Designation: ~~E2448 – 18~~ E2448 – 22

Standard Test Method for Determining the Superplastic Properties of Metallic Sheet Materials[1]

This standard is issued under the fixed designation E2448; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes the procedure for determining the superplastic forming properties (SPF) of a metallic sheet material. It includes tests both for the basic SPF properties and also for derived SPF properties. The test for basic properties encompasses effects due to strain hardening or softening.

1.2 This test method covers sheet materials with thicknesses of at least 0.5 mm but not greater than 6 mm. It characterizes the material under a uni-axial tensile stress condition.

NOTE 1—Most industrial applications of superplastic forming involve a multi-axial stress condition in a sheet; however it is more convenient to characterize a material under a uni-axial tensile stress condition. Tests should be performed in different orientations to the rolling direction of the sheet to ascertain initial anisotropy.

1.3 This method has been used successfully between strain rates of 10^{-5} mm/mm/s to 10^{-1} mm/mm ~~per~~ /s second.

1.4 This method has been used successfully on Aluminum and Titanium alloys. The use of the method with other metals should be verified.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E4 Practices for Force Calibration and Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

[1] This test method is under the jurisdiction of ASTM Committee E28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.02 on Ductility and Formability.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E646 Test Method for Tensile Strain-Hardening Exponents (***n*** -Values) of Metallic Sheet Materials
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

3. Terminology

3.1 *Definitions:* Terms common to mechanical testing. Definitions such as true stress (σ), true strain (ε), normal engineering stress (S), and engineering strain (e) are defined in Terminology E6. Thus,

$$\varepsilon = \ln(L/L_0)$$

$$\sigma = S(1+e)$$

3.1.1 *indicated temperature, engineering strain, e, n*—the temperature indicated by aa dimensionless value that is the change in length (Δ*L* temperature measuring device using good pyrometric practice.) per unit length of original linear dimension (L_0) along the loading axis of the specimen; that is, $e = (\Delta L)/L_0$.

3.1.2 *nominal temperature, engineering stress, S* [FL^{-2}],*n*—the intended test temperature.normal stress, expressed in units of applied force, *F,* per unit of original cross-sectional area, A_0; that is, $S = F/A_0$.

3.1.3 *true strain, ε, n*—the natural logarithm of the ratio of instantaneous gauge length, *L*, to the original gauge length, L_0; that is, $\varepsilon = \ln(L/L_0)$ or $\varepsilon = \ln(1+e)$.

3.1.4 *true stress, σ* [FL^{-2}],*n*—the instantaneous normal stress, calculated on the basis of the instantaneous cross-sectional area, *A*; that is, $\sigma = F/A$; if no necking has occurred, $\sigma = S(1+e)$.

3.1.5 Refer to Terminology E6 for the definitions of the terms extensometer system, indicated temperature, necking, specified temperature, strain hardening, and stress-strain diagram.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *gauge length, L,* [L],*n*—the instantaneous distance between the shoulders of the test couponspecimen during the test

3.2.2 *testing machine crosshead velocity, V,* [L/T],*n*—the velocity of the traveling member of the testing machine to which one of the test specimen clamps is attached.

3.2.3 *strain rate, ε̇,* [1/T],*n*—the time rate of change of the true strain in the test specimen, measured as: $\frac{V}{L_0(1+e)}$

where:

L_0 = original gauge length
V = machine crosshead velocity

3.2.3.1 *Discussion*—
This is an operational definition of strain rate.

3.2.4 *strain rate sensitivity, m, n*—(ln Δσ)/ (ln Δε̇)ε˙.

3.2.4.1 *Discussion*—
In practical terms, $m = \frac{\ln(\sigma_2/\sigma_1)}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}$ under stated test conditions, see 7.2.1.

3.3 *Symbols Specific To This Standard: V* = machine crosshead velocity, the velocity of the traveling member of the test machine to which one of the coupon clamps is attached

$\dot{\varepsilon}$ = strain rate, measured as: $V/[L_0(1+e)]$

NOTE 2—This is an operational definition of strain rate.

m = strain rate sensitivity, defined as (ln Δ σ)/ (ln Δ ε̇). In practical terms, $m = \log(\sigma_2/\sigma_1)/\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1)$ under stated test conditions, see 7.2.1.

4. Significance and Use

4.1 The determination of the superplastic properties of a metallic sheet material is important for the observation, development and comparison of superplastic materials. It is also necessary to predict the correct forming parameters during an SPF process. SPF tensile testing has peculiar characteristics compared to conventional mechanical testing, which distort the true values of stress, strain, strain hardening, and strain rate at the very large elongations encountered in an SPF pull test, consequently conventional mechanical test methods cannot be used. This test method addresses those characteristics by optimizing the shape of the test ~~coupon~~specimen and specifying a new test procedure.

4.2 The evaluation of a superplastic material can be divided into two parts. Firstly, the basic superplastic-forming (SPF) properties of the material are measured using the four parameters of stress, temperature, strain, and strain rate. These are obtained using conversions from the raw data of a tensile test. Secondly, derived properties useful to define an SPF material are obtained from the basic properties using specific equations.

4.3 The test ~~coupon~~specimen undergoes an essentially uniform and constant ~~neck~~necking along its length, and *S* and *e* are assumed in this standard to be valid. However at the junction to the clamp sections of the test ~~coupon~~specimen the cross section reduces from the original value to the final value, over a length of approximately 4 % at each end. Also, there are local small instabilities of cross section over the gauge length. These contribute to an error in the calculated values of ε and σ. In the absence of currently available extensometers that could operate in the ~~high temperature~~ elevated-temperature environment of an SPF test, ε and σ are to be inferred from crosshead extension and force.

4.4 The derived term *m* is widely used to describe the SPF properties of a material. It should be used with caution, as it is dependent on strain, strain rate and temperature. Many references in the literature do not identify the strain condition at which the readings were taken, or allow multiple strains to be used in the determination of *m*.

4.5 Many superplastic alloys exhibit strain hardening. However, the conventional strain hardening exponent n as defined in Test Method E646 is not valid for superplastic materials as strain hardening in the latter is usually a coefficient of strain, rather than an exponent. The mechanism of strain hardening in superplastic flow is essentially due to grain growth, and although the stress/strain relationship is often linear, it is not universal for all superplastic materials. Consequently, there is no simple definition of a strain hardening coefficient and this standard does not define one. Consideration of strain hardening in superplastic deformation is discussed in Ghosh and Hamilton's, "Influences of Material Parameters and Microstructure on Superplastic Forming."[3]

4.6 It is assumed no local necking takes place and the cross section of the test ~~coupon~~specimen is constant over the entire gauge length. ~~For some materials, cavitation inside the material increases the volume of the gauge section as the test progresses, and the true cross-sectional area has to be compensated for any strain. For other materials, the coupon can develop a ribbed or other local texture, and in this case, the minimum cross section has to be measured. During the test there is an increasingly non uniform cross section at each end of the test coupon where the gauge section transitions to the original width at the clamp section. This effect is small and can usually be ignored.~~

NOTE 2—For some materials, cavitation inside the material increases the volume of the gauge section as the test progresses and changes the true cross-sectional area. For other materials, the test specimen develops a ribbed or other local texture, and changes the minimum cross section.

4.7 It is assumed that the increasingly non uniform cross section that develops at each end of the test specimen where the gauge section transitions to the original width at the clamp section is small and can be ignored.

5. Apparatus

5.1 The ~~accuracy~~ force-measuring system of the testing machine shall ~~be within the permissible variation specified in~~ conform to the requirements of Practices E4.

5.2 The apparatus shall be calibrated according to appropriate standards or manufacturer instructions.

[3] Ghosh, A. K., and Hamilton, C. H., "Influences of Material Parameters and Microstructure on Superplastic Forming," *Met Trans A*, Vol 13A, May 1982, pp. 733-742.

5.3 No extensometer system is used in this test method, and the extension of the test ~~coupon~~specimen is measured at the testing machine crosshead. The accuracy of the recorded crosshead position ~~should~~shall be better than 0.25 mm. The testing machine compliance shall be determined before testing, and the amount of compliance subtracted from the crosshead position if it exceeds 1 % of the original gauge length of the test ~~coupon.~~specimen.

NOTE 3—One method of determining compliance is to mount a 6 mm thick test ~~coupon~~specimen in the clamps without heating, then load the testing machine to the estimated maximum force of the test and measure the movement of the crosshead. Due to the low ~~loads~~forces of these tests (typically 100 N maximum) compliance is likely to be small.

5.4 The tensile ~~test~~testing machine shall be computer controlled and capable of varying the testing machine crosshead ~~speed~~velocity in order to maintain a near constant strain rate. The testing machine crosshead ~~speed~~velocity may be increased in steps. The instantaneous strain rate may vary up to 1 % from nominal strain rate.

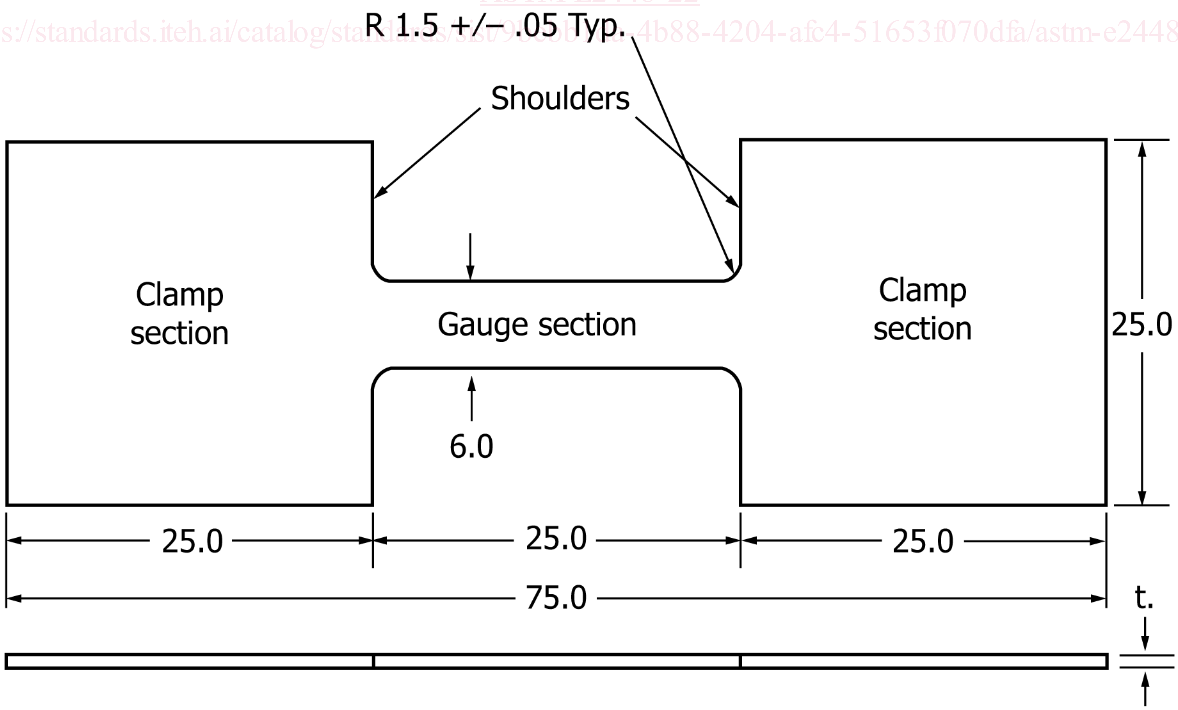
5.5 The tensile ~~test~~testing machine shall be provided with clamps that hold the test ~~coupon~~specimen at and under the shoulders adjacent to the ~~gage~~gauge section. The test ~~coupon~~specimen shall not be compressed by the clamps, as this will induce superplastic flow out of the clamp area during the test. Clamp design should follow that shown in Fig. 2.

5.6 The apparatus shall be provided with a furnace that shall maintain the test ~~coupon~~specimen at a constant temperature throughout the test. Test equipment shall meet the requirements of Test Methods E21 for temperature measuring, calibration, and standardization.

6. Procedure

6.1 Test ~~coupons~~specimens shall be made to the dimensions shown in Fig. 1. The test ~~coupon~~specimen width and ~~gage thickness~~gauge thickness, *t*, shall be measured and recorded at a minimum of four places in the ~~gage~~gauge section, to a tolerance of 1 % of reading, or 12 µm, whichever is greater.

6.2 If material oxidation affects the superplastic behavior of the material, the furnace may be flooded with argon or other inert gas to reduce the effects of oxidation.



Dimensions in mm. Tolerance ±0.25 mm except where noted.

FIG. 1 Dimensions of Test ~~Coupon~~Specimen

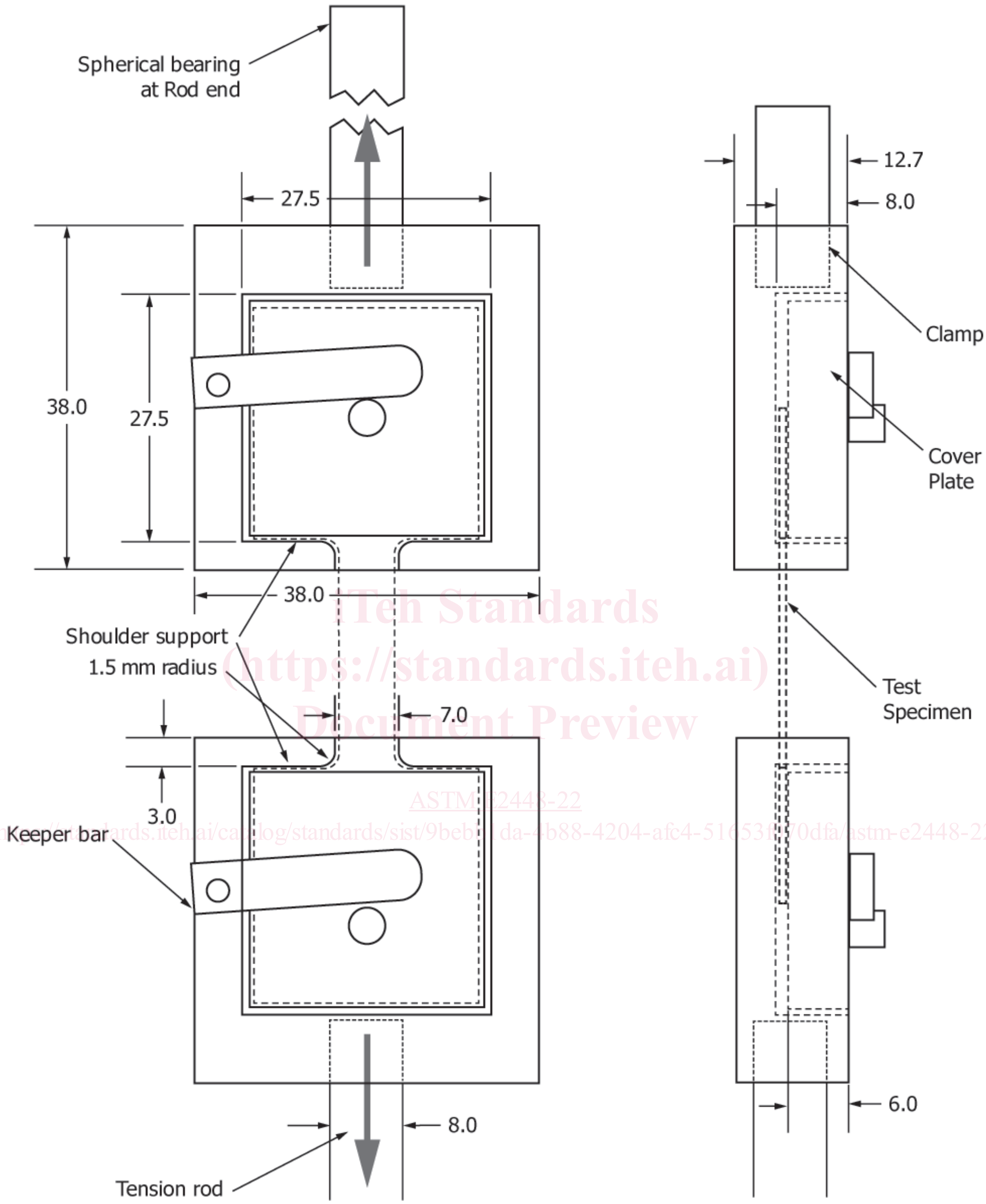


FIG. 2 Test ~~Coupon~~Specimen Grip Configuration

6.3 Before starting the test, bring the furnace up to the ~~nominal~~specified temperature and stabilize the temperature. ~~Load~~Install the test ~~coupon~~specimen into the clamps. During the heat up of the test ~~coupon, important to~~ specimen, minimize external ~~stress~~force from the testing machine to the test ~~coupon.~~specimen.

NOTE 4—Many ~~test~~testing machines incorporate a “protect specimen” or “load control” option during the heating phase to accommodate the thermal expansion of the test ~~coupon/grip~~specimen/grip assembly inside the furnace and to prevent buckling of the test ~~coupon.~~specimen. This control option ensures “almost” zero ~~loading~~force on the test specimen during heating through the movement of the cross-head beam.

6.4 ~~The test should not commence until the test coupon has reached thermal equilibrium. This will be reached when the cross-head beam ceases to move under the “protect specimen” control, indicating that no more thermal expansion is taking place. However this time can be long enough to allow grain growth in the test coupon, which distorts the superplastic properties being evaluated. Therefore the time taken for the thermocouples to come within tolerance can be used instead if grain growth is considered significant. The cross-head extension shall then be “zeroed.” At this point, any movement of the crosshead is assumed to be the same as the moving clamp on the test coupon, and is~~Load the test specimen as soon as the indicated temperature is within the allowable range specified in 6.5~~equivalent to the extension of the test coupon.~~.

NOTE 5—In normal tensile testing, the test specimen is not loaded until test specimen and load train have reached thermal equilibrium. A common method for determining thermal equilibrium is to observe that the crosshead has ceased to move under the “protect specimen” control, indicating that no more thermal expansion is taking place. However, this time can be long enough to allow grain growth in the test specimen, which distorts the superplastic properties being evaluated.

6.4.1 The start of loading may be delayed until thermal equilibrium is achieved if it is known that grain growth during thermal equilibration is small enough so that SPF properties will not be affected.

6.5 ~~Loading shall start as soon as the coolest thermocouple reaches the minimum specified temperature range to minimize the effect of grain growth on SPF properties.~~ For the duration of the test, defined as the time from ~~initiation~~start of loading until the termination of test or fracture, the ~~allowed tolerance~~ difference between indicated temperature and ~~nominal test temperature is ±3°C up~~ specified temperature shall not exceed the following limits:
~~to 700°C and~~Specified temperatures less than or equal to 700 °C: ±3 °C
~~±6°C above 700°C.~~Specified temperatures greater than 700 °C: ±6 °C.

~~NOTE 5—As the clamp extension rod is pulled out of the furnace, it cools and contracts, thereby altering the distance between crosshead and clamp. This error in reading is small compared to the test coupon length L and can be ignored for most testing.~~

6.6 ~~Increase the~~ During the test, increase the testing machine crosshead velocity, V, according to the equation

~~$$V = \dot{\varepsilon}[L_0(1+e)] \quad (1)$$~~

$$V = \dot{\varepsilon}_{nom}\left(\frac{L_0}{1+e}\right) \quad (1)$$

to ~~an accuracy of ±1 % to maintain a constant true strain rate~~maintain the true strain rate, $\dot{\varepsilon}$, to within ±1 % of the nominal strain rate, $\dot{\varepsilon}_{nom}$, until a predetermined strain value is reached or until ~~fracture.~~fracture:

$$\left|\frac{\dot{\varepsilon} - \dot{\varepsilon}_{nom}}{\dot{\varepsilon}_{nom}}\right| \leq 0.01 \quad (2)$$

~~NOTE 6—If early fracture occurs at the interface between clamp and gauge section, then the material is unlikely to be superplastic.~~

6.7 Record the force and crosshead extension at least twice per second to an accuracy of ±1 % of the recorded value.

6.7.1 As the clamp extension rod is pulled out of the furnace, it cools and contracts, thereby altering the distance between crosshead and clamp. This error in reading is small compared to the test specimen gauge length, L, and may be ignored.

6.8 At the conclusion of the test, measure the height, width and thickness in the clamp area to measure any superplastic flow in that section. Record these values.

6.9 To determine the basic SPF properties, employ a constant true strain rate test as described above.

6.10 To determine the derived ~~“~~superplastic~~m”~~ strain rate sensitivity value, a step test may be employed, in which the true strain rate is periodically stepped to 20 % above ~~nominal,~~ nominal strain rate, then back to nominal, starting at a true strain of ~~0.15~~0.15 mm ~~mm/mm~~ /mm and stepping up and down every 0.1 mm/mm strain.

7. Analysis

7.1 *Basic SPF Properties*—Convert force and extension measurements from the ~~test~~testing machine to true stress ~~$\sigma [= S(1+e)]$~~ $\sigma = S(1 + e)$ and true strain ~~$\varepsilon [= \ln(L/L_0)]$~~ $\varepsilon = \ln(L / L_0)$. Present the basic SPF properties of a material at a specified strain rate and temperature as a ~~graph~~ stress-strain diagram of true stress versus true strain as shown in Fig. 3. Several strain rates may be plotted on the same ~~graph.~~stress-strain diagram.

NOTE 6—The usual presentation of ~~stress/strain~~stress-strain data records engineering stress on the *Y*-axis. This is not applicable for an SPF test due to the significant elongation, and subsequent cross section area reduction, of the test ~~coupon.~~specimen.

7.2 *Derived SPF Properties*—In addition to the basic properties, the superplastic behavior of a material ~~can been~~may be described by constitutive equations, generally of the form:

$$\sigma = k_1 + k_2 \dot{\varepsilon}^m \tag{3}$$

where:

~~m = superplastic strain rate sensitivity exponent.~~

m = strain rate sensitivity.

7.2.1 Determine the strain rate sensitivity, *m*, ~~value~~ from the test described in 6.10.

NOTE 7—The result of such a test is shown in Fig. 4. One method to determine *m* is to chose a number of points (usually 10) on either side of the step and extrapolate the stresses to the step to determine the two stress levels σ_1 and σ_2 at the point of change.

~~$$m = \log(\sigma_2/\sigma_1)/\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1) \tag{4}$$~~

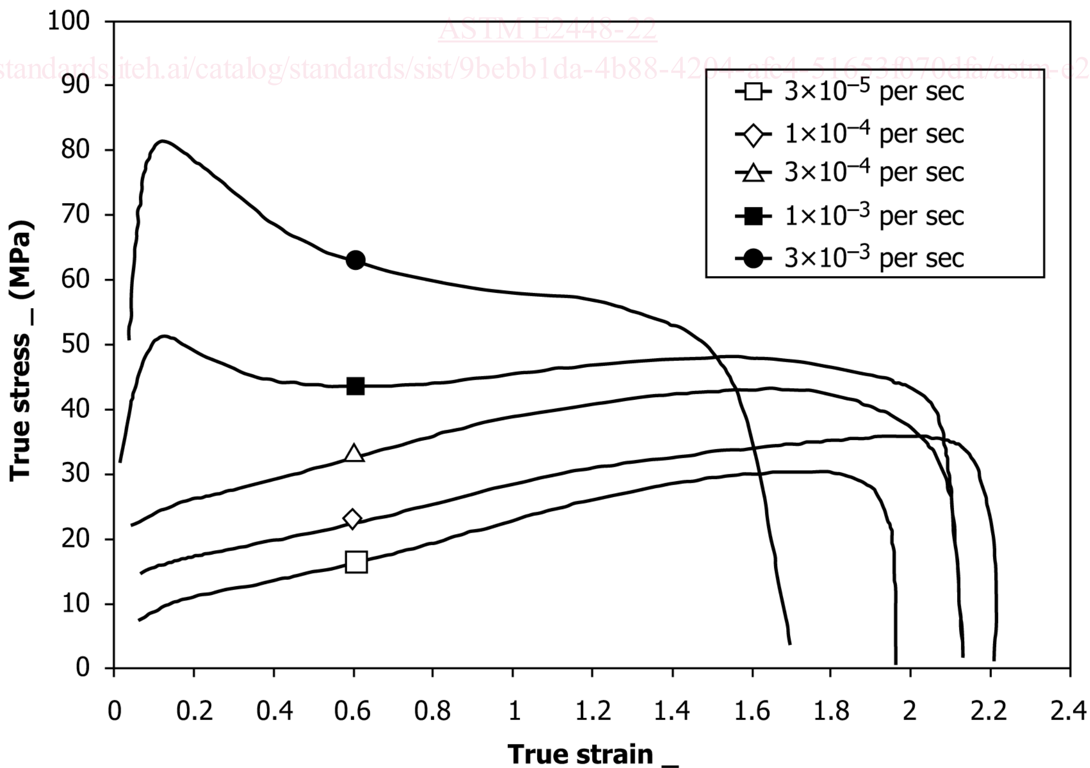


FIG. 3 Basic SPF Properties for Fine Grain Ti-6Al-4V Alloy at ~~775°C,~~775 °C, Transverse Direction