjected to high-rate distortion has been hampered by lack of a practical laboratory testing machine that is capable of routine testing of bulk samples under conditions of high force and rapid, controlled distortion rate. Material evaluation with presently available high-speed testing apparatus is limited to testing speeds of only 15,000 in./min. and to moderate load levels.

This paper describes a tensile and compressive test apparatus that can be used for routine testing at speeds up to 100,000 in./min. and for specialized experimentation at speeds as high as 200,000 in./min. The instrument develops instantaneous loading rates in excess of 5×10^8 lb./sec. and can withstand peak dynamic loads of 25,000 lb. in tension testing or 100,000 lb. in compression testing.

The problem of stress transient propagation in tensile samples at high testing speeds is also discussed, in connection with a description of stress–strain measurements that were made on cast polyurethan.

THE DU PONT MODEL 2 HIGH RATE TESTER

General Description

The Du Pont Model 2 high rate tester (Fig. 1) is an apparatus designed for tensile and compressive testing of metallic or nonmetallic materials at high rates of distortion. A gas-actuated piston, which can be operated with compressed air or smokeless powder, is used to displace one end of a suitably designed test sample. The apparatus combines a hydraulic moderator system, which regulates the piston speed and linearizes the piston motion, with a hydraulic arrest system, which stops the piston at the end of its stroke. Adjustable tension and compression specimen supports, as well as custom designed load cells, specimen grips, and calibrating accessories, are used. A commercially available capacitance transducer measures piston displacement. The operating principles of the tester are outlined in the following paragraphs.

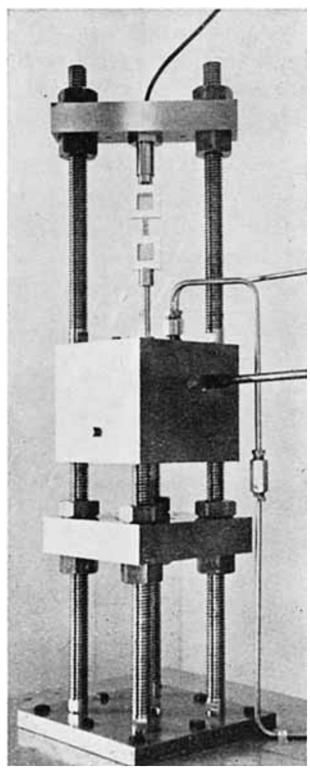

Fig. 1. The Du Pont Model 2 high rate tester.

Operating Principles

After assembly, the tester (Fig. 2) is prepared for operation by filling the arrest, annulus, and

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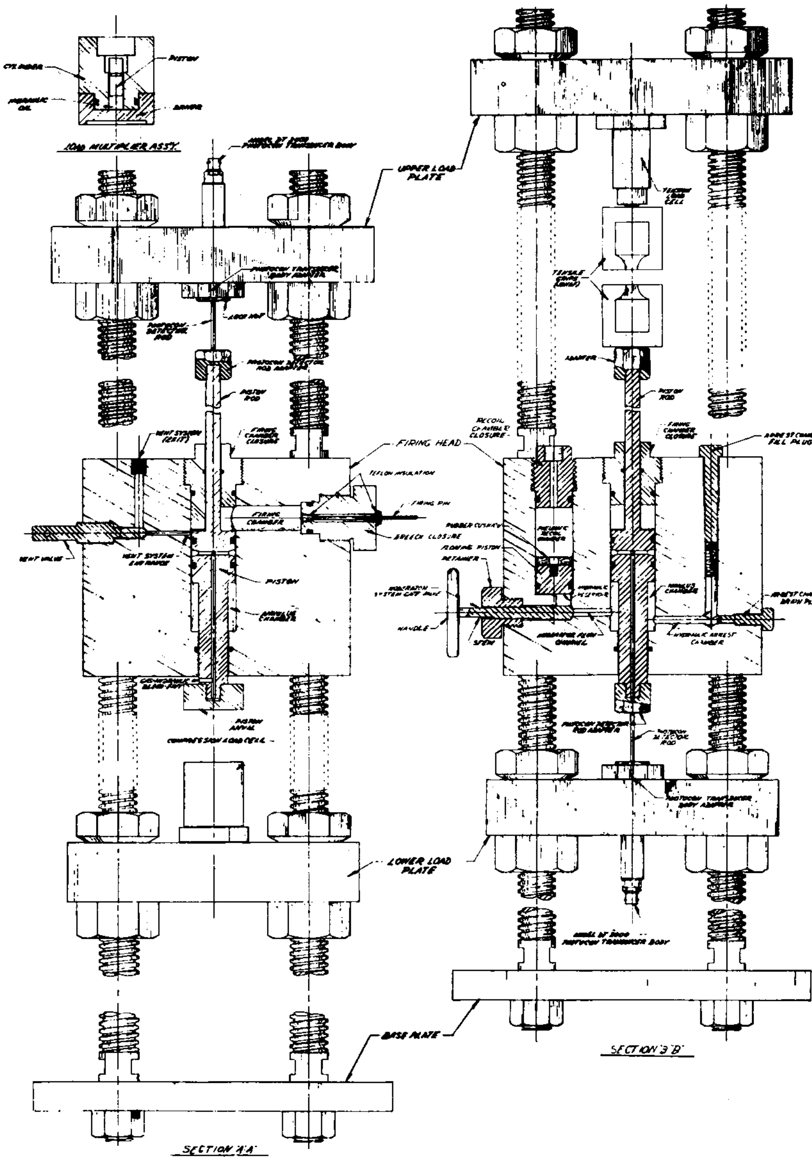

Fig. 2. Model 2 high rate tester (assembly).

moderator flow chambers with hydraulic fluid and loading the smokeless powder actuating charge into the firing chamber (compressed air operation is discussed later). When the smokeless powder is initiated, the firing chamber gases force the piston down, pumping hydraulic fluid from the annulus chamber through the moderator flow channel, past the moderator gate valve or throttle aperture. Controlled fluid flow through the moderator system performs two functions: the throttle aperture controls the rate of piston descent; and restraint by pressure in the hydraulic system stabilizes the piston velocity, even when rather large loads are exerted on a sample. This latter function tends to make the testing speed independent of the properties of the material being tested.

As the bottom edge of the enlarged section of the piston passes the moderator flow channel entrance, the flow of hydraulic fluid from the annulus chamber into this channel is interrupted. The piston then compresses the fluid in the arrest chamber and the bottom of the annulus chamber, slowing to a stop as it does so. Compression of fluid in the arrest and annulus chambers will stop the piston in $^1/_4$ in. of travel if hydraulic fluid with a compressibility of 50×10^{-6} volumes/atm. is used and the tester is operated at a speed of 100,000 in./min.

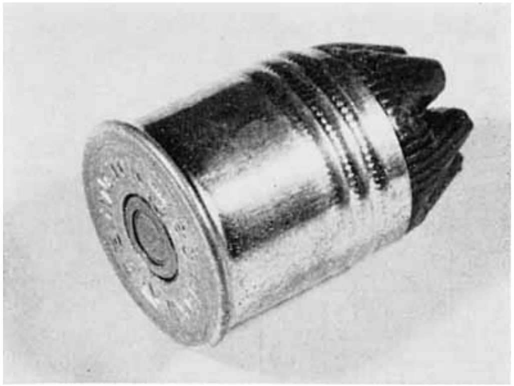

Fig. 3. A 12-gage smokeless powder cartridge for the Model 2 high rate tester.

The hydraulic fluid forced past the moderator system gate valve passes into the hydraulic reservoir, raising the floating piston and compressing the air in the pneumatic recoil chamber. The compressed air in this chamber exerts a recoil force through the hydraulic fluid against the bottom of the piston, returning the piston to its initial position when the firing chamber gases are vented. The floating piston serves as a moving seal in the hydraulic system, preventing mixing of air and fluid in the reservoir chamber. The pneumatic recoil chamber is connected to an air pressurization system, to facilitate control of the recoil force and to allow a pressure bias to be established in the firing chamber. The pressure bias regulates the firing chamber pressure at which first motion of the piston occurs. This in turn controls the initial burning characteristics of the smokeless powder, and thereby allows a limited degree of control over the acceleration rate of the piston.

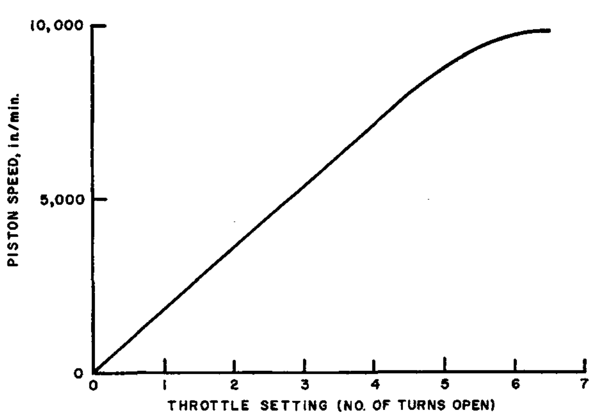

Fig. 4. Piston speed vs. throttle setting for compressed air operation of Model 2 high rate tester: accumulator pressurization, 1550 psig; recoil bias pressure, 50 psig; A-602 hydraulic fluid; maximum throttle aperture, 0.437 in. diameter.

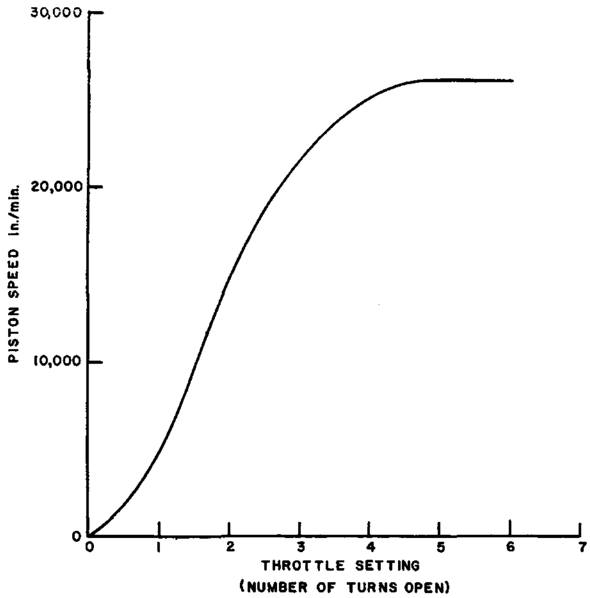

Fig. 5. Piston speed vs. throttle setting for smokeless powder operation of Model 2 high rate tester: 2 g. PB-2 smokeless charges; A-602 hydraulic fluid; maximum throttle aperture, $^1/_4$ in.

The piston has double O-ring seals with a bleed channel between. A small amount of leakage of both smokeless gases and hydraulic fluid past the O-ring seals is inevitable. The bleed channel provides a low-pressure escape route for these leakages and prevents the formation of a gas bubble in the hydraulic system. The presence of an air bubble in the hydraulic system would destroy the linearity of piston displacement and jeopardize successful functioning of the arrest system.

Compressed air operation of the tester is carried out by sealing the firing chamber, opening the vent valve, and channeling compressed air from an accumulator past a quick-opening valve into the tester via the vent channel. Operation of the tester is otherwise the same as described above, except that control is achieved with a valve rather than a switch.

The preceding paragraphs summarize the main operational features of the actuating and arrest system of the tester. The apparatus is employed in materials testing after attachment of suitable specimen grips, load measuring devices, and a displacement transducer. For tensile testing, as indicated in Figure 2, section BB, the displacement transducer body is mounted in the load plate, its detecting rod is fastened to the bottom of the piston, a specimen grip is fastened to the top of the piston rod, and the tension load cell together with the

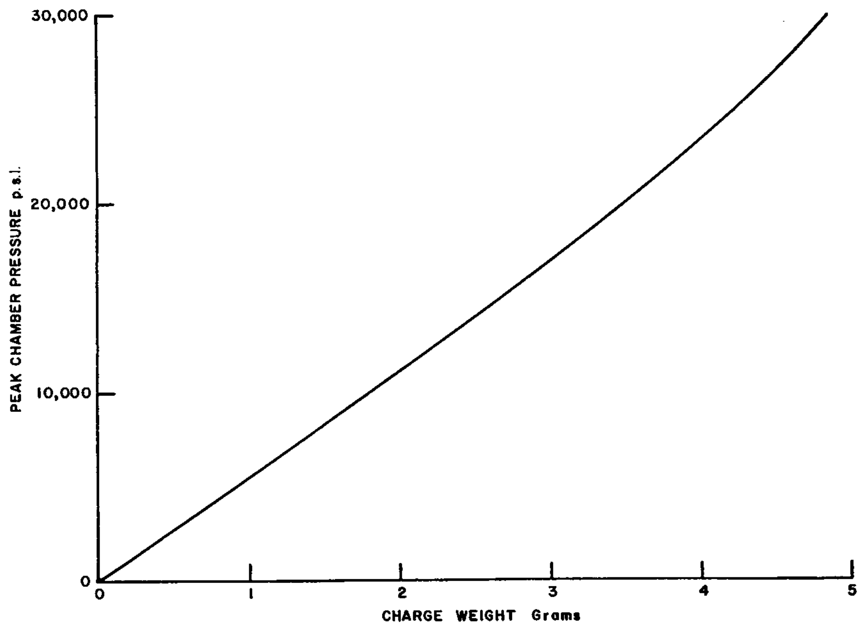

Fig. 6. Peak pressure vs. charge weight of PB-2 (Model 2 high rate tester).

other specimen grip is attached to the upper load plate. When used in compression testing (Fig. 2, Section AA), the displacement transducer body is mounted in the upper load plate, the detector rod is fixed to the top of the piston, the piston anvil is attached to the bottom of the piston, and the compression load cell is mounted on the lower load plate.

The smokeless charges used in the apparatus are cased in modified 12-gage shotgun shells that are primed with M52A3 electric initiators (Fig. 3).

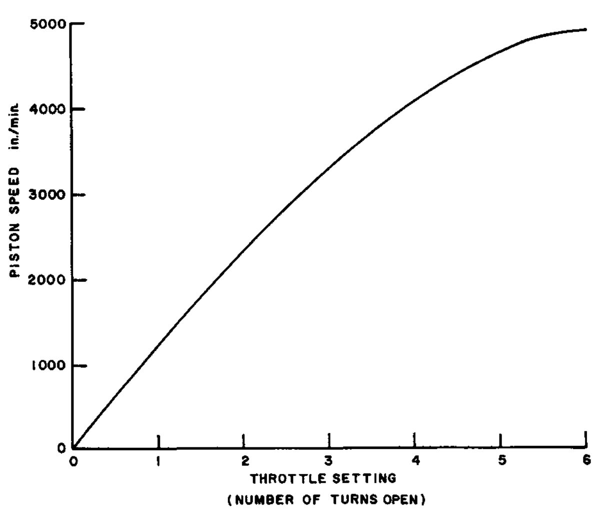

Fig. 7. Piston speed vs. throttle setting for compressed air operation of Model 2 high rate tester: accumulator pressurization, 2000 psi; A-602 hydraulic fluid; 1/4 maximum throttle aperture, 1/4 in.

TABLE I
Model 2 High-Rate Tester Operating Specifications

Piston stroke,[a] in.	$1^1/_4$
Maximum actuating pressure (dynamic factor of safety $\simeq$ 2), psi	50,000
Piston displacement rate, in./min.	
Compressed air operation at an actuating pressure of 2000 psi	10–5,000
Smokeless powder operation	1000–100,000
Accuracy of displacement rate control, %	5
Load capacity in compression (dynamic, factor of safety $\simeq$ 2), lb.	100,000
Load capacity in tension (dynamic, factor of safety $\simeq$ 2), lb.	25,000

[a] Can be increased to 2 in. for compressed air operation by modification of piston.

The peak pressure developed by these charges is controlled by the loading density or amount of smokeless powder per unit volume in the firing chamber (Fig. 4). Pressure-time characteristics in the firing chamber can be varied widely through use of different grades of smokeless powder and, to some extent, by control of loading density. The smokeless powder used in these tests (Du Pont PB-2) is a very fast-burning grade that develops peak pressure before the tester piston has moved more than a few hundredths of an inch. A calibration curve showing piston velocity versus throttle setting, for 2-g. charges of Du Pont PB-2 smokeless powder (loading density = 0.085), is shown in Figure 5. The peak chamber pressure obtained with this charge is approximately 11,000 psi (Fig. 6). A similar calibration curve for compressed air operation at an accumulator pressure of 2000 psi is illustrated in Figure 7.

The operational specifications for the tester are summarized in Table I. These specifications are conservative in nature. There are, however, practical limitations on operation of the tester near its maximum speed. At piston speeds greater than 50,000 in./min., frequent maintenance of critical tester parts and replenishment of hydraulic fluid are required. The tester can be operated at piston speeds as high as 200,000 in./min. At such speeds, however, it is necessary to regard each test as an individual problem, and consideration must be given to the various operating hazards attendant upon the high pressures and large forces involved. Special techniques for operation of the tester at speeds above 100,000 in./min. will not be described here.

TENSILE TESTS OF CAST POLYURETHAN

Preparation of Specimens

The tensile specimens used in these tests were JANAF dumbbells, modified to obtain effective gage lengths of 2.0 or 2.3 in. (Fig. 8). Determinations of effective gage lengths were made on a

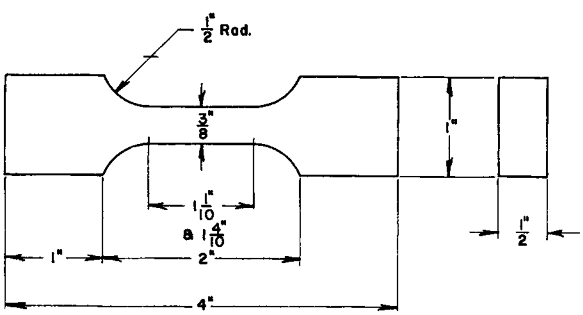

Fig. 8. Tensile specimen for high-speed testing of polyurethan.

standard tensile testing machine at ambient temperature and a crosshead speed of 1 in./min. Calculation of strain at all testing speeds was based on these determinations. Samples were saw-cut from $^1/_2$-in. thick cast slabs of a standard polyurethan formulation (Table II). After aging for 1–3 days, the samples were conditioned at 20°F. for 2–4 hr., placed in the tester grips, and pulled within 30 sec. after removal from the conditioning cabinet.

TABLE II
Composition and Cure of Polyurethan[a]

	Parts by weight
Adiprene L	100.0
2,4-Butanediol	3.5
Trimethylolpropane	1.0

[a] Mixed under vacuum at 70°C., cured at 70°C. for 48 hr.

Data Recording and Reduction

Load transmitted through a sample and piston displacement, both versus time, were recorded simultaneously on Polaroid film, with the use of a Textronix 535 oscilloscope with a two-channel chopper input amplifier. The load cell used in the tests was designed and built at the Eastern Laboratory. This cell and a Photocon Model DT-2000 capacitive displacement transducer, which measured piston displacement, were calibrated statically. Stress calculations were based on the unstressed cross-sectional area of a specimen. Piston speeds dx/dt, as determined from measurement of the displacement–time record, were converted to strain rates $d\epsilon/dt$ by use of the effective gage length L_g of a specimen:

$$d\epsilon/dt = (dx/dt)/L_g$$

In tests where the testing rate varied during elongation of a specimen, the mean rate for the final 90% of the piston stroke was measured. Strain was calculated directly as the ratio of piston displacement divided by effective gage length.

DISCUSSION OF TESTS

Tensile tests at strain rates between 48 and 2100 in./in./min. were made by injecting compressed air onto the firing chamber of the tester. Under these conditions, the piston accelerates to maximum speed in approximately the first $^1/_{10}$ in. of travel and continues at that speed to the end of its $1^1/_4$-in. stroke. A representative oscilloscope record for a strain rate of 1450 in./in./min. is illustrated in Figure 9.

Tensile tests at strain rates between 660 and 13,250 in./in./min. were made with 2-g. charges of Du Pont PB-2 smokeless powder for actuation of the piston. This series of tests quickly established that, although extremely rapid acceleration of the piston to its maximum speed may be a laudable design objective, it is not always desirable. Rapid acceleration, even to low testing speeds, causes an intense stress transient to de-

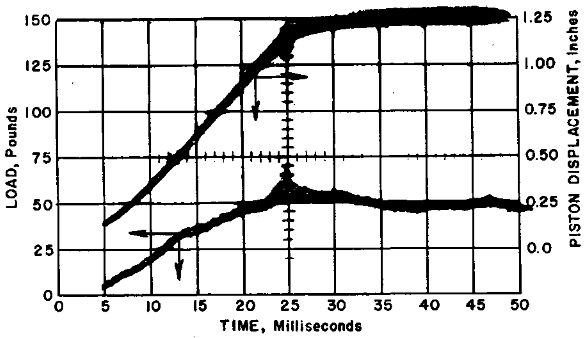

Fig. 9. Tensile test of cast polyurethan: test temperature, 20°F.; strain rate, 1450 in./in./min.; piston speed, 3340 in./min.

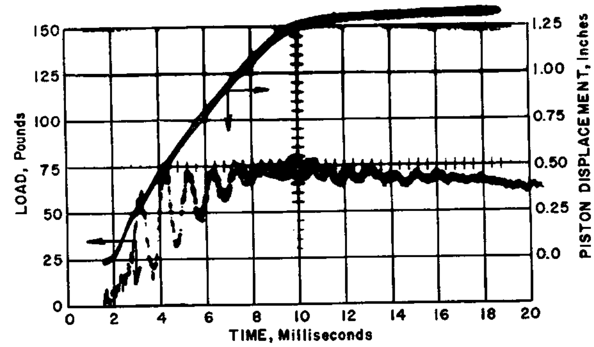

Fig. 10. Tensile test of cast polyurethan: test temperature, 20°F.; strain rate, 4690 in./in./min.; piston speed, 9380 in./min.

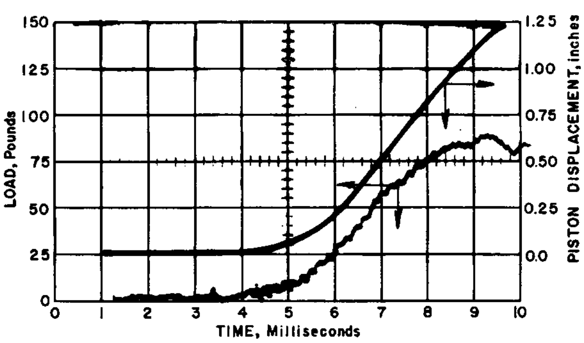

Fig. 11. Tensile test of cast polyurethan: test temperature, 20°F.; strain rate, 6120 in./in./min.; piston speed, 14,000 in./min.

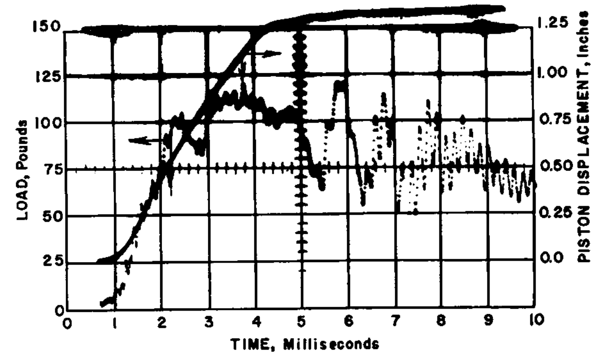

Fig. 12. Tensile test of cast polyurethan: test temperature, 20°F.; strain rate, 12,500 in./in./min.; piston speed, 25,000 in./min.

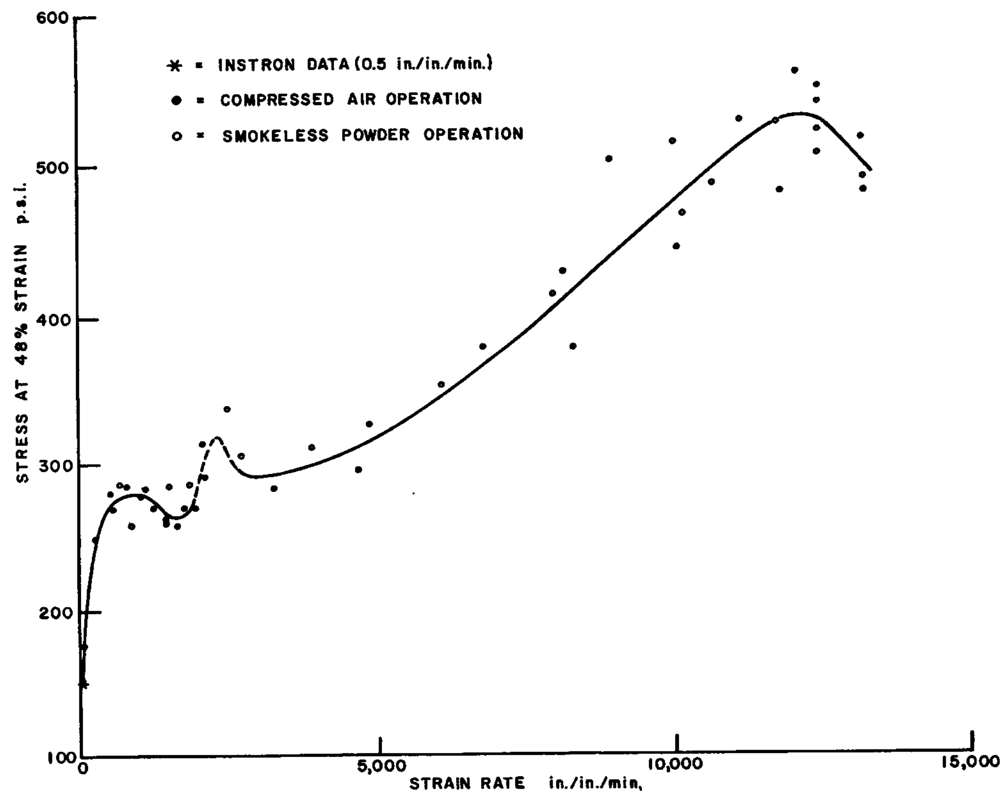

Fig. 13. Stress at 48% strain vs. strain rate at 20°F. in cast polyurethan.

velop in test specimens that have low sonic velocities. This effect is illustrated in Figure 10, where a strong sonic transient can be seen superimposed on the stress–time trace of a tensile test in which the maximum strain rate was only 4900 in./in./min. Control of the initial acceleration rate of the piston, as described earlier in this paper, does allow meaningful tests to be performed at much higher strain rates. Figures 11 and 12 illustrate records of tensile tests at strain rates of 6120 and 12,500 in./in./min.

It is obvious from the preceding comments that tests of elastomeric materials can be extended to ultra-high distortion rates only at the cost of sacrificing test rate linearity. Furthermore, there will be a rate beyond which meaningful results will not be obtained, except in terms of sonic behavior in the material. In this series of tests, samples strained at rates beyond 13,500 in./in./min. resulted in stress records that exhibited only large-amplitude stress waves.

The $1^1/_4$-in. maximum stroke of this tester was not sufficient to elongate a polyurethan test specimen to rupture at any strain rate up to 16,000 in./in./min. Data obtained from these tests were therefore reduced to give stress at an arbitrary level of strain (48%), plotted as a function of strain rate (Fig. 13). The data summarized in Figure 13 illustrate the nonlinear behavior of polyurethan with respect to strain rate. It is clear that increasing amounts of elastic energy are degraded as the testing rate increases. Indeed, polyurethan formulations similar to the one used in these tests have exhibited outstanding capabilities for absorbing explosively generated mechanical energy without fracture at distortion rates of 10^6–10^7 in./in./min.

Development of the high-rate test apparatus described in this paper was supported by the Special Projects Office, U.S. Navy. Mr. Reid Earnhardt of Eastern Laboratory developed the design concepts for the tester. His untimely death from cancer terminated a promising career and ended a valued friendship before this project reached fruition. Mr. D. L. Sagers of Eastern Laboratory prepared the polyurethan used in these experiments. The assistance of Dr. H. F. Ring, under whose supervision this work was done, is gratefully acknowledged.

Synopsis

A tensile and compressive test apparatus actuated by smokeless powder with a test speed capability in the 10^5 in./min. range is described. Preliminary tensile property data for cast polyurethan elastomer is discussed.

Résumé

Un appareil de mesure d'extension et de compression mis en mouvement par une poudre sans fumée avec une capacité de vitesse de mesure dans le domaine de 10^5 pouces par minute a été décrit. Des données préliminaires des propriétés d'extension pour des élastomères de polyuréthanne durcis ont été discutées.

Zusammenfassung

Ein mit rauchlosem Schiesspulver betriebener Apparat für Zug- und Kompressionsprüfungen mit erreichbaren Beanspruchungsgeschwindigkeiten im Bereich von 10^5 Zoll pro Minute wird beschrieben. Vorläufige Ergebnisse für die Zugeigenschaften eines Polyurethanelastomeren werden mitgeteilt.

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