SAE International™

SURFACE VEHICLE RECOMMENDED PRACTICE

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High Strain Rate Tensile Testing of Polymers

RATIONALE

Not applicable.

1. AIMS AND SCOPE

1.1 This recommended practice is a guideline for generating high strain rate tensile properties under defined conditions of unreinforced and reinforced plastics used in the automotive industry. Several types of test specimens are identified to suit different types of materials and test rates.

1.2 This document is intended for strain rates between 10^{-3}/s and 10^{3}/s. Test procedures for rates of 10^{-2}/s and below; i.e., quasi-static conditions, are described in ASTM D 638 and ISO 527-1. The procedures in this document include quasi-static testing in order to provide a common test rate for both quasi-static and dynamic test programs. The general procedures listed in ASTM D 638 and ISO 527-1 should be followed when appropriate.

1.3 The main purpose of this document is to determine the relative effects of increasing strain rate on the measured material properties. Data generated from these tests are comparative in nature. High rate tensile tests will not generate basic material properties as accurately as those generated by quasi-static tests.

1.4 The scope of this document covers

- Rigid and semi-rigid thermoplastic molding and extrusion materials, including filled and reinforced compounds in addition to unfilled types, and
- Rigid and semi-rigid thermoplastic sheets.

Thermosetting materials, rigid cellular materials, and sandwich structures containing cellular material were not evaluated as part of this document. However, the test procedures may be used as a general guideline for these materials. This document is not recommended for materials whose internal structure is on the scale of the gage width and length of the selected specimen configuration. Fiber-filled polymers may require additional testing using an alternate sample geometry to establish the effect of strain rate on the measured properties.

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein.

2.1.1 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: (610) 832-9585, www.astm.org.

ASTM D 638 Standard Test Method for Tensile Properties of Plastics

ASTM D 883 Standard Terminology Relating to Plastics

ASTM D 1822 Standard Test Method for Tensile-Impact Energy to Break Plastics and Electrical Insulating Materials

2.1.2 ISO Publications

Available from American National Standards Institute (ANSI), 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ISO 294-1 Plastics—Injection moulding of test specimens of thermoplastic materials—Part 1: General principles, and moulding of multipurpose and bar test specimens

ISO 527-1 Plastics—Determination of tensile properties—Part 1: General principles

ISO 527-2 Plastics—Determination of tensile properties—Part 2: Test conditions for molding and extrusion plastics

ISO 3167 Plastics—Multipurpose test specimens

ISO 8256 Plastics—Determination of tensile-impact strength

2.2 Related Publications

The following publications are provided for information purposes and are not a required part of this document.

2.2.1 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: (610) 832-9585, www.astm.org.

ASTM D 3641 Standard Practice for Injection Molding Test Specimens of Thermoplastic Molding and Extrusion Materials

2.2.2 European Structural Integrity Society Publications

Available from TC 5 Subcommittee on Dynamic Testing at Intermediate Strain Rates, ESIS, Geesthacht, Germany, www.esisweb.org.

Copies can be obtained from: Professor K-H Schwalbe, GKSS-Forschungszentrum Geesthacht, 21502 Geesthacht, Germany, schwalbe@gkss.de.

ESIS P7–00 Procedure for Dynamic Tensile Tests

Available from ISO Technical Committee ISO/TC 61, Plastics, Subcommittee SC 2, Mechanical Properties

ISO/FDIS 18872 2006(E) Final Draft Plastics—Determination of tensile properties at high strain rates

3. INTERFERENCE

3.1 Specimens may be molded or machined to final dimensions, or cut or punched from finished and semi-finished products such as moldings and extruded or cast sheet. The specimen preparation methods may affect the test results[1], and guidance on preparation may be found in appropriate material specifications. The procedures specify preferred test specimen dimensions based on the maximum test rate. Tests that are carried out on specimens of different dimensions may produce results that are not directly comparable, especially with regard to plastic deformation behavior.

3.2 Specimens must be properly conditioned after molding or extrusion to allow the material to come to thermal equilibrium with the environment and allow materials to go through stages of secondary crystallization or amorphous densification. Failure to properly condition the material may influence final test results. Guidance on conditioning may be found in appropriate material specifications.

3.3 Other factors, such as the load application, strain measuring device, equipment response, etc., can also influence results. Consequently, these factors must be carefully controlled and recorded.

4. TERMINOLOGY

The terms and abbreviations used in this document are listed in Table 1. Additional terms and definitions are described in ASTM D 638, ASTM D 883, and ISO 527-1.

5. SIGNIFICANCE AND USE

5.1 Stress waves of varying amplitudes are present in the gage section during a high rate test and a homogeneous stress state does not exist. The goal in high strain rate tests is to introduce enough stress waves in the gage area to produce an approximate equilibrium relatively quickly after load is introduced into the specimen. Thus, a "quasi-homogeneous" stress and strain field will exist and the nominal stress and strain states can be defined.

1 ASTM 638-01 Section 6.1.4 Notes 6 and 11, ISO 294-1:1996 Introduction.

TABLE 1 - TERMINOLOGY AND SYMBOLS

Symbol	Unit	Term
d	m	Displacement
E	Pa	Elastic modulus
ε_{calc}		Calculated strain
$\dot{\varepsilon}_{nom}$	s^{-1}	Nominal plastic strain rate
$\dot{\varepsilon}$	s^{-1}	Strain rate
$\dot{\varepsilon}_{elas}$	s^{-1}	Elastic strain rate
$\dot{\varepsilon}_{plas}$	s^{-1}	Plastic strain rate
ε_y		Yield strain
l_s	m	Length of narrow parallel-sided portion of specimen
L_{fixt}	m	Length of fixturing from grip end closest to load-measuring device and load-measuring device.
L_{dbg}	m	Distance between grip locations on specimen
LVDT		Linear variable differential transformer
N_{gage}		Number of reflected waves in gage length
ρ	kg/m^3	Density
$\dot{\delta}$	m/s	Displacement rate (Velocity of crosshead or actuator)
r		Repeatability
R		Reproducibility
$s_{\bar{x}}$	MPa	Standard deviation of cell averages
s_r	MPa	Repeatability standard deviation
S_r	MPa	Reproducibility standard deviation
t_{wave}	s	Travel time for a single wave
t_{yield}	s	Time to yield
v_{fixt}	m/s	Wave propagation speed in fixturing
v_m	m/s	Wave propagation speed through material
$\bar{x}$	MPa	Cell average

High rate tests dictate the use of a small specimen in order to maximize the number of reflected stress waves along the gage length. Use of a small specimen may violate the spirit of some static test methods. However, if it is assumed that specimen geometry will bias the results equally over the range of strain rates used, the strain rate dependency of the material properties can be determined.

5.2 Many properties of polymeric materials vary with logarithmic changes in strain rate. Therefore, it is often necessary to test across at least four orders of magnitude in strain rate to properly determine the effects of strain rate on the measured material properties. The same specimen geometry and test procedures should be used across all tested rates.

6. SPECIMEN CONFIGURATION

6.1 The recommended specimen configuration will depend on the maximum desired strain rate, material stiffness, material density, yield strain, stroke displacement rate (crosshead or actuator speed), and equipment resonant frequency. The same specimen geometry should be used across all tested rates so that specimen geometry will not be a source for variability in the data.

It is difficult to predict the relative response at high rates. Appendix A describes how to select an initial specimen geometry. The specimen geometries listed in Appendix A are general guidelines. Analysis of the test results should be the final guide as to whether changes in specimen geometry or equipment are needed.

6.2 Data obtained from samples that fail outside the narrow test section, such as in the grip area or in the radius region, should be eliminated from the data set.[2] Figure 1 defines the gage, grip and radius region of the test specimen. If a significant fraction of the failures in a sample population are unacceptable, the method of loading, specimen geometry/preparation, and/or material being tested should be reexamined for suitability to this method of high strain rate testing.

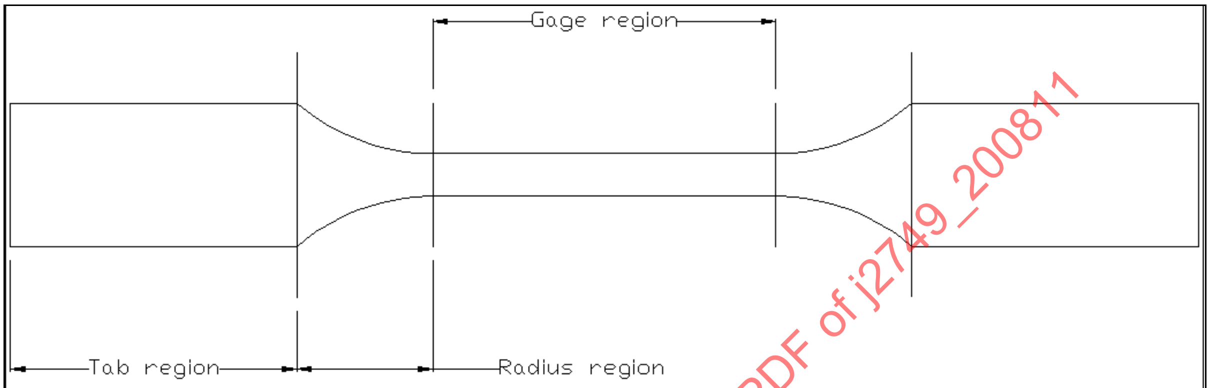

FIGURE 1 - IDENTIFICATION OF THE GRIP, GAGE AND RADIUS REGION OF A TEST SAMPLE

7. APPARATUS

7.1 Ideally, the test machine will provide a constant displacement rate from the onset of load application through the point of necking/instability. This document allows a tolerance in the displacement rate of ±15%, excluding the region at the onset of loading. The displacement rate should be constant by the time the specimen is loaded to a level equivalent to 25% of its yield load. Deviations from these percentages should be reported and potential causes and potential effects on the results should be included.

The effect of a changing crosshead rate during a test is dependent on the material. If the material is not strain-rate sensitive, then larger changes in crosshead rate (e.g. >15%) should not affect the material properties. If a material is strain-rate sensitive, then a 15% tolerance band on the rate may not be tight enough.

7.2 Damping at the onset of loading is recommended for strain rates above 10/s. The damping method should have a minimal effect on the initial material response to the load application. Any damping-related effects should be gone by the time the applied load is at 25% of yield.

7.3 Grips should be lightweight to minimize inertial effects.

7.4 Load can be measured with standard devices for strain rates less than 1/s if the –0.5 dB frequency of the complete measuring equipment chain is at least 250 Hz. Rates above 1/s require proportionally higher frequency responses. A test system with a resonant frequency response of at least 4 kHz is needed when testing above 200/s. A lower system resonant frequency may result in unacceptably high amplitude stress waves in the response. Appendix A provides more details.

7.5 The displacement signal of a LVDT or comparable device should be used with caution to determine strain. The displacement data reflect the global behavior of the load train and normally do not have the resolution to record the transition from elastic to plastic deformation or to determine the modulus of elasticity. In addition, the displacement measurement may not accurately reflect the post-yield strain, especially if a localized reduction in the cross-section occurs, i.e. necking.

[2] ASTM 638–01 Section 7.3 and ISO 527-1:1993 Section 7.2.

Strain along the gage length may be measured with various techniques, such as strain gages, low inertia extensometers, clip-on extensometers, and non-contact extensometers. Care should be taken that the measurement techniques do not affect the test results, as mentioned in Appendix B.

The practical upper test rate to use attached extensometers will depend on the weight and durability of the extensometer. Inertial effects may be a significant factor at strain rates as low as 1/s.

7.6 It is necessary to determine whether the equipment is capable of accurately recording the test. The maximum test rate for a given test system will depend on the frequency response of the transducers, signal conditioners, signal amplifiers, and recorders. Further, each component of the test system, as well as the whole system, may have a characteristic resonant frequency. It is necessary to determine the combined effect of all of the system components in order to identify the maximum test rate. Details are provided in Appendix A.

7.7 The potential for system resonance; i.e. ringing, increases with the test rate. Discreet waves can occur in the elastic or plastic portion of the response, as described in Appendix A and shown in Figure 2. The relative wave amplitude may be significant, especially in the pre-yield response. Ringing can be minimized by:

- Use of a damping method for strain rates above 10/s.
- Use of lightweight grips to minimize inertial effects.
- Minimizing the length of the load train.
- Measuring load with a high frequency response device.
- Selecting a specimen that has a small enough gage area to ensure that at least 10 or 15 stress waves propagate through the gage section before yield, as described in Appendix A.

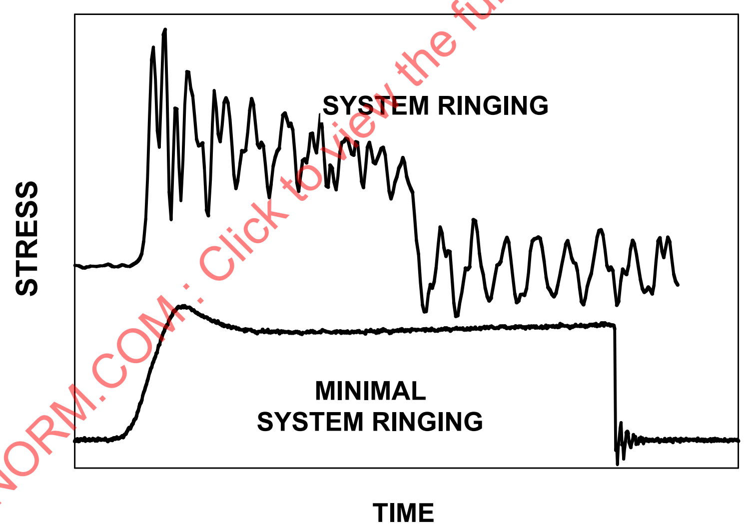

FIGURE 2 - DATA OBTAINED FROM A TEST EXHIBITING MINIMAL SYSTEM RINGING AND SIGNIFICANT SYSTEM RINGING

8. DATA ANALYSIS

The procedures described in ASTM D 638 and ISO 527 should be used where appropriate to identify and determine items such as yield stress, ultimate stress, and modulus. The relative combined effect of specimen size, system resonant frequency, and material can be significant.

8.1 Strain Rate

The strain rate normally varies greatly during a test. If large amplitude stress waves are observed, the instantaneous strain rate may vary from large positive to large negative values.

It is important to report the method of rate calculation and the strain range over which the rate is calculated. A nominal strain rate, given by the following equation,

$$\dot{\varepsilon}_{nom} = \dot{\delta}/l_s \tag{Eq. 1}$$

is often used as a rough estimate of the plastic strain rate. The nominal strain rate assumes that the specimen plastically deforms and that all of the strain occurs within the straight parallel gage section. The nominal strain rate is not a good indicator of the actual strain rate in brittle materials. The strain rate in brittle materials generally increases up to failure because plastic deformation may not occur.

The elastic strain rate can vary by an order of magnitude from the onset of stress to yield. In contrast, the plastic strain rate can often be approximated by a constant in a region just past yield up to the point of instability. Unless otherwise indicated, the rate for a dynamic test will be described by the plastic strain rate.

8.2 Modulus

The user shall indicate the method of modulus determination. The same method should be used across all test rates. It should be noted that it might become difficult to define an “elastic” range for modulus measurement as the test rate increases. Bending often occurs during the onset of load. Compensation for bending is necessary for capturing strain data in the elastic and pre-yield region (refer to Appendix B for details).

8.3 Time Shift

A measurable time lag may be noted between the various recorded data channels, such as load and strain, as the test rate increases. These data streams may need to be reconciled.

8.4 High Amplitude Stress Waves

The relative amplitude and frequency of the ringing can vary with material, fixturing, and equipment. The circled area in Figure 3 illustrates how ringing can make data interpretation difficult, especially for low elongation materials. The identified failure or peak stress is a function both of the material and the amplitude of the ringing response.

No quantitative method currently exists to define unacceptable system ringing. One can differentiate on a qualitative basis, such as that shown in Figure 4. However, the end-user must examine both the qualitative and quantitative aspects of the data being provided by the testing laboratory and is the final judge.

9. REPORT

In addition to the reporting requirements of ASTM D 638 or ISO 527, the report shall indicate the following: type of test equipment, filtering (if applicable), sampling rate, specimen configuration, failure location, strain measurement method, nominal strain rate (per Eq. 1), plastic strain rate and region over which plastic strain rate is calculated (if strain is directly measured). As indicated in both ASTM D 638 and ISO 527, it is very important that information be provided on specimen conditioning as this can greatly affect the test results. If strain data are calculated, the report should indicate the calculation method used and the point at which the strain data are calculated. An electronic copy of the data file for each specimen test should be provided which will contain, as a minimum, the unmanipulated, i.e. raw, data.

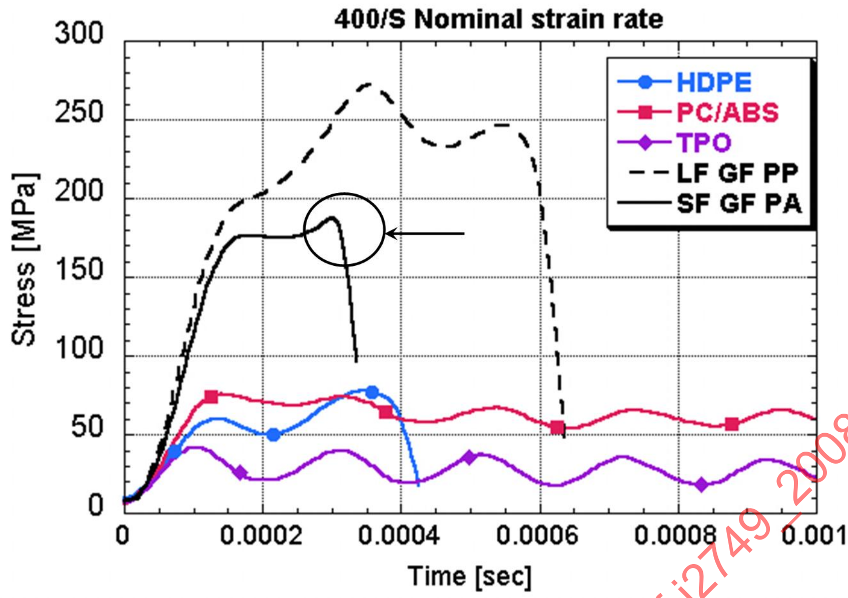

FIGURE 3 - ILLUSTRATION OF RINGING IN VARIOUS MATERIALS AND THE DIFFICULTY IN IDENTIFYING FAILURE OR PEAK STRESS UNDER SUCH CONDITIONS

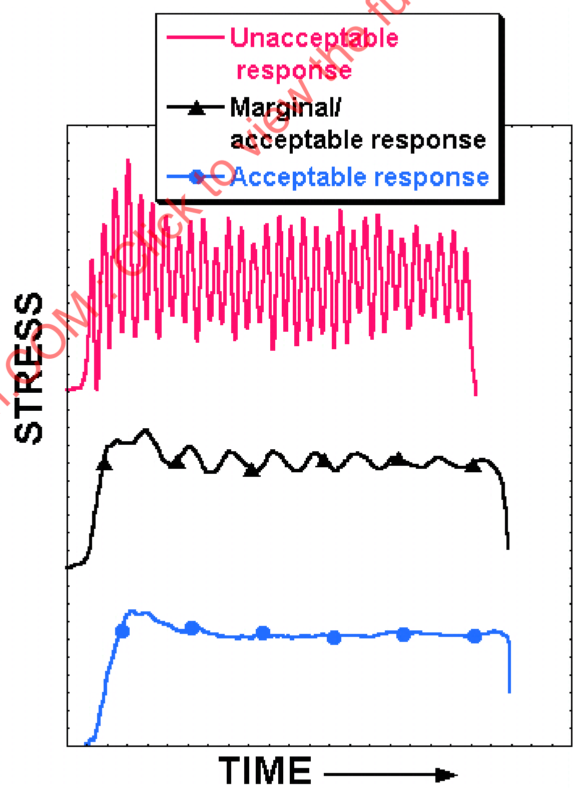

FIGURE 4 - QUALITATIVE DEFINITION OF ACCEPTABLE AND UNACCEPTABLE RINGING

10. PRECISION

10.1 The precision statistics for the maximum tensile stress data shown in Tables 2 and 3 were determined through an interlaboratory test program involving twelve laboratories and five polymeric materials. The interlaboratory test program was conducted in accordance with the ASTM E 691, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of a Test Method. Tensile tests were conducted at ambient conditions on five polymers at nominal plastic strain rates of 40/s and 400/s. The polymers included in this study were high density polyethylene (HDPE), polycarbonate/acrylonitrile-butadiene styrene terpolymer (PC/ABS), thermoplastic elastomer-olefinic (TPO), long glass (11 mm) fiber 40% filled polypropylene (GF PP), and short glass (2-3 mm) fiber 30% filled polyamide 66 (GF PA). Data generated from the 40% long glass fiber-filled PP at a rate of 400/s were eliminated from the interlaboratory test program because a majority of the test samples had an unacceptable failure mode.

The raw data set generated from this study was thoroughly examined. The data set was censored by eliminating data generated for samples that had an unacceptable failure mode, were tested at the wrong rate, had instrumentation problems or were otherwise tested in a manner not consistent with the method described in the document. The precision statistics generated from the censored data set in accordance with ASTM E 691 are provided in Table 2. The value x is the average of the cell averages across the laboratories, s is the cell standard deviation, Sr is the repeatability standard deviation, SR is the reproducibility standard deviation, r is the repeatability, and R is the reproducibility. The values of S_r/X and S_R/X represent the repeatability and the reproducibility coefficients of variation, respectively. These values provide a relative comparison of the repeatability (within laboratory precision) and reproducibility (between laboratory precision) of the test method described in this document for generating high strain rate tensile stress values.

TABLE 2 - PRECISION STATISTICS FOR PEAK STRENGTH

Units in MPa

Material	$\dot{x}$		$s_{\bar{x}}$		s_r		s_R		r		R	
	40/s	400/s	40/s	400/s	40/s	400/s	40/s	400/s	40/s	400/s	40/s	400/s
HDPE	0.470	0.500	0.022	0.023	0.014	0.029	0.025	0.036	0.039	0.081	0.070	0.101
PC/ABS	0.480	0.600	0.021	0.090	0.006	0.030	0.022	0.090	0.017	0.084	0.062	0.252
TPO	0.190	0.250	0.010	0.044	0.001	0.018	0.011	0.047	0.001	0.050	0.031	0.132
PP with 40% long glass fiber	1.500	1.800	0.180	0.180	0.150	0.110	0.220	0.200	0.420	0.308	0.616	0.560
PA 6 with 30% short glass fiber	1.400	1.700	0.220	0.240	0.050	0.070	0.220	0.250	0.140	0.196	0.616	0.700

10.2 The statistical analysis conducted on the censored data set revealed high values of reproducibility coefficients of variation for many of the materials tested at the 400/s rate. Closer examination of the individual stress versus time curves revealed a significant amount of pre- and post-yield ringing in some of the curves. The presence of ringing can result in significant variation in the analysis of the ultimate tensile strength for a given sample. A qualitative assessment was made of the individual stress versus time curves to identify those that had unacceptable ringing, per Figure 2. The data set was further censored by eliminating those data points generated from stress versus time curves that were found to have unacceptable ringing. Table 3 provides the precision statistics for the resultant data set. Fewer than six laboratories had data that were valid at the 400/s rate; therefore precision statistics could not be determined for the 400/s data.

TABLE 3 - PRECISION STATISTICS FOR PEAK STRENGTH AT 40/S MODIFIED BY ELIMINATING DATA GENERATED FROM CURVES HAVING UNACCEPTABLE RINGING

Units in MPa

Material	$\dot{x}$	$S_{\bar{x}}$	s_r	s_R	r	R
	40/s	40/s	40/s	40/s	40/s	40/s
HDPE	0.470	0.014	0.015	0.019	0.041	0.054
PC/ABS	0.480	0.014	0.001	0.015	0.002	0.041
TPO	0.190	0.001	0.005	0.008	0.014	0.024
PA 6 with 30% short glass fiber	1.450	0.215	0.043	0.219	0.120	0.613

10.3 In comparing Tables 2 and 3, it can be concluded that the presence of ringing can greatly affect the reproducibility of the data generated from high strain rate testing. Currently, only a qualitative method exists to identify unacceptable ringing. A quantitative method needs to be developed which will allow for improved consistency in data analysis and the treatment of data for high strain rate testing. Until a quantitative method has been developed identifying "acceptable versus unacceptable" curves, the end-user needs to evaluate both the numerical data generated in accordance with this document and the quality of the material response curves.

11. ACKNOWLEDGEMENTS

Development of this document was a direct result of the contributions of the SAE High Strain Rate Plastics Subcommittee members and the University of Dayton Research Institute. It was prepared by the SAE High Strain Rate Plastics Subcommittee.

12. NOTES

12.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE HIGH STRAIN RATE PLASTICS SUBCOMMITTEE
OF THE SAE PLASTICS COMMITTEE

APPENDIX A - CONSIDERATIONS FOR DYNAMIC TESTS

Three areas of concern in dynamic tests are specimen size, the resonant frequency of the test system, and the frequency response of the measurement system. These three areas are discussed in the following sections.

A.1 SPECIMEN SIZE

Selection of a specimen is primarily dictated by the material properties and the maximum test rate. The goal is to have at least 10, preferably 15, stress waves propagating through the material before yield to ensure an approximate equilibrium in the gage section. If this is not the case, the accuracy in determining elastic properties and yield point becomes difficult.

The same specimen geometry should be used across all tested rates so that specimen geometry is not a source for variability. The maximum desired test rate is often the deciding factor in selecting a specimen size for use across all the tested rates.

The nominal plastic strain rate for a given test rate is defined as

$$\dot{\varepsilon}_{nom} = \dot{\delta}/l_s \qquad \text{(Eq. A1)}$$

Table A1 summarizes the nominal strain rates expected at various test rates for several specimen configurations. Figure 1 illustrates the strain rates one can achieve at a given test rate for different specimen configurations.

TABLE A1 - NOMINAL PLASTIC STRAIN RATES FOR SEVERAL SPECIMEN SIZES

	Strain rate			
Crosshead Rate m/s (in/s)	ASTM D 638 Type I ISO 527 1B	ISO 527 Type 1BA	ISO 527 Type 1BB	ASTM D 638 Type V ASTM D 1822 Type L ISO 8256 Type 2 or Type 3
0.01 (0.39)	0.167–0.175 s^{-1}	0.3 s^{-1}	0.83 s^{-1}	1.0-1.05 s^{-1}
0.1(3.9)	1.67-1.75 s^{-1}	3.3 s^{-1}	8.3 s^{-1}	10-10.5 s^{-1}
1 (39)	16.7-17.5 s^{-1}	33.3 s^{-1}	83 s^{-1}	100-105 s^{-1}
5 (197)	83-88 s^{-1}	166 s^{-1}	416 s^{-1}	500-525 s^{-1}

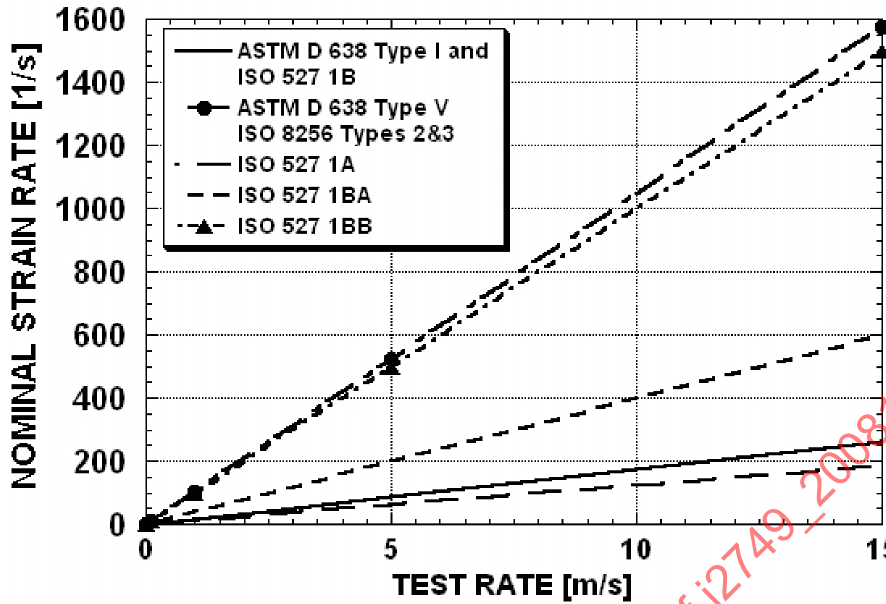

FIGURE A1 - RELATIONSHIP BETWEEN TEST RATE AND NOMINAL PLASTIC STRAIN RATE FOR DIFFERENT SPECIMEN CONFIGURATIONS

A.2 REFLECTED WAVES

The strain rates listed in Table A1 provide a general guideline for selecting a specimen configuration. Stress wave propagation through the specimen and load train during the test must also be considered.

The load introduction into the specimen will result in stress waves propagating through the specimen and the load train. Reflected waves will occur at each change in impedance, such as changes in the specimen profile, interfaces in the gripping mechanism, interfaces between the specimen and gripping mechanism, and interfaces between the components of the load train. The goal is to have numerous stress waves in the specimen so that an approximate equilibrium exists during the test.

A.2.1 Reflected Waves in the Gage Section as a Function of Material Properties

For a given test setup, the number of reflected waves present in the gage section is a function of the test rate and material properties. As stated in Section A1, the goal is to have at least 10, preferably 15, stress waves propagating through the gage section before yield. The time for the selected number of reflected waves to travel through the gage section should be much less than the nominal time-to-yield, t_{yield}. The reflected wave generated between the points of load application on the ends of the specimen can be considered to be the primary wave. The travel distance of the reflected wave in the gage section is twice the distance between the points of load application on the specimen, i.e., grip ends.

The time of travel for a reflected elastic stress wave is dependent on the wave propagation speed in the polymer, i.e.,

$$v_m = \sqrt{\frac{E}{\rho}} \qquad \text{(Eq. A2)}$$

The time of travel for one reflected stress wave can be estimated by

$$t_{wave} \approx \frac{2L_{dbg}}{v_m} \qquad \text{(Eq. A3)}$$

The time-to-yield is dependent on the yield strain and the strain rate, as shown,

$$t_{yield} \approx \frac{\varepsilon_y}{\dot{\varepsilon}_{elas}} \quad \text{(Eq. A4)}$$

Experience has shown that the elastic strain rate from 50 to 90% of yield is slower than the nominal plastic strain rate by a factor of 2 to 3. The elastic strain rate in Eq. A4 can be modified to reflect this relationship to

$$\dot{\varepsilon}_{elas} \approx 0.5\dot{\varepsilon}_{plas} \quad \text{(Eq. A5)}$$

where the nominal plastic strain rate is defined as

$$\dot{\varepsilon}_{plas} \approx \frac{\dot{\delta}}{L_{dbg}} \quad \text{(Eq. A6)}$$

Eq. A4 can be rewritten as

$$t_{yield} \approx \left(\frac{\varepsilon_y}{\dot{\varepsilon}_{elas}}\right) \approx \left(\frac{2\varepsilon_y L_{dbg}}{\dot{\delta}}\right) \quad \text{(Eq. A7)}$$

As mentioned above, numerous stress waves are needed in the gage section to have an approximate equilibrium. Therefore, one could estimate the number of reflected waves as a function of the test rate by combining Eqs. A3 and A7, as

$$\text{Number of Waves}_{\text{gage section}} \approx N_{gage} \approx \frac{t_{yield}}{t_{wave}} \quad \text{(Eq. A8)}$$

$$N_{gage} \approx \frac{\left(\frac{2\varepsilon_y L_{dbg}}{\dot{\delta}}\right)}{\left(\frac{2L_{dbg}}{v_m}\right)} \quad \text{(Eq. A9)}$$

or,

$$N_{gage} \approx \frac{\varepsilon_y v_m}{\dot{\delta}} \quad \text{(Eq. A10)}$$

The effect of changes in material and test rate can be quickly determined by using Eq. A10. As mentioned before, a minimum of 10 reflected waves are desired for an approximate equilibrium. An example follows.

Example: ASA (acrylonitrile styrene acrylate) with a modulus of 2.4×10^9 Pa, yield strain of 0.034, and a density of 1.07×10^3 kg/m^3. The calculated v_m is 1498 m/s, per Eq. A2. Per Eq. A10, the number of elastic stress waves in the gage section before yield is

$$N_{gage} \approx \frac{(\varepsilon_y v_m)}{(\dot{\delta})} \approx \frac{(0.034)(1498)}{(\dot{\delta})} \quad \text{(Eq. A11)}$$

or,

$$N_{gage} \approx \frac{51}{\dot{\delta}} \quad \text{(Eq. A12)}$$

If one wishes to have at least 10 reflected waves before yield, then the test rate should not exceed 5 m/s.

The relationship given in Eq. A10 can be used as an estimate. Examination of the data at the test rate should be the final guide in determining the maximum test rate for a given material.

A.2.2 Reflected Waves in the Load Train

The guidelines described in Section A.2.1 can be used when considering the reflected waves through the entire load train. As mentioned before, a minimum of 10 reflected waves in the gage section of the specimen are desired for an approximate equilibrium.

The time of travel for the reflected stress wave is dependent on the wave propagation speed in the specimen and the fixturing. One can consider the primary stress wave generated at the lower grip point and reflected back at the load-measuring device. This distance consists of the distance between the grips, L_{dbg}, plus the distance from the load measuring device to load transfer region on the grip closest to the load measuring device.

The travel time for one reflected stress wave can be estimated by

$$t_{wave} \approx 2\left[\frac{L_{fixt}}{v_{fixt}} + \frac{L_{dbg}}{v_m}\right] \quad \text{(Eq. A13)}$$

Typical fixturing will be made of metal and the wave propagation speed through the fixturing will be faster than through the specimen.

The equation for the yield time in the polymer in Eq. A7 is still valid. Eq. A8 can be modified to show the contribution of the added length traveled through the fixturing as shown below.

$$N_{gage} \approx \frac{\left(\dfrac{2\varepsilon_y L_{dbg}}{\dot{\delta}}\right)}{2\left[\dfrac{L_{fixt}}{v_{fixt}} + \dfrac{L_{dbg}}{v_m}\right]} \quad \text{(Eq. A14)}$$

$$N_{gage} \approx \frac{\left(\dfrac{\varepsilon_y L_{dbg}}{\dot{\delta}}\right)}{\left[\dfrac{L_{fixt} v_m + L_{dbg} v_{fixt}}{v_{fixt} v_m}\right]} \quad \text{(Eq. A15)}$$

$$N_{gage} \approx \left(\frac{\varepsilon_y L_{dbg} v_{fixt} v_m}{\dot{\delta}\left(L_{fixt} v_m + L_{dbg} v_{fixt}\right)}\right) \quad \text{(Eq. A16)}$$

The relative importance of the overall length of the load train can be seen in Eq. A16. The estimated number of waves given by Eq. A16 is one more point to consider when optimizing the test system response. An example using the ASA properties described in Section A.2.1 is given below.

Example: ASA (acrylonitrile styrene acrylate) with a modulus of 2.4 x 10^9 Pa, yield strain of 0.034 mm/mm, density of 1.07 x 10^3 kg/m^3, and calculated v_m of 1498 m/s. Assume: Load train consisting of steel fixturing with a wave propagation speed of 5200 m/s, L_{fixt} of 0.24 m, and ASTM D 638 Type I specimen with L_{dbg} of 0.115 m.

Per Eq. A16, the number of reflected waves at a test rate of 5 m/s is

$$N_{gage} \approx \frac{(0.034)(0.115)(5200)(1498)}{5\left[(0.24)(1498)+(0.115)(5200)\right]}$$

and

$$N_{gage} \approx 6.36$$

The estimated number of waves is lower than the desired 10 reflected waves before yield. Therefore, an approximate equilibrium may not exist. Shortening the load train would increase the number of reflected waves.

A.2.3 Resonant Frequency of the Test System

Stress waves are also generated if the rate of loading excites the loading system's natural, or resonant, frequency. An example is shown in Figure A2. The test specimen will experience this ringing. Therefore, it is desired to keep the amplitude of the test system's resonant frequency to a minimum so that the strain rate during the test is relatively constant with only minor ripples.

A similar argument can be made for a minimum resonant frequency as was described in Section A.2 concerning reflected waves. The accuracy of yield point determination is reduced as the resonant frequency of the test system is decreased. Experience has shown that approximately 10 to 15 cycles before yield will result in accurate yield load determinations.

A simple check of the resonant frequency of the test system is to induce system ringing, such as that generated by tapping the load-measuring end. The response can be captured and measured. An alternative method[3] describes testing a strong but brittle specimen. The initial section of the post-failure frequency will be the natural frequency of the test system. Modifications in the test system can result in large changes in the system resonant frequency.

Figure A3 shows the difference in the material response of ASA tested under different system resonant frequencies. As seen in the curve, the higher resonant frequency system results in a smoother stress-time curve.

[3] Cheresh, M. C, and McMichael, S., "Instrumented Impact Test Data Determination", Instrumented Impact Testing of Plastics and Composite Materials, Kessler, et. al, ed., ASTM STP936, ASTM, Philadelphia.

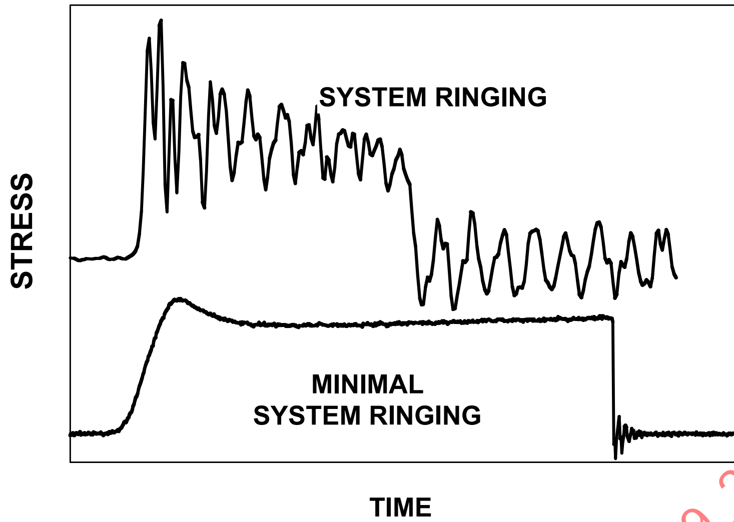

FIGURE A2 - TEST RUNS WITH AND WITHOUT SYSTEM RINGING

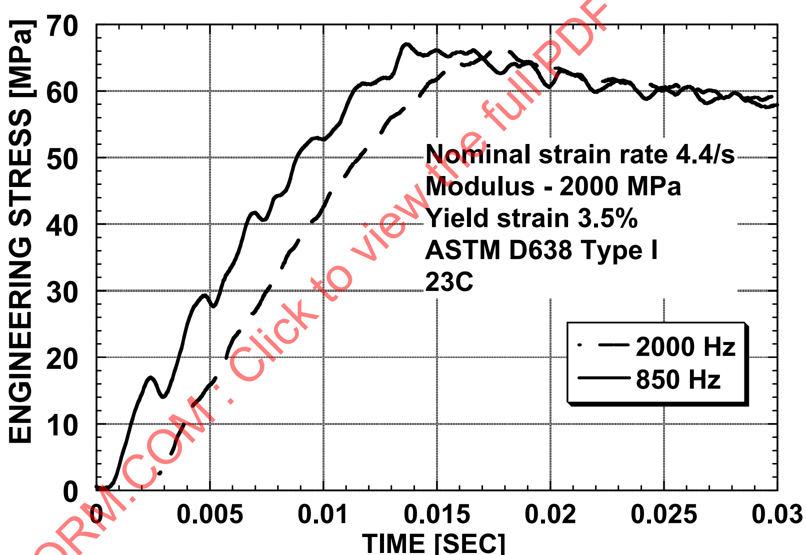

FIGURE A3 - DIFFERENCE IN MATERIAL RESPONSE UNDER DIFFERENT TEST SYSTEM CONDITIONS; SYSTEM RESONANCE IS VISIBLE IN THE 850 Hz SIGNAL (THE CURVES ARE SHIFTED IN TIME TO SHOW THE COMPARISON IN THE ELASTIC REGION)

A.3 FREQUENCY OF THE MEASUREMENT SYSTEM

To ensure the accuracy of the data, the system should be able to accurately record the fastest signal change during the test. This can be expressed as a minimum slew rate, measured in Volts/second or Volts/microsecond. However, it is more common to use the frequency response of the measurement system.

A measurement system’s response is normally measured in decibels (dB). The frequency response of sound amplifiers is normally given as the –3 dB point. This corresponds to a reduction of approximately 30% in the signal. However, the –3 dB point is not sufficient in a load measuring system. It is more common to use the –0.5 dB point (or –5%). If the frequency response of the system is low, then the high rate response will be underestimated.

As an example, consider a test where the time to yield is 1 millisecond. If the load signal up to yield is approximated as the first quarter of a sine wave, the frequency of the load signal is

$$F_{\text{load signal}} \approx \frac{0.25}{t_{\text{yield}}} \approx \frac{0.25}{0.001} \approx 250 \text{ Hz} \qquad \text{(Eq. A17)}$$

The rise time of the measurement system should be much less than the rise time of the load signal, preferably by at least an order of magnitude. A slow response of the measurement system may not define the material response with respect to yield, ultimate stress, or fracture.

Figure A4 shows the frequency response of a measurement system with a low pass filter. The system represented in Figure A3 has a drop-off of –.5 dB at 100 Hz, and a –3 dB drop-off by 200 Hz. This system would be inadequate to measure a 250 Hz load signal.

The effects of an inadequate response in the measurement system are illustrated in Figures A5 and A6. The system with the low pass filter shows a gradual decrease in stress after failure instead of a clear fracture point. In addition, the elastic response, shown in Figure A5, is underestimated.

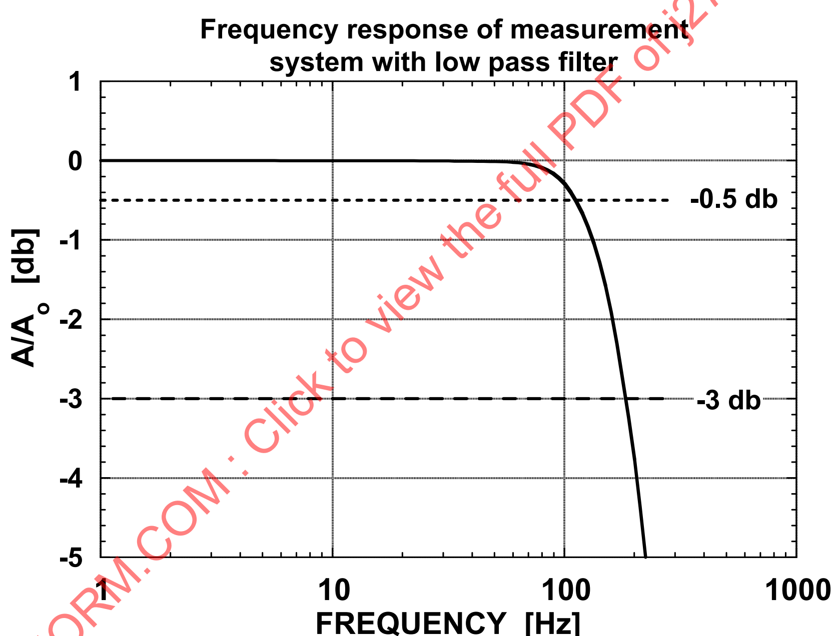

FIGURE A4 - FREQUENCY RESPONSE OF LOAD MEASUREMENT SYSTEM WITH A LOW PASS FILTER

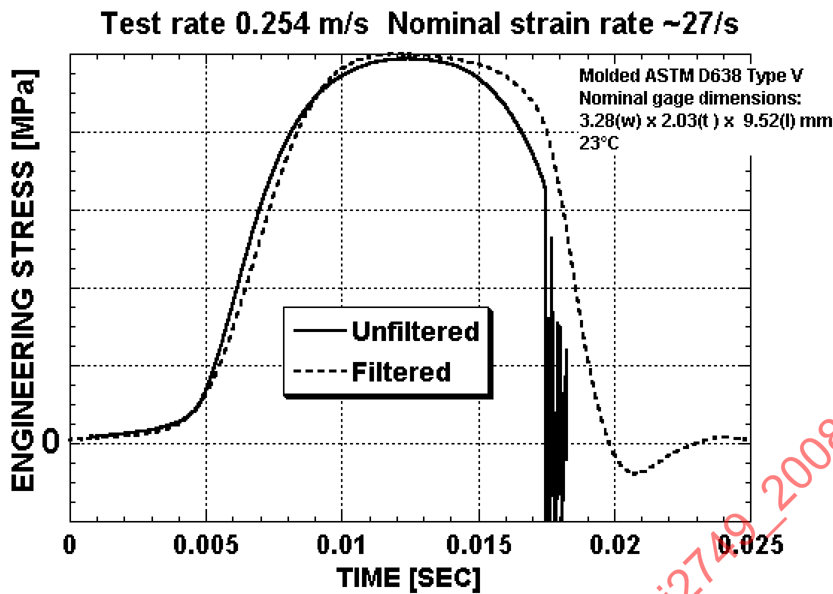

FIGURE A5 - EFFECTS OF A SLOW MEASUREMENT FREQUENCY RESPONSE WITH A LOW PASS FILTER ON THE RECORDED STRESS SIGNAL

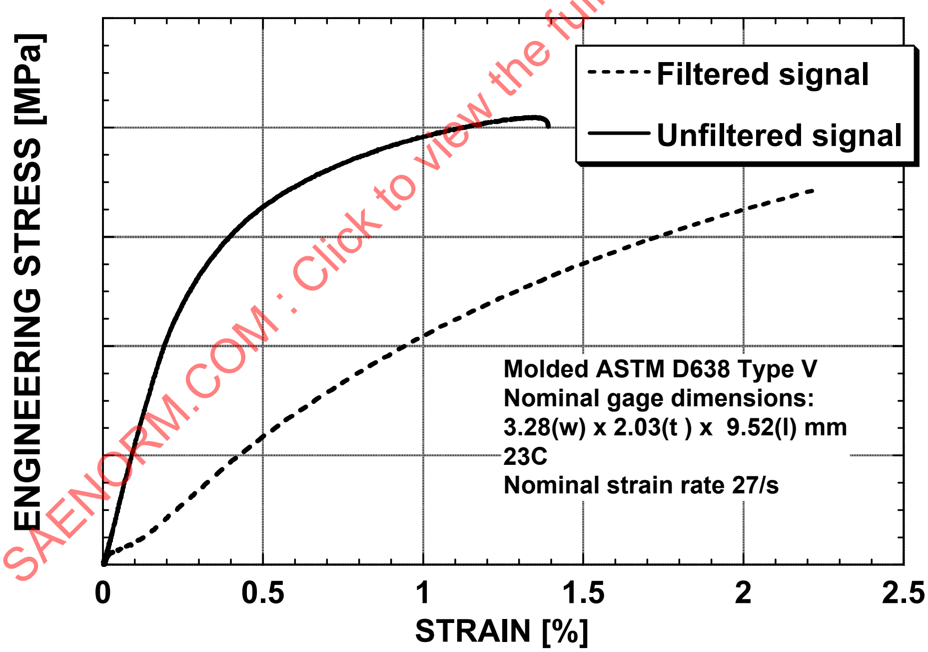

FIGURE A6 - EFFECT OF A LOW-PASS FILTER IN THE RECORDED STRESS-STRAIN RESPONSE

A.4 SPECIMEN SELECTION GUIDELINES

Table A2 gives some suggested maximum nominal strain rates for various specimen configurations. Analysis of the test results should be the final guide as to whether changes in specimen geometry or equipment are needed.

TABLE A2 - GUIDELINE FOR SPECIMEN SELECTION

Commonly Used Specimen Configurations	Distance Between Grip Ends on Specimen mm (in)	System Resonant Frequency (Hz)	Maximum Suggested Nominal Strain Rate (1/s)
ASTM D 638 Type I	≥115 (4.5)	<1000	≤1
		1000<2000	≤1-10
ISO 527 Type 1A and 1B	≥104 to 120 (4.1 to 4.7)	2000+	≤10-20
ASTM D 638 Type V	25.4 (1)	<1000	≤5
		1000<4000	≤5-100
ISO 527 1BB ISO 8256 Type 2 or 3	23-30 (0.9-1.18)	4000+	≤100-1000

APPENDIX B - STRAIN MEASUREMENT

B.1 STRAIN MEASUREMENT REFERENCED IN STANDARDS

There are several recommended practices or standards related to high rate testing of metals and polymers. Some are listed in Section 2. References. All but ISO/DIN 18872 refer to direct strain measurement at high rates above 10/s. Strain based on displacement is not recommended. Inertia-free strain measurement methods are preferred at rates above 1/s.

B.2 CURRENT METHODS USED TO MEASURE STRAIN

Several commercial strain measurement methods are used for quasi-static testing. These methods include strain gages, mechanical extensometers, and optical-based systems, such as laser extensometers, video, and speckle interferometery. High rate tests require a measurement technique with a fast frequency response (>250 kHz) to correctly capture the strain. Inertial effects become an important factor as the test rate increases. Therefore, the faster rates (i.e. over ~25 mm/sec or 1/s) require a non-contact method. The advantages and disadvantages of the different techniques are discussed below.

B.2.1 Strain gage

Strain gages are available in a variety of grid patterns and sizes. The small gage section of most high rate tensile specimens (3 - 9 mm wide) limits the selection. Most applicable strain gages have a maximum rated strain limit of 0.02 mm/mm to 0.15 mm/mm in the gage sizes needed for high rate specimens. This limit is insufficient to capture failure strain for most polymers. In addition, the techniques and adhesives used to ensure a good bond of the gage to the polymer can cause premature failure, reinforcement, or embrittlement. The resulting material response may not be representative of the actual behavior of the polymer.

Strain gage data are very useful for defining the behavior at lower levels of strain, such as the yield strain and secant or elastic modulus. It can provide measured strain data across the full strain rate regime from quasi-static to +1000/s for short elongation polymers. One can also compensate for potential bending by using back-to-back strain gages. Gages can be used in a variety of environments and temperatures. High elevated temperatures, i.e. greater than ~230 °C, require ceramic-based adhesive. The measurable strain at high temperatures is usually limited by the brittleness of the adhesive.

B.2.2 Mechanical Extensometer (ME)

The weight of the ME becomes the limiting factor for the effective use of this method. Most lightweight clip-on extensometers can be used up to a test rate of ~25 mm/sec. The survivability of the extensometer also becomes an issue since one cannot stop the test to remove the extensometer before specimen failure. The ME can be calibrated or selected to provide data for low to high elongation materials. However, most have a maximum limit of ±5 to 6 mm for a gage length of 6 mm. This corresponds to a maximum strain reading of 80 to 100%. Strain beyond the ME limit is calculated using either the cross-head displacement or the strain rate before the ME limit is reached. As with the strain gage, the ME can be used in a variety of environments and temperatures. Temperatures that require the ME to be physically outside of an environmental chamber limit the maximum useable test rate. The extended arms add weight and increase the likelihood of inertial effects.

B.2.3 Laser Doppler Vibrometer (LDV)

The LDV tracks the Doppler shift between the scattered laser light of a reference beam and the measurement beam. It is usually used to measure small vibrational displacements, but specific models can measure velocity. Multiple heads are needed for elongation measurements and to provide 3-D imagery of the moving surface. The measured surface must have sufficient roughness for proper operation of the LDV. It can be used in various environments as long as the optical path is clear.

B.2.4 Electro-optical extensometer (EO)

The EO tracks the movement of two markers or flags that have highly contrasting regions. A separate lens focuses on the contrasting areas of each marker. The relative ratio of light to dark within the field of view is the reference signal. The output signal is related to a change in the ratio as the marker moves out of the field of view. Different lens assemblies can be used to capture different amounts of total marker movement. Elongation beyond the EO limit must be calculated. The EO is sensitive to illumination and care must be taken to have uniform lighting over the expected range of movement. Testing in an environment is dependent on a clear optical path to the target and maintaining the light intensity and uniformity. Data analysis is relatively straightforward.

B.2.5 Laser Doppler Extensometer (LDE)

The LDE utilizes the Doppler shift of scattered laser light to measure the velocity of a volume of material. Two fixed regions are tracked and elongation is determined from the relative motion between the two. Surface preparation is important for optimum operation since the unit relies on measuring the relative amount of scattered light. The LDE can be used in various environments as long as the optical path is not blocked. Data analysis requires care in order to identify the valid portions of the signals.

B.2.6 High Speed Digital Video (HSDV)

HSDV is becoming more popular as the maximum framing rate of commercial cameras increases. HSDV cameras with framing rates from 250 to 1M frames per second (fps) are now available. The limiting factor becomes the required resolution and illumination. It is not unusual for the actual frame rate to be lower than the rated fps by a factor of 10. The number of frames capturing the event can range from only 4 to over 2000 frames, depending on the type of polymer, resolution, test speed, and type of camera. The specific application will determine whether the number of images is sufficient. Multiple camera heads can be used to generate 3-D images. The high intensity lighting requirements may require the use of “cold” illumination.

Commercial software is available to provide the digital image correlation. Most software track discrete points, elements, or shapes on the coupon surface. Maintaining the contrast and integrity of the tracked image(s) throughout the test is critical. Several methods are used to apply the image(s), such as spraying speckle pattern or adhering markers. The software output can provide 2 D or 3 D analysis of global or local deformation.

B.3 CALIBRATION

The calibration method depends on the technique used. Strain gage calibration usually involves scaling the sensitivity of the instrumentation so that the registered output corresponds to a predetermined input. The EO calibration is performed by the manufacturer. The end-user of the EO performs calibration checks by comparing the measured marker movement to traceable gage blocks, a calibrator, or displacement transducer output. The correlation for the analysis software for HSDV is derived from the comparison of traceable patterns (i.e. lengths) to the images. The calibration method of the LDE and LDV is based on the HeNe laser wavelength. The LDE and LDV equipment performs internal calibration checks and adjusts the signal output as-needed. The end-user does not need to perform any calibration.

B.4 STRAIN MEASUREMENT TECHNIQUE’S AFFECT ON MATERIAL RESPONSE

Strain measurement techniques may affect the material response, such as the peak stress and time-to-failure. A limited number of specimens should be tested to see if there is a measurable effect. The actual number of specimens will depend on the material variability. Comparison of the load (stress) traces of un-instrumented and instrumented specimens should identify any differences.

An example of an early failure due to strain gaging is shown in Figure B1. As seen in the graph, the time-to-failure of the un-instrumented specimen is longer than the strain-gaged specimens. The post-yield response of the strain-gaged specimen is not representative of the material behavior.