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New High-Speed Tensile Tester for Polymer Films

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INTRODUCTION

There has been increasing concern in recent years over the effect of strain rate on measured strength properties of various materials. Some published material has appeared, but very little has been reported on self-supporting films, such as cellophane, polyethylene, and Mylar polyester film (Du Pont's registered trademark). This is true in spite of the fact that the strain rates involved in many applications of films greatly exceed the rates conventionally employed in the usual laboratory strength testing conditions (i.e., 100%/min. or less).

Polymer films, like other materials, fail owing to mechanical stresses when physical and/or chemical bonds become severed. Moderate stresses do not cause complete failure when all of the input energies are dissipated through (*a*) elastic yielding or (*b*) nonelastic flow. Normal concepts of such stress relief consider the two processes occurring stepwise or simultaneously, but in practice thus far little attention by polymer scientists has been given to the effects on each of the rates at which strains are applied. The experimental work covered in this report† included design and fabrication of a high-speed tester suitable for providing data to answer some of these questions involved.

DESCRIPTION OF TESTER

The source of breaking force in any high-speed tensile tester should possess sufficient energy so that the per cent of energy lost during stressing is negligible, thus permitting essentially constant strain rates (based on initial specimen length, i.e., constant speed of grip separation). We initially built a small tester using a motor-driven, 66-cm. bicycle wheel having a lead tire as the source of kinetic energy. After a thorough evaluation of this apparatus in preliminary work, a larger tester was designed and built in which we capitalized on faults found in the prototype, and it is this second one that is to be described here.

The tester has two rotating wheels connected by gears. A flywheel (Fig. 1) weighing about 48 kg. and having a diameter of about 46 cm. is rotated by a 2-hp. electric motor at speeds from 100 to 1600 rpm. The inertia of the wheel is sufficient to supply a 115-kg. force through a distance of 15 cm. at a minimum velocity of 800 rpm, with no more than a 1% loss in flywheel velocity. At speeds less than 800 rpm, the available energy decreases in proportion to the square of the velocity.

Stress is applied to the test sample by means of a retractable fork (Figs. 2 and 3) mounted on the rim

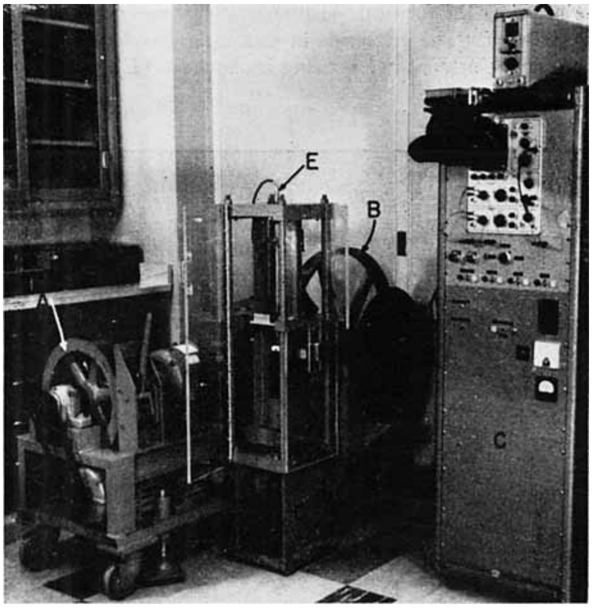

Fig. 1. General view of high-speed tensile tester, showing (*A*) the belt-driven flywheel, at left, connected through gear-drives to (*B*) the crosshead-driving wheel, rear center, (*C*) instrumentation cabinet with oscilloscope camera at right, and (*D*) frame to support the grip assembly and (*E*) strain gage in front center.

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† A similar instrument is described by L. E. Amborski and T. D. Mecca (Du Pont Film Department, Buffalo, New York) in another paper (see p. 332).

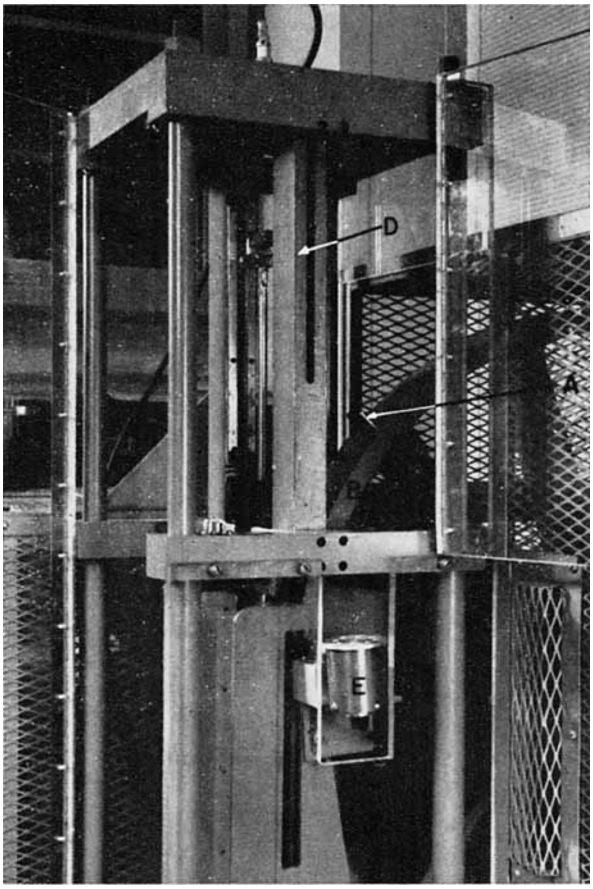

Fig. 2. Close-up of retractable fork (*A*) shown also in Fig. 3 in its forward position on the crosshead-driving wheel (*B*). The grips ride in restraining tracks (*D*). The triggering light source housing is shown at (*E*).

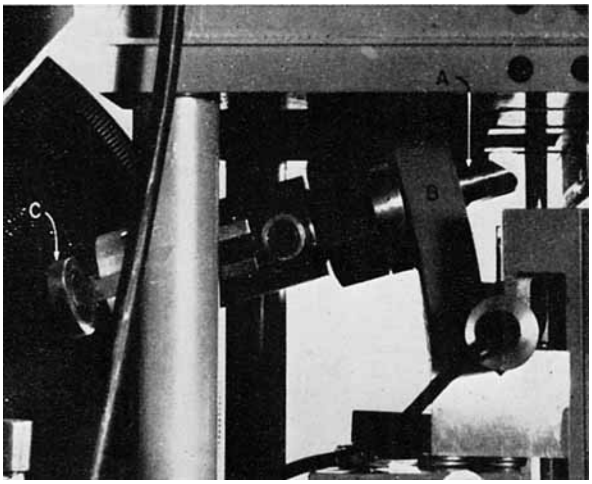

Fig. 3. Close-up of retractable fork (*A*) shown in its forward position on the crosshead-driving wheel (*B*). The fork is released at the proper instant by a cam (out of sight) which is rotated into position, making contact at the arm (*C*). See also Fig. 2.

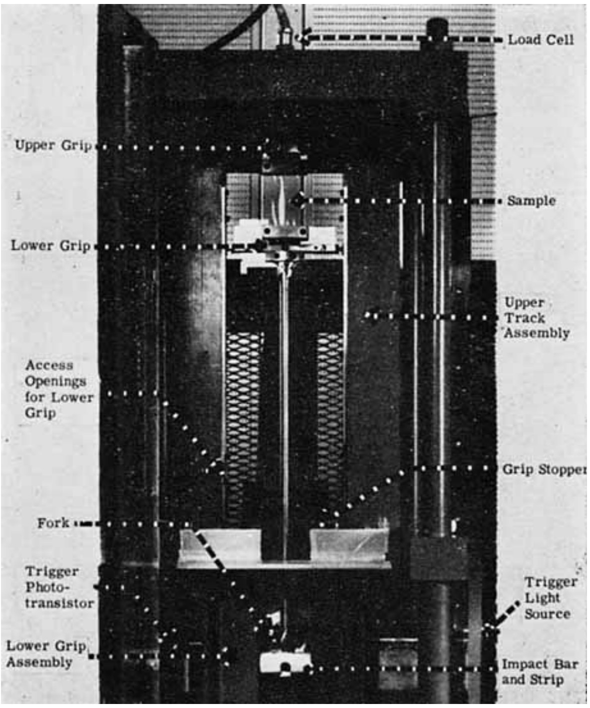

Fig. 4. Head-on view of grip assembly showing various parts as labeled.

of an 80-cm. diameter crosshead-driving (or impellent) wheel. This second wheel is driven by the flywheel through a transmission consisting of a four-speed gear-shaft drive and a right-angle reducer worm-gear drive. By using the complete range of the motor and the four choices of the gear-shaft drive, the crosshead-driving wheel can be operated at peripheral velocities from 10 to 730 m./min. A cam actuated by a rotating solenoid engages the fork-release arm at a point three-fourths of a revolution ahead of the point of contact with the rod connected to the movable grip.

The frame for supporting the grip assembly which holds the test specimen is completely separate from the main frame on which the wheels, gears, and motor are mounted. A force gage is mounted in its tension position at the top of this frame, and the specimen is attached vertically to an upper grip which is fastened to the force gage by means of a tongue and yoke. The lower end of the specimen is held by a lower grip which itself is guided by tracks, thus restraining its horizontal motion so that only tension forces are applied to the test specimen. The force, provided by the retractable fork, is transmitted to the lower grip by means of an impact bar and rod (Fig. 4). The impact bar has a plastic striker pad and it rides in a separate pair of tracks. These tracks are fastened to the main frame so as to maintain proper position of the impact bar in relation to the fork, as well as to minimize vibrational effects on the force gage.

Force Detection

Forces are measured by a Dynisco (strain gage) force pickup (Dynamic Instrument Company). The gages used are of the four-active-arm Wheatstone-bridge type having natural frequencies of the order of 10 to 20,000 cycles/sec. Being quite insensitive to transverse forces, the gages do not generate extraneous signals which would obscure the final stress–time curve. Such extraneous signals were found to occur in piezoelectric detectors. A preamplifier connects the gage output to one channel of a Tektronix dual beam oscilloscope. To protect the gage from destructive overloading, one section of the tongue which connects the top grip to the gages has been turned down to a diameter narrower than the threads by which it is fastened to the gage.

Grip Distance Detection

A precision slotted disk is mounted on the shaft of the crosshead-driving wheel. The distance between each slot corresponds to a precise distance of travel of the lower grip (about 0.5 cm.). By means of a stationary light source and a phototransistor pickup (Texas Instruments, Model 800), the passing of the slots can be detected as the wheel rotates and the accompanying signal displayed on the second channel of the oscilloscope. These constitute a measure of strain versus time.

The maximum distance of travel is limited by the 15 cm. of travel that the fork is in contact with the impact bar.

Results are recorded by using a Polaroid camera to photograph the force–time curve and the distance marker (strain)–time curves on the dual-beam oscilloscope.

Specimen Grips

The film sample is held by a pair of flat-faced grips which may be serrated or faced with various antislip materials to minimize slippage and reduce damage to specimens. A jig is used during specimen mounting to hold both grips at correct separation distances to assist in proper mounting of samples. During testing, both grips (Fig. 2) are restrained in movements other than in the direction of the applied load. The yoke of the upper grip slips over the tongue which links it securely to the force gage and is held in place by a tapered pin. On either side of the lower grip is a stub shaft with nylon bushings which ride in tracks to prevent extraneous grip movement. A vertical rod connects the lower grip to the impact bar which is covered with a plastic pad to minimize the "ringing" otherwise caused by metal-on-metal impact which would result when the fork strikes the bar. This pad also reduces the friction as the fork slides off the bar due to the circular path of the fork. The bar also rides in tracks which are lined up with the tracks of the lower grips, thus assuring linear tensioning of the test specimen.

Triggering of the scope is accomplished by the interruption of a light beam by the rotating fork, which fires a thyratron and produces a continuous steady voltage to the triggering circuit in the oscilloscope until the operator interrupts the function of the thyratron by pressing a reset button.

The flywheel is coupled to the motor by means of a timing belt pulley. The motor's speed is controlled by a potentiometer regulating an eddy-current clutch. Constant speed of this shaft is maintained by a circuit which matches the voltage generated by a tachometer-generator (mounted on the output shaft) with the magnetic amplifier voltage within a control unit supplied with the motor. Strain rates can be reproduced precisely, since the magnetic clutch can be turned on and off independently of the potentiometer setting. The tachometer voltage is also used to indicate flywheel speed by placing in the circuit a high-resistance voltmeter which reads directly in revolutions per minute.

EXPERIMENTAL RESULTS

Grip Behavior

By means of high-speed motion picture photography, it was determined that no extraneous motion occurs in the upper grip for moderate speed ranges. For 5.1-cm. specimen lengths at strain rates exceeding 10^5%/min., the lower grip would rotate only slightly about the axis of the stub shafts. Small oscillations of about 2.5 cycles for rates of 3×10^5%/min. and 3 cycles for rates of 5×10^5%/min. were observed. No related variations in the force-gage output were observed. The steel rod connecting the impact bar and the lower grip bent somewhat with a sweeping action but received no permanent deformation. The nylon bushings initially fit somewhat loosely in the tracks, permitting transverse wobbling in the grip, but final machining to reduce tolerances has since minimized this motion.

For thin films, the forces required to break specimens are a small fraction of the available force. The excess forces tend to accelerate the impact bar to velocities exceeding the velocity of the fork. This means that the distance-marking "pips" on the oscilloscope, which represent fork movement, may lag behind the actual grip positions. It also means that stresses may not result from a perfectly regular application of strain. Thus far, these problems have shown very minor effects on the main results.

Specimen Behavior

High-speed motion picture studies of film samples have been made in which we utilized two means of observing the behavior. Grid lines printed or stamped on the film specimen gave reliable indications of strain in localized areas. Crossed polaroids were used to observe stress patterns and distributions. Motion pictures were taken at rates of 3000 to 5000 frames/sec. with a conventional Fastax camera. Illumination was supplied by a strobe lamp which produced individual frame exposure times in the microsecond range. Observation of the grid line markings on the film in these movies proved that grip slippage is quite small. On the other hand, the pattern of neckdown is variable. It usually starts near (but not at) one end and propagates to the other. While it often is uniform with some materials, there are instances when the neckdown width varies. The point of failure does not consistently occur at regions of greatest neckdown. Often the break will occur near one grip where the region of relatively uniform neckdown ends. In one case, a sample broke at both ends of this region simultaneously. Since fracture occurs much faster than 0.2 msec., it has not been possible to determine precisely where it actually originates. Several fractures have been observed which are obviously tears starting at one edge. Subsequent microscopic examination of the broken edges has shown that the two ends of the broken edge are not identical, one being quite angular and the other distinctly curved. This is true of "clean breaks" of the brittle type and may indicate the point of origin of failure.

Behavior of Force and Strain Transducers

The four-arm strain gage proved more than adequate to produce voltages properly amplifiable for recording the force–time curves on one beam of the double-beam oscilloscope. Its natural frequency was sufficiently high to eliminate "hash," often seen with certain other types of transducer construction. At very high strain rates, "ringing" or vibrations on various parts of the tester upon impact may superimpose on the main voltage output of the force gage (Fig. 5). These, however, are characteristic enough to permit smoothing out to reveal the main force trace for approximating the tensile strength quite precisely. On the other hand, it is possible that these apparent periodic variations in the forces truly represent specimen behavior under conditions of sonic stress wave reflection.

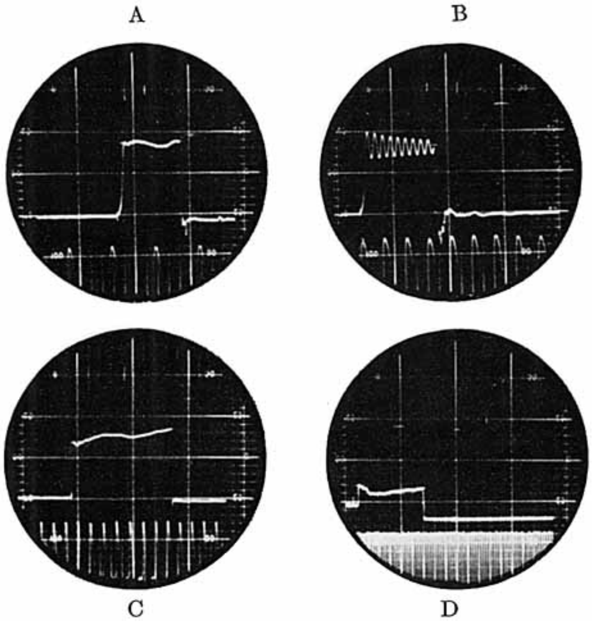

Fig. 5. Examples of high-speed stress-strain curves for typical films: (*A*) PUD-O cellophane (plain, uncoated, unsoftened cellulose) transverse direction at 320,000%/min.; initial dimensions: length 1.27 cm., width 1.27 cm., thickness 0.0236 mm.; tensile strength, 14.0 kg./mm.^{2}; elongation, 60%. (*B*) PUD-O cellophane (plain, uncoated, unsoftened cellulose) transverse direction at 300,000%/min.; initial dimensions: length 5.08 cm., width 2.54 cm., thickness 0.0238 mm.; tensile strength, 13.6 kg./mm.^{2}; elongation, 34%. (*C*) 1-mil Mylar A, transverse direction at 110,000%/min.; initial dimensions: length 2.54 cm., width 1.27 cm., thickness 0.0254 mm.; tensile strength, 10.3 kg./mm.^{2}; elongation, 160%. (*D*) Polyethylene, transverse direction at 110,000%/min.; initial dimensions: length 2.54 cm., width 2.54 cm., thickness 0.0391 mm.; tensile strength, 0.5 kg./mm.^{2}; elongation, 520%.

The strain "pips" derived from the precision-slotted wheel interrupting a light beam focussed on a phototransistor, very successfully provide a clean record to calculate actual strain rates and per cent elongation at break. They provide evidence also for possible acceleration or deceleration of the wheel at the slower rates or in cases where high stresses are required to break the specimen.

Preliminary Observations

The data obtained so far permit certain tentative observations: for example that per cent elongation at break is inversely related to sample length. Also, the general trend with cellophanes, for example, is for the tensile strength to increase with strain rate.

Brittle fractures occur regularly above certain strain rates which vary for different polymers and, in certain cases, for different orientations and crystallinities for a given polymer. This has encouraged the study of critical strain rates (that is, that strain rate above which elongations at break are suddenly so low that brittle fracture may be presumed). These are very sensitive to specimen dimensions, and seem to correlate with bag durability. For example, in high-speed movies of cellophane bag-drops, the following were quite evident in all pictures taken: (*1*) principal stresses are horizontal when the bag is dropped vertically; (*2*) all failures are tears travelling vertically and usually start at pinholes when they are present; (*3*) strain rates exceeding 6000%/min. were *always* observed, the most common range being 40×10^3 to 700×10^3%/minute; (*4*) tearing rates range in the hundreds of m./sec.; (*5*) tensile test specimens intended to test samples for packaging applications should be wider than they are long in order to more nearly duplicate the biaxial forces present in bag failure—the length-to-width ratio should not exceed 1/2.5 in order to achieve the proper degree of biaxiality and to minimize edge effects; (*6*) elongations at break range from 1 to 25% and failure times generally were between 1 and 4 msec. Such results will be published subsequently.

CONCLUSIONS

The new tester operates at speeds between 10 and 700 m./min., providing over 100 kg. of force through a distance of 15 cm. with no more than 1% loss in velocity on samples up to 7.5 cm. wide. Reliable instrumentation permits accurate measurement of force and position parameters.

Invaluable assistance in design and evaluation of this tester was provided by W. C. Stetter and T. D. Mecca. Design details and construction were the responsibility of W. E. Seningen, Jr., E. R. Thomas, and R. R. Leavitt, and were patterned after a model built by J. A. Galt, Research Centre, Du Pont of Canada, Ltd., Kingston, Ontario. Assistance in the high-speed photography work was provided by W. O. Johnson and D. C. Knodel.

Synopsis

Design characteristics are described of a rotating-wheel tensile tester suitable for stressing a vertical specimen with a force of 115 kg. through a distance of 15 cm. in a velocity range of 10 to 730 m./min. with no more than 1% loss in velocity, thereby assuring constant speed of grip separation. Provision is made for specimens up to 7.5 cm. width in order to achieve multiaxial distributions of stresses which are important in bag failure and leading to the determination of critical strain rates. Instrumentation provides reliable triggering of stress and strain traces on a double-beam oscilloscope. Straight-line travel of the moveable specimen grip is assured by the use of tracks which restrain horizontal motions without hindering the desired vertical motion.

Résumé

On décrit les caractéristiques techniques d'une roue tournante servant à mesurer l'élongation lors de l'extension d'un échantillon vertical avec une force de 115 kg sur une distance de 15 cm dans un domaine de vitesse allant de 10 à 730 m./min. avec pas plus de 1% de perte de vitesse, en assurant une vitesse constante d'écartement des attaches. On prévoit la possibilité d'assurer pour les échantillons ayant une largeur jusque 7,5 cm des distributions multiaxiales des tensions qui sont importantes pour les cassures et conduisant à la détermination des vitesses critiques d'élongation. L'appareillage assure un étirement rapide reproductible et les traces de tension sur un oscilloscope à double faisceau. Le mouvement en ligne droite de l'attache du spécimen mobile est assuré par l'emploi de guides qui limitent les mouvements dans le sens horizontal sans empêcher le mouvement vertical désiré.

Zusammenfassung

Der Entwurf eines Zugfestigkeitsprüfgerätes mit rotierendem Rad wird beschrieben, welches zur Spannung einer vertikalen Probe mit einer Kraft von 115 kg über eine Distanz von 15 cm in einem Geschwindigkeitsbereich von 10 bis 730 m/min geeignet ist, wobei die Geschwindigkeit nicht um mehr als 1% abnimmt und dadurch eine konstante Entfernungsgeschwindigkeit der Probenhalter von einander garantiert. Um eine multiaxiale Spannungsverteilung zu erhalten, die beim Reissen von Verpackungsmaterial wichtig ist und zur Bestimmung kritischer Verformungsgeschwindigkeiten führt, wurde die Verwendung von bis zu 7,5 cm breiten Proben vorgesehen. Zur Ausrüstung gehört ein Doppelstrahloscilloskop zur verlässlichen Aufzeichnung des Spannungs-Dehnungsverhaltens. Geradlinige Verschiebung des beweglichen Probenhalters wird durch Verwendung von Führungen erreicht, welche horizontale Bewegungen unmöglich machen, ohne die gewünschte vertikale Bewegung zu behindern.

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