Designation: E2448 – 11$^{\varepsilon 1}$

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.

ε^1 NOTE—Footnote 4 was editorially corrected in October 2015.

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} to 10^{-1} per 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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
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*—Definitions such as gage length (L and L_0), true stress (σ), true strain (ε), normal engineering stress (S), and engineering strain (e) are defined in Terminology E6. Thus,

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

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

NOTE 2—Engineering stress S and strain e are only valid up to the point of necking or instability of cross section. For superplastic deformation, the coupon undergoes an essentially uniform and constant neck 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 coupon 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 environment of an SPF test, ε and σ are to be inferred from crosshead extension and force.

---

[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.

Current edition approved June 1, 2011. Published July 2011. Originally approved in 2005. Last previous edition approved in 2008 as E2448–08. DOI: 10.1520/E2448-11E01.

[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.

3.2 *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 3—This is an operational definition of strain rate.

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

NOTE 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.

NOTE 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]

3.2.1 The gage length (L) is defined as the instantaneous distance between the shoulders of the coupon during the test.

NOTE 6—It is assumed no local necking takes place and the cross section of the coupon is constant over the entire gage length. For some materials, cavitation inside the material increases the volume of the gage 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 coupon where the gage section transitions to the original width at the clamp section. This effect is small and can usually be ignored.

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 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.

5. Apparatus

5.1 The accuracy of the testing machine shall be within the permissible variation specified in Practices E4.

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

5.3 No extensometer is used in this test method, and the extension of the test coupon is measured at the machine crosshead. The accuracy of the recorded crosshead position should be better than 0.25 mm. The machine compliance shall be determined before testing coupons, and the amount of compliance subtracted from the crosshead position if it exceeds 1 % of the original gauge length of the coupon. A method of determining compliance would be to mount a 6 mm thick coupon in the clamps without heating, then load the machine to the estimated maximum force of the test and measure the movement of the crosshead. Due to the low loads of these tests (typically 100 N maximum) compliance is likely to be small.

5.4 The tensile test machine shall be computer controlled and capable of varying the crosshead speed in order to maintain a near constant strain rate. Step increases in crosshead speed are allowed, a variation of 1 % from nominal strain rate is permitted.

5.5 The tensile test machine shall be provided with clamps that hold the test coupon at and under the shoulders adjacent to the gage section. The coupon is not to 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 is provided with a furnace that shall maintain the coupon 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 shall be made to the dimensions shown in Fig. 1. The coupon width and gage thickness t shall be measured and recorded at a minimum of four places in the gage section, to a tolerance of 1 % of reading, or 12 µm, whichever is greater.

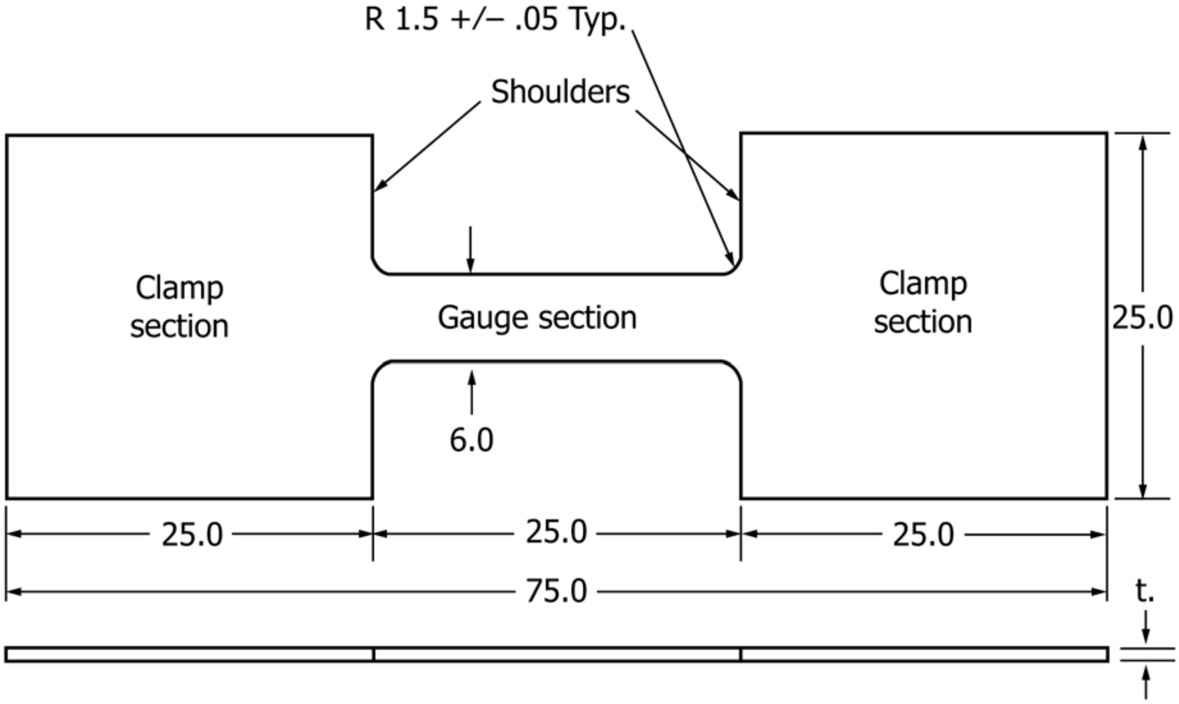
6.2 If material oxidation affects the superplastic behavior of the material, the furnace can be flooded with argon or other inert gas to reduce the effects of oxidation.

6.3 Before starting the test, the furnace is bought up to the desired temperature and stabilized. The coupon is loaded into the clamps. During the heat up of the coupon, it is important to minimize external stress from the machine to the coupon. Many test machines incorporate a "protect specimen" or "load control" option during the heating phase to accommodate the thermal expansion of the coupon/grip assembly inside the furnace and to prevent buckling of the coupon. This control option ensures "almost" zero loading on the test specimen during heating through the movement of the cross-head beam.

6.4 Ideally the test should not commence until the coupon has reached thermal equilibrium. This will be reached when the

---

[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.



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

FIG. 1 Dimensions of Test Coupon

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 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 coupon, and is equivalent to the extension of the coupon.

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 of loading until the termination of test or fracture, the allowed tolerance between indicated and nominal test temperature is ±3°C up to 700°C and ±6°C above 700°C.

NOTE 7—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 coupon length L and can be ignored for most testing.

6.6 The machine crosshead velocity is increased according to the equation $V = \dot{\varepsilon}\left[L_0(1+e)\right]$ to an accuracy of ±1 % to maintain a constant true strain rate until a predetermined strain value is reached or until fracture. (If early fracture occurs at the interface between clamp and gauge section, then the material is unlikely to be superplastic).

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

6.8 At the conclusion of the test, a measurement of height, width and thickness should be taken in the clamp area to measure any superplastic flow in that section; this value shall be recorded.

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

6.10 To determine the derived "*m*" value, a step test can be employed, in which the true strain rate is periodically stepped to 20 % above nominal, then back to nominal, starting at a true strain of 0.15 and stepping up and down every 0.1 strain.

7. Analysis

7.1 *Basic SPF Properties*—Force and extension measurements from the test machine are converted to true stress $\sigma\left[= S(1+e)\right]$ and true strain $\varepsilon\left[= \ln(L/L_0)\right]$. The basic SPF properties of a material at a specified strain rate and temperature shall be presented as a graph of true stress versus true strain as shown in Fig. 3. Several strain rates can be plotted on the same graph.

NOTE 8—The usual presentation of 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 coupon.

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

$$\sigma = k_1 + k_2\,\dot{\varepsilon}^m \tag{1}$$

where:

m = superplastic strain rate sensitivity exponent.

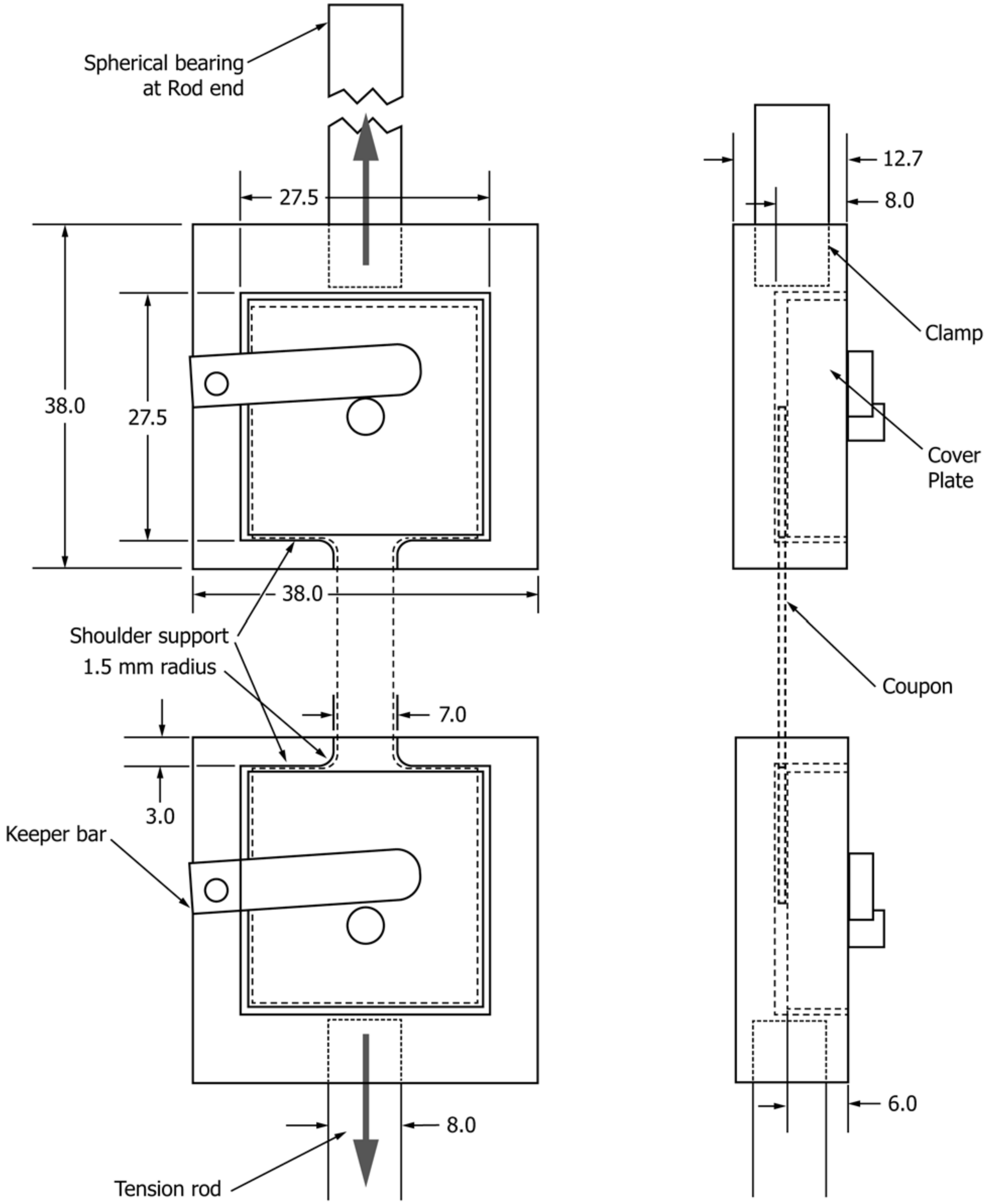


FIG. 2 Test Coupon Grip Configuration

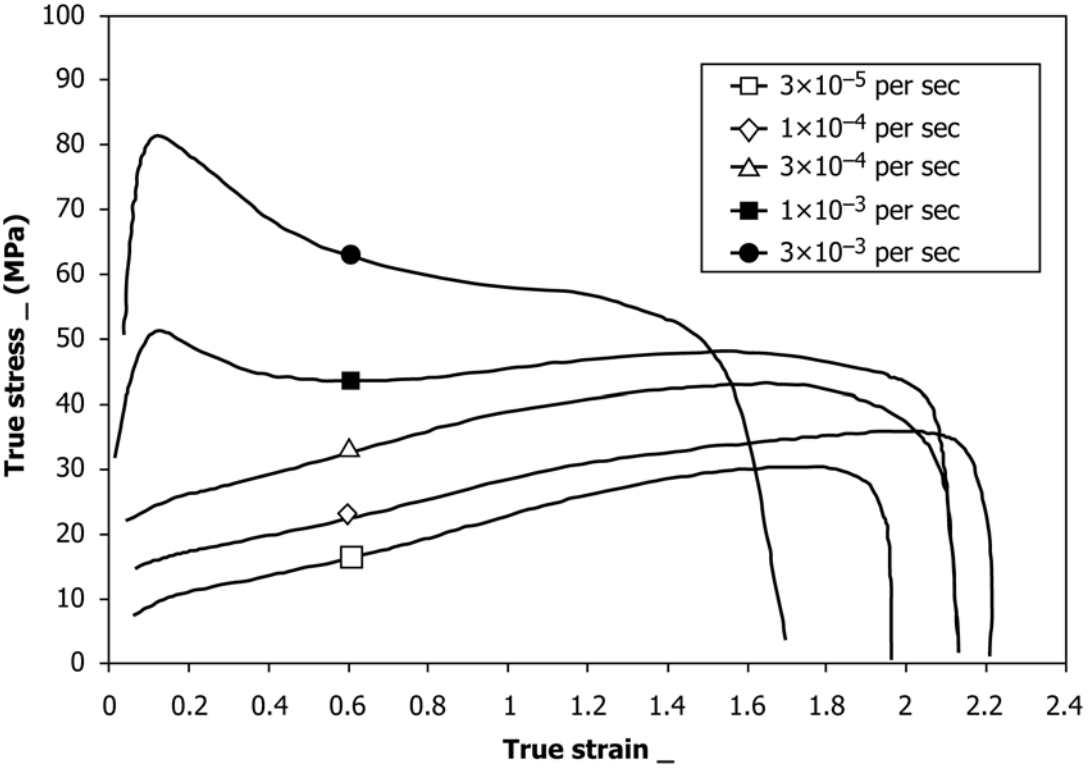


FIG. 3 Basic SPF Properties for Fine Grain Ti-6Al-4V Alloy at 775°C, Transverse Direction

7.2.1 The *m* value is determined from the test described in 6.10. The result of such a test is shown in Fig. 4. A number of points (usually 10) on either side of the step are taken and lines are extrapolated to the step, thus the two stress levels at the point of change are known.

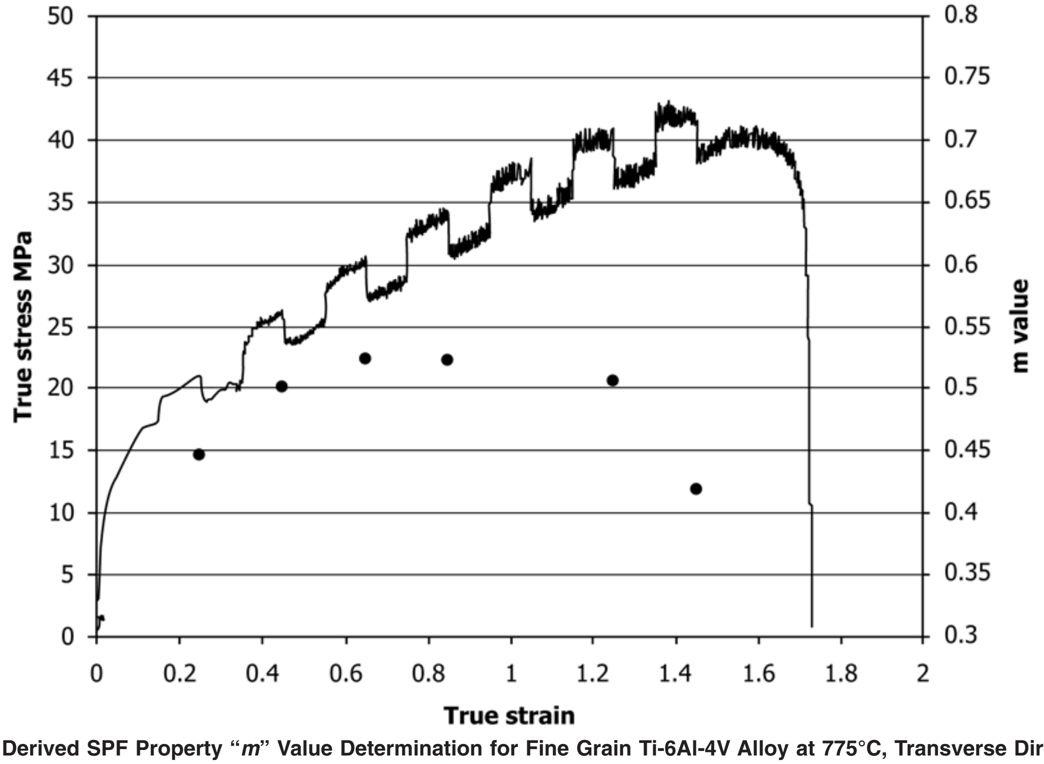


FIG. 4 Derived SPF Property "*m*" Value Determination for Fine Grain Ti-6Al-4V Alloy at 775°C, Transverse Direction

$$m = \log(\sigma_2/\sigma_1)/\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1) \qquad (2)$$

7.3 The value of *m* varies both with strain and strain rate. Therefore a quoted value of *m* must include the corresponding temperature, strain, and strain rate.

7.4 The default strain rate is that for maximum *m*, and the default strain is 0.693 (100 % engineering strain). Values of *m* for different strain rates and strains may be quoted in particular cases.

7.5 An example of *m* value calculation is as follows. A sample of 26 data points around the step at 0.650 strain graph 4 is shown in the following table.

Data point	Strain rate	Stress MPa	Strain
1	3.60E-04	30.076	0.646
2	3.60E-04	29.941	0.646
3	3.60E-04	29.910	0.647
4	3.60E-04	29.889	0.647
5	3.60E-04	30.556	0.648
6	3.60E-04	30.080	0.648
7	3.60E-04	29.820	0.649
8	3.60E-04	30.300	0.649
9	3.60E-04	29.985	0.650
10	3.60E-04	29.966	0.650
11	3.00E-04	28.596	0.650
12	3.00E-04	28.212	0.651
13	3.00E-04	27.930	0.651
14	3.00E-04	28.026	0.652
15	3.00E-04	27.607	0.652
16	3.00E-04	27.343	0.653
17	3.00E-04	27.465	0.653
18	3.00E-04	27.557	0.654
19	3.00E-04	27.006	0.654
20	3.00E-04	27.380	0.655
21	3.00E-04	27.251	0.655
22	3.00E-04	27.449	0.656
23	3.00E-04	27.222	0.656
24	3.00E-04	27.080	0.657
25	3.00E-04	27.475	0.657
26	3.00E-04	27.326	0.658

For the particular machine used in the test, a plot of the measured force and displacement from the table above would show that the test machine actually takes a finite time to change speed and stabilize. To allow for this, the 5 data points (representing 0.08% elongation) after the step change at point 11 are not included. The average stress for points 1 thru 10 is 30.052 MPa, and for points 17 thru 26 is 27.321 MPa.

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

m = log (30.052/27.321)/log (3.6x10-4/3.0x10-4)

m = 0.522

m values for other strains are also shown.

8. Report

8.1 The report shall include the following:

8.1.1 The material tested, including the heat and lot number,

8.1.2 The temperature and strain rate conditions of the test, and

8.1.3 A graph to the format of Fig. 3.

8.2 The report can include the following options:

8.2.1 The "*m*" value to the conditions of 7.4, or to other stated conditions.

9. Precision and Bias

9.1 The precision of this test method is based on an interlaboratory study of E2448, Standard Test Method for Determining the Superplastic Properties of Metallic Sheet Materials, conducted in 2007. Analytical results in this study were obtained from four laboratories, testing two different materials, for measurable stress at four strain levels. Every "test result" reported represents an individual determination. All participating laboratories were asked to report three replicate test results for each material. Except for the use of data from only four reporting laboratories, and the limited number of materials, Practice E691 was followed for the design and analysis of the data; the details are given in ASTM Research Report No. RR:E28-1030.[4]

9.1.1 *Repeatability limit (r)*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the "*r*" value for that material; "*r*" is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day in the same laboratory.

9.1.1.1 Repeatability limits are listed in Tables 1-4.

TABLE 1 Stress (MPa) at 50% Strain

Material	Average[A]	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	S_r	S_R	r	R
A	24.5087	0.7372	0.9880	2.0643	2.7663
B	12.3576	0.1509	0.2441	0.4224	0.6834

[A] The average of the laboratories' calculated averages.

TABLE 2 Stress (MPa) at 100% Strain

Material	Average[A]	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	S_r	S_R	r	R
A	27.6659	0.6013	1.2739	1.6836	3.5669
B	12.5571	0.1745	0.1912	0.4885	0.5354

[A] The average of the laboratories' calculated averages.

TABLE 3 Stress (MPa) at 150% Strain

Material	Average[A]	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	S_r	S_R	r	R
A	30.6486	0.3964	1.7334	1.1099	4.8536
B	12.0455	0.2139	0.3250	0.5990	0.9099

[A] The average of the laboratories' calculated averages.

---

[4] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E28-1030.

9.1.2 *Reproducibility limit (R)*—Two test results shall be judged not equivalent if they differ by more than the "*R*" value for that material; "*R*" is the interval representing the critical difference between two test results for the same material, obtained by different operators using different equipment in different laboratories.

TABLE 4 Stress (MPa) at 200% Strain

Material	Average[A] $\bar{x}$	Repeatability Standard Deviation S_r	Reproducibility Standard Deviation S_R	Repeatability Limit r	Reproducibility Limit R
A	32.8724	0.3015	1.9432	0.8443	5.4409
B	11.0762	0.1708	0.3062	0.4782	08575

[A] The average of the laboratories' calculated averages.

9.1.2.1 Reproducibility limits are listed in Tables 1-4.

9.1.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.

9.1.4 Any judgment in accordance with statements 9.1.1 and 9.1.2 would normally have an approximate 95% probability of being correct, however the precision statistics obtained in this ILS must not be treated as exact mathematical quantities which are applicable to all circumstances and uses. The limited number of materials tested, and laboratories reporting results, guarantees that there will be times when differences greater than predicted by the ILS results will arise, sometimes with considerably greater or smaller frequency than the 95% probability limit would imply. The repeatability limit and the reproducibility limit should be considered as general guides, and the associated probability of 95% as only a rough indicator of what can be expected.

9.2 *Bias*—At the time of the study, there was no accepted reference material suitable for determining the bias for this test method, therefore no statement on bias is being made.

9.3 The precision statement was determined through statistical examination of 186 summarized data points[5], from four laboratories, on two materials. The two materials tested were identified as the following:

Material A: Ti-6AL-4V titanium alloy sheet 2.54mm thick, heat lot 4076, longitudinal direction, to Boeing spec BMS7-385

Material B: 5083 Aluminum at 500C to SKY spec L-121

To judge the equivalency of two test results, it is recommended to choose the material closest in characteristics to the test material.

10. Keywords

10.1 constant strain rate; metallic materials; *m* value; SPF; superplastic forming; superplastic properties; temperature; true strain; true stress

---

[5] Due to the observed fluctuations in stress caused by non linear crosshead velocity speed increases, 10 data points either side of the desired strain were measured and averaged.