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Digital Recording and Automatic Computation of Film Tensile Stress–Strain Data*

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INTRODUCTION

Automation in manufacturing processes is an established trend and has already proven its utility in a variety of areas. In the testing laboratory however, in spite of major advances in measurement instrumentation technology, the advantages to be gained from automation have lacked sufficient recognition to enjoy a comparable development. This paper describes a system designed for advancing one phase of laboratory testing, more specifically, stress–strain testing, toward a further degree of automation.

The tensile parameters which may be obtained by subjecting a polymeric film to tensile stress and strain have long been recognized as important in the characterization of film "toughness." Accordingly, great importance has been placed by the researcher, producer, and consumer on basic film tensile properties such as initial tensile modulus, tensile stress at break, and ultimate elongation (total strain at break).

Although these properties are extremely useful, they constitute only a part of the information which can be obtained from a tensile stress–strain diagram. For example, one could obtain a measure of the initial slack in the specimen tested, the yield stress, yield strain, maximum tensile stress, and work-to-break. However, with the slow procedures involved in manual computation, or even with the use of the more rapid desk-type calculator, this would be a tedious, time-consuming, and, therefore, costly effort. Of even greater consequence is the decreased reliability of the data so produced, because of the numerous errors interjected through the judgment necessary in the selection of data points and their manipulation as the arithmetic process proceeds.

Furthermore, since in most laboratories it is common to perform at least five replicate determinations per test sample, it is highly desirable that the standard deviation of any replicate set be calculated to obtain a statistical measure of the scatter about the average. It has been estimated that for each hour spent in polymer film testing, 4 to 5 hr. would be required for the complete reduction of data by hand or desk-calculator computations.

EXPERIMENTAL

System Requirements

After completion of a detailed study of the available tensile testers, systems which would automatically record a stress–strain curve, process, and compute tensile and statistical parameters in a practical amount of time were studied. To ensure the realization of maximum potential from any one of the large number of systems available it was felt that the following specifications should be met.

(*1*) The system must be digital and must record the stress–strain curve simultaneously with its generation in the tensile tester.

(*2*) Accuracy and precision of the recording should be equivalent to that defined by tensile tester limitations.

(*3*) Provision must be made for manual insertion into the record of test identification, constants.

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and test parameters subject to change, when required, for automatic computer processing.

(*4*) All information developed by the instrumentation must be completely documented digitally, and all of this must be entered into the computer.

(*5*) Costs of generating the integrated system should not exceed those experienced in manual computational procedures.

(*6*) Manipulation of the automatic system should be relatively simple and suitable for use by nontechnical personnel.

(*7*) Components of the system should be general purpose in nature and suitable for use in other physical measurements.

Apparatus

The system chosen is shown schematically in Figure 1 and consists of four units: the tensile tester (A), which is under control of the incremental pulse recorder (E), an incremental pulse reader (F), under control of the computer (G) and its captive typewriter output device (H). Suitably located on the tensile tester are the stress encoder (B) and the strain encoder (C). Output of the encoders is fed directly to the incremental pulse recorder (E). The keyboard (D) which can control the tensile tester provides for manual insertion of necessary test identifications and constants into the magnetic tape record.

In operation, film specimens are strained at a constant rate of crosshead motion on an electromechanical tensile tester (Instron universal tensile tester).[1,3] Simultaneously with the development of a graphic record of the stress–strain curve on a strip-chart recorder, encoders, appropriately positioned on the tensile testers, cause stress and strain pulses to be deposited on magnetic tape. The tape is then played back on a reader which accumulates the stress and strain pulses and stores them, in the form of X,Y coordinates, in the computer memory. A suitable internally stored program then "recalls" the coordinates for computation of the desired tensile parameters.

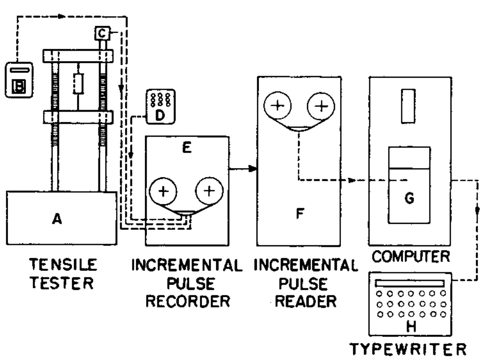

Fig. 1. Schematic diagram of automatic tensile data processing system: (A) tensile tester; (B) stress encoder mounted on pen-drive motor; (C) strain encoder mounted on crosshead screw; (D) keyboard for manual data input; (E) incremental pulse recorder (magnetic tape); (F) incremental pulse reader; (G) digital computer; (H) electric typewriter.

1. Tensile Tester. The tensile tester, of the constant rate-of-crosshead-motion type, has been slightly modified (Fig. 2) to accept encoders which supply digital pulses on the stress and strain axes during a tensile test.

Fig. 2. View of tensile tester showing placement of stress encoder at (A) and strain encoder at (B).

The strain encoder, a photoelectric type, analog-to-digital converter has been mounted on the right-hand lead screw of the tensile instrument and supplies 1024 (or 2048 in the case of the table model tester) electrical pulses per inch of crosshead travel. Pulses per unit of time, therefore, vary directly with the rate of crosshead travel selected.

The stress encoder is a brush or wiping-contact type and is connected directly to the slidewire shaft which drives the recorder pen. It provides 222 pulses over the full-scale load range selected (100 divisions on the strip-chart recorder). However, the pulse rate is dependent upon actual rate of movement of the pen as the stress event occurs.

2. Incremental Pulse Recorder. Output of the encoders is fed directly into the incremental pulse recorder (IPR) (Fig. 3). The IPR is a seven-channel magnetic-tape recorder which, in use, has direct control of the tensile tester and on which pulses (bits) are deposited during a stress–strain test. Each time the strain changes by one pre-

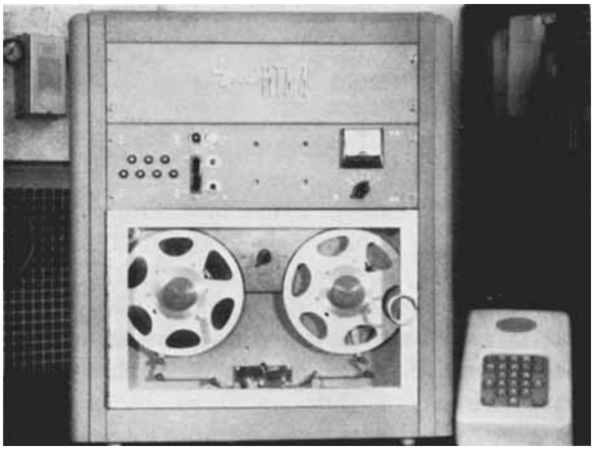

Fig. 3. Incremental pulse recorder (magnetic tape) with keyboard.

determined increment, a pulse is deposited on channel 3 and another into channel 1 or 2, depending on whether the strain bit was positive or negative. Likewise, each time the stress changes by 1 bit, a pulse is deposited on channel 6 and another in channel 4 or 5, depending on whether the stress bit was positive or negative. In this manner a complete record on magnetic tape is made in the form of two 3-bit words, each recording increments of stress or strain.

Information regarding test conditions and identification, in addition to constants required for computation, is inserted onto the magnetic tape through a keyboard which controls the IPR. Information so entered is deposited in channels 1–6, depending upon the information keyed in; however, each time information is entered through the keyboard a pulse is deposited in channel 7 which then differentiates a stress or strain count from a keyboard entry.

Initially, the operator prepares the tensile tester for operation by using the standard calibrating technique. A specimen is then mounted in the tester jaws. With a magnetic tape in place and the IPR prepared for operation, the operator enters into the record through the keyboard the request number, sample code number, test temperature, test direction code, operator number code, crosshead speed, sample width and length, and full-scale load. On signal from the keyboard, the tape moves over the recording head and simultaneously the tensile tester crosshead moves downward. When the specimen breaks, an electronic break detection unit stops the IPR and returns the crosshead to the preset specimen gage length. The operator then, by keyboard insertions, either accepts or rejects the completed tensile test, enters a new specimen thickness, and carries on with replicate determinations.

Three recording speeds, 1.5, 5, and 15 in./sec., are available; however, there are some limitations imposed on recording speed with regard to pulse density which results from the rate of crosshead travel. In our work, recordings at 5-in./sec. are suitable in the majority of cases.

3. Incremental Pulse Magnetic Tape Reader. The incremental pulse magnetic tape reader (IPMTR) is an accessory which is under control of the computer (Fig. 4). Its purpose is to accept magnetic tape prepared on the IPR, read the pulses from the tape, and supply the information in a form acceptable to the computer. Essentially the IPMTR accumulates the strain count, and, when it encounters a stress count, it forms a number representing an X,Y coordinate on the tensile curve. This accumulation of stress and strain increments is stored into computer memory.

Fig. 4. Computer system (left to right): incremental pulse reader, digital computer, and typewriter.

Strain count accumulation then continues until the next stress count is encountered, at which time another X,Y coordinate number is formed and stored in computer memory. Counting is then resumed, and the numbers formed are stored in the computer memory until the curve is completely characterized and stored.

Reading speeds of 5, 8, and 15 in./sec. are provided on this instrument; however, reading at 15 in./sec. magnetic tapes recorded at 5 in./sec. (IPR record at 5 in./sec.) provides for maximum fidelity with respect to pulse counting and the greatest saving in time with respect to magnetic tape processing.

4. General Description of the Computer. The computer used in this work is a general-purpose magnetic-drum digital computer (Bendix G-15D). Basically it is a straight binary machine having a storage capacity of 2176 words of 29 bits each. Primary input-output is by electric typewriter, but a photoelectric tape reader, magnetic tape readers, or punched cards may be used as input devices.

For general calculation work special routines are available, including the several interpretive Intercom systems which operate in floating decimal arithmetic, using six significant figures in the fractional part and an excess 50-exponent range between 12 and 88. For example, numbers as large as 10^{+38} or as small as 10^{-38} may be developed by the computer during computation.

Stress–Strain Data Program

This program* (a list of instructions for data input, solving of mathematical equations, and typewriter output format) accomplishes the conversion of incremental digital stress–strain data stored on magnetic tape into various parameters useful in tensile testing. The input to the computer consists of magnetic tape containing the keyboard entries already described and stress and strain increments, terminated by the "OK" or "NG" (no good) keyboard signals. The program exists in permanent form on punched paper tape and is first read into the computer by means of its photoreader. A single command then starts the magnetic tape read-in and subsequent computation. Output follows automatically on the typewriter, with the data for each specimen arranged on a separate line so that similar values line up in vertical columns. Following computation of a group of specimens, the averages and standard deviations for each column are typed.

1. Computational Approach. The program is read photoelectrically into the computer only at the beginning of a series. The entire program is then internally stored in the computer and may be used indefinitely for any number of computations until deliberately replaced or until the computer is shut off.

The program places the input data into usable form by means of a special input and storage routine to read the recorded stress–strain data and keyboard entries into the computer memory, and a special reader-scan routine converts the data to the X,Y coordinate form.

One block of recorded information consists of a series of keyboard entries, the X,Y data pairs representing the stress–strain curve, and an "OK" or "NG" keyboard code. The input routine discards those blocks of data which terminate with an "NG" code. The sequence of keyboard entries is analyzed to determine whether the test represents the first break of a sample. This routine expects to find the sequence of keyboard entries as one of those described in the operating instructions. Deviations from an acceptable sequence are thereby picked up and error typeouts occur.

2. Actual Computations. The program is designed to permit a point-by-point analysis of the stress–strain coordinates and, with the use of the appropriate constants, to compute the following parameters for films: *(1)* corrected length of specimen; *(2)* initial maximum tensile modulus; *(3)* offset yield stress (at 3%, or other selected value); *(4)* strain at break (%); *(5)* strain at maximum stress (%); *(6)* tensile stress, maximum; *(7)* tensile stress at break; *(8)* work to break (kg.-cm./mm.^{2}). Also provided are averages and standard deviations of each of these parameters for the number of replicates made per sample.

The approximate sequence of computational operations is as follows. The first ten (or other preselected number) X,Y points are picked up, and the slope of the least-squares straight line through these points is computed. The first X,Y point is subtracted and the eleventh X,Y point is added to the appropriate sums and a new slope is calculated. If the second slope is greater than the first, the process is repeated; if it is less, the first slope is used to calculate the initial tensile modulus.

This approach to obtaining the modulus was chosen as the best mathematical compromise in duplicating the method conventionally used in choosing the proper portion of the initial stress–strain curve visually. It successfully eliminates human variability in selecting the best linearity. It also provides a basis for computing a correction for the slack unavoidably present in the specimen in the tester jaws when mounted. The program extrapolates this slope to zero stress and utilizes this intercept to calculate the corrected initial length, which in turn is used for subsequent strain computations. The specimen initial cross-sectional area is also computed (from the keyboard entries of width and thickness).

The program then starts scanning of consecutive

* Available to members of the Bendix G-15 Users Exchange Organization through the Program Distribution Secretary.

TABLE I

Typical Type-Out of Computer Tensile Test Data (for Mylar Polyester Film)

Identification Code: 9999.999; Test Code: 23.01.01; Crosshead Speed = 2.00; Specimen Width = 1.000; Specimen Length = 2.00; Full-Scale Pounds = 50.0

Thickness, mils	Corrected length, in.	Modulus, Kpsi	Yield stress, Kpsi	Elongation at break, %	Elongation at S_{max}, %	Stress at max, Kpsi	Stress at break, Kpsi	Work-to-break, kg.-cm./mm.²
1.00	2.020	537.6	13.9	131.3	129.6	22.2	21.8	81.01
1.00	2.024	556.8	13.9	135.9	135.9	23.1	22.7	86.36
1.00	2.022	576.3	14.4	141.3	141.3	24.5	24.5	92.98
1.00	2.020	573.0	14.6	139.0	139.0	24.5	24.5	91.88
1.00	2.027	623.4	14.1	151.8	151.8	25.8	25.8	103.64
Avg. 1.00	2.023	573.4	14.2	139.9	139.4	24.0	23.9	91.17
Std. dev. 0.00	0.003	28.5	0.3	6.8	7.6	1.2	1.4	8.04

X,Y pairs for a maximum Y and accumulates the area starting with the middle point used in the initial slope calculation. When a maximum Y is found, the current area (A_1) is saved and a new area (A_2) is accumulated while the scan continues to look for a new Y_{max}. If another maximum in Y is found which is higher than the previous one, the new Y_{max} is stored, the A_2 is added to A_1 and the process is repeated until all data have been so handled.

The strain at maximum stress is computed from the X,Y pair corresponding to the maximum Y (stress). The strain at break is computed from the X,Y pair immediately preceeding the break signal produced by the break detector (which may also be manually entered at the keyboard). Both strains are typed out in units of per cent elongation.

The maximum stress and the stress at break are similarly computed from the same X,Y pairs which were used for the corresponding strains. Output may be in Kpsi (thousands of psi) or in kg./mm.². Of course, for many types of film specimens, the stress-strain points at maximum and at break will coincide.

Offset yield stress is computed from the initial maximum modulus slope, offset a predetermined per cent strain. The intersection of this off-set slope line with the stress-strain curve provides the required yield stress.

Work-to-break is obtained by integration of the entire area under the stress-strain curve and is reported in metric units as kg.-cm./mm.².

Errors which occur as a result of operator faults have special type-outs to identify what the error was. Provision is made to correct these keyboard slip-ups, should the data be important enough to warrant it. Likewise, tests rejected by the "NG" keyboard signal are so identified.

Failure of the automatic break-detector results in erroneous type-outs of breaking stress and strain, although the parameters at maximum stress are still obtained and may be equally useful if the specimen fracture occurred at this point.

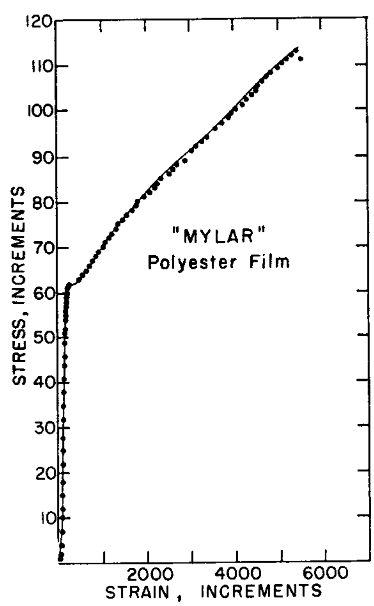

Fig. 5. Plot of digital data from magnetic tape record of a typical stress-strain test (●) compared with (——) pen recorder trace.

Multiple copies are, of course, available on the typewriter.

3. Output. The type-out occurs as shown in Table I. Figure 5 shows a typical stress-strain curve of Mylar (du Pont registered trademark) polyester film illustrating the faithfullness of reproduction of the strip-chart record.

CONCLUSIONS

Experience thus far, has demonstrated the following advantages.

1. Reduction of Human Error. This system suffers, in common with other automation systems, such limitations as reduced flexibility and complete dependence on correct instructions (both in permanent program and test parameters). However, it completely wipes out the arithmetical errors which are possible in the tedious manual calculation approach.

2. Increased Productivity. Total man-hours necessary to process a given quantity of test results are reduced considerably, due to elimination of repetitive manual calculations. Data previously not obtained routinely because of excessive time requirements, may now be economically produced. Complete sample data may be obtained more rapidly, assuming scheduled computer time is immediately available. Statistical data (standard deviation), too expensive to be provided routinely, are now regularly produced. Both the strip-chart record and the digital computations are available in permanent form.

3. Complete Digital Documentation of Test Information. The stress–strain data may be stored as long as desired for repeated computational modifications, etc. Unlike direct read-out devices which require reading of a limited number of data points by the operator, the entire record is obtained in this system. The program has built-in flexibility, enabling a qualified computer operator to alter either the test parameters or the program itself, both to correct errors and to conduct a variety of special studies.

4. Standardization of Computational Assumptions. Interpretation of stress–strain curves involves assumptions and compromises. A digital computer enables these to be carried out in standard fashion far more reproducibly then do manual methods involving human judgment. Other uses can, of course, be made of both the digital system and the program. Modifications of the program are possible for measurement of other strength properties of films (tear, compressive strength, modulus vs. temperature for T_g, etc.). Furthermore, the digitizers themselves can be attached to any rotation-analog device (i.e., most chart recorders) to measure a wide range of variables in such fields as spectrophotometry, rheology, titrimetry, light scattering or other measurements involving a chart recorder.

The computer can be used with appropriate programs to produce statistical correlations relating tensile properties to process studies and/or molecular structure. A program modification allowing punched tape output of the desired parameters in addition to the regular typeout facilitates this kind of study.

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Synopsis

A system is described for automatic collection of stress–strain data for polymeric films on magnetic tape for subsequent automatic data reduction and computation of a variety of stress–strain parameters. Two shaft analog-to-digital encoders attached to a conventional tensile tester feed digital information to an incremental pulse recorder which stores all stress and strain data in two channels on 0.625-in. magnetic tape. Specimen information and test constants are inserted by the operator through a keyboard located at the tensile tester. The tape is subsequently fed into a standard digital computer through a special incremental pulse magnetic tape reader. The data pulses are internally stored and converted by means of a special program into eight significant stress–strain parameters for polymeric film samples, plus averages and standard deviations for groups of replicate determinations. These parameters include: corrected length of specimen, initial maximum tensile modulus, offset yield stress, strain at break, strain at maximum stress, maximum tensile stress, tensile stress at break, and work to break. While the program described applies to polymer film testing, both it and the digital recording equipment accessories are applicable with suitable modification, to any analog experimental data. Significant savings in man-hours and increased information output result from use of this system.

Résumé

On décrit un système qui recueille automatiquement sur bande magnétique les données force de tension-allongement pour des films polymériques, dans le but d'employer ces données à calculer automatiquement une série de paramètres caractéristiques des courbes tension-allongement.

Deux transmissions analogues à des codificateurs manuels et attachées à un appareil conventionnel de mesure d'élasticité fournissent les informations mécaniques à un enregistreur d'impulsions différentiel; celui-ci emmagasine toute les données de tension-allongement en deux canaux sur une bande magnétique de 0.625 pouce. Les informations concernant l'échantillon et les constantes de test sont introduites par l'opérateur par l'intermédiaire d'un clavier situé sur l'appareil de mesure. Les données de la bande magnétique sont ensuite introduites dans une calculatrice ordinaire par l'intermédiaire d'un lecteur d'impulsions différentiel spécial. Les résultats sont emmagasinés et transformés par une programmation spécifique en huit paramètres significatifs des courbes tension-allongement pour les films polymériques en plus des déviations standard et moyenne pour des groupes de mesures identiques. Ces paramètres comprennent: la longueur corrigée de l'échantillon, le module d'élasticité initial maximum, la tension à laquelle la courbe devient nonlinéaire, l'élongation à la rupture, l'allongement à la tension maximum, la force de tension maximum, la tension à la rupture et le travail de rupture. Bien que la programmation et l'équipement d'enregistrement manuel qui sont décrits aient été appliqués à l'étude des films polymériques, ils peuvent être adaptés à tous résultats expérimentaux analogues moyennant une modification adéquate. L'emploi de ce système permet un gain de temps appréciable ainsi que l'obtention de résultats plus nombreux.

Zusammenfassung

Es wird ein System zur automatischen Aufzeichnung von Spannungs-Dehnungs-Daten von Polymerfilmen auf Magnetband zur darauffolgenden automatischen Reduzierung dieser Daten und Berechnung einiger Spannungs-Dehnungs-Parameter beschrieben. Von einem konventionellen Spannungsprüfgerät wurden mittels zweier angeschlossener Analog-Digital-Verschlüsselungsreinrichtungen die Daten an einen Differentialimpulsschreiber übertragen, der sämtliche Spannungs- und Dehnungsdaten in zwei Kanälen auf 0,625-in. Magnetband speicherte. Probendaten und Prüfkonstanten wurden mittels des Operators durch eine Verschlüsselungsvorrichtung, die sich am Spannungsprüfgerät befand, eingeführt. Das Magnetband wird anschliessend in einen Standard-Digitalcomputer durch einen speziellen Differentialimpulsleser für Magnetband eingebracht. Die Impulse der Daten werden innerhalb der Apparatur gespeichert und mit Hilfe eines speziellen Programms in acht charakteristische Dehnungs-Spannungs-Parameter für Polymerfilme, zusätzlich der Mittelwerte und Standardabweichungen für Gruppen von Parallelbestimmungen, umgewandelt. Diese Parameter beinhalten: Korrigierte Probenlänge, maximaler Anfangsspannungsmodul, Spannungsgrenze, Dehnung beim Bruch, Dehnung bei maximaler Spannung, maximale Zugspannung, Zugspannung beim Bruch und Brucharbeit. Obwohl das beschriebene Programm zur Prüfung von Polymerfilmen angewandt wird, können sowohl das Programm als auch das Digital-Recorder-Zubehör, mit entsprechenden Abänderungen, für sämtliche analogen experimentellen Daten angewandt werden. Durch Verwendung dieses Systems spart man Arbeitsstunden und erhält eine gesteigerte Ausbeute an Informationen.

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