Designation: ~~E2218 – 15~~ E2218 – 23

Standard Test Method for Determining Forming Limit Curves[1]

This standard is issued under the fixed designation E2218; 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 gives the procedure for constructing a forming limit curve (FLC) for a metallic sheet material by using a hemispherical deformation punch test and a uniaxial tension test to quantitatively simulate biaxial ~~stretch~~stretching and deep drawing processes.

1.1.1 Fig. 1 shows an example of a forming limit curve on a schematic forming limit diagram (FLD).

1.2 FLCs are useful in evaluating press performance by metal fabrication strain analysis.

1.3 The method applies to metallic sheet from 0.5 mm (0.020 in.) to 3.3 mm (0.130 in.).

1.4 The values stated in SI units are to be regarded as the standard. The ~~inch-pound equivalents are approximate.~~values given in parentheses after SI units are provided for information only and are not considered standard.

1.5 *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~~safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *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]

A568/A568M Specification for Steel, Sheet, Carbon, Structural, and High-Strength, Low-Alloy, Hot-Rolled and Cold-Rolled, General Requirements for
E6 Terminology Relating to Methods of Mechanical Testing
E8/E8M Test Methods for Tension Testing of Metallic Materials
E517 Test Method for Plastic Strain Ratio ***r*** for Sheet Metal
E646 Test Method for Tensile Strain-Hardening Exponents (***n*** -Values) of Metallic Sheet Materials
E2208 Guide for Evaluating Non-Contacting Optical Strain Measurement Systems

[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.

3. Terminology

3.1 ~~Terminology~~The ~~E6 shall apply including the special terms used in this method shown in~~terms accuracy, gauge length, necking, precision, strain hardening, engineering strain, and true strain ~~3.2~~are used as defined in Terminology E6.

3.2 ~~*Definitions:*~~*Definitions of Terms Common to Mechanical Testing:*

~~3.2.1 *biaxial stretching*—a mode of metal sheet forming in which positive strains are observed in all directions at a given location.~~

~~3.2.1.1 *Discussion*—~~

~~See Fig. 1.~~

~~3.2.2 *deep drawing*—a metal sheet forming operation in which strains on the sheet surface are positive in the direction of the punch travel (e_1) and negative at 90° to that direction.~~

~~3.2.2.1 *Discussion*—~~

~~Deep drawing, see Fig. 1, occurs in the walls of a drawn cylinder or the corner walls of a deep drawn part when the flange clamping force is sufficient to restrain metal movement and wrinkling, while permitting the punch to push the center area of the blank into the cavity of the die. Strain conditions that can cause wrinkling or thickening are shown in Fig. 2.~~

~~3.2.2.2 *Discussion*—~~

~~In forming a square pan shape, metal from an area of the flange under a reduced clamping force is pulled into the die to form the side wall of the part.~~

~~3.2.3 *forming limit diagram (FLD)*—a graph on which the measured major (e_1) and associated minor (e_2) strain combinations are plotted to develop a forming limit curve.~~

~~3.2.3.1 *Discussion*—~~

~~See Fig. 2.~~

3.2.1 *forming limit curve,* ~~(FLC)—~~FLC,*n*—an empirically derived curve showing the biaxial strain levels beyond which localized through-thickness thinning (necking) and subsequent failure occur during the forming of a metallic sheet.

3.2.1.1 *Discussion*—

The forming limit curve is sometimes referred to as the "forming limit."

~~3.2.4.1 *Discussion*—~~

~~See Fig. 3.~~

~~3.2.4.2 *Discussion*—~~

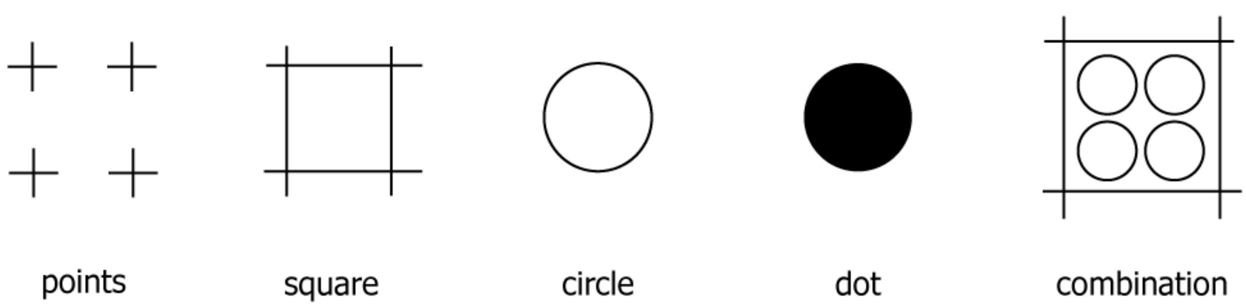
~~The curve of Fig. 3 is considered the forming limit for the material when the metal is subjected to a stamping press operation. It was obtained for a drawing quality aluminum killed steel sheet. The curve of Fig. 3 correlates with the upper curve of Fig. 2, a generic curve representing a metallic sheet material with a FLD_o of 40 %.~~

~~3.2.4.3 *Discussion*—~~

~~The strains are given in terms of percent major and minor strain measured after forming a series of test specimen blanks by using a grid pattern. The gauge lengths before and after forming the part are measured to obtain the percent strain. The curve for negative (e_2) strains will generally follow a constant surface area relationship to the associated (e_1) strain.~~

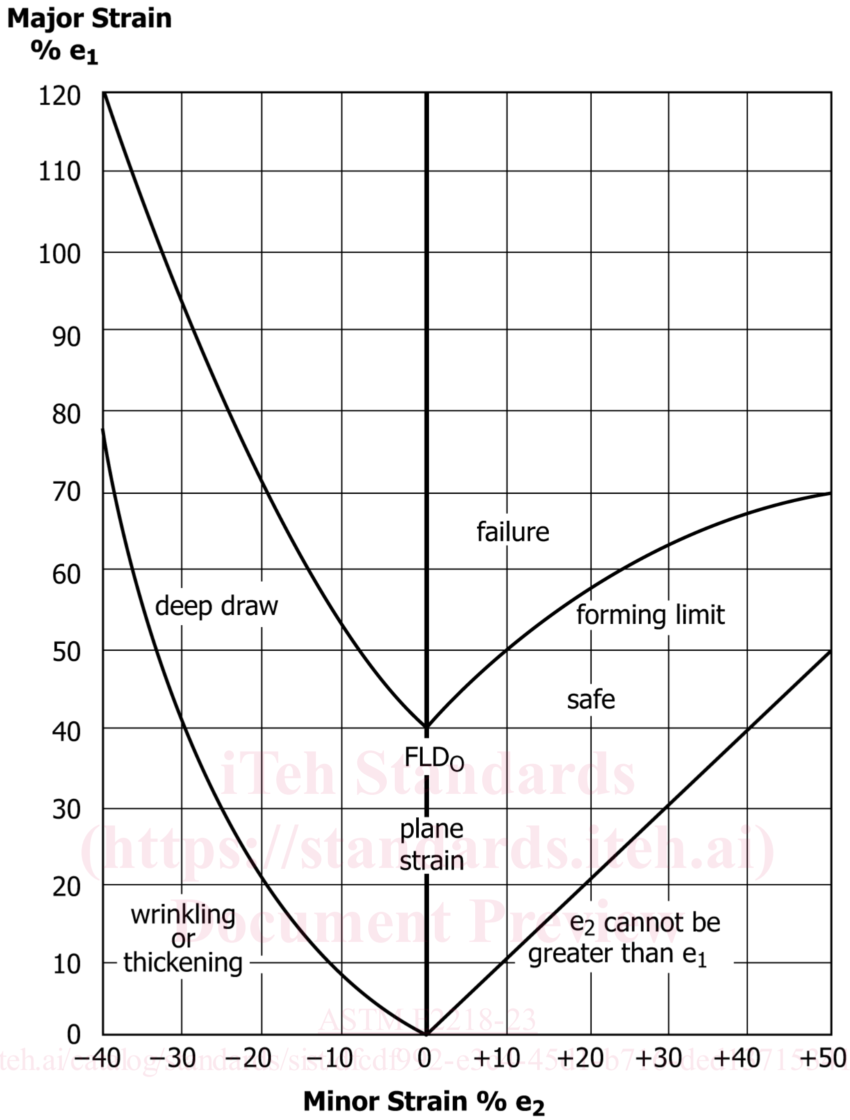
~~3.2.4.4 *Discussion*—~~

~~The range of possible major strain (e_1) is from 0 % to over 200 %. The range of possible minor strain (e_2) is from −40 % to over +60 %.~~



NOTE 1—The basic ~~pattern is reapeated~~gauge length measurement unit is repeated over the area of the part to be studied on a flat ~~specimen blank.~~test specimen.

FIG. 4 Examples of ~~patterns for Gauge Length measurement units used~~ Gauge Length Measurement Units for Various Patterns Used in Determining Forming Limit Curves (FLC)



NOTE 1—The upper curve ~~is representative of~~ represents the forming ~~limit.~~ limit curve. Strains below the lower curve do not occur during forming metallic sheet products in the most stamping press operations. Curves to the left of % e_2= 0 are for constant area of the ~~sheet~~ test specimen surface.

FIG. ~~2~~1 Schematic Forming Limit Diagram

3.2.2 ~~*limiting dome height*~~*forming limit diagram,* ~~(LDH)~~ FLD,~~*test*—~~*n*—~~an evaluative test for metal sheet deformation capability employing a hemispherical punch~~ a graph on which the measured major (e_1~~and a circumferential clamping~~) and associated minor (e_2 ~~force sufficient to prevent metal in the surrounding flange from being pulled into the die cavity.~~) strain combinations are plotted to develop a forming limit curve.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 ~~*grid pattern*—~~*biaxial stretching, n*—a ~~pattern applied to the surface of a metal sheet to provide an array of precisely spaced gauge points prior to forming the metal into a final shape by the application of a force.~~mode of metal sheet forming in which positive strains are observed in all in-plane directions at a given location.

3.3.1.1 *Discussion*—
See Fig. 2.

3.3.2 *deep drawing, n*—a sheet metal forming operation in which strains on the test specimen surface are positive in the direction of the punch travel (e_1) and negative at 90° to that direction.

3.3.2.1 *Discussion*—
Deep drawing, see Fig. 2, occurs in the walls of a drawn cylinder or the corner walls of a deep drawn part when the flange clamping

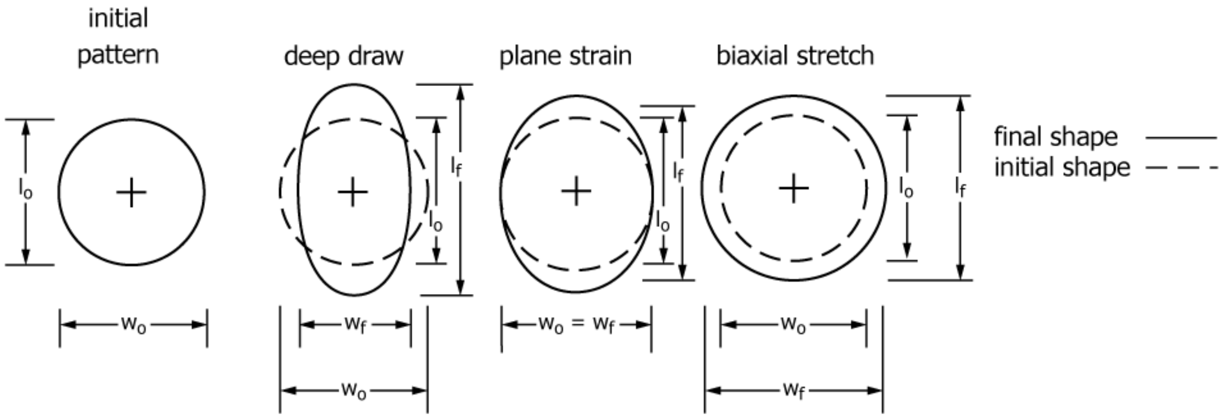


FIG. 2 Possible Changes in the Shape of the Circular Grid Pattern Gauge Length Measurement Units Caused by Forming Operations on Metallic Sheet Products

force is sufficient to restrain metal movement and wrinkling, while permitting the punch to push the center area of the test specimen into the cavity of the die. Strain conditions that can cause wrinkling or thickening are shown in Fig. 1.

3.3.2.2 *Discussion—*
In forming a square pan shape, metal from an area of the flange under a reduced clamping force is pulled into the die to form the side wall of the part.

3.3.3 *FLD_o, n—*the location on the forming limit curve that has the lowest major strain (e_1).

3.3.4 *fractured, adj—*the visual classification of deformed individual gauge length measurement units, where the unit is separated by a fracture into two parts.

3.3.4.1 *Discussion—*
This classification is also referred to as fail.

3.3.4.2 *Discussion—*
The strain in the deformed individual gauge length measurement unit is beyond the forming limit.

3.3.5 *gauge length measurement unit, n—*the portion of a pattern, with either a defined or measured gauge length prior to forming, used to measure local major and minor strains.

3.3.6 *good, adj—*the visual classification of deformed individual gauge length measurement units, where the unit lies entirely outside the necked region of the test specimen.

3.3.6.1 *Discussion—*
This classification is also referred to as no localized necking, pass, or acceptable, on production parts.

3.3.7 *limiting dome height (LDH) test, n—*an evaluative test for metal sheet deformation capability employing a hemispherical punch and a circumferential clamping force sufficient to prevent metal in the surrounding flange from being pulled into the die cavity.

3.3.8 *major strain,* ~~*(ee1)—*~~*(e_1), n—*the largest strain, developed at a given location ~~in the sheet~~on the test specimen surface.

3.3.8.1 *Discussion—*
The major strain (e_1) is measured either along the stretched line of a ~~square pattern,~~ pattern of squares, or along the major axis of the ellipse resulting from deformation of a ~~circular grid pattern,~~pattern of circles, or along the direction of the maximum surface strain using a non-contacting optical strain measurement technique.

3.3.9 *marginal, adj—*the visual classification of deformed individual gauge length measurement units, where the unit lies in a region of localized thinning or a trough in the test specimen surface.

3.3.9.1 *Discussion—*
This classification is also referred to as localized necking or borderline.

3.3.10 *minor strain,* ~~*(ee2)—*~~*(e_2), n—*the strain ~~in the sheet~~ on the test specimen surface in a direction perpendicular to the major strain.

3.3.10.1 *Discussion—*
The minor strain (e_2) is measured at 90° to the major strain, either along the shorter dimension of the final rectangular shape of a part formed using a square pattern, gauge length measurement unit, or along the shorter axis of the ellipse resulting from deformation of a circular grid pattern,pattern of circles, or along the direction of the minimum surface strain using a non-contacting optical strain measurement technique.

3.3.11 *pattern, n—*a regular array or randomly placed set of features applied, prior to forming, to the surface of a test specimen, that are used as gauge length measurement units.
3.3.11.1 *Discussion—*
A regular array of features, such as lines, circles, or dots, is often called a "grid pattern" or "circle grid pattern."
3.3.11.2 *Discussion—*
A random placed set of features, such as paint overspray for digital image correlation, is often called a "speckle pattern".

3.3.12 *plane strain, FLD$_o$n*——the condition in metal sheet forming that maintains a near zero (0(0 % to +5 %) minor strain (e_2) while the major strain (e_1) is positive (in tension)tension).
3.3.12.1 *Discussion—*
Plane strain is the most severe deformation mode and ideally causes a low point in the forming limit curve (FLC). (FLC), see Fig. 1. For convenience, many FLCs are shown with the low point at 0 % (e_2), = 0 % or a slightly positive value; however, such an abrupt reversal of (e_1) strain does not occur. See Fig. 3 and Figs. X2.1-X2.3.

4. Summary of Test Method

4.1 Determination of a forming limit curve (FLC) involves selecting a style of testing apparatus, deforming multiple test specimens biaxially, measuring the resulting strain (including judgingclassifying if these strains are localized), and drawing a curve through the measured points.

4.2 Various test apparatus (see Section 6) may be used to deform test specimens biaxially including a hemispherical punch testing machine such as an LDH tester, testing machine, a sub press in a universal testing machine, or a hydraulic bulge testing machine.

4.2.1 Contact surfaces of the blank undeformed test specimen and punch are lubricated for the hemispherical punch test.

4.2.2 The flanges of a blank test specimen are securely clamped in serrated or lock bead, blank-holder lock-bead test-specimen-holder dies for the hemispherical punch and hydraulic bulge tests.

4.3 Stretching the central area of the blank biaxially or pulling in the tension test is performed without interrupting the force.

4.3.1 A series of grid pattern blankspatterned test specimens is prepared with different widths and a common length suitable for being securely grippedheld in the test apparatus.

4.3.2 Negative minor strains (e_2) strains can be obtained using sheared narrow strips strip test specimens stretched over the punch of a hemispherical punch tester.testing machine.

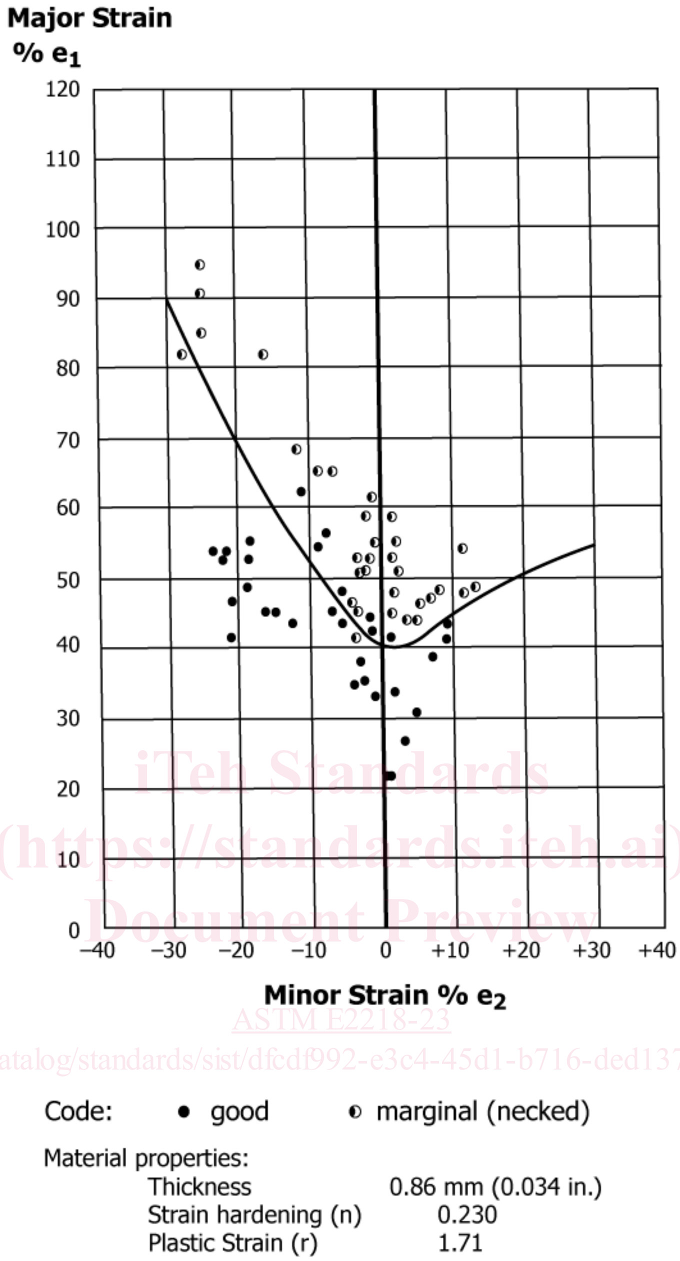
4.3.3 If possible, the punch advance or the force is stopped when a localized through-thickness neck (localized necking) is observed, or as soon as the test specimen fractures.

4.3.4 Unless there is a defect in the material, the test specimen will not split across the nose of the punch. Instead, when the punch is advanced beyond the forming limit of the material, necking or fracturing, or both, will occur in a ring encircling the round cap of the formed region.

NOTE 1—Lubrication improves sliding of the material over the surface of the punch and causes rupture to occur closer to the nose of the punch. This does not change the forming limit, as the minor strain (e_2) adjusts to the increased major strain (e_1).

4.4 The major (e_1) and the minor (e_2) strains of the grid individual gauge length measurement units of the pattern on the surface area are measured near the neck of all the test specimens for the series and recorded.

4.4.1 The strain measurements may include good (no localized necking), marginal (localized necking), and fracturefractured areas.



Cold Rolled Drawing Quality Aluminum Killed Steel
Longitudinal Mechanical Properties

Thickness		Yield Strength		Tensile Strength		% El in 50 mm	*n* Value	*r* Value
mm	(in.)	MPa	(ksi)	MPa	(ksi)			
~~0.866~~	~~(0.034)~~	~~163.4~~	~~(23.7)~~	~~304.7~~	~~(44.2)~~	~~43.5~~	~~0.230~~	~~1.71~~

Cold Rolled Drawing Quality Aluminum Killed Steel
Longitudinal Mechanical Properties

Thickness		Yield Strength		Tensile Strength		% El in 50 mm	*n* Value	*r* Value
mm	(in.)	MPa	(ksi)	MPa	(ksi)			
0.86	(0.034)	163.4	(23.7)	304.7	(44.2)	43.5	0.230	1.71

Chemical Composition

Element	C	S	N	Mn	Al	P	Si
Percent	0.035	0.006	0.006	0.19	0.29	0.006	0.004

FIG. 3 Forming Limit Diagram (FLD) with Forming Limit Curve (FLC) for a Cold Rolled Drawing Quality Aluminum Killed Steel ~~Sheet.~~ Sheet that shows the Forming Limit Curve

4.4.2 The measured strain combinations are plotted on a forming limit diagram (see Fig. 3).

4.4.3 If other than good (no localized necking) locations are included, then each measured point is visually evaluated and noted as illustrated in Fig. 3.

4.5 The FLC is established by drawing a curve on the FLD based on the criteria in ~~13.4~~12.4.

NOTE 2—The curve of Fig. 3 is considered the forming limit for the material when the metal is subjected to a stamping press operation. It was obtained for a drawing quality aluminum-killed steel sheet. The curve of Fig. 3 correlates with the upper curve of Fig. 1, a schematic curve representing a metallic sheet material with an FLD_o of 40 %.

NOTE 3—The curve for negative minor strains (e_2) will generally follow a constant surface area relationship to the associated major strains (e_1).

5. Significance and Use

5.1 The forming limit curve (FLC) is specific to the material sampled. It can change if the material is subjected to cold work or any annealing process. Thus, two samples from a given lot of material can produce different curves if their processing is varied.

5.2 The processing history of the material must be known if the test is to be considered representative of a grade of a product.

5.3 A forming limit curve (FLC) defines the maximum (limiting) strain that a given sample of a ~~metallic~~ sheet metal can undergo for a range of forming conditions, such as deep drawing, ~~stretching~~ plane strain, biaxial stretching, and bending over a radius in a press and die drawing operation, without developing a localized zone of thinning (localized necking) that would indicate incipient failure.

5.3.1 FLCs may be obtained empirically by using a laboratory hemispherical punch biaxial stretch test and also a tension test to strain metal sheet ~~specimens~~ test specimens, from a material ~~sample~~ sample, from beyond their elastic ~~limit,~~ limit to just prior to localized necking and fracture.

5.3.1.1 Since ~~this~~ the location of localized necking and fracture cannot be predetermined, one or both surfaces of test specimens are covered with a ~~grid~~ pattern of gauge ~~lengths~~ length measurement units, usually as squares or small diameter circles, by a suitable method such as scribing, photo-grid, or electro-etching, and then each test specimen is formed to the point of localized necking, or fracture.

5.3.2 Strains in the major (e_1) and minor (e_2) directions are measured using ~~points~~ individual gauge length measurement units on the ~~grid~~ pattern in the area of the localized necking or fracture.

5.3.2.1 ~~Blanks~~ Test specimens of varied widths are used to produce a wide range of strain states in the minor (e_2) direction.

5.3.2.2 The major strain (e_1) ~~strain~~ is determined by the capacity of the material to be stretched in one direction as simultaneous surface forces either stretch, do not change, or compress, the metal in the minor strain (e_2) direction.

5.3.2.3 In the tension test deformation process, the minor strains (e_2) ~~strains~~ are negative, and the ~~metal~~ test specimen is narrowed both through the thickness and across its width.

5.3.3 These strains are plotted on a forming limit diagram ~~(FLD)~~(FLD), and the forming limit curve (FLC) is drawn to connect the highest measured ~~(~~e_1 and e_2~~)~~ strain combinations that include good data points.

5.3.3.1 When there is intermixing and no clear distinction between good and ~~necked~~marginal data points, a best fit curve is established to follow the maximum good data points as the FLC.

5.3.4 The forming limit is established at the maximum major strain (e_1) ~~strain~~ attained prior to necking.

5.3.5 The FLC defines the limit of useful deformation in forming metallic sheet products.

5.3.6 FLCs are known to change with material (specifically with the mechanical or formability properties developed during the processing operations used in making the ~~material),~~material) and the thickness of the sheet ~~sample.~~metal.

5.3.6.1 The strain hardening exponent (*n* value), defined in Test Method E646, affects the forming limit. A high *n* value will raise the limiting major strain (e_1), allowing more stretch under positive ~~(+~~minor strain conditions (e_2~~) strain conditions.~~ > 0).

5.3.6.2 The plastic strain ratio (*r* value), defined in Test Method E517, affects the capacity of a material to be deep drawn. A high *r* value will move the minor ~~(–~~strain (e_2) ~~strain~~ into a less severe area to the left of the FLD_o~~,~~ ($e_2 < 0$), thus permitting deeper draws for a given major strain (e_1~~) strain.~~).

5.3.6.3 The thickness of the material will affect the FLC since a thicker test specimen has more volume to respond to the forming process.

5.3.6.4 The properties of the steel sheet product used in determining the FLC of Fig. 3 included the *n* value and the *r* value.

5.3.7 FLCs serve as a diagnostic tool for material strain analysis and have been used for evaluations of stamping operations and material selection.

5.3.8 The FLC provides a graphical basis for comparison with strain distributions on parts formed by sequential press operations.

5.3.9 The FLC obtained by this method follows a constant proportional strain path where there is a nominally fixed ratio of major (e_1) to minor (e_2) strain.

5.3.9.1 There is no interrupted loading, or reversal of straining, but the rate of straining may be slowed as the test specimen approaches ~~neck-down,~~necking or fracture.

5.3.9.2 The FLC can be used for conservatively predicting the performance of an entire class of ~~material~~materials provided the *n* value, *r* value, and thickness of the material used are representative of that class.

5.3.10 Complex forming operations, in which the strain path changes, or the strain is not homogeneous through the metal sheet thickness, ~~may~~can produce limiting strains that do not agree with the forming limit obtained by this method.

5.3.11 Characterization of a material's response to plastic deformation can involve strain to fracture as well as to the onset of necking. These strains are above the FLC.

5.3.12 The FLC is not suitable for lot-to-lot quality assurance testing because it is specific to that sample of a material which is tested to establish the forming limit.

6. Apparatus

6.1 Data points for minor strains (e_2) near 0 % and for positive minor strains ~~(+~~(e_2~~)~~ > 0) associated with major strains (e_1) may be obtained using a hemispherical punch testing machine such as a LDH ~~tester,~~ testing machine, a sub press in a universal testing machine, or a hydraulic bulge testing machine.

~~NOTE 1—The LDH test was designed to give a repeatable measure of punch movement among specimens of a specific metal sheet sample; thus the only measured value would be the punch height at incipient fracture. Problems with maintaining a secure clamp result in variation of the measured LDH value. A modification of the LDH test using a strip in the range of 200 mm (8 in.) wide was found to give (e)$_1$ values near 0 % (e_2), when the surface strains were measured using a grid pattern. On this basis, a test was developed to use a sheared strip of metal sheet 200 mm (8 in.) wide and sufficiently long to be securely clamped in the LDH test fixture. The height at incipient fracture was to correlate with FLD_o. The test was not sufficiently repeatable to be employed for evaluation of metal sheet samples. The equipment is used to stretch specimens, with grid patterns that have been sheared to various widths and is one method to obtain a range of (e_2) and associated (e_1) values for plotting a FLC on a FLD.~~

NOTE 4—The LDH test was designed to give a repeatable measure of punch movement among specimens of a specific metal sheet sample; thus the only measured value would be the punch height at incipient fracture. Problems with maintaining a secure clamp result in variation of the measured LDH value. A modification of the LDH test using a strip approximately 200 mm (8 in.) wide as a test specimen, for a 200 mm (8 in.) LDH hemispherical punch, was found to give values of e_2 near 0 %, when the surface strains were measured using a grid pattern. On this basis, a test was developed to use a sheared strip of metal sheet 200 mm (8 in.) wide and sufficiently long to be securely clamped in the LDH test fixture. The height at incipient fracture correlated with FLD_o. The test was not sufficiently repeatable to be employed for evaluation of metal sheet samples. The equipment is used to stretch test specimens that have been sheared to various widths and have been patterned, and is one method to obtain a range of e_2 and associated e_1 values for plotting a FLC on a FLD.

6.1.1 The hydraulic bulge testing machine may employ a liquid or a soft elastic material ~~as~~ to apply the forming force.

6.2 Data points for the negative minor ~~(−~~strain (e_2) ~~strain~~ < 0) associated with a major strain (e_1) ~~strain~~ may be obtained using various width strips in a LDH ~~tester~~ testing machine and also a universal testing machine and Test Method E8/E8M for a tension test of a test specimen that has a ~~grid~~ pattern on the ~~surface.~~surface to be used as gauge length measurement units.

6.2.1 A series of test specimens having different widths of reduced parallel sections or a series of sheared full length strips with ~~grid~~ patterns may be used to obtain a range of ~~(~~e_2~~)~~ strains.

6.3 The ~~press~~testing apparatus shall be capable of securely clamping the test ~~blank~~specimen to prevent, or minimize, draw-in of flange metal.

6.3.1 Serrated dies work well with equipment using 75 mm (3 in.), or 100 mm (4 in.) diameter punches. If an interlocking ring bead is used, the fit between the two clamping parts ~~shall~~should be such that no area of the test specimen flange is pulled-in by the forming force.

NOTE 5—Restriction of the pull-in of flange metal is not critical ~~in obtaining~~ when using sheared strips for measuring ~~(~~e_1~~)~~ and associated ~~(~~e_2~~)~~ strains to establish the forming limit.

NOTE 6—Unlike the forming limit curve test that uses strain measurements, secure clamping of the flange is critical for the LDH test in which only the punch height is recorded.

~~6.3.2 Secure clamping of the flange is critical for the LDH test in which only the punch height is recorded.~~

6.4 The test system shall have sufficient force and stroke to ensure the hemispherical punch can be driven until the metal sheet ruptures.

6.5 The apparatus shall produce sufficient force to both hold down the flanges and advance the punch to complete the deformation of the ~~blank.~~test specimen.

6.6 Although no punch ~~displacement or load measuring~~ displacement- or force-measuring capabilities are required for determining data, such devices are helpful in conducting the test.

6.7 The hemispherical punch is advanced against the center of the clamped test specimen at a constant rate until the material exhibits localized necking (through thickness thinning) and a fracture appears in the surface of the test specimen.

6.7.1 The punch advance may be slowed at the end of the forming process to aid in stopping at the start of localized necking, or when fracture begins.

6.7.2 The nominal punch speed shall be measured and reported.

~~6.7.3 Unless there is a defect in the material, it should not split across the nose of the punch. Instead, when the punch is advanced beyond the forming limit of the material, necking or fracturing, or both, will occur in a ring encircling the round cap of the formed region.~~

~~NOTE 3—Lubrication improves sliding of the material over the surface of the punch and causes rupture to occur closer to the top. This does not change the forming limit, as the minor (e_2) strain adjusts to the increased major (e_1) strain.~~

6.8 The punch shall have a hemispherical nose with a nominal diameter of at least 75 mm (3 in.). Diameters of 100 mm (4 in.) and 200 mm (8 in.) have been used.

6.8.1 The 100 mm (4 in.) diameter limiting dome height (LDH) testing equipment is well suited to straining narrow strips and full size ~~(square,~~(square or round) ~~specimen blanks~~test specimens to obtain data for determining the forming limit curve (FLC).

6.8.2 A ~~75mm~~ 75 mm (3 in.) round ball seated in a spherical mount may be used as a hemispherical nose punch.

6.9 Clearance between the ~~forming~~hemispherical punch and hold down dies shall be large enough to prevent pinching of the metal if the punch advances to full penetration of the die.

6.10 The draw approach radius of the hold down die shall be sufficient to avoid fracture of the test ~~blank~~specimen in that area during stretching.

6.10.1 Wide ~~blanks may~~ test specimens can wrinkle or produce an edge tear in the periphery near the hold down bead areas. This is not considered ~~a failure.~~as fractured.

6.11 The punch nose and hold down dies shall have a minimum hardness of 50.0 ~~HRC ± 5.0.~~HRC.

7. Materials

7.1 The ~~grid~~ pattern shall adhere to the metal so that it will not be moved on the surface or rubbed off by the forming operation.

7.1.1 The ~~suggested dimension for the~~ gauge length ~~is~~ should be 2.5 mm (0.10 in.).

7.1.1.1 After the part has been formed, measure the critical areas ~~are measured~~ for the resulting ~~gauge length changes~~ change in the gauge lengths in the long dimension from ~~(l~~l_o~~)~~ to ~~(l~~l_f~~)~~ of the ~~pattern,~~ gauge length measurement unit, and in the width dimension ~~(w~~w_o~~)~~ to ~~(w~~w_f~~)~~ at 90° to the long dimension as shown in Fig. ~~1~~2. The major strain (e_1) and associated minor strain (e_2) at 90° to ~~(~~e_1~~)~~ are calculated from these ~~gauge length changes.~~ changes from the gauge lengths. The strains may be either engineering or true strain based on the ~~original gauge length, or true strain.~~gauge lengths.

7.1.2 Larger gauge lengths, of 6 mm (0.25 in.) up to ~~125 mm~~ 125 mm (5 in.), may be used to measure low strain levels on formed parts, but shall not be used in determining the FLC.

7.2 A ~~grid~~ pattern may be printed on one or both surfaces of the test specimen.

~~7.2.1 Printing on both surfaces is sometimes necessary when studying a production formed part, but not for the specimens used in establishing the FLC.~~

NOTE 7—Printing on both surfaces is sometimes done when studying a production formed part, but not usually for the test specimens used in establishing the FLC.

7.3 The ~~grid~~ pattern shall cover an area of the test specimen ~~blank~~ sufficient to encompass the critically strained areas.

7.4 The type of pattern (for example, square, circle, ~~random) of grid pattern~~ random speckle) and the application method are specific to the measurement technique and the sample material.

7.5 The preferred ~~grid~~ pattern consists of 2.50 mm (0.100 in.) squares, or circle diameters, as the gauge ~~length. Other grid~~ length measurement units. Other patterns, such as those that incorporate random designs, may be used in conjunction with non-contacting optical strain measurement techniques using 2.5 mm (0.10 in.) as the ~~effective gauge length.~~gauge length measurement unit size.

7.6 An alternative to circles is a pattern of solid dots of precise diameter that ~~are~~is measured across the diameter of the dot.

7.7 For the preferred pattern, print an array of squares, or circles, or both, ~~is printed~~ on the surface of the test specimen. Suggested ~~patterns~~ gauge length measurement units are shown in Fig. 4.

~~NOTE 4—Refer to Specification A568/A568M, Appendix X4–Procedures for Determining the Extent of Plastic Deformation Encountered in Forming or Drawing, for procedures to apply photographic and electrochemically printed grid patterns and a review of strain analysis.~~

NOTE 8—Refer to Specification A568/A568M, Appendix X4–Procedures for Determining the Extent of Plastic Deformation Encountered in Forming or Drawing, for procedures to apply photographic and electrochemically printed patterns and a review of strain analysis.

7.7.1 ~~Suggested dimensions for the gauge lengths are 2.5~~ The gauge lengths should be 2.50 mm (0.100 in.) for the sides of a square ~~pattern,~~ gauge length measurement unit, or a diameter of a ~~circle pattern.~~ circular gauge length measurement unit.

7.7.2 Circles should be used for deformations where the major strain (e_1) ~~does~~might not align with the lines of a square ~~pattern. This condition is less likely in the process of determining the FLC than in production stamping evaluations. These circles commonly have diameters of 2.5 mm (0.100 in.) and may be spaced up to 2.5 mm (0.100 in.) apart. They are measured across the diameter of the circle when the line width is minimal. For wider lines, the enclosed area of the etched circle should be consistent from one circle to another and the measurement made across the inside diameter. This is more critical with wider line width patterns and at high~~ or grid of points defining the gauge length measurement units.~~e_T strains when the line spreads as the metal surface stretches.~~

NOTE 9—This condition is less likely in the process of determining the FLC than in production stamping evaluations where the major strain direction often will not align the lines of a square or grid of points defining the gauge length measurement units.

7.7.2.1 These circles commonly have diameters of 2.50 mm (0.100 in.) and may be spaced up to 2.50 mm (0.100 in.) apart.

7.7.2.2 Measure the circles across the diameter of the circle when the pattern line width is minimal. For wider lines, the enclosed area of the etched circle should be consistent from one circle to another and the measurement made across the inside diameter. This is more critical for patterns with wider line widths and at high e_1 strains when the line width spreads as the metal surface stretches.

7.7.3 Prepared stencils of suitable size and accurate dimensions may be used with electrochemical etching equipment, photo grid, or other transfer method to produce ~~grid~~ patterns of squares, circles, or dots, or combination thereof.

7.7.3.1 The dimensions of the ~~grid~~ pattern shall be checked for each stencil at the start of each test series and periodically during use to ensure that dimensions are not changing due to stretching or shrinking.

7.7.3.2 Wrinkling of the stencil shall be prevented to ensure precise gauge lengths over the pattern area.

7.7.3.3 Dimensions of transferred patterns on the metal sheet ~~blank~~ test specimen shall be confirmed by measuring at random locations on the test specimen.

7.7.4 Techniques for applying ~~grids~~patterns are explained in Appendix X1 of this method.

~~7.7.4.1 Refer to Specification A568/A568M, Appendix X4, for the photographic and electrochemical etching techniques. Improper application of the electric current and time can affect the line appearance so that establishing the line edge becomes difficult when the pattern is magnified for measurement.~~

NOTE 10—Refer to Specification A568/A568M, Appendix X4, for the photographic and electrochemical etching techniques. Improper application of the electric current and time can affect the line appearance so that establishing the line edge becomes difficult when the pattern is magnified for measurement.

~~7.7.4.2 A grid pattern with a dark thin line maximizes the precision of readings.~~

NOTE 11—A pattern with a dark thin line maximizes the precision of readings.

7.7.5 The surface of the test specimen may be cleaned before applying the pattern.

NOTE 12—Cleaning will not affect the results. Patterns have been successfully applied to metallic coated and pre-lubricated surfaces.

7.7.6 ~~Rectangular and circle grid patterns~~ Patterns using circular or square gauge length measurement units made with a metal scribing tool may be used.

7.7.6.1 ~~It is necessary to measure each~~ Each scribed circle and rectangle shall be measured prior to forming the test ~~blank~~specimen to establish the ~~initial~~ gauge length in the final measured directions.