



Standard Test Method for Determining the Superplastic Properties of Metallic Sheet Materials¹

This standard is issued under the fixed designation E 2448; 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} 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 given in SI units are to be considered the 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

E 4 Practices for Force verification of Testing Machines

E 6 Terminology Relating to Methods of Mechanical Testing

E 21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials

E 646 Test Method for Tensile Strain Hardening Exponents (n-Values) of Metallic Materials

E 691 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 E 6. Thus,

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

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

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.

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

$\dot{\epsilon}$ = 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 $(\ln \Delta \sigma)/(\ln \Delta \dot{\epsilon})$. In practical terms, $m = \log(\sigma_2/\sigma_1)/\log(\dot{\epsilon}_2/\dot{\epsilon}_1)$ 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 E 646 is not valid for superplastic materials as strain hardening in the

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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.

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 E 4.

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 E 21 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.

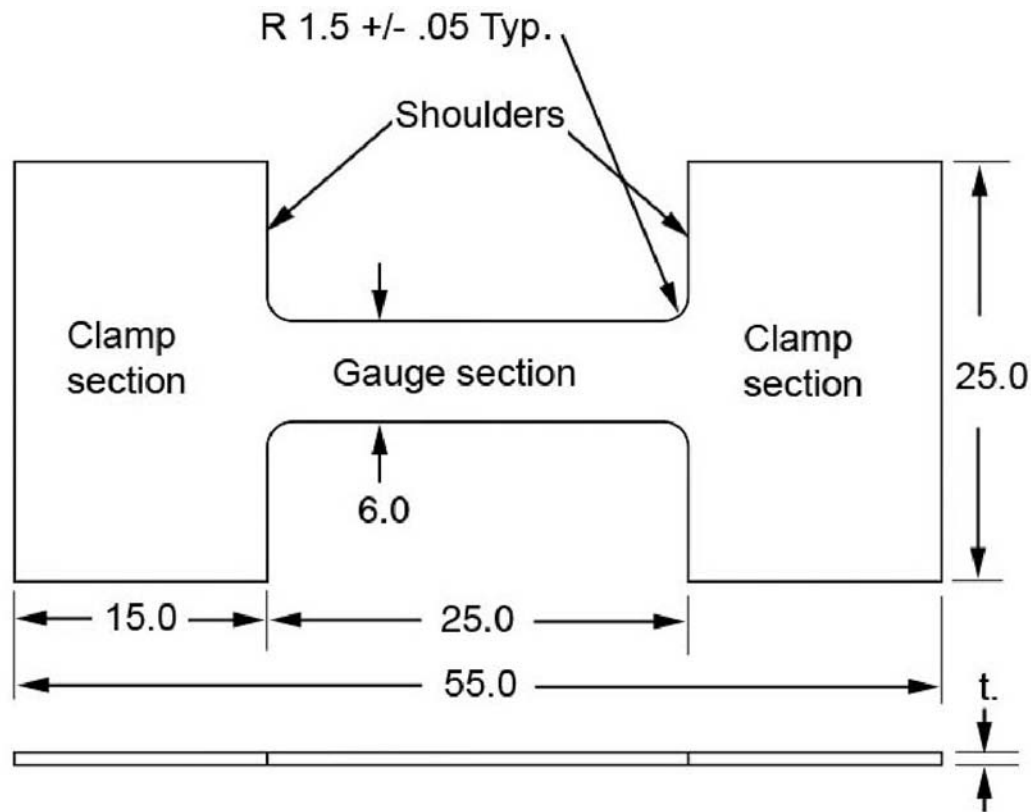
6.2 If material oxidation affects the superplastic behavior of the material, the furnace can be flooded with argon or other inert gas to reduce the effects of oxidation.

6.3 Before starting the test, the furnace is brought 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 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 $\pm 3^\circ\text{C}$ up to 700°C and $\pm 6^\circ\text{C}$ above 700°C .

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 +/- .25mm except where noted

FIG. 1 Dimensions of Test Coupon

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 $V = \dot{\epsilon} [L_0(1 + e)]$ to an accuracy of $\pm 1\%$ 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 $\pm 1\%$ 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 σ [$= S(1 + e)$] and true strain ϵ [$= \ln (L/L_0)$]. 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 be described by constitutive equations, generally of the form:

$$\sigma = k_1 + k_2 \dot{\epsilon}^m \quad (1)$$

where:

m = superplastic strain rate sensitivity exponent.

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.

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

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.

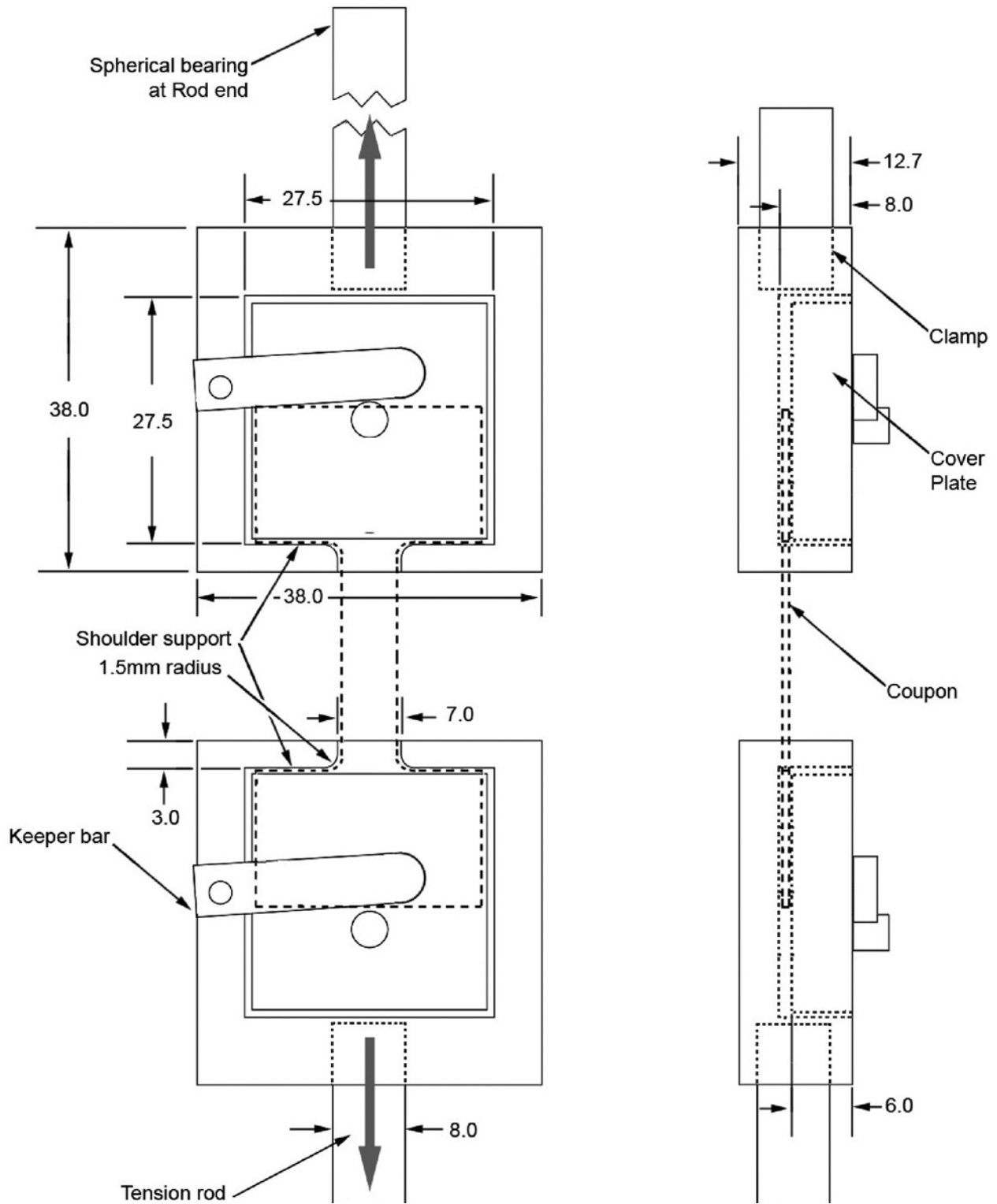


FIG. 2 Test Coupon Grip Configuration

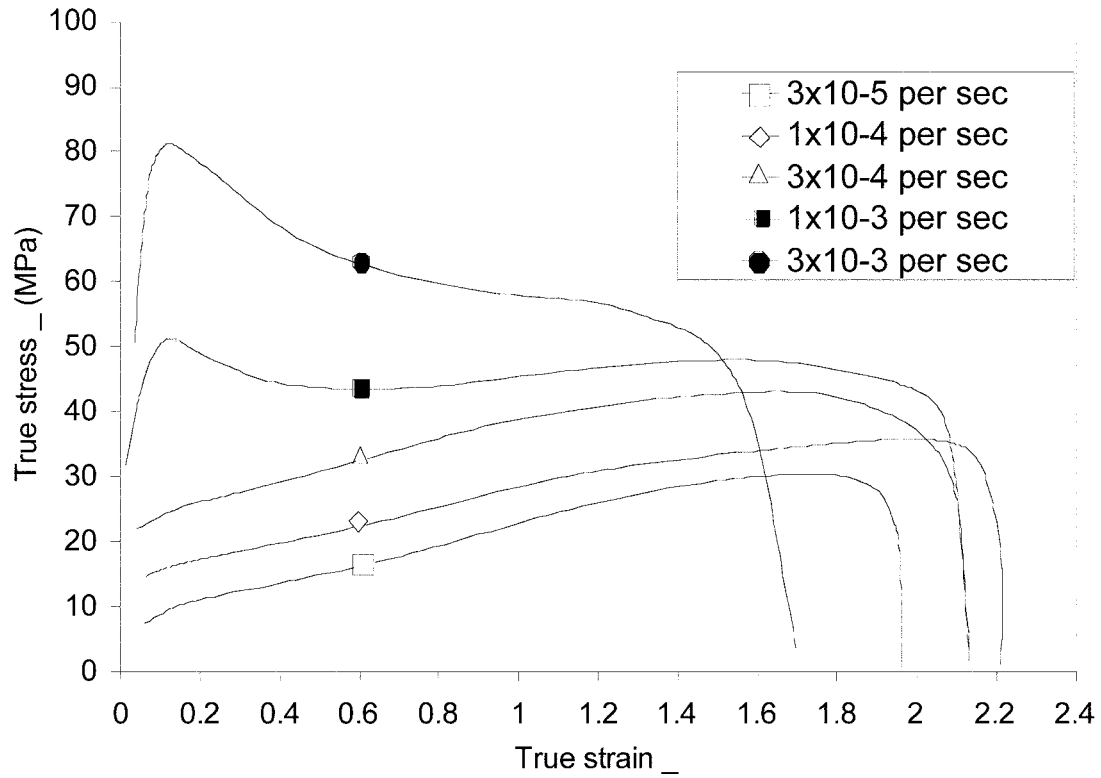


FIG. 3 Basic SPF Properties for Fine Grain Ti-6Al-4V Alloy at 775°C, Transverse Direction

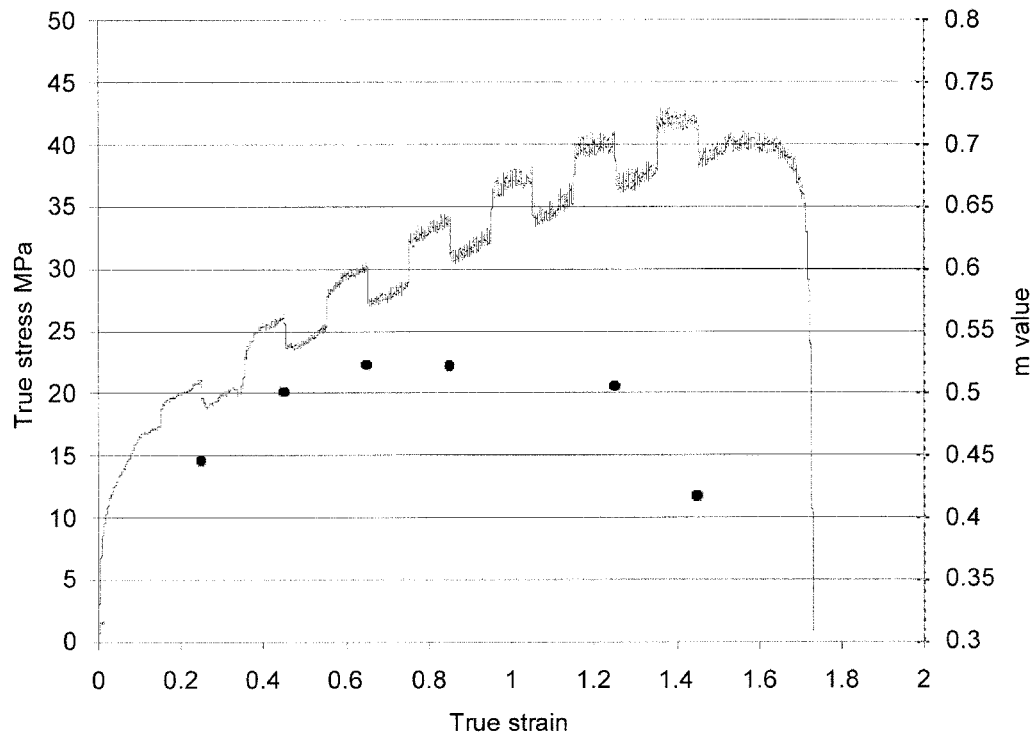


FIG. 4 Derived SPF Property "m" Value Determination for Fine Grain Ti-6Al-4V Alloy at 775°C, Transverse Direction

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 table below.

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.

$$m = \log(\sigma_2/\sigma_1)/\log(\epsilon_2/\epsilon_1)$$

$$m = \log(30.052/27.321)/\log(3.6 \times 10^{-4}/3.0 \times 10^{-4})$$

$$m = 0.522$$

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 In order to determine repeatability and reproducibility of the test, in accordance with Practice E 691, a sheet of fine grain Ti-6Al-4V titanium alloy and a sheet of superplastic 5083 aluminum were procured, and coupons to the geometry of Fig. 1 were machined. Superplastic Properties were determined according to this standard on 6 coupons from each material. The titanium test was conducted at 775°C at a strain rate of

3×10^{-4} per second, and the aluminum was conducted at 500°C at the same strain rate. For each coupon a set of stress v. strain values was obtained.

9.2 Per 8.1.3, the Superplastic Properties data is to be presented in graphical form as in Fig. 3. At the present time there is no statistical method to compare curves, and so the stress value at one strain, 0.693148 (100 %) was taken for statistical analysis. Due to variations in the way data is collected from the machine, and the method by which cross-head speed is adjusted on many machines, it is prudent to take the average of several stress readings around the nominal strain value. In this case the nominal reading plus 10 readings either side of nominal were taken, for a total of 21 readings. The variation in strain for the 21 readings was 0.7 %.

9.3 The stress values for fine grain Ti-6Al-4V alloy are shown in the following table:

Commercially available fine grain Ti-6Al-4V						
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Stress MPa	41.730	40.795	40.323	41.214	40.884	40.467
	40.821	41.145	40.887	41.222	42.072	40.028
	41.092	41.804	40.209	40.695	41.401	40.643
	41.843	41.156	40.936	39.998	40.983	40.731
	41.242	40.757	41.098	41.033	41.995	39.824
	40.649	41.634	40.153	40.209	41.771	40.827
	41.740	41.657	40.925	41.203	41.016	40.968
	41.770	40.754	41.222	41.127	41.816	40.113
	40.988	41.653	40.560	41.236	41.938	40.947
	41.601	41.757	41.014	40.956	41.121	41.063
Nominal	41.825	40.893	40.646	40.506	41.972	40.539
	41.044	41.669	40.460	40.424	42.062	40.023
	41.347	41.754	40.990	40.557	41.156	41.055
	41.860	40.857	40.541	39.997	42.087	40.863
	41.284	41.710	40.374	41.091	41.922	40.151
	40.790	41.794	40.706	40.827	41.067	40.814
	41.746	40.907	39.881	41.168	42.102	40.996
	41.033	41.875	40.858	40.803	41.253	40.278
	41.860	41.730	40.690	39.957	42.342	40.277
	41.824	41.055	39.912	40.986	42.285	41.033
	41.163	41.141	40.911	40.234	41.336	40.459
Average	41.393	41.357	40.633	40.735	41.647	40.576

9.3.1 The average stress for the 6 coupons is 41.1 MPa and the standard deviation is 0.462 MPa. The 95% within laboratory repeatability limit is 1.294 MPa.

9.4 The stress values for the 5083 aluminum alloy are shown in the following table:

Commercially available superplastic 5083 aluminum alloy						
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Stress MPa	11.984	12.318	12.484	13.192	12.118	12.293
	12.651	12.893	12.918	13.170	12.727	12.080
	12.629	12.993	12.982	13.245	12.746	12.334
	12.742	12.709	13.068	12.701	12.780	12.754
	12.472	12.469	12.695	12.515	12.152	12.717
	11.984	12.557	12.398	12.884	12.071	12.323
	12.529	12.917	13.001	13.253	12.750	12.129
	12.712	12.901	13.042	13.272	12.847	12.166
	12.788	13.044	13.084	12.829	12.801	13.104
	12.496	12.368	12.463	12.756	12.370	12.902
Nominal	12.003	12.194	12.451	13.305	12.191	12.576
	12.360	12.922	13.065	13.320	12.910	12.308
	12.651	12.921	13.086	12.882	12.752	12.162
	12.656	13.088	12.861	12.641	12.803	12.770
	12.290	12.377	12.413	12.599	12.318	12.828
	12.090	12.297	12.669	13.206	12.711	12.655
	12.008	13.033	13.134	13.285	12.861	12.363
	12.602	12.909	13.055	13.068	12.736	12.778
	12.503	12.793	12.844	12.586	12.490	12.807
	12.497	12.540	12.404	12.855	12.175	12.901

Commercially available superplastic 5082 aluminum alloy

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
	12.221	12.277	13.000	13.208	12.068	12.846
Average	12.422	12.691	12.815	12.989	12.542	12.562

9.4.1 The average stress for the 6 coupons is 12.7 MPa and the standard deviation is 0.206 MPa. The 95% within laboratory repeatability limit is 0.577 MPa

10. Keywords

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

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