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The Application of Data Processing to Mechanical Testing: Part 1: Tensile Testing of Thermoplastics

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The Application of Data Processing to Mechanical Testing: Part 1: Tensile Testing of Thermoplastics

by

B L Hammant

SUMMARY

The use of data-logging and data-processing techniques for the calculation of the results of tensile tests on polymers is described. It is shown that values obtained in this way do not differ significantly from those obtained by conventional means, and result in a considerable saving in time and effort. In addition, the results are consistently reproducible, and use of a data logger can give better recording accuracy than does a chart recorder.

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Reference: WAC/213/041

1 INTRODUCTION

The use of polymeric materials under exacting and critical conditions has resulted in the need for more information about their properties. Routine mechanical testing provides an important means of characterising materials, and consequently there has been a large increase both in the number of these tests and the amount of information required to be extracted from any one test. A large amount of the time to obtain results is spent in reading charts and in the calculation of properties from experimental measurements. This time may be greatly reduced by the use of computer processing of suitable data with an accompanying increase in accuracy and reproducibility.

A system is described in this report which has this capability; the report also describes its application to the tensile testing of thermoplastic materials. The use of the system with other mechanical tests will be described in a future report.

2 EXPERIMENTAL

A general view of the system is shown in Fig 1. The testing machine used is a 10 000 kg capacity Monsanto Tensometer Type E, which has electrical sensing of both load and strain. This machine was modified by the manufacturer to provide analogue signals proportional to load and strain which are independent of the chart recorder. The signals are scaled so that the maximum value of any load range and extensometer does not exceed 1 volt. These signals are supplied to a data logger, an Electronic Associates DART (Data Acquisition and Recording Terminal), which makes digital measurements of the signals, and punches the values onto paper tape via a Data Dynamics 110 punch. Values are recorded as 4 digit numbers; thus the maximum value would be 9999, equivalent to 1 volt in this case. Sequential values of load and strain are recorded at constant discrete time intervals. The speed of the punch, which is the limiting factor, allows up to 10 sequential data pairs to be recorded in a second; this was found to be adequate for the tests described herein. The DART is capable of higher rates of recording, up to 50 data-pairs a second using an incremental tape-recorder, for the study of higher testing rates.

Information about the specimen and test conditions is recorded at the start of each test, by means of a manual entry unit, developed by Electronic Associates Ltd. (See upper unit, Fig 2.) This consists of 6 blocks of thumb-wheel switches which are used to enter the following information onto the punched tape:

Specimen Number	Width (B)	Thickness (D)
Crosshead Rate (RT)	Load Range (LR)	Extensometer Code (II)

The test is conducted in the normal way, except that immediately before each test, the heading data is recorded on paper tape, and the data recording is started. During the course of a test, information about the next specimen may be set up on the manual entry unit, ready for immediate recording when the next specimen is inserted into the testing machine.

An Algol computer program has been developed, which operates on the logged data, and calculates the following properties:

Modulus	(E)	at yield and/or break
Stress	(σ)	
Strain	(ϵ)	
Energy/unit volume	(VW)	
Total energy dissipated	(TW)	

At the end of a batch of replicate tests, the following statistical results are calculated for the properties listed above:

- Mean
- Variance
- Standard Deviation
- Coefficient of Variation
- Sample size

3 DATA REDUCTION

A flow diagram of the computer program, simplified for the sake of clarity, is shown in Fig 3.

The working variables are L and ϵ, which normally represent load and extension respectively, but at the beginning of each test are used to input the value of specimen number and width. All extensometers used are numbered, and the extensometer code II indicates the correct electrical and strain characteristics to be used in calculations.

The first number on the heading unit consists of four digits, and is used for coding and numbering specimens. This number is automatically preceded by a digit '2', and thus can have any value from 20000 up to 29999. All other numbers, including logged data, have a maximum of 9999, and this fact is used to indicate the termination of a test.

The value of a control character is used to indicate the 'first-test' condition, and has the effect of causing control to jump round the 'print' and 'store' statements. When the next values of L and ϵ are read, if L is greater than 10^4, then control returns to START 1, and the first-test condition is again operative. This allows heading data to be corrected and re-entered, should an error be discovered before starting the test.

Values of L and ϵ are then read, and stored in open-ended arrays. The value of the variable moves through the array as successive data are read, until it is eventually discarded. Thus the arrays store current data, for use in calculations and for break detection.

The onset of meaningful data is determined as the condition when a number of successive values of load are shown to be increasing, ie

$$L_1 < L_2 \ldots\ldots < L_n$$

where the value of n is determined by the values of testing rate and sampling rate. When the value of ϵ reaches 9999, and the extensometer has reached its limiting value of strain, then further values are ignored, and the strain is replaced by crosshead displacement, calculated from elapsed time and crosshead rate. When this occurs, the values of energy/unit volume become meaningless, and are not printed.

4 CALCULATION OF ENERGY

Energy/unit volume, VW, is defined as the energy absorbed within the gauge length by the original volume of material. The incremental change with each pair of load/strain values is defined as

$$\delta VW = (\epsilon_2 - \epsilon_1)\, L_2/BD \qquad (1)$$

The total energy dissipated by the testing machine, TW, is assumed to be all absorbed by the specimen. The incremental change is given by

$$\delta TW = \frac{L_1 + L_2}{2} \times \frac{RT}{30\ S} \qquad (2)$$

where $\frac{RT}{30\ S}$ is the distance moved by the crosshead in the time between successive load determinations; RT is the crosshead rate, in mm/min, and S is the scanning rate, as data points per second.

5 BREAK DETECTION

Each value of load is compared with the previous value, and if found to be less, then the specimen is assumed to have either yielded or broken. The occurrence of break is ascertained by comparing the highest value reached at the time of detection with subsequent load values. If the values of load, L, fall rapidly to less than half its maximum, then break is indicated, and the highest value is taken as breaking load. Values of breaking stress, σ_B, breaking strain or extension, ϵ_B, and the energy to break, VW_B where applicable and TW_B, are calculated. Should break occur with no previous yield, then the results are printed in place of those for yield, and the words 'NO YIELD' are printed.

6 YIELD DETECTION

If load values are decreasing, but break is not detected, then the specimen has yielded. The yield point is determined as being where dL/dt, the slope of the load/time curve, equals zero. This is found by using Equation 4A in the Appendix:

$$L_y = \left[(L_3 - L_1) f + (L_4 + L_1 - L_2 - L_3) \frac{f^2}{2} \right] \frac{1}{2h} + L_2 \qquad (3)$$

where h is time interval separating load values, and f is defined as

$$f = (L_3 - L_1)/(L_2 + L_3 - L_1 - L_4) \qquad (4)$$

for $0 \leq f \leq 1$.

The strain, ϵ_y, at which yield occurs, is also calculated, again using Equation 3. Then values of yield stress, σ_y, and energy are calculated. The value of a control character is used to indicate the occurrence of yield, and any subsequent, similar effects are ignored.

7 MODULUS CALCULATION

Load and extension values are sequentially recorded at constant time intervals. The computer calculates a value of $\frac{dL}{dt}$ for each value of L, using Equation 5, with f = 1 (see Appendix, Equation 2A)

$$\frac{dL}{dt} = \frac{L_3 - L_1 + f\,(L_1 + L_4 - L_2 - L_3)}{2h} \qquad (5)$$

Equation 5, written in terms of ϵ is used to interpolate corresponding values of $\frac{d\epsilon}{dt}$ ($f = \frac{1}{2}$), and the gradient of the load/strain function, at time t, is then given by

$$\left(\frac{dL}{d\epsilon}\right)_t = \left(\frac{dL}{dt}\right)_t \div \left(\frac{d\epsilon}{dt}\right)_t$$

Similarly, values of $\frac{d\epsilon}{dt}$ are calculated for each ϵ value, and the corresponding values of $\frac{dL}{dt}$ are interpolated, to allow further values of $\frac{dL}{d\epsilon}$ to be calculated. Over a limited strain-range, it was found that plots of $dL/d\epsilon$ against L and ϵ were good approximations to straight lines, giving relationships of the form

$$\frac{dL}{d\epsilon} = aL + b$$

and

$$\frac{dL}{d\epsilon} = a^1\epsilon + b^1$$

where b and b^1 both represent the value $(\frac{dL}{d\epsilon})_0$, the slope at zero load and strain. A least-squares regression method is used to determine values of b and b^1, giving two estimates of $(\frac{dL}{d\epsilon})_0$; these are averaged, and used to calculate the modulus, E. The strain range for which $dL/d\epsilon$ values are computed is from 0.05 up to 0.3%. The occurrence of break, before the upper limit is reached, causes modulus to be estimated on the results obtained up to break.

8 TERMINATION OF TEST

If a value of L is read and found to be greater than 10^4 indicating that a new set of heading data has been reached, then control is returned to START 1; the test results are printed and conditions are reset for the start of another test.

9 DELETION OF RESULTS

After completing a test, if the heading data is recorded, with the second block (width B) set to 0000, then this will instruct the computer to print an asterisk against the results of that test, and not to store them for inclusion in the statistical analysis.

10 END OF BATCH

When the tests on a batch of replicate specimens are finished, the heading data is entered with both the second and third blocks (width B, thickness D) set to 0000. This causes the computer to print and store the last set of results, and then to carry out the statistical procedure. Width, thickness and all properties calculated from the test data are included, and the statistical results are printed out under the appropriate headings.

11 DISCUSSION OF RESULTS

Figs 4 and 5 illustrate the format of the computer results. Properties of a polycarbonate, which fails in a ductile manner, are shown in Fig 4; Fig 5 shows results for polymethylmethacrylate, representing a brittle type of failure. All tests were conducted at a crosshead rate of 25 mm min^{-1}.

A paired t-test was used to compare data-processed results with those calculated by hand from chart records of the same tests. These results are listed in Table 1, for two data sampling rates, 2.5 and 10 load/extension data-pairs a second. Only the properties commonly obtained are given, since normally time does not permit assessments of energy to be made. Energy values are calculated by the computer, at a negligible cost in time.

It is apparent from Table 1 that there are significant differences between the results calculated by the two methods. Inspection shows a tendency for the computer results and their associated scatter to be higher than those obtained from the chart record; values of failing strain show a particularly large discrepancy. It was suspected that these differences arose from limitations in the response of the chart recorder, and hence its inability to accurately follow fast changes. This was confirmed by repeating the trial at a tenth of the crosshead rate, ie 2.5 mm min^{-1}. The statistical comparison of results for this rate is given in Table 2, and it shows that the differences have been virtually eliminated.

Table 3 gives a comparison of properties obtained at the two data sampling rates, using a 2 sample t-test. Since any differences are shown to exist in both computer and manually calculated results, and are thus characteristic of the samples, it appears that the lower rate of sampling is adequate. Thus the quantity of recorded data may be minimised, so reducing the time of processing. A further implication is that by using the higher sampling rate, the system may be used with crosshead rate increased by a factor of four, with no loss of resolution.

The time taken to obtain the final results by data processing was approximately a tenth of that needed for manual calculation, using a desk calculating machine, and which did not include the statistical analysis or a typed record.

It is concluded that if a computer facility is available, then the use of data processing techniques in conjunction with mechanical tests has the following advantages:

(i) It reduces the time required for calculating results, and frees staff from this tedious task to do other work.

(ii) It removes the possibility of subjective assessment in measurements, and allows more information to be extracted from any one test.

(iii) Since the method of recording has a fast response, it can extend the range of application of the mechanical test equipment, and give more accurate results, within the limitations of any numerical methods which are used.

(iv) Results are obtained as a clear, typed format, which may be used for direct inclusion in reports or data sheets.

NUMERICAL TECHNIQUES

Numerical methods for interpolation and differentiation have been developed, but are not necessarily original. The methods are based on the assumption that a small region of an X,Y plot approximates to a second degree equation and the second derivative, $\frac{d^2Y}{dX^2}$ is essentially constant, ie the slope is changing in a uniform manner. A constant, small interval is assumed between successive values of X (see Fig 6).

DIFFERENTIATION

For a point (X,Y) such that $X_2 \leqslant X \leqslant X_3$, we define f as

$$f = \frac{X - X_2}{X_3 - X_2}$$

$$= \frac{X - X_2}{h}$$

Thus f is the fractional value of h from X_2 to X along the abscissa, and takes values between 0 and 1.

Assuming $\frac{d^2Y}{dX^2}$ is constant, then the slope, $m = \frac{dY}{dX}$, at (X_n, Y_n) is given by

$$m_n = \frac{Y_{n+1} - Y_{n-1}}{2h}$$

By the 'method of mixtures',

$$m_X = m_2 (1 - f) + m_3 f$$

$$= m_2 + f (m_3 - m_2) \qquad (1A)$$

and by substitution

$$\left(\frac{dY}{dX}\right)_X = \frac{(Y_3 - Y_1) + f [(Y_4 - Y_2) - (Y_3 - Y_1)]}{2h} \qquad (2A)$$

When used to calculate modulus, f takes the values 0, $\frac{1}{2}$, 1, to permit $\frac{dL}{dt}$ and $\frac{d\epsilon}{dt}$ to be calculated for the same points in time.

TURNING POINTS

At a maximum (or minimum) $\frac{dY}{dX} = 0$; thus Equation 2A becomes equal to 0, and by rearrangement

$$f = \frac{Y_3 - Y_1}{(Y_3 - Y_1) - (Y_4 - Y_2)} \qquad (3A)$$

The value of X at the turning point is given by

$$X_f = X_2 + f\,h$$

If the region of the turning point is found by inspection, f and X_f may be calculated.

Interpolation

As defined, f is a simple function of the independent variable, X, and if we arbitrarily define h as having the value of unity, then

$$f = X - X_2$$

Hence
$$\frac{dX}{df} = 1$$

Then Equation 1A may be restated as

$$\frac{dY}{df} = m_2 + f\,(m_3 - m_2)$$

and
$$dY = [m_2 + f\,(m_3 - m_2)]\,df$$

Integrating

$$Y_f = m_2\,f + (m_3 - m_2)\,\frac{f^2}{2} + \text{constant}$$

Since this is only true for $Y_2 \leqslant Y \leqslant Y_3$, then the constant has the value of Y_2, therefore

$$Y_f = \frac{(Y_3 - Y_1)\,f + [(Y_4 - Y_2) - (Y_3 - Y_1)]\,\frac{f^2}{2}}{2} + Y_2 \qquad (4A)$$

Together with Equation 3A, this result is used to determine the values of L and ϵ at yield, the maximum in the load/strain relationship.

TABLE 1

COMPARISON OF COMPUTER AND MANUALLY CALCULATED RESULTS, USING A PAIRED T-TEST. CROSSHEAD RATE = 25 mm min^{-1}

Property	Mean*		Variance*		Significance Level
	Computer	Manual	Computer	Manual	
Polycarbonate					
2.5 s^{-1}					
Modulus	3.03	2.94	0.003	0.015	0.1
Yield Stress	6.17	6.10	0.001	0.000	0.001
Yield Strain	6.09	3.84	0.006	0.003	0.001
Break Stress	5.96	5.90	0.291	0.282	0.001
10 s^{-1}					
Modulus	3.10	3.03	0.010	0.019	0.1
Yield Stress	6.19	6.12	0.000	0.000	0.1
Yield Strain	5.94	3.79	0.016	0.006	0.001
Break Stress	6.09	6.05	0.438	0.454	0.001
PMMA					
2.5 s^{-1}					
Modulus	4.22	4.39	0.018	0.129	0.1
Break Stress	7.62	7.65	0.148	0.078	0.1
Break Strain	3.46	2.64	0.613	0.143	0.01
10 s^{-1}					
Modulus	4.14	4.50	0.004	0.021	0.001
Break Stress	7.91	7.83	0.058	0.063	0.01
Break Strain	4.01	2.81	0.219	0.074	0.001

*For clarity, the exponent terms have been omitted

TABLE 2

COMPARISON OF COMPUTER AND MANUALLY CALCULATED RESULTS, USING A PAIRED T-TEST. CROSSHEAD RATE = 2.5 mm min^{-1}

Property	Mean*		Variance*		Significance Level
	Computer	Manual	Computer	Manual	
Polycarbonate					
Modulus	3.14	3.10	0.035	0.010	0.1
Yield Stress	5.85	5.79	0.000	0.000	0.02
Yield Strain	5.88	5.77	0.031	0.001	0.1
Break Stress	5.98	5.97	0.303	0.269	0.1
PMMA					
Modulus	3.71	3.71	0.416	0.002	0.1
Break Stress	6.23	6.22	0.383	0.261	0.1
Break Strain	3.41	3.46	2.88	2.83	0.05

*For clarity, the exponent terms have been omitted

TABLE 3

COMPARISON OF RESULTS OBTAINED AT THE TWO DATA SAMPLING RATES, FOR BOTH COMPUTER AND MANUAL CALCULATION METHODS, USING A 2 SAMPLE T-TEST

Property	Significance Level	
	Computer	Manual
Polycarbonate		
Modulus	0.1	0.1
Yield Stress	0.1	0.05
Yield Strain	0.05	0.05
Break Stress	0.1	0.1
PMMA		
Modulus	0.1	0.1
Break Stress	0.1	0.1
Break Strain	0.1	0.1

KEY TO FIGURES

S No 51/72/CJ

ERDE TR 99

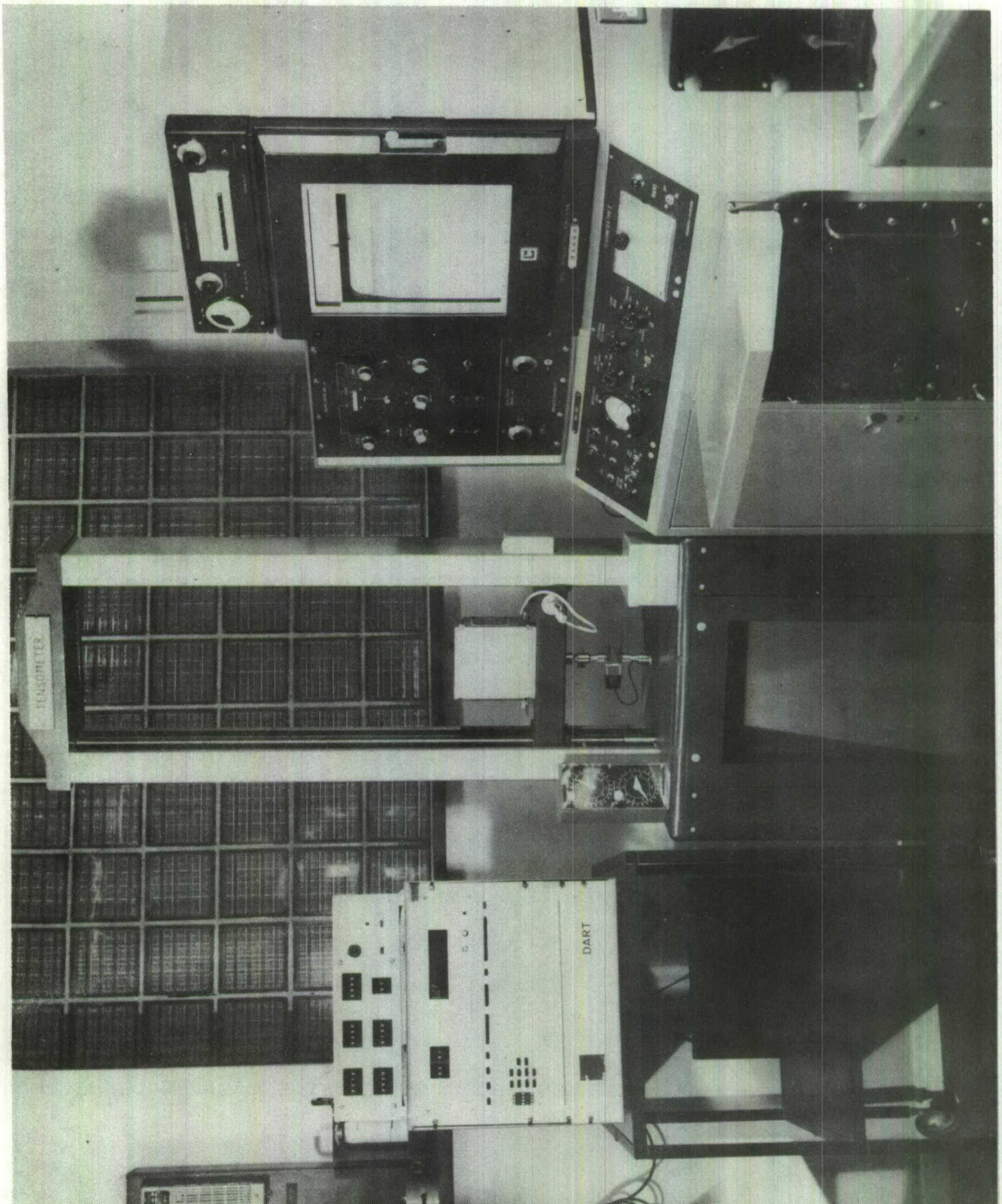


FIG. 1

ERDE TR 99

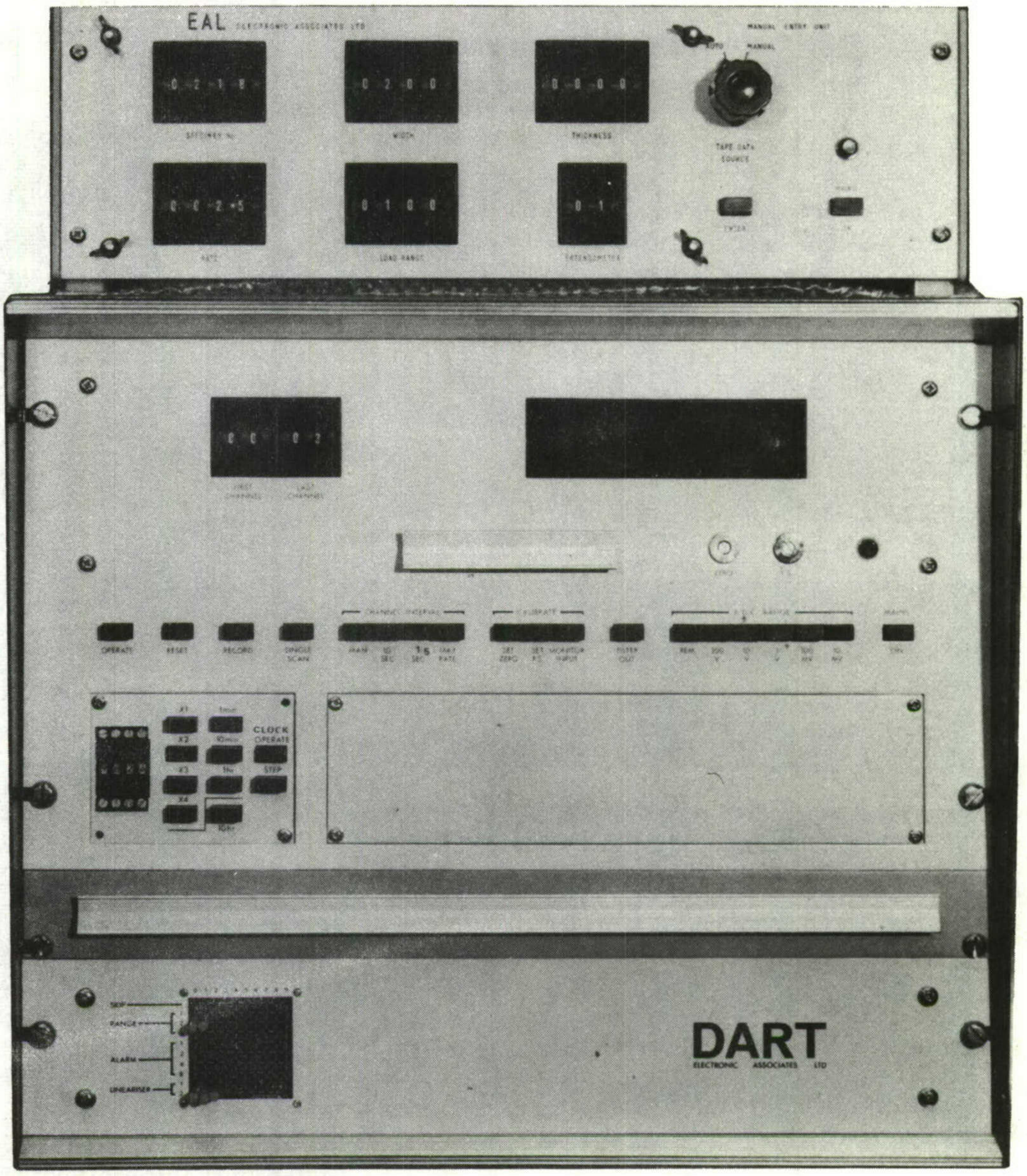


FIG. 2

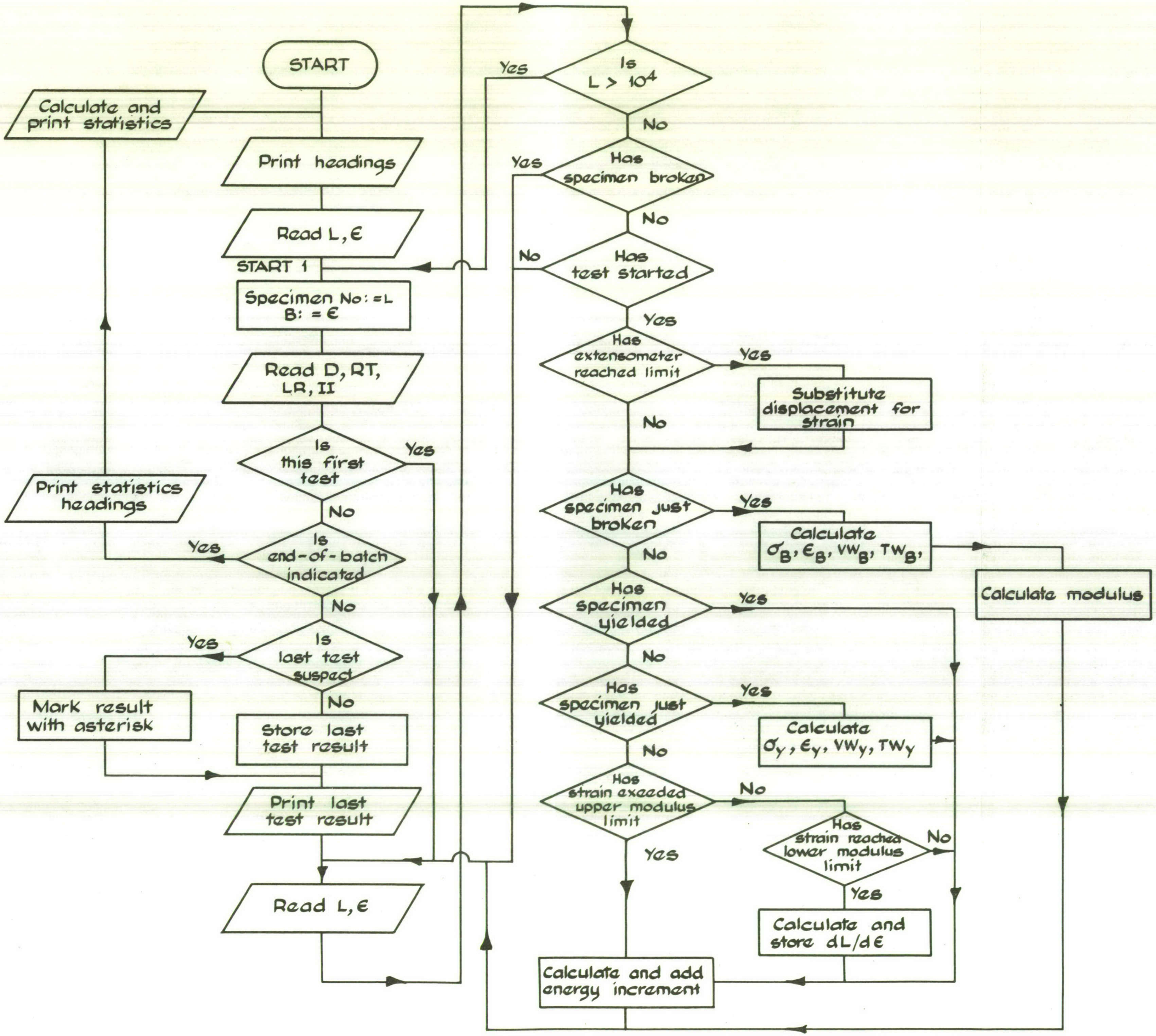

START
Print headings
Read L, ϵ
START 1
Specimen No: =L
B: = ϵ
Read D, RT, LR, II
Is this first test
Yes
No
Is end-of-batch indicated
Yes
No
Print statistics headings
Calculate and print statistics
Is last test suspect
Yes
No
Mark result with asterisk
Store last test result
Print last test result
Read L, ϵ
Is L > 10^4
Yes
No
Has specimen broken
Yes
No
Has test started
No
Yes
Has extensometer reached limit
Yes
No
Substitute displacement for strain
Has specimen just broken
Yes
No
Calculate σB, ϵB, VWB, TWB,
Calculate modulus
Has specimen yielded
Yes
No
Has specimen just yielded
Yes
No
Calculate σy, ϵy, VWy, TWy
Has strain exceeded upper modulus limit
No
Yes
Has strain reached lower modulus limit
No
Yes
Calculate and store dL/dϵ
Calculate and add energy increment

FIG.3

PDP101 N.M.SUPERINTENDENCY

THERMOPLASTIC MATERIALS.

TENSILE PROGRAM.

VW = ENERGY ABSORBED/UNIT VOLUME IN GAUGE LENGTH.
TW = TOTAL ENERGY ABSORBED BY SPECIMEN.
IF NO VALUE IS GIVEN FOR VW, THEN THE STRAIN QUOTED UNDER THAT HEADING IS THE TOTAL SPECIMEN EXTENSION, IN CM., DERIVED FROM CROSS-HEAD DISPLACEMENT.
* DENOTES SUSPECT SPECIMEN.

					YIELD OR BREAK		BREAK		YIELD OR BREAK		BREAK	
NO.	RATE	WIDTH	DEPTH	E	STRS	STRN	STRS	STRN	VW	TW	VW	TW
	MM/MIN	MM	MM	N/M↑2 X10-9	N/M↑2 X10-7	% OR CM	N/M↑2 X10-7	% OR CM	J/CC	J	J/CC	J
7	25.00	4.530	3.170	3.005	6.184	6.04	6.831	4.17	2.73	1.68	----	32.4
8	25.00	4.510	3.180	3.203	6.161	5.76	6.553	3.59	2.68	1.66	----	26.9
9	25.00	4.500	3.170	.2055	2.613	.477	NO BREAK		----	.622	----	----*
9	25.00	4.520	3.170	3.217	6.196	5.88	6.004	2.83	2.75	1.75	----	20.3
10	25.00	4.510	3.180	3.049	6.183	6.08	5.978	2.86	2.76	1.71	----	20.5
11	25.00	4.520	3.180	3.048	6.204	5.94	5.105	2.11	2.69	1.68	----	14.6

STATISTICAL ANALYSIS.

				YIELD OR BREAK		BREAK		YIELD OR BREAK		BREAK	
	WIDTH	DEPTH	E	STRS	STRN	STRS	STRN	VW	TW	VW	TW
	MM	MM	N/M↑2 X10-9	N/M↑2 X10-7	% OR CM	N/M↑2 X10-7	% OR CM	J/CC	J	J/CC	J
MEAN	4.518	3.176	3.104	6.186	5.94	6.094	3.11	2.72	1.70	0.00	23.0
VARIANCE	.0001	.0000	.0096	.0003	.016	.4384	.622	.001	.001	0.00	46.8
ST.DEV.	.0084	.0054	.0982	.0162	.128	.6621	.789	.038	.033	0.00	6.84
C. OF V.	.1850	.1716	3.162	.2612	2.16	10.86	25.4	1.38	1.92	0.00	29.8
N	5	5	5	5	5	5	5	5	5	0	5

FIG.4

PDP101 N.M.SUPERINTENDENCY

THERMOPLASTIC MATERIALS.

TENSILE PROGRAM.

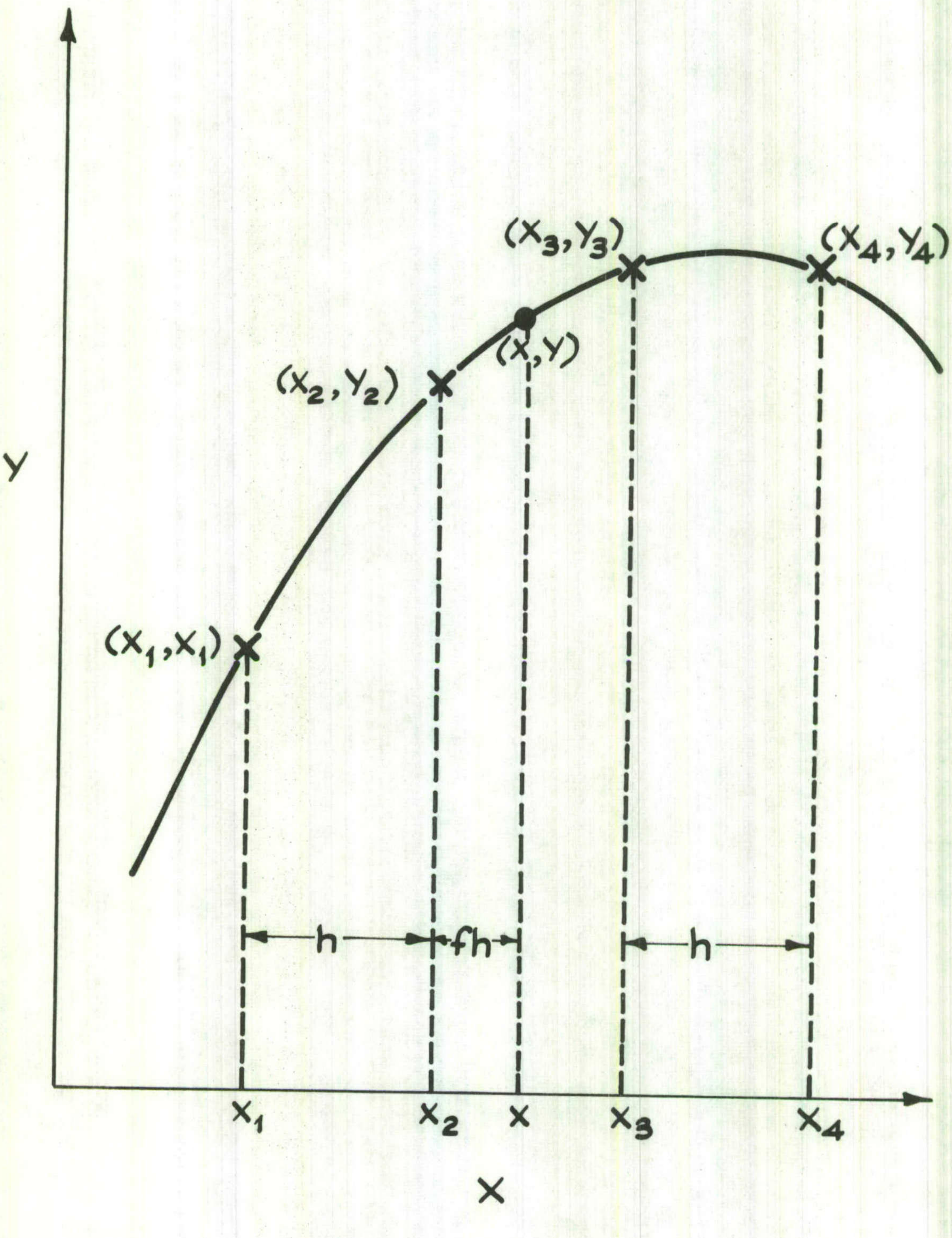
VW = ENERGY ABSORBED/UNIT VOLUME IN GAUGE LENGTH.
TW = TOTAL ENERGY ABSORBED BY SPECIMEN.
IF NO VALUE IS GIVEN FOR VW, THEN THE STRAIN QUOTED UNDER THAT HEADING IS THE TOTAL SPECIMEN EXTENSION, IN CM., DERIVED FROM CROSS-HEAD DISPLACEMENT.
* DENOTES SUSPECT SPECIMEN.

					YIELD OR BREAK		BREAK		YIELD OR BREAK		BREAK	
NO.	RATE	WIDTH	DEPTH	E	STRS	STRN	STRS	STRN	VW	TW	VW	TW
	MM/MIN	MM	MM	N/M↑2 X⏨-9	N/M↑2 X⏨-7	% OR CM	N/M↑2 X⏨-7	% OR CM	J/CC	J	J/CC	J
17	25.00	4.520	3.180	4.175	8.019	4.28	NO YIELD		2.32	1.65	----	----
18	25.00	4.540	3.190	4.028	7.502	3.37	NO YIELD		1.55	1.20	----	----
19	25.00	4.520	3.180	4.137	8.139	4.59	NO YIELD		2.55	1.73	----	----
20	25.00	4.540	3.190	4.136	7.959	3.77	NO YIELD		1.91	1.44	----	----
21	25.00	4.550	3.190	4.214	7.925	4.03	NO YIELD		2.10	1.52	----	----

STATISTICAL ANALYSIS.

				YIELD OR BREAK		BREAK		YIELD OR BREAK		BREAK	
	WIDTH	DEPTH	E	STRS	STRN	STRS	STRN	VW	TW	VW	TW
	MM	MM	N/M↑2 X⏨-9	N/M↑2 X⏨-7	% OR CM	N/M↑2 X⏨-7	% OR CM	J/CC	J	J/CC	J
MEAN	4.534	3.186	4.138	7.909	4.01	0.000	0.00	2.08	1.51	0.00	0.00
VARIANCE	.0002	.0000	.0048	.0584	.221	0.000	0.00	.148	.043	0.00	0.00
ST.DEV.	.0134	.0054	.0694	.2416	.470	0.000	0.00	.385	.208	0.00	0.00
C. OF V.	.2958	.1709	1.677	3.055	11.7	0.000	0.00	18.5	13.8	0.00	0.00
N	5	5	5	5	5	0	0	5	5	0	0

FIG.5



$0 \leq f \leq 1$

FIG. 6

Technical Report No 99
Explosives Research and Development Establishment
THE APPLICATION OF DATA PROCESSING TO MECHANICAL TESTING: PART 1: TENSILE TESTING OF THERMOPLASTICS
Hammant B L
11 pp, 3 tabs, 6 figs

The use of data-logging and data-processing techniques for the calculation of the results of tensile tests on polymers is described. It is shown that values obtained in this way do not differ significantly from those obtained by conventional means, and result in a considerable saving in time and effort. In addition, the results are consistently reproducible, and use of a data logger can give better recording accuracy than does a chart recorder.

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