



SURFACE VEHICLE RECOMMENDED PRACTICE

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High Strain Rate Tensile Testing of Polymers

RATIONALE

This document was written to standardize high strain rate test procedures used to simulate vehicle crash calculations. The study has been completed and procedures are now set. There is no reason to review the standard for further changes and the Plastics Committee has determined to stabilize the method.

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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 results¹, 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
$\dot{\epsilon}_{\text{nom}}$	s^{-1}	Nominal plastic strain rate
$\dot{\epsilon}$	s^{-1}	Strain rate
$\dot{\epsilon}_{\text{elas}}$	s^{-1}	Elastic strain rate
$\dot{\epsilon}_{\text{plas}}$	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.

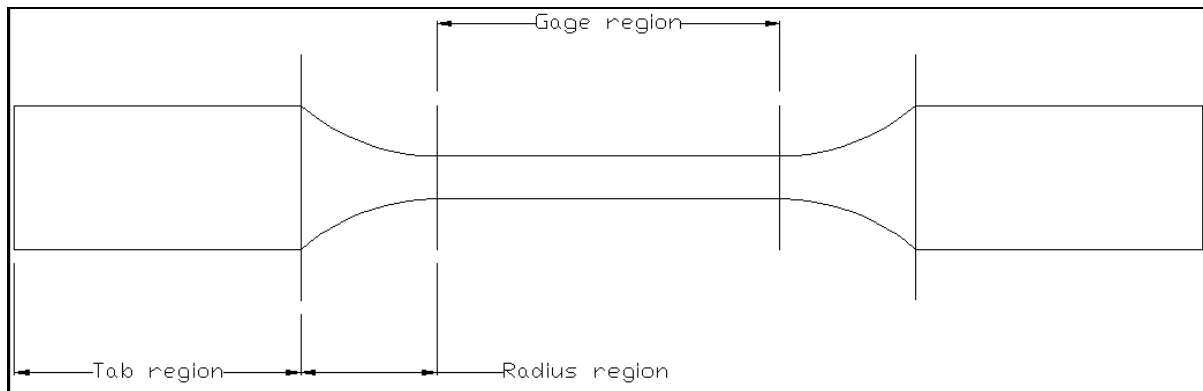


FIGURE 1 - IDENTIFICATION OF THE GRIP, GAGE AND RADIUS REGION OF A TEST SAMPLE

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 $\pm 15\%$, 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.

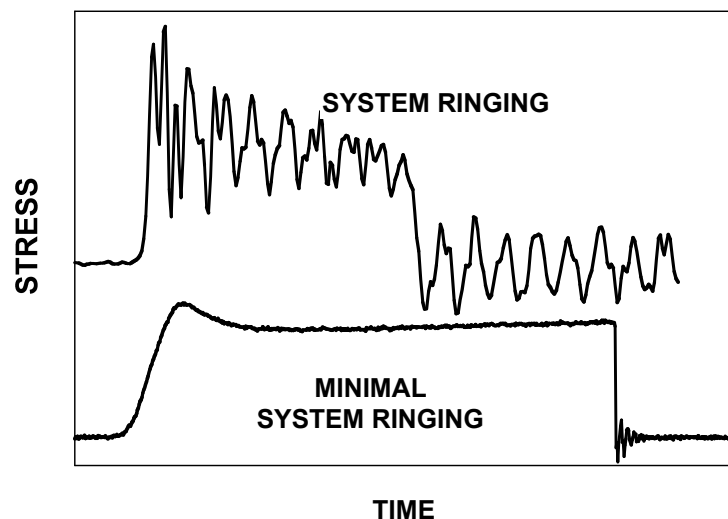


FIGURE 2 - DATA OBTAINED FROM A TEST EXHIBITING MINIMAL SYSTEM RINGING AND SIGNIFICANT SYSTEM RINGING

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,

$$\dot{\epsilon}_{\text{nom}} = \frac{\dot{\delta}}{l_s} \quad (\text{Eq. 1})$$

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.

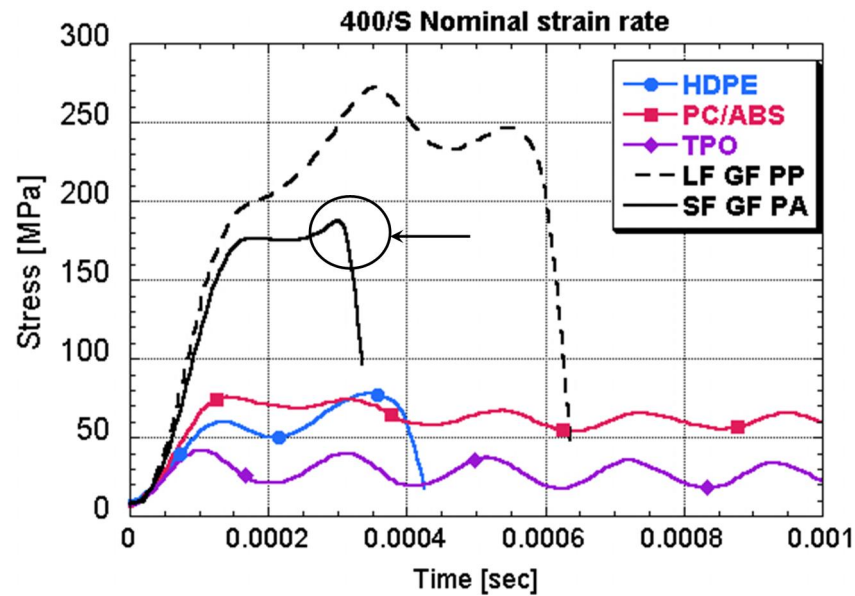


FIGURE 3 - ILLUSTRATION OF RINGING IN VARIOUS MATERIALS AND THE DIFFICULTY IN IDENTIFYING FAILURE OR PEAK STRESS UNDER SUCH CONDITIONS

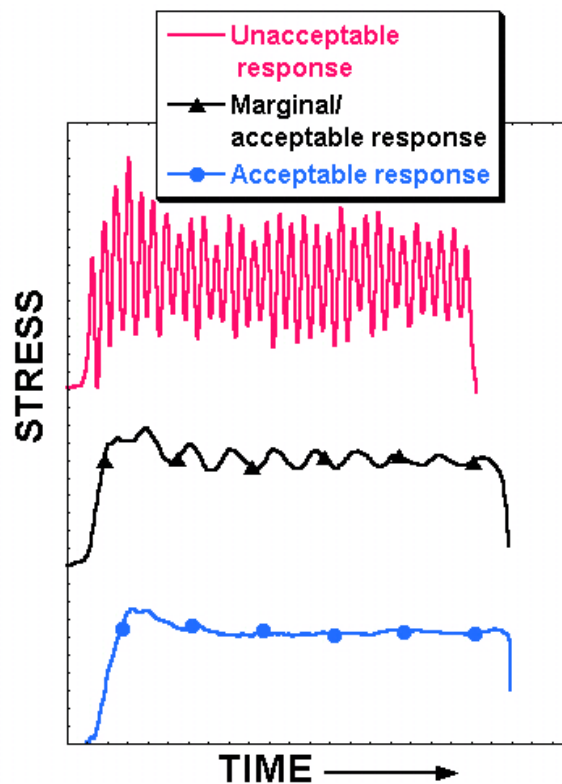


FIGURE 4 - QUALITATIVE DEFINITION OF ACCEPTABLE AND UNACCEPTABLE RINGING