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Adaptation of a Ballistic Tool for Obtaining Strain Rates Above 20,000 Inch/Inch/Minute

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Synopsis

A low cost, dynamic tensile tester was designed and developed, using a simple ballistic piston tool as the driving force. The principal purpose of the device was to provide performance data on the response of high molecular weight, linear polyethylene subjected to strain rates between 20,000 and 50,000 in./in./min. at temperatures ranging from 75 to −40°F. Tests were made on samples of linear polyethylene, conventionally formed, and of linear polyethylene, formed by a special process, to produce a highly oriented, highly crystalline structure. Both materials were tested in the direction of forming and at right angles. Basically, the unit consists of a ballistic tool that fires a captive piston against a block to which a specimen is attached. A load cell, in series with the sample, records the developed force and a simple cantilever beam strain gauge is used to record the cross head travel. The rate of strain is controlled by the propellant charge (piston velocity) and a buffer device. The unit is relatively light and portable. For cold temperature firing, the whole unit is placed in a cold box and both the samples and the device are soaked to the desired temperature. Firing takes place in the cold box to insure uniformity of sample temperature.

INTRODUCTION

A program was undertaken for the purpose of studying the behavior of specially processed, highly oriented, linear polyethylenes subjected to strain rates well in excess of 20,000 in./in./min. At the time this program was initiated, little was published about the dynamic properties of high density linear polyethylenes, and even less about highly oriented polyethylenes. Consequently, this investigator was faced with the task of finding a method by which the materials could be tested at the required strain rates.

Commercially available dynamic tensile testers were found to be limited to a maximum strain rate of 15,000 in./in./min. at moderate energy levels. More specialized devices, as those using high powered ballistic systems, provided high energy levels and strain rates up to 100,000 in./in./min. However, to this observer, these latter devices, not readily available, appeared both costly and unwieldly. Since, in essence, what was required was a *high* velocity and *low* energy device, it appeared that a small scale, ballistically actuated apparatus was an ideal solution. Moreover, the power source for such an apparatus was readily available in the Pow-R-

Set tool, a ballistically operated piston tool manufactured by the Winchester-Western Division of Olin. (Such tools are widely used in the construction field to drive fasteners into construction materials.)

In actuation, the ballistic tool functions much like a gun system in that a propellant charge is ignited and the resulting high pressure gases are used to accelerate a piston. The kinetic energy imparted to the piston is directly proportional to the propellant weight. Normally, work is accomplished by piston impact with the fastener or with other receiving materials. Since piston velocities of 100 to 300 ft./sec. could readily be obtained, such high velocity power sources, suitably adapted, offered a practical power source. Thus, it was decided to design a high speed, tensile testing apparatus. There remained, however, the problem of how to deliver the piston energy to the test specimen to achieve the required strain rate. The manner in which this was accomplished is perhaps the most important of the design features.

This paper describes the development of the apparatus and presents some of the principles behind the design of the energy transmitting device and the gauges used. In addition, some of the test results which were obtained are presented.

A. General Description

A photograph of the apparatus which was developed is shown in Figure 1. It illustrates the manner in which the ballistic tool was adapted for use and points out the principal elements of the dynamic tensile tester. Basically, the apparatus consists of the tool, an anvil, a driving buffer, a cross head (or block), a displacement gauge, and a force gauge. A test sample is also shown clamped in position. The tool is a modified experimental version of the commercially available Pow-R-Set tool. This particular tool, however, has two design features not normally found in the Pow-R-Set tool; a fiber glass buffer to arrest excess piston velocity, and an exceptionally heavy piston to provide the required energy at relatively low velocities.

The apparatus functions in the following manner. When the tool is fired, the piston is accelerated to a predetermined velocity and it then impacts the anvil. The anvil in turn is coupled to the cross head block through a driving buffer to allow smooth acceleration of the block which rides between two guiding channels to insure proper load alignment. On one side of the tool the specimen is clamped to the block and to a load cell. On the other side, a displacement gauge is located, which consists of an inclined plane which rests against a cantilever beam. The inclined plane is fixed to the block and as the block moves, the beam follows the inclined plane. Strain gauges mounted on the beam produce a change in resistance which is proportional to the block displacement.

The rate of block acceleration is variable and depends on the driving buffer material and design. In most tests this acceleration is normally complete within 0.050 to 0.070 in. of block travel. During its motion, the block rides the channels, breaks the specimen, and then flies free. A simple

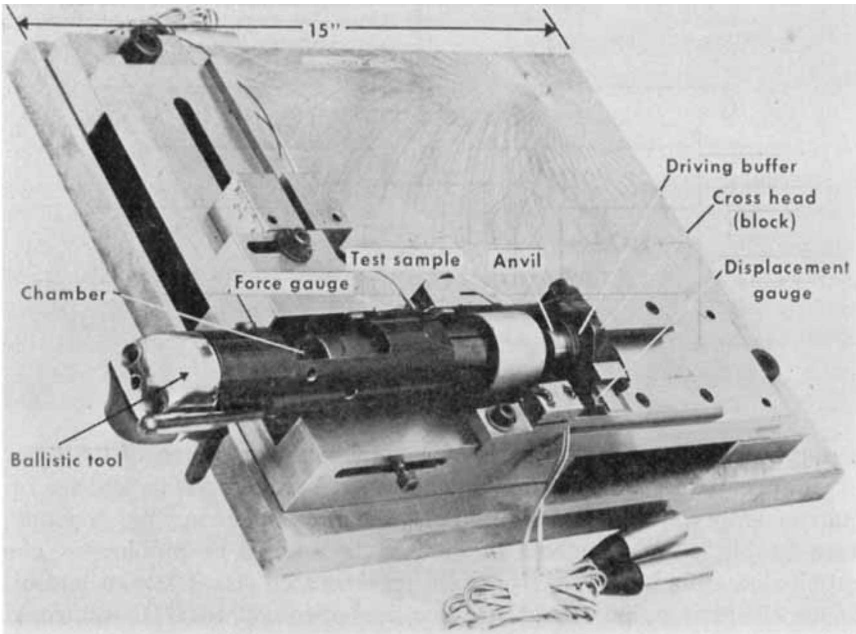


Fig. 1. Dynamic tensile tester.

catch bucket filled with polyurethane foam is used to stop the block. The tool fires standard 0.22 caliber loads and in the tests which were conducted block velocities up to 55 ft./sec. were attained.

The samples used were about one-half the size of the standard test specimen and had a one inch effective test span. Thus, the corresponding strain rates were essentially equal to the block velocities. Only high density, linear polyethylenes were studied and these were tested at high strain rates at temperatures ranging from 75 to −40°F.

DESIGN OF APPARATUS

A. Design Requirements

In selecting a ballistic device to accomplish a particular task, certain performance requirements must be established. The three most important considerations are (*1*) energy, (*2*) momentum, and (*3*) rate of energy delivery. With the particular problem at hand, the task was to show discrete differences in the dynamic response of high density, highly oriented, linear polyethylenes which were manufactured by various forming processes. From a preliminary study of the problem and the material performance requirements, the test conditions were established. These indicated that (*1*) the testing strain rate was to be such as to reach the peak stress level between 0.2 to 0.4 msec, and (*2*) testing was to be accomplished at temperatures as low as −40°F. The sample size shown in Figure 2 was

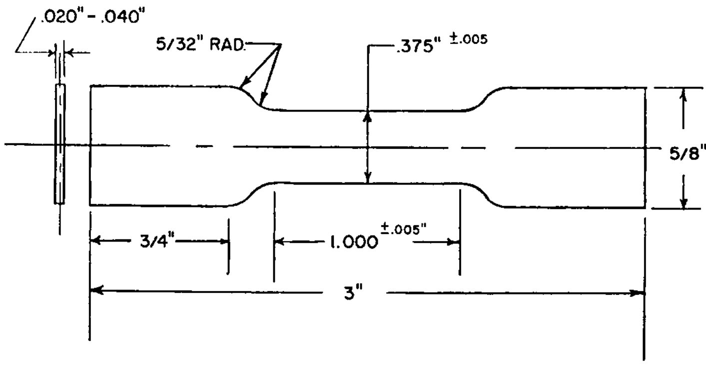


Fig. 2. Tensile bar.

predetermined, and on the basis of a maximum stress area of 0.016 sq. in., it appeared that the maximum load would be about 400 lb. and the required energy would be 20 ft.-lb. Thus, the force and energy requirements were established and for ballistic devices these posed no problems. The anticipated cross head velocity, based on estimated elastic strains and ultimate elongations, indicated that velocities between 30 to 50 ft./sec. would be required. The corresponding maximum strain rate would be 36,000 in./in./min. On the basis of further design analysis, the following requirements were established: (*1*) the block, to which the specimen was to be mounted, was to be accelerated rapidly to avoid excessive initial straining of the test specimen before the proper strain rate could be achieved; (*2*) the block was not to be directly coupled to the piston, but was to be accelerated by piston impact with an anvil because of the relatively long piston acceleration; (*3*) the block was to be coupled to the anvil by a flexible buffer to avoid *impact loading conditions* and to provide some adjustment on the rate of block acceleration; (*4*) gauges were to be incorporated for measuring the force induced in the test sample and the block travel; and (*5*) the unit was to be operable with little change in performance throughout the required temperature range.

B. Description of Apparatus

The sectional drawing shown in Figure 3 illustrates the relative positions of block, tool, and the piston in start position. During the firing cycle, the piston (*1*), which weighs 0.42 lb., is accelerated over 0.5 in. and for approximately 0.8 msec., at which point the propellant gases are dumped. Thus, the piston is essentially in free flight when the forward end of the piston is flush with the forward end of the tool. An interesting feature of this particular experimental tool is the forward fiber glass buffer (*3*),[1] which is used to stop the piston after 1.6 in. of total travel and absorb any residual energy. A second buffer (*4*) is used to shock-mount the tool to the base in order to reduce the high accelerating forces generated during the firing cycle. After the firing cycle is complete, the piston emerges from the barrel

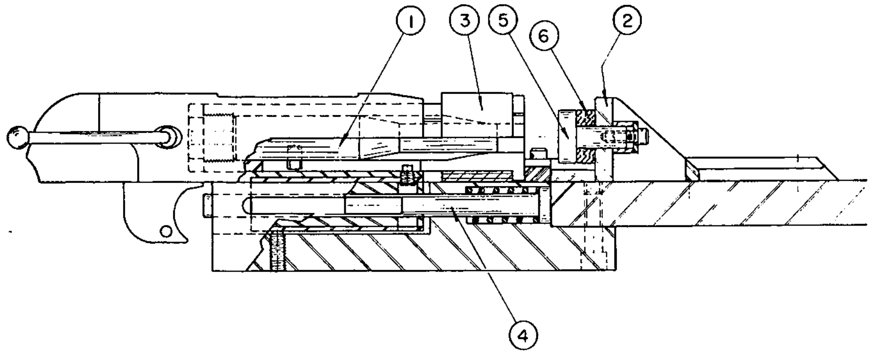


Fig. 3. The relative positions of block, tool, and the piston in start position.

and strikes the anvil (*5*), which in turn compresses the driving buffer (*6*). The driving buffer therefore accelerates the block (*2*) and, as previously stated, the rate of acceleration is variable, depending on: the buffer size; the nature of the buffer material; the initial buffer compression (adjustable); the block weight; the piston weight; and the piston impact velocity. The test sample is located between the block and the load cell and can be preloaded to iron out any distortion of the specimen. Both the force gauge and holding clamp are movable to allow for difference in sample lengths, or for variation in the block position. The whole unit is attached to a steel plate (Fig. 1) for rigidity and to add to the recoiling mass. For cold temperature firing, the whole unit is placed and fired in a cold box. Thus, its portability offers a decided advantage over many of the high speed testing units.

The driving buffer is perhaps the single most important element in this design. While the ballistic tool and the charge determine the maximum amount of available energy, the driving buffer in turn controls the amount of this energy delivered to the block, the block acceleration, and the block velocity during the work phase. Moreover, it damps out the high transient stresses which usually result during the firing cycle. Furthermore, because it eliminates all sharp discontinuities and step-forcing functions, the difficulties in obtaining gauges with reliable response characteristics are minimized.

The following paragraphs discuss the guiding principles behind the design of the driving buffer, the strain gauge, and the load cell.

1. Driving Buffer

From the previous discussion on the performance requirements of the apparatus, we note that the strain rate was to range between 20,000 to 40,000 in./in./min. Therefore, some provision was to be added to allow a variation in the block velocity. In the ballistic tool, the energy delivered to the piston is directly proportional to the amount of propellant used, so that some control is possible by varying the propellant charge. However,

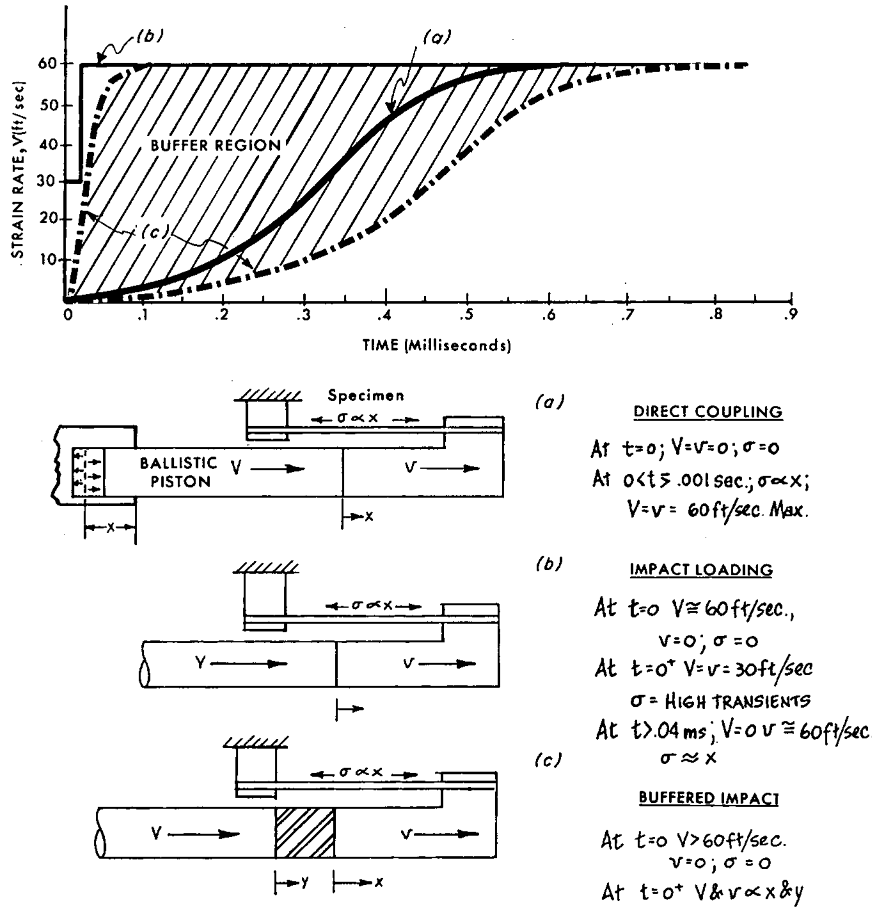
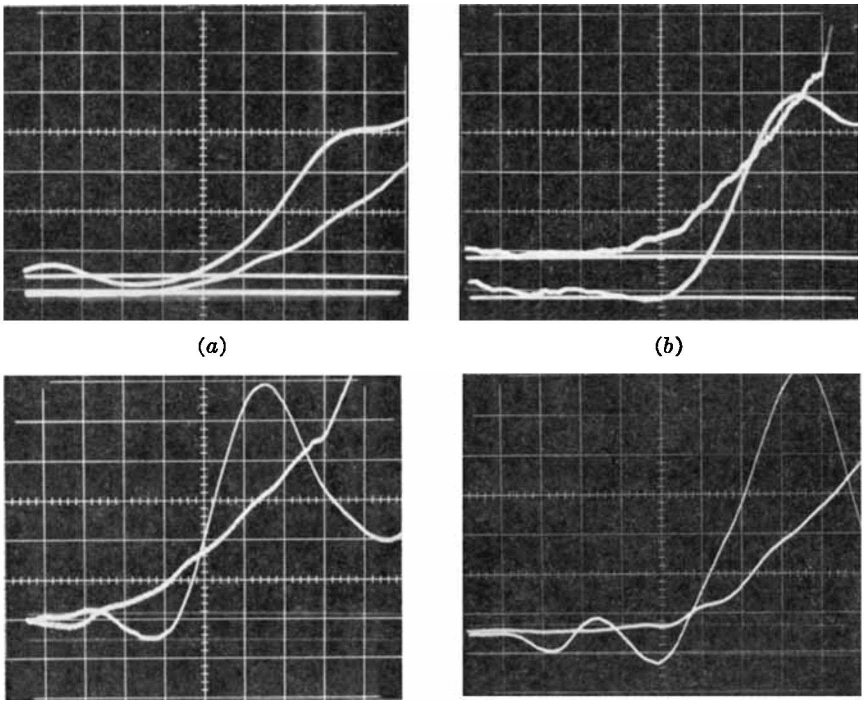


Fig. 4. Block velocity versus time.

once the energy is delivered to the piston, the means by which the energy is then transmitted to the receiving material bears primary consideration. This energy transmission may be accomplished by essentially three methods: (*a*) *direct coupling* of the cross head block to the piston, so that the block has the same motion as the piston; (*b*) *impact loading* of the block, so that the piston impacts at the required velocity and transmits the energy within microseconds; and (*c*) *buffered loading* of the block, whereby the piston is allowed to impact an anvil which is coupled to the block through a compressible member. Figure 4 illustrates the manner of applying any one of the types of loading techniques just described, and the following paragraphs discuss the consequences of applying these techniques.

a. Direct Coupling. This results in a cross head block velocity which is at all times equal to the piston velocity and thus the block velocity varies according to the amount of propellant used. However, as can be noted in Figure 4, the piston acceleration is relatively slow but, most important,



(*a*) (*b*) (*c*) (*d*)

Fig. 5. Stress-time and yield time of high density, linear polyethylene Types I-A and I-P: (*a*) axial sample at 70°F., yield 18,500 psi (upper), strain rate 20,000 in./in./min., sweep rate .1 × 10^{-3} sec./cm.; (*b*) axial sample at 70°F., yield 26,000 psi (lower), strain rate 43,200 in./in./min., sweep rate .1 × 10^{-3} sec./cm.; (*c*) biaxial sample at 70°F., yield 10,200 psi, strain rate 39,000 in./in./min., sweep rate .1 × 10^{-3} sec./cm.; and (*d*) biaxial sample at −10°F., yield 11,500 psi, strain rate 48,200 in./in./min., sweep rate .1 × 10^{-3} sec./cm.

it takes place over a considerable distance. Thus, when the specimen is subjected to the defined maximum strain rate, the block has already moved 0.5 in. and the specimen has then been elongated by this amount. Moreover, the strain rate is continuously variable throughout this period. Obviously, the method of direct coupling is to be avoided unless the manner of loading is particularly suited for the application.

b. Impact Loading. Impact loading of the block provides the most rapid means of acceleration. However, unless the consequences of impact loading are understood, the test results can prove unreliable. To test a material at a defined strain rate obviously means the material must be accelerated to the corresponding velocity. The rate at which the acceleration takes place is important because, as noted above, at too slow a pace too much elongation is permitted before the appropriate strain rate is reached, and too high an acceleration produces high transient stresses which are likely to rupture the material even though the *strain rate* is not appreciable. Again, reference Figure 4(*b*). Assuming the piston and block are more or less identical in size and weight, and are made of steel, the well-known theory of impact states that the stress generated is given by the equation

$$s/v = \rho c$$

where s is the stress lb./in.^{2}, ρ is the mass density of impacting material, c is the sonic velocity in material; and v is the change in block velocity.

For similar steel members impacting, the stress developed is about 2,000 psi/ft./sec. of velocity change. Thus, the stress wave propagates through the block and accelerates to 30 ft./sec. then reflects and accelerates the block to 60 ft./sec. within some 20×10^{-6} sec. after impact. After the block separates from the piston, the block *surges* along for some distance at the indicated velocity. The transient impact stresses and surge stresses are transmitted to any material in contact with the block, including the specimen and gauges. If the density of the specimen is very different from the steel, the high frequency, high level transient stresses are not readily transmitted, *but* the rapid motion is transmitted and the material (specimen) develops a sharp front stress of short duration, which is also determined by the foregoing equation. If the material being tested is high density, linear polyethylene, the stress developed at 60 ft./sec. velocity change is about 4,500 psi. For some of the polyethylenes tested, this level is close to the ultimate and the yield strength of the material. Thus, high impact loading for this material is undesirable.

c. Buffered Loading. In order to satisfy the requirements of high acceleration, yet reduce or eliminate the high transients resulting from impact loads, the impact of the piston can be suitably buffered to meet any strain rate required. A possible range of velocity-time relationships is, again, indicated and described in Figure 4 (*c*). The high rates indicated were actually obtained with the apparatus described in this report, without the usually attendant high transient disturbances (see Fig. 5).

In some cases where dynamic or shock load phenomena are being studied, the tendency is to shock-mount the gauges to eliminate or reduce the occurrence of high transients superimposed on the primary signal. Obviously, this technique tends to reduce the gauge response. However, in this case the driving force which is responsible for the high transients is transmitted through a material which damps out or prevents the occurrence of high transients. Thus, the resulting or buffer driving force produces a continuous and smooth block acceleration. The gauges thus provide legible data even at very high load and strain rates.

2. Strain Gauges

Block displacement (or strain) is measured by an inclined plane which is fixed to the block, and a cantilever beam which rides on the inclined plane. When the block is in ready position, the beam strain gauge is at a point of maximum deflection. As the block moves away, the beam follows the inclined plane and strain gauges mounted on the beam respond to this deflection. The resulting resistance change is recorded as a voltage change on an oscilloscope. The beam, with a natural frequency of 1500 cps, was designed to follow the block motion rather than to be driven by the block. In starting, the beam is depressed to its maximum stress level, and its accelerating force is therefore highest when the block is also subjected to its highest acceleration. The technique of having the beam follow instead of being driven, allowed the gauge response and reliability to be easily verified by a simple test procedure. This procedure consisted of insulating the beam from its holder and making electrical contact through the beam to the inclined plane and to ground. If the block moves away from the beam then the voltage signal would be interrupted and the resulting trace would indicate this. In testing this possibility, the unit was fired at maximum charge with a relatively stiff buffer, under no-load conditions. The resulting traces indicated that the beam output was reliable with the accelerations developed and with velocities up to 1,000 in./sec.

Strain gauges were located on the top and bottom of the beam and fed into a bridge circuit where the resistance changes were electronically subtracted. This arrangement compensated for any extraneous longitudinal stresses which might have occurred.

3. Load Cell

In order to reduce the turning moment acting on the block, the test specimen and clamps were located as closely as possible to the centerline of the applied load. Moreover, in order to get a high gauge response, it was necessary to have the load cell in series with the test sample. The gauge was simply a steel strip with the same configuration as the test sample. Strain gauges were placed on both sides of the strip and their outputs were electronically added to eliminate extraneous signals due to possible bending stresses. The gauge was a.c. coupled to an oscilloscope, with a time constant of 100 msec.; thus, with an action time of one msec. maximum, less than a 1% error could result from signal decay.

EXPERIMENTAL TESTS

As previously stated, the purpose of the material behavior study was highly specific in that it sought to find discrete, significant differences between various samples of high density, linear polyethylenes which had been formed by a special process.

The particular problem was that samples of high density polyethylene obtained from different sources were processed in the same manner, yet they performed quite differently as a product. Standard laboratory tests did not reveal any differences in the physical properties of these materials and consequently it was hoped that the technique of high speed testing might exaggerate those differences which affected the product performance level.

In the past a number of investigators have found that thermoplastics

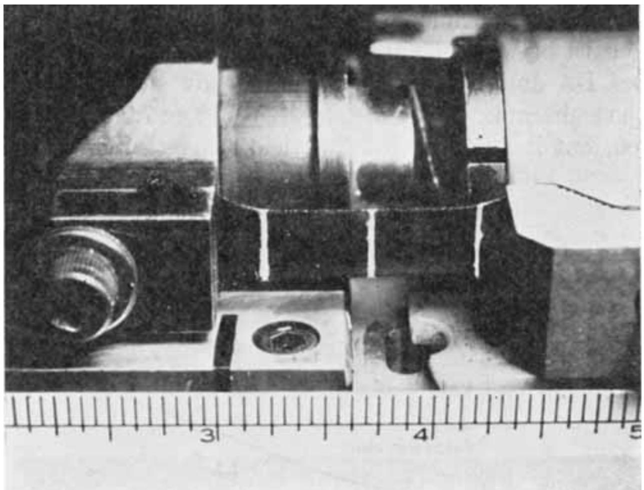
TABLE I
High Density Linear Polyethylene[a]

Sample	Strain rate (in./min.)	Yield stress psi	Maximum stress psi	Dynamic modulus
Type I-A[b]	20,000	18,500	—	229,000
	30,000	20,500	26,500	209,000
	31,000	21,000	24,000	165,000
	31,000	24,000	27,000	230,000
	34,000	24,000	—	149,000
	38,000	28,000	—	239,000
	39,000	24,000	28,000	—
	39,000	25,000	34,000	210,000
	42,000	28,000	—	168,000
	43,200	26,000	—	171,750
	44,000	27,000	—	156,000
	2 (Instron)	15,000	—	—
Type I-P[c]	21,500	7,200	—	110,000
	31,000	8,800	—	56,800
	32,000	11,600	—	112,000
	37,000	10,400	—	72,000
	39,000	11,000	—	72,000
	2 (Instron)	4,800		—
Type II-A[d]	25,000	6,200	—	54,000
	34,500	6,200	—	49,000
	49,000	8,800	—	43,000
Type II-P[e]	17,000	5,000	—	73,000
	30,000	5,700	—	43,000
	38,250	9,000	—	69,000

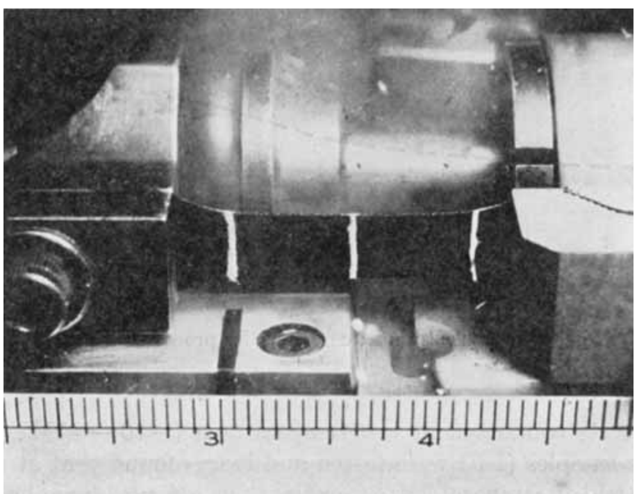
[a] All tests conducted at 70°F.
[b] I-A is the sample produced by special process and cut in axial (machine) direction.
[c] I-P is the sample produced by special process and cut in perpendicular direction.
[d] II-A is the sample produced by conventional process and cut in axial direction.
[e] II-P is the sample produced by conventional process and cut in perpendicular direction.

generally display an increase in yield strength, ultimate strength, and Young's Modulus, when the material is subjected to loading at decreasing temperatures, or when it is subjected to increasing strain rates. This investigator sought to compare the dynamic properties of these materials following the same line of investigation as previous experimentors. However, testing these materials at strain rates up to 50,000 in./in./min. and at temperatures as low as −40°F. revealed no significant differences in the dynamic properties.

In the early stages of development of the apparatus, some polyethylenes were tested that displayed significant differences in dynamic response characteristics. These differences are a function of process alone. The results obtained from these materials are presented to illustrate the degree of reliability and performance of the test apparatus, and perhaps present some useful data on the dynamic behavior of high density, linear polyethylenes. These samples, which were tested, are all high density, linear polyethylenes. However, two parameters have been investigated: (I) the material was



(*a*)



(*b*)

Fig. 6. (*a*) Still shot: sample mounted in grips, ready for testing; and (*b*) action shot: sample at 22% elongation at a strain rate of ~36,000 in./in./sec.

formed by a special process to produce a high degree of orientation, and (II) the material was formed by a conventional process to produce very little orientation. The experimental data obtained is shown in Table I.

A review of the data will show that the yield stress values for the samples manufactured by the conventional process are much lower than those manufactured by the special process. Moreover, in the special process, the axial strength developed is more than twice the perpendicular directional strength. The dynamic modulus also appears to increase as the tensile strength increases. However, the modulus for any one group tested does not seem to follow a definable pattern. A more significant relationship appears to exist between strain rate and yield stress. The results of tests with Types I-A and I-P were plotted to show how the yield strength varies with strain rate. These are shown in Figure 7. Again, only a trend is indicated, but it appears that the yield strength increases with strain rate.

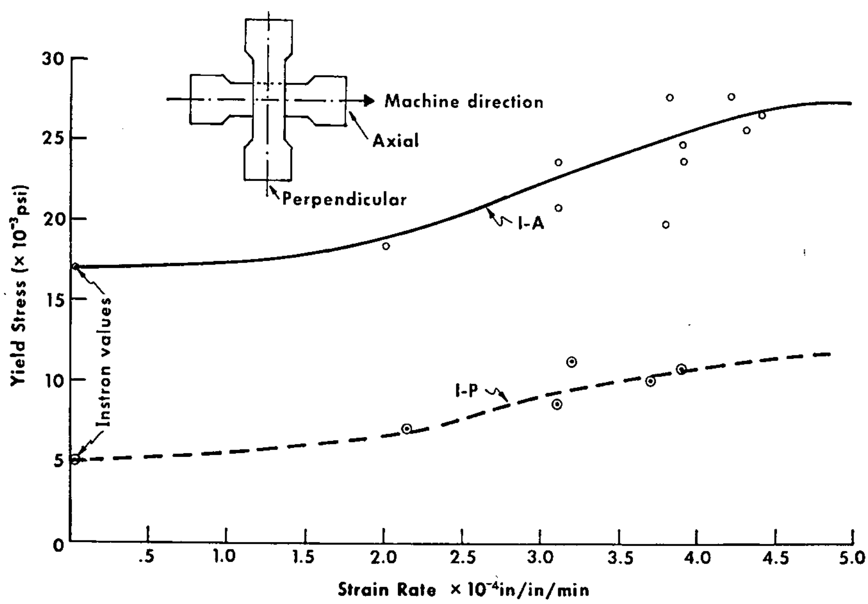


Fig. 7. Yield stress versus strain rate of specially processed linear polyethylene.

In the tests conducted at low temperatures (−10—−40°F.) only perpendicular samples (I-P) were tested and it was found that at these temperatures, and at comparable strain rates, the maximum stress levels ranged between 9,000 psi and 12,000 psi. Now, it is important to note that when this material (I-P) was tested at low temperatures, a large number of samples were tested at each level. At each level, the average strength was approximately 11,000 psi. Therefore, by maintaining the same strain rate and dropping the temperature, no difference in yield strength was noted. This fact, coupled with the results shown in Table I, suggest that we had reached an ultimate in tensile strength for this material and that the curve shown in Figure 7 does not rise beyond 28,000 for the axial samples and 12,000 for the perpendicular samples.

DISCUSSION OF RESULTS

As previously stated, the data and photographs presented in this report were not intended as a treatise on the behavior of highly crystalline polyethylene under extremely high rates of loading, but rather to show some of the results which were obtained with a ballistically driven dynamic tensile device, so that the reader is given the opportunity to evaluate its performance.

However, one significant phenomenon did occur which warrants some discussion. This is the fact that the material appears to reach a limiting strength level. It is important to question whether the material indeed behaves in this manner, or whether the manner in which the strain rates were produced caused a type of localized failure which yielded erroneous results.

As stated previously, impact loads are undesirable, because for even low impact velocities they can produce high local stresses and localized failure. This condition was avoided by the use of an adjustable driving buffer which eliminated such impact stresses. However, since the accelerations produced were still high, it thus appears the question of localized failure is a valid one.

The actual rate of strain a material can withstand is related to its sonic velocity, and recent investigators[2] show the sonic velocity in high density polyethylene is as high as 75,000 in./sec. This means that the time required for a pulse to travel along the sample length used in these tests is approximately 0.014×10^{-3} sec. The minimum time to peak stress recorded was 0.2×10^{-3} sec. Since the ratio of the time of loading over the materials response time is much greater than five, a commonly accepted figure, it appears the material could not have been subjected to localized stresses. Also reported[2] were dynamic moduli which compared favorably with those shown in Table I; again, it appears the dynamic modulus would change radically if localized yielding occurred.

The two photographs in Figure 6 show a clear picture of the anvil, driving buffer, block, and test sample, before and during a firing test. A strip of black tape and a scale are used to indicate the extent of block travel and the degree of strain. The test was made using the maximum powder charge. The action shot clearly shows a rather symmetrical elastic deformation at about 22% elongation. In all the tests conducted, including those at −40°F. with high strain rates, fracture occurrence varied along the test span, indicating no localized stress patterns due to rapid loading. However, the nature of specimen fracture was different, depending on the material, the machine direction of material, and the temperature at which it was tested. Thus, it appears the apparatus performed satisfactorily and the data produced was reliable.

The author is indebted to Mr. C. G. Irish, Head of the Electronics Laboratory, and to Mr. F. G. Parisi, Designer; both of Winchester-Western Division's Research Department, for their invaluable assistance in the design, development, and instrumentation of this device.

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Résumé

Un appareil bon marché pour mesurer la tension dynamique a été inventé et développé en utilisant un simple piston ballistique comme force motrice. Le principal but de l'invention a été de fournir de résultats concernant la réponse du poids moléculaire élevé du polyéthylène linéaire soumis à des vitesses d'élongation situées entre 20.000 et 50.000 in/in/min, à des températures variant de 75 à −40°F Les essais ont été effectués sur des échantillons de polyéthylène linéaire fabriqué d'une façon conventionnelle et sur du polyéthylène linéaire fabriqué par un procédé spécial destiné à produire une structure fortement orientée et très cristalline. Les deux matériaux ont été étudiés dans la direction de formation et aux angles droits. Essentiellement l'unité consiste en un système ballistique qui lance un piston contre un bloc sur lequel est attaché un échantillon. Une cellule de charge, en série avec l'échantillon, en régistre la force développée et une simple jauge de contrainte, est utilisée pour enrégistrert le principal mouvement transversal. La vitesse d'élongation contrôlée par la charge du propulseur (vitesse du piston) et un système tampon. L'unité est relativement légère et transportable. Pour combustible à basse température, l'unité entière est placée dans une enceinte refroidie et les échantillons ainsique l'appareil sont soumis à le température désirée. Le combustible est placé dans l'enceinte refroidie pour assurer l'uniformité de la température de l'échantillon.

Zusammenfassung

Ein billiger dynamischer Zugtester wurde mit Hilfe einer einfachen ballistischen Kolbenvorrichtung als treibende Kraft entworfen und entwickelt. Der Hauptzweck der Vorrichtung war es, Daten für das Verhalten von hochmolekularem, linearem Polyäthylen bei Verformungsgeschwindigkeiten zwischen 20.000 und 50.000 in/in/min bei Temperaturen in Bereich von 75° bis −40°F zu liefern. Tests wurden an Proben von linearem, auf konventionelle Weise gebildeten Polyäthylen und linearem, nach einem speziellen, zur Bildung einer hochorientierten, hochkristallinen Struktur führenden Verfahren gebildeten Polyäthylen angestellt. Beide Materialien wurden in der Bildungsrichtung und im rechten Winkel dazu getestet. Im Grund besteht das Instrument aus einer ballistischen Vorrichtung, die einen Kolben gegen einen Block abfeuert, an dem die Probe befestigt ist. Eine, mit der Probe in Serie geschaltete Belastungsvorrichtung misst die entwickelte Kraft, und ein einfacher Ausleger- Verformungsmesser wird zur Aufzeichnung der Bewegung des Kreuzkopfes benützt. Die Verformungsgeschwindigkeit wird durch die Treibstoffladung (Kolbengeschwindigkeit) und eine Puffervorrichtung kontrolliert. Das Instrument ist verhältnismässig leicht und tragbar. Für Tieftemperaturtests wird das ganze Instrument in eine Kältebox gebracht, und sowohl die Proben als auch die Anordnung werden bis zu der gewünschten Temperatur abgekühlt. Das Abfeuern findet in der Költebox statt, um eine einheitliche Probentemperatur zu gewährleisten.