Designation: E2218 – 15

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 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 and deep drawing processes.

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.

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 practices and determine the applicability of regulatory limitations prior to use.*

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

3. Terminology

3.1 Terminology E6 shall apply including the special terms used in this method shown in 3.2.

3.2 *Definitions:*

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.

3.2.4 *forming limit curve (FLC)*—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.

3.2.4.1 *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

[1] This 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 Oct. 1, 2015. Published December 2015. Originally published in 2002. Last previous edition approved in 2014 as E2218–14$^{\varepsilon 1}$. DOI: 10.1520/E2218-15

[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.

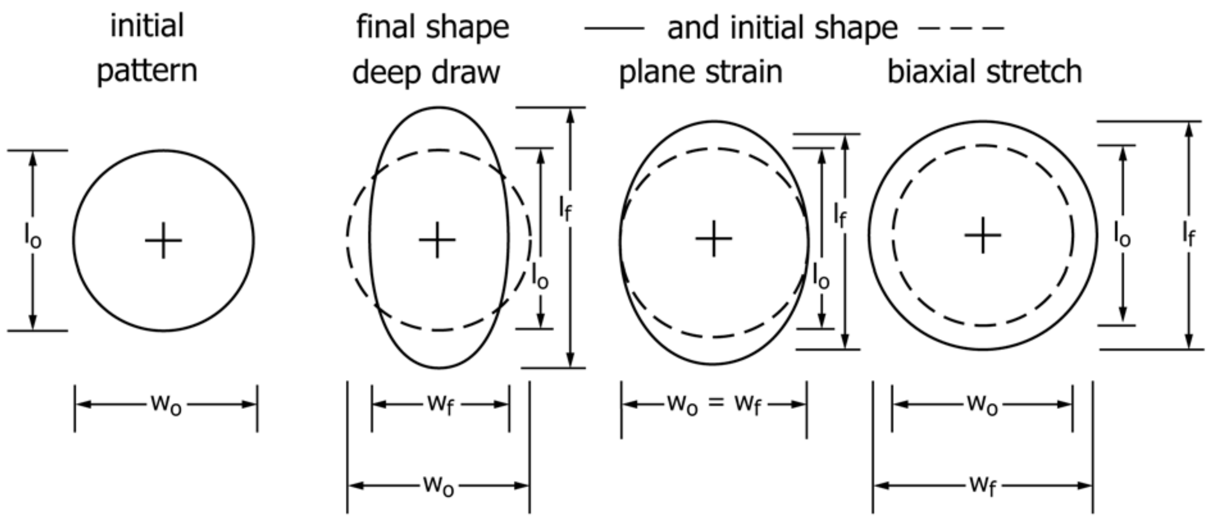


FIG. 1 Possible Changes in Shape of the Grid Pattern Caused by Forming Operations on Metallic Sheet Products

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 %.

3.2.5 *limiting dome height (LDH) test*—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 *Definitions of Terms Specific to This Standard:*

3.3.1 *grid pattern*—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.

3.3.2 *major strain, (e_1)*—the largest strain, developed at a given location in the sheet specimen surface.

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

3.3.3 *minor strain, (e_2)*— the strain in the sheet surface in a direction perpendicular to the major strain.

3.3.3.1 *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, or along the shorter axis of the ellipse resulting from deformation of a circular grid pattern, or along the direction of the minimum surface strain using a non-contacting optical strain measurement technique.

3.3.4 *plane strain, FLD_o*—the condition in metal sheet forming that maintains a near zero (0 to +5 %) minor strain (e_2) while the major strain (e_1) is positive (in tension)

3.3.4.1 *Discussion*—Plane strain is the most severe deformation mode and causes a low point in the forming limit curve (FLC). For convenience, many FLCs are shown with the low point at 0 % (e_2), 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 specimens biaxially, measuring the resulting strain (including judging 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 specimens biaxially including a hemispherical punch testing machine such as an LDH tester, a sub press in a universal testing machine, or a hydraulic bulge testing machine.

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

4.2.2 The flanges of a blank are securely clamped in serrated or lock bead, blank-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 blanks is prepared with different widths and a common length suitable for being securely gripped in the test apparatus.

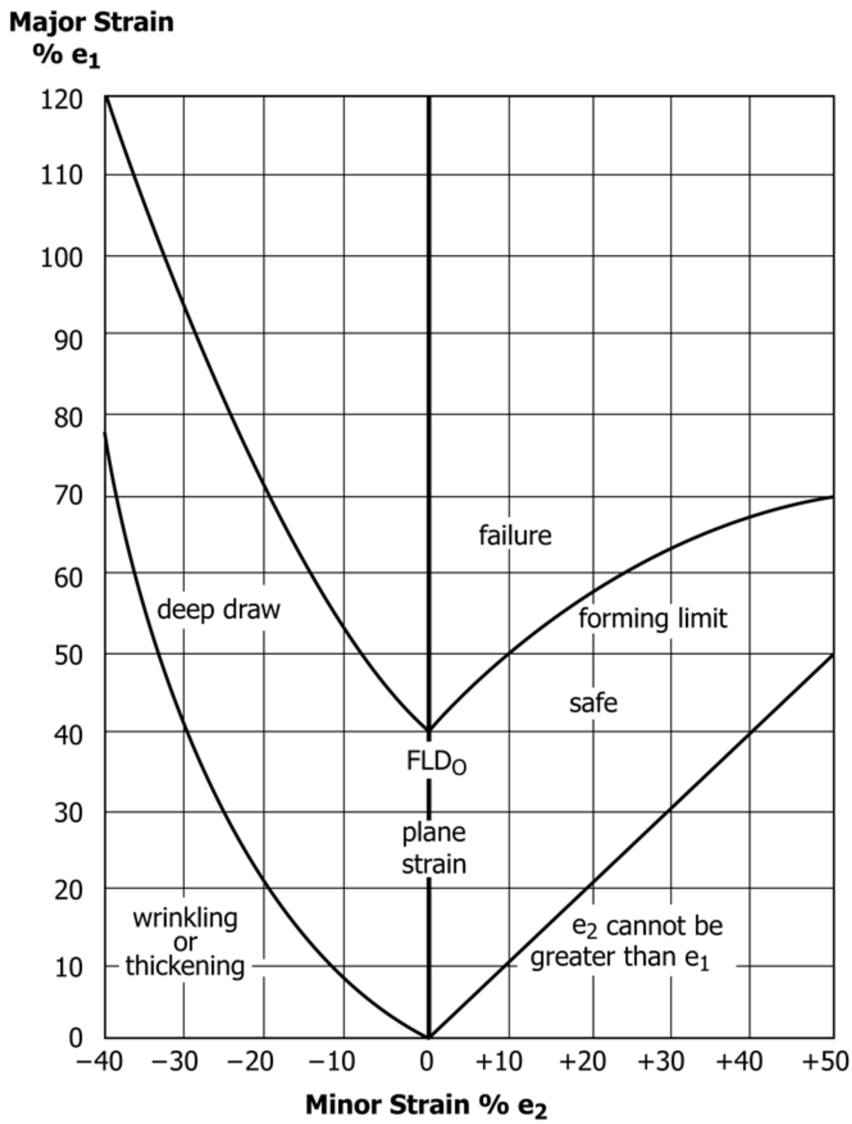
4.3.2 Negative (e_2) strains can be obtained using sheared narrow strips stretched over the punch of a hemispherical punch tester.

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 specimen fractures.

4.4 The (e_1) and the (e_2) strains of the grid 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 fracture areas.

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



NOTE 1—The upper curve is representative of the forming limit. 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 surface.

FIG. 2 Forming Limit Diagram

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.

5. Significance and Use

5.1 A forming limit curve (FLC) defines the maximum (limiting) strain that a given sample of a metallic sheet can undergo for a range of forming conditions, such as deep drawing, 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.

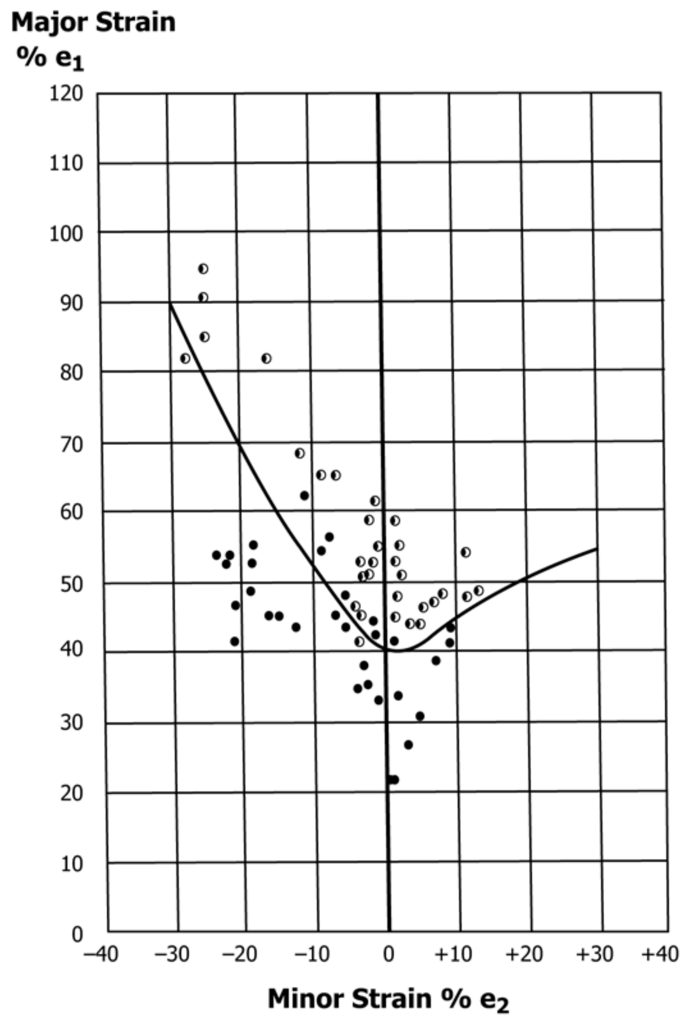
5.1.1 FLCs may be obtained empirically by using a laboratory hemispherical punch biaxial stretch test and also a tension test to strain metal sheet specimens from a material sample beyond their elastic limit, just prior to localized necking and fracture.

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

5.1.2 Strains in the major (e_1) and minor (e_2) directions are measured using points on the grid pattern in the area of the localized necking or fracture.

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

5.1.2.2 The major (e_1) strain is determined by the capacity of the material to be stretched in one direction as simultaneous



Code: ● good ◐ Marginal (necked)

Material properties:

Thickness	0.866 mm (0.034 in.)
Strain hardening (n)	0.230
Plastic Strain (r)	1.710

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

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 Curve (FLC) for a Cold Rolled Drawing Quality Aluminum Killed Steel Sheet.

surface forces either stretch, do not change, or compress, the metal in the (e_2) direction.

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

5.1.3 These strains are plotted on a forming limit diagram (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.

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

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

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

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

5.1.6.1 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 ($+e_2$) strain conditions.

5.1.6.2 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 ($-e_2$) strain into a less severe area to the left of the FLD_o, thus permitting deeper draws for a given major (e_1) strain.

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

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

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

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

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

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

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

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

5.1.11 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.

5.1.12 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 strains ($+e_2$) associated with major strains (e_1) may be obtained using a hemispherical punch testing machine such as a LDH tester, 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.

6.1.1 The hydraulic bulge may employ a liquid or a soft elastic material as the forming force.

6.2 Data points for the negative minor ($-e_2$) strain associated with a major (e_1) strain may be obtained using various width strips in a LDH tester and also a universal testing machine and Test Method E8/E8M for a tension test of a specimen that has a grid pattern on the surface.

6.2.1 A series of 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 apparatus shall be capable of securely clamping the test blank 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 be such that no area of the specimen flange is pulled-in by the forming force.

NOTE 2—Restriction of the pull-in of flange metal is not critical in obtaining strips for measuring (e_1) and associated (e_2) strains to establish the forming limit.

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.

6.6 Although no punch displacement or load 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 specimen at a constant rate until the material exhibits localized necking (through thickness thinning) and a fracture appears in the surface of the 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, or round) specimen blanks to obtain data for determining the forming limit curve (FLC).

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

6.9 Clearance between the forming 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 in that area during stretching.

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

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

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 2.5 mm (0.10 in.).

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

7.1.2 Larger gauge lengths, of 6 mm (0.25 in.) up to 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.

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

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

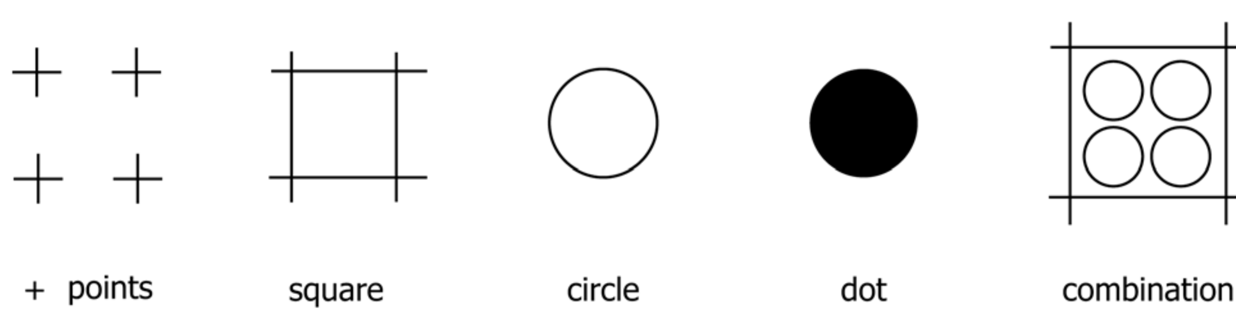
7.5 The preferred grid pattern consists of 2.50 mm (0.100 in.) squares, or circle diameters, as the gauge length. Other grid patterns, such as random designs, may be used in conjunction with non-contacting optical strain measurement techniques using 2.5 mm (0.10 in.) as the effective gauge length.

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

7.7 For the preferred pattern, an array of squares, or circles, or both, is printed on the surface of the specimen. Suggested patterns 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.

7.7.1 Suggested dimensions for the gauge lengths are 2.5 mm (0.100 in.) for the sides of a square pattern, or a diameter of a circle pattern.



NOTE 1—The basic pattern is reapeated over the area of the part to be studied on a flat specimen blank.

FIG. 4 Examples of patterns for Gauge Length measurement units used in Determining Forming Limit Curves (FLC)

7.7.2 Circles should be used for deformations where the major strain (e_1) does 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 e_1 strains when the line 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 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 shall be confirmed by measuring at random locations on the specimen.

7.7.4 Techniques for applying grids 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.

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

7.7.5 Rectangular and circle grid patterns made with a metal scribing tool may be used.

7.7.5.1 It is necessary to measure each scribed circle and rectangle prior to forming the test blank to establish the initial gauge length in the final measured directions.

7.7.6 The length of each side of the square pattern and the diameters of all circles shall be within ±0.025 mm (0.001 in.) of the established gauge length.

7.7.6.1 Due to possible line width variations within a printed pattern, the measurements shall be from the inside of the line on one side of the square, or circle, to the inside of the opposite line. This is important when measuring high strains where the line width has increased.

7.7.7 Solid dots may be used in place of square or open circle patterns. These are preferred for some electronic measuring devices employing a camera and a programmed computer.

7.8 When using non-contacting optical strain measurement techniques, a grid pattern and an application method specific to the technique shall be used.

NOTE 5—Appendix X3 has suggested guidance for the use of digital image correlation.

8. Sampling

8.1 Blanks to be tested shall be representative of the properties of the material, as specified in the applicable product specification, and shall be from a common known source, such as a single sample.

8.1.1 For coil processed materials, the rolling direction shall be identified on the sample and the specimens.

NOTE 6—The forming limit curve (FLC) is specific to the tested sample of a material. It is possible for the forming limit curve (FLC) to be different for separate samples of a given grade of metal. Some causes of this are differences in the strain hardening exponent (*n* value), material non-homogeneity, specimen thickness, and the cold rolling and annealing processing methods used in producing the material.

9. Sample Preparation

9.1 Several specimen blanks are required to establish the forming limit curve (FLC).

9.1.1 For example, the 64 data points of Fig. 3 are from 32 specimens of different widths that were formed by several methods.

9.1.2 Specimens over a range of widths are used to obtain different (e_2) strains.

9.1.3 All specimens for a series shall have their long dimension in the same orientation, relative to the original process rolling direction of the sample and that direction noted in the report.

9.2 The blanks shall be sufficiently long in the major strain direction of the forming operation to allow secure clamping in the holding grips and allow a free span over which stretching occurs.

9.2.1 For the tension strain applied in a universal testing machine, either standard reduced-section 50 mm (2 in.) sheet specimens, or sheared parallel strips of various widths, may be used.

9.2.2 For hemispherical punch tests, the blanks must be sufficiently long to be securely clamped in the holding die without excessive pull-in.

9.2.2.1 This secure clamping condition for the flange is not critical for the FLC determination, but it is necessary for the limiting dome height (LDH) test.

9.2.3 Example lengths are 180 to 225 mm (7 to 9 in.) for a test using a hemispherical punch diameter of 100 mm (4 in.) and also for the tension test specimen.

9.3 The width of each set of specimen blanks is different in order to produce a range of minor strain (e_2) values.

9.3.1 Several sets of specimens may be needed to provide sufficient data.

9.3.2 Rectangular strips are cut to various widths, typically ranging from 12 mm (0.50 in.) up to 180 or 200 mm (7 to 8 in.) in increments of 12 mm (0.50 in.), or 25 mm (1 in.).

9.4 Test blanks from a given sample shall all be sheared to width in the same direction, either across the rolling direction or along the rolling direction, of the sheet product.

9.5 The width cut shall be made using a shear with sharp blades and a blade clearance of approximately 10 % of sheet thickness to minimize double shear and edge burr effects that could be a safety hazard when handling test specimens.

9.5.1 A moderate amount of shear burr will not affect the test results.

9.5.2 The rake angle of the upper shear blade should be less than 3° to prevent curling of the narrow specimens.

9.6 Edges of the specimen blanks may be polished to remove excessive edge burr.

9.7 Specimens shall have edges that are parallel within 1 % of their length.

10. Calibration

10.1 Tests for forming limit curves made in hemispherical punch forming presses and universal testing machines do not require measurements of the forces applied.

10.2 The measurements of (e_1) and (e_2) strain shall be accurate to ±2.5 % strain.

10.3 The procedure used to make these measurements when the preferred grid pattern (that is, square, circles, spots, or combination of these) is used may involve one of the five following devices, or it may be a comparable technique and device that gives equivalent precision:

10.3.1 A machinist's microscope with 10× magnification and incorporating a calibrated scale.

10.3.1.1 The surface being measured shall be held perpendicular to the microscope.

10.3.2 A steel scale with 0.25 mm (0.01 in.) divisions. The scale lines shall be read from center to center of the line widths.

10.3.3 A magnifier that incorporates a calibrated scale.

10.3.4 A tapered wedge scale on clear plastic (Mylar) that gives the strain in percent for an established gauge length, which effectively magnifies the strain.

10.3.5 A circle grid analyzer employing a camera and computer imaging that makes multiple simultaneous readings.

10.4 The procedure to measure the strains when using a non-contacting optical strain measurement technique should follow the suggestions of the measurement equipment manufacturer.

10.4.1 If the measurements are made while the force is still applied to the specimen, then this should be noted in the report along with the method that was used.

NOTE 7—The measurement methods described in 10.3 are typically performed on samples removed from the testing machine in the unloaded condition. Some non-contacting optical techniques can be used to perform measures while load is still being applied. These measurements can result in higher strains than if the same specimen was unloaded and then measured.

10.4.2 The gauge length used shall meet the requirements of 7.5.

10.4.3 The technique shall be able to measure strains on the curved surface of the specimens.

10.4.4 The strain measurement accuracy shall meet the requirements of 10.2.

NOTE 8—E2208 Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems describes methods to assist users in understanding the issues related to the accuracy of non-contacting optical strain measurement systems.

NOTE 9—Appendix X3 has suggested guidance specific to the use of three-dimensional surface digital image correlation with this method.

10.5 Curvature of the surface of specimens formed over a hemispherical punch is not critical over the distance of the 2.5 mm (0.100 in.) initial gauge length.

11. Conditioning of Specimens

11.1 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 varied.

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

11.3 Applying the grid pattern may require cleaning the surface of the sample. This will not affect the results. Grids have been successfully applied to metallic coated and prelubricated surfaces.

12. Procedure

12.1 Wipe the test blanks clean and dry to remove grit and soil. A lubricant of any suitable type may be used between the hemispherical punch and the specimen's surface.

NOTE 10—Lubricants increase the amount of stretch before localized necking and move the location toward the nose of the punch. Mineral oil plus a polyethelene sheet, and graphite drawing compounds are good lubricants, while kerosene is not because it cleans the metal and prevents the metal from sliding over the punch. Lubrication changes the e_1 and e_2 strains, but does not affect the FLC. Data points move along the curve due to the change of the e_2 strain becoming more positive in the stretch region and more negative in the draw region of the FLD when effective lubricants are used in press forming.

12.2 Remove any metal pick-up on the punch prior to the test.

NOTE 11—Cold welding can occur if there is no lubricant; heat, pressure, and coatings on the specimen can cause metal pick-up.

12.3 The punch speed (or rate at which the deformation of the specimen occurs) shall be such that the test can be stopped when localized necking or fracture occurs.

12.3.1 Initial application of the forming force shall not be abrupt.

12.3.2 Incremental loading, in which the force is removed and reapplied, shall not be used in determining the FLC.

12.4 Center the test blank over the punch, especially the width for narrow strips formed over a hemispherical punch. If only one surface has an applied grid pattern, it shall be away from the punch contact surface.

12.4.1 Any metallic sheet deformation process may be used if it is continuous and not interrupted before the test conclusion. For examples, a LDH machine using a 200 mm (8 in.) diameter hemispherical punch, other ball punch testing machines using round ball punches, and a standard tension test in a universal testing machine can apply controlled force to form the metallic sheet. For a tension test specimen, follow the standard procedure of Test Methods E8/E8M for testing sheet type specimens, shown in Fig.1 of Test Methods E8/E8M

12.5 Activate the testing machine to stretch the blank continuously until the onset of localized necking, as observed visually or by monitoring for a drop in the testing machine applied force.

13. Results and Calculations

13.1 Selection of gauge lengths to be measured:

13.1.1 It is not necessary to measure each gauge location.

13.1.1.1 With a dot pattern, all locations may be measured by using a circle grid analyzer, but this would be extremely time consuming if done by a hand held scale and a magnifier.

13.1.2 Deformed circles may appear as ellipses with widened lines at the long dimension ends. These shall be measured from the inside of one line to the inside of the opposite line.

13.1.3 All gauge lengths that are to be measured shall be near the location on the specimen where localized necking initiated, no more than 2 or 3 gauge lengths away from the necked, or fractured, site in the radial direction relative to the nose of the punch.

13.1.4 If fracture has occurred, it will be on one side of the hemisphere pole. Suitable grids for measuring the strain levels at localized necking can be found on the opposite side of the pole.

13.2 Visual rating of the individual deformed grid areas shall be made, with each classified as being good (no localized necking), marginal (contains localized necking), or fractured, defined as follows:

13.2.1 *Good (also referred to as no localized necking, pass, or acceptable, on production parts)*—The deformed grid lies in an area entirely outside the necked region of the specimen.

13.2.2 *Marginal (also called localized necking, or borderline)*—The deformed grid lies in a region of localized thinning, or a trough in the specimen surface.

13.2.2.1 For circle grid patterns, if the ellipse is tear-drop shaped, indicating nonuniform strain, it shall not be measured. The condition can be corrected by using a smaller diameter grid.

13.2.3 *Fractured* (also called fail)—A split through the specimen separates the gauge length of the grid in two and the area is beyond the forming limit. Each piece may be measured for information purposes.

13.3 *Strain Measurements:*

13.3.1 The major (e_1) and minor (e_2) strains of the selected deformed grids shall be measured to within ±2.5 %. For a 2.5 mm (0.100 in.) initial gauge length, this is ±0.075 mm (0.0025 in.).

13.3.2 If a square pattern becomes skewed into parallelogram shape, it shall not be used to measure strain.

13.3.3 Schematic diagrams of the three ways the circle grid can deform are shown in Fig. 1, representing draw, plane strain and biaxial stretch.

13.3.4 The calculations of the major strain and the associated minor strain are illustrated. The major strain (e_1) is defined to coincide with the major deformation direction and the minor strain (e_2) is at 90° to the major strain direction.

$$\text{Major strain} = \frac{L_f - L_o}{L_o} \times 100 = e_1(\%)$$

$$\text{Minor strain} = \frac{W_f - W_o}{W_o} \times 100 = e_2(\%)$$

where:

L = length,
W = width,
o = original, and
f = final.

13.4 *Forming Limit Curve (FLC)*

13.4.1 Plot the data for the (e_1) and (e_2) strains of the selected grids on a FLD as shown in Fig. 3.

13.4.2 Identify each data point by the code as being good (no localized necking), or marginal (localized necking). Fractured grid areas are normally not measured.

13.4.3 Draw a smooth curve above the uppermost good (no localized necking) (e_1) strains over the associated (e_2) strain range used in the study.

13.4.3.1 For practical purposes, the specimens that have been strained to a localized neck-down, or through thickness fracture, condition may be measured at a location on the opposite side of the hemispherical bulge from the fracture, in a good (no localized necking) location, to obtain values to establish the FLC.

13.4.3.2 Another acceptable procedure is to measure the grid near the necked, or fracture, location and identify these data points in determining the forming limit curve. This procedure was used in locating the FLC of Fig. 3.

13.4.3.3 Establishing the FLC depends on judgement. Note that in Fig. 3 there are several good (no localized necking) data points above the FLC and two marginal points below the FLC.

13.4.3.4 If some good (no localized necking) data points are intermixed with marginal (localized necking) points, draw the curve below these marginal points unless additional strain measurements on the same or a similar specimen show a preponderance of good data points in the area on the FLD.

NOTE 12—The range of major (e_1) strains can be from 0 % to over 200 %. The range of minor (e_2) strains can go from –40 % to over +60 %.

13.4.4 The FLD for a material may be reduced in range. If the lower limit of the major strain (e_1) dimension is not shown as 0 %, note this in the report.

14. Report

14.1 The forming limit curve (FLC) report shall include the following information:

14.1.1 Forming limit diagram, with the lower limit of the major strain axis noted if it is different from 0 % (e_1) on the FLD. The graduated scales on the FLD shall be in percent strain, calculated from the initial gauge length. The distance between FLD percentage increments shall be the same for both the major strain (e_1) ordinate (parallel to the vertical y axis) and minor strain (e_2) abscissa (parallel to the horizontal x axis) unless the difference is noted in the report. For convenience, the forming limit curve (FLC) may be plotted on a reduced range of the forming limit diagram (FLD), for example, from +20 % to +80 % major (e_1) strains and from –20 % to +30 %

minor (e_2) strain. If the lowest (e_1) strain increment of the FLD is not 0 % e_1, note that value in the report.

14.1.2 Forming limit curve (FLC) drawn on a forming limit diagram (FLD).

14.1.3 Material designation, and processing if not standard for the grade.

14.1.4 Material thickness.

14.1.5 Orientation of the long dimension of the blanks relative to the coil processing direction.

14.1.6 Temperature of testing facility, if other than ambient.

14.1.7 Diameter of any hemispherical punch used to stretch form the specimen.

14.1.8 Punch speed of nominal advance during the test, exclusive of final slow down.

14.1.9 Lubricant used on the contact surfaces.

14.1.10 Blank sizes, length and widths used.

14.1.11 Quantity of a repeated specimen size tested, for example, single, duplicate, triplicate.

14.1.12 Gauge length(s) of the grid used.

14.1.13 Method used for measuring the grid pattern.

14.2 The report may include the FLD_o value.

15. Precision and Bias

15.1 This method is not believed to introduce any systematic bias.

15.2 Using calibrated scales to measure sufficiently magnified grid patterns of determined precision, the accuracy of individual readings of e_1 and associated e_2 strains of 2.5 mm (0.100 in.) initial gauge length should be within ±0.5 % (0.012 mm or 0.0005 in.).

15.3 Due to the subjectiveness of the method of selecting areas to measure and classify as necked, or not necked, variations of forming limit curves (FLC) for a specific material may show disagreement among testers. For a given material the forming limit curve (FLC) should be repeatable within ±5 %.

16. Keywords

16.1 circle grid; forming limit curve (FLC); forming limit diagram (FLD); limiting dome height (LDH); major strain; minor strain; strain analysis

APPENDIXES

(Nonmandatory Information)

X1. TECHNIQUES FOR APPLYING GRID PATTERNS

INTRODUCTION

There are several methods available for applying gauge marks to the surface of metallic sheets used in determining the strains for plotting data on a FLD from which to obtain a FLC. For convenience, these are usually in the form of a grid pattern consisting of squares, circles, dots, or combinations of these patterns.

X1.1 *Punch Marks*—A punch mark is the simplest method, with two making up a gauge length for the major (e_1) strain and a third at a right angle providing the 90° minor (e_2) strain. It is necessary to measure the distances between the two before and after forming the specimen, and then to calculate the percent strain based on the initial gauge length in each direction. Punch marks shall be shallow and could cause premature failure in some materials. For this reason, punch marks shall only be used when evaluating highly formable materials.

X1.2 *Scribed Square*—A square pattern of scribed lines was used in early studies of drawn metal sheet parts to evaluate strains. For the precision required to construct a FLC, the intersection of each scribe line in the critical areas would have to be measured, as for the punch marks.

X1.3 *Scribed Circles*—Using a compass with a steel point to locate circles on the surface of a part to be studied for strain distribution is commonly done over areas subjected to low strain levels. These are usually 125 mm (5 in.) diameter to detect strains of less than 5 %. Similar circles of 2.5 mm (0.10) in. could be used for determining a FLC.

X1.4 *Photogrid*—A photographic print of a pattern can be printed on the surface using the technique described in Specification A568/A568M, Appendix X4. This can be used to obtain a fine lined pattern over a surface. One problem is that the pattern can detach from the surface under high strains, which can result in false readings.

X1.5 *Silk Screen*—A pattern of circles, squares, or any desired shape can be made by the silk screen process. This was used extensively in the early development of the circle grid technique. One problem is resolution, in that gauge lengths less than 25 mm (1 in.) cannot be established precisely using silk screen inks or paint.

X1.6 *Electrochemical Etching*—This is a refinement of the silk screen method. Stencils are available commercially with many different patterns for use on a variety of materials, to accommodate the needs of the user. For FLC determinations, a pattern with a fine line width on a non-stretching backing is required.

X1.6.1 This technique was first used to imprint logos and information on metal parts.

X1.6.1.1 Considerations are necessary for specific applications, and it is recommended that anyone using the electrochemical etching method should first be properly trained by a knowledgeable person.

X1.6.2 Special transformers and etching solutions are available from suppliers of the stencils. Early methods of stenciling used a weight and pressure pads soaked in the chemical. Rollers and pads soaked with the chemical are now most frequently used.

X1.6.3 A rectifier unit is required, operating with 115 volt, 60 Hz, AC power input that applies up to 10 amps of output and from 0 to 26 volts. One lead from this is connected to the work and the other to the roller.

X1.6.4 The stencil is coated with the etching solution and placed on the material to be etched. A pad soaked with the same chemical, specific for the metal being etched, is placed over the stencil. It is necessary to have sufficient solution on the pad, but too much solution will create problems. Pad thickness should be about 3 mm (1⁄8 in.).

X1.6.5 The current is turned on at the rectifier and the roller is slowly rolled across the width of the stencil pad. It is not advisable to roll the roller back and forth, as a double print of the pattern can result due to slippage of the stencil under the pad.

X1.6.5.1 If the print is too light, more etching solution may be needed on the pad, or if it is too dark and broad, the voltage can be adjusted to give a correct pattern.

X1.6.5.2 Caution should be exercised to not touch the metal roller and the material being etched, as a mild electric shock to the operator can result. Hold the roller by the handle and turn the current on only during the etching process.

X1.6.6 The pad and stencil are removed from the metal sheet being etched, and a uniform dark lined pattern should be on the surface. This dark pattern should dry before it is handled, as it can be rubbed off, leaving a light etched pattern that is more difficult to read.

X1.6.7 Several different solutions are available from the stencil suppliers for use on surfaces of steel, stainless steel, aluminum, brass, zinc and other metals.

X1.6.7.1 AC or DC current can be used, depending on the desired finish (black or frosty) to the pattern and the material being etched.

X1.6.8 The etching solution is mildly corrosive and if not rinsed, or neutralized with a second solution, the surface of steel sheet will rust when exposed to air for a short time. This can be minimized by not having excess solution on the pad. Some solutions contain a rust inhibitor.

X1.6.9 Wiping the etched surface with a lubricating oil will prevent excessive rusting.

X1.6.10 The gauge length of the grid shall be checked at random locations over the test specimen prior to use to ensure that the gauge length has not been affected by stretching the stencil pattern.

X2. SAMPLE FORMING LIMIT DIAGRAMS FOR ALUMINUM KILLED DRAWING QUALITY STEEL, ALUMINUM TYPE 3003-0, AND BRASS ALLOY C260 SHEET PRODUCTS

INTRODUCTION

Forming limit curves (FLC) were determined for three materials using the procedure described in this method.

X2.1 The first material is an aluminum killed cold rolled steel sheet similar to that used for Fig. 2 of the method. The method for establishing the forming limit involved locating the FLC above the good locations (solid circles) and below the marginal data points (half filled circles).

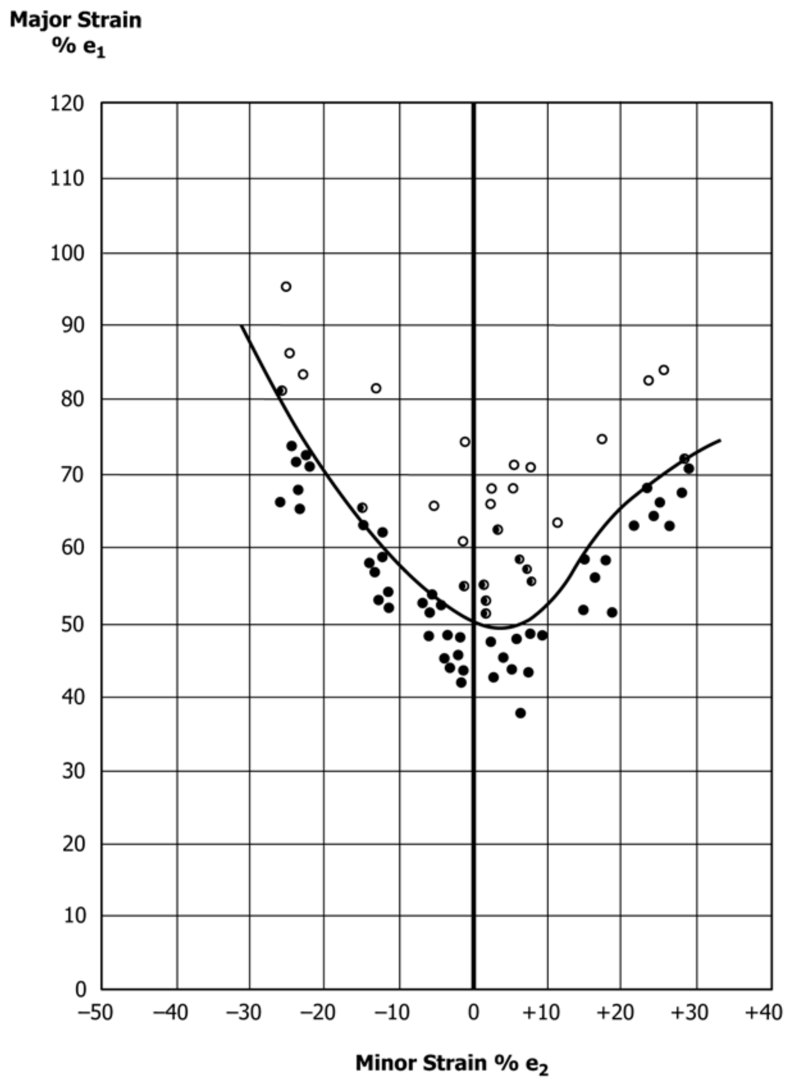
X2.1.1 The minimum point for this steel is around +5 % e_2 to give a FLD_o of 49 % e_1.

X2.2 The second material is a 3003-0 aluminum sheet.

X2.2.1 The minimum point for this aluminum is around +5 % e_2 and the FLD_o is 40 % e_1.

X2.3 The third material is a 260 brass sheet.

X2.3.1 The minimum point on the FLC curve for this brass sheet is between 0 and +5 % e_2 and the FLD_o is at 46 % e_1.



Code: ● good ◐ marginal (Necked) ○ fail

Material properties:

Thickness 0.990 mm (0.039 in.)

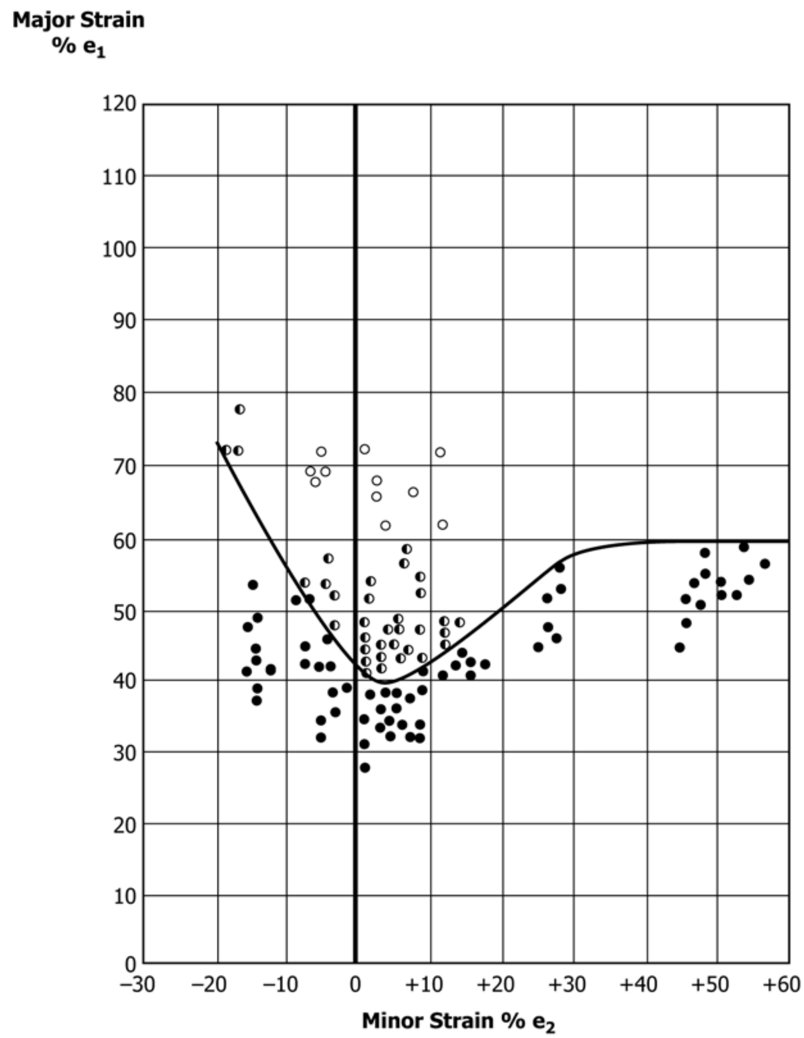
Strain hardening (n) 0.222

Test result: FLD_o 49 %

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)			
0.990	(0.039)	173	(25.1)	303	(44.0)	43	0.228	1.94

FIG. X2.1 Forming Limit Curve (FLC) for a Cold Rolled Drawing Quality Aluminum Killed Steel Sheet



Code: ● good ◐ marginal (necked) ○ fail

Material properties:

Thickness 1.020 mm (0.040 in.)

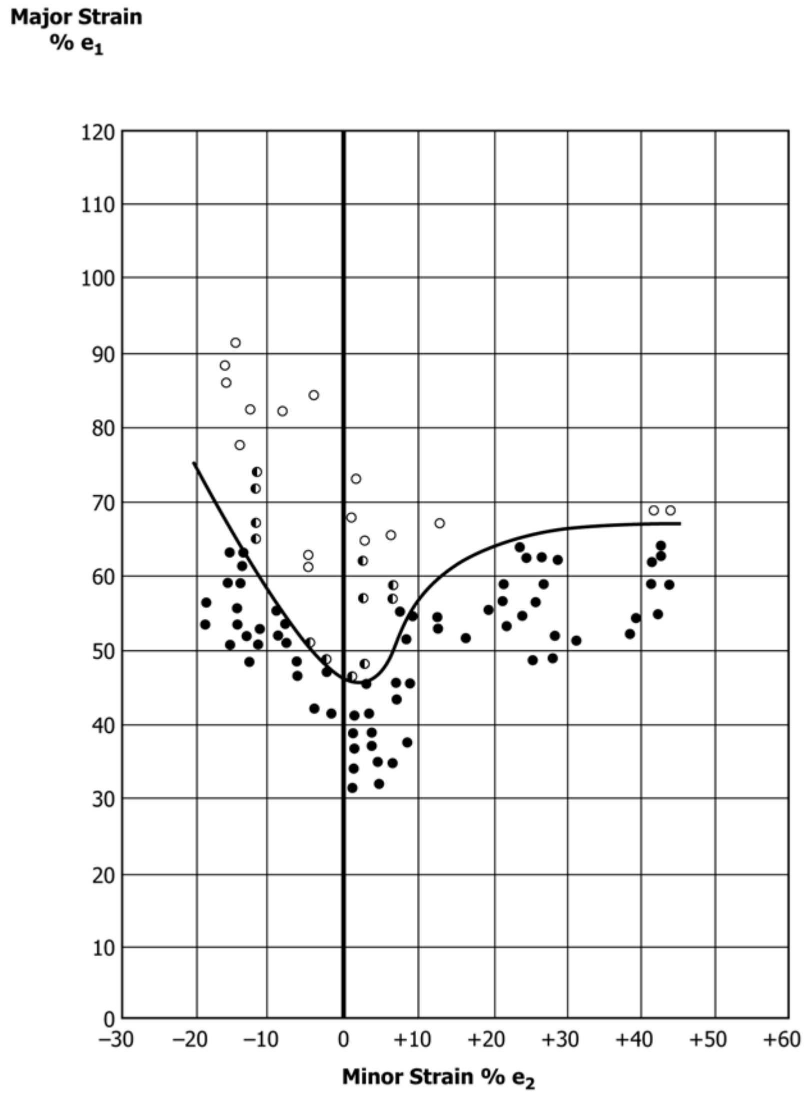
Strain hardening (n) 0.245

Test result: FLD_o 40 %

3003-0 Aluminum
Longitudinal Mechanical Properties

Thickness		Yield Strength		Tensile Strength		% El in 50 mm	*n* Value	*r* Value
mm	(in.)	MPa	(ksi)	MPa	(ksi)			
1.016	(0.040)	44	(6.3)	113	(16.4)	37	0.248	0.86

FIG. X2.2 Forming Limit Curve (FLC) for a 3003–0 Aluminum Alloy Sheet



Code: ● good ◐ marginal (necked) ○ fail

Material properties:

Thickness	1.140 mm (0.045 in.)
Strain hardening (n)	0.393
Plastic strain (r)	0.950

Test result: FLD_o 46%

260 Brass
Longitudinal Mechanical Properties

Thickness		Yield Strength		Tensile Strength		% El in 50 mm	*n* Value	*r* Value
mm	(in.)	MPa	(ksi)	MPa	(ksi)			
1.143	(0.045)	136	(19.7)	349	(50.7)	57	0.397	1.05

FIG. X2.3 Forming Limit Curve (FLC) for a C260 Brass Sheet

X3. FORMING LIMIT STRAIN MEASUREMENT USING THREE-DIMENSIONAL SURFACE DIGITAL IMAGE CORRELATION

INTRODUCTION

Digital image correlation (DIC) is a non-contacting optical method to measure the surface strains of a test piece undergoing deformation. This appendix suggests methods and good practices to apply this technique to measure the strains associated with forming limit testing similar to the other grid pattern methods, but does not supersede any of the requirements within the Standard. For those users experienced with the circle or square grid pattern method that will start using 3D surface DIC, it is suggested that comparison tests be performed using both methods to confirm the 3D surface procedures used.

X3.1 General

X3.1.1 *Three-Dimensional (3D) Surface DIC:*

X3.1.1.1 The curved shape of the specimen surface after being formed over the hemispherical punch requires that the digital image correlation system be able to compensate for the out of plane shape. This is typically achieved using a DIC system employing two or more digital cameras to simultaneously image the specimen surface of interest (see Fig. 2b of Guide E2208).

X3.1.1.2 Although two or more cameras may be used to simultaneously image the surface for subsequent measurement, this Appendix will use the term "image pair" to refer to the simultaneously acquired images.

X3.1.1.3 The images using more than one camera for DIC are taken at an angle to the specimen surface. This results in a difference in the magnification across each image. An average magnification may be determined in the area of interest.

X3.1.1.4 3D surface DIC measures the three-dimensional location of the grid pattern and many locations on the specimen surface. These locations are then tracked in 3D space from before deformation to after deformation. Strains may then be calculated from these measured changes in displacement and measured initial spacing.

X3.1.1.5 3D surface DIC displacement data can be used to calculate the major and minor strains, as well as their direction, and thus does not require a grid pattern aligned to the major and minor strain axes.

X3.1.2 The grid pattern is measured before and after the forming process. For 3D surface DIC measurements this requires that a minimum of two image pairs that include the region of interest are recorded, one before and one after the deformation.

X3.1.3 The area that is to be measured should be clearly visible in the image pair.

X3.1.4 Proper focus and depth of field should be checked, due to the out of plane shape and motion.

X3.1.5 If the DIC data will be taken during the forming process the following should be considered: prevent motion blur, provide uniform and constant lighting, prevent excessive heat currents, minimize vibration in the cameras, and protect the camera system from potential damage if specimen failure should occur.

X3.2 Grid Pattern

X3.2.1 *Pattern application methods:*

X3.2.1.1 Various methods of creating an acceptable grid pattern exist and have been used successfully.

X3.2.1.2 The system manufacturer may have suggestions for specific specimen materials, surface preparation, and expected strain levels.

X3.2.1.3 A light coat of matte white paint with a dusting of matte black paint over-spray (or white paint on black) has been found to make an acceptable pattern for many materials. The ability of the paint to stay adhered to the surface should be verified up to maximum strain level to be measured (see 7.1 for requirements).

X3.2.1.4 If the grid pattern is applied to the specimen surface (for example, painted) then the specimen may need to be cleaned before patterning to remove any lubricants or anti-corrosives that would reduce the adhesion to the surface.

X3.2.1.5 Additional lubricants added after grid patterning may reduce the pattern adhesion and/or change the pattern detrimentally.

X3.2.2 The pattern should be of sufficient contrast and spatial variation for the correlation method used.

X3.2.3 An appropriate pattern will vary with the imaging parameters including: magnification, digital camera resolution, exposure time, lighting intensity and position, and angle between the cameras and the surface.

X3.2.4 The actual pattern used (especially for randomly created patterns) may require changes to correlation parameters. If this occurs, the correlation parameters used for the reported results should also be used in the noise floor assessment.

X3.2.5 If DIC is used to measure the grid pattern on the specimen surface outside of the forming apparatus (only before and after the forming process), then the pattern can be on either or both sides of the surface, as long as it adheres and is not damaged in the process. Typically for forming limit testing, only the top exposed surface is patterned and measured.

X3.3 DIC Analysis Parameters

X3.3.1 Correlation is performed over small subsets of the image pairs before and after deformation. The subset size is often described by the number of pixels in the horizontal and vertical directions in the image. The initial subset location may be described based on a specific horizontal and vertical pixel location on one image.

X3.3.2 Correlations are performed on many subsets that may be spaced in a grid across the image in the area to be measured.

X3.3.3 Depending on the correlation algorithm used, additional adjustable parameters may exist. It is recommended that the same parameters used for strain measurements be used for any type of accuracy assessment.

X3.3.4 *Strain calculation:*

X3.3.4.1 In general, DIC strain calculations are made using some number of neighboring displacement measurements.

X3.3.4.2 Often DIC systems incorporate some spatial averaging/smoothing either during or after the strain calculation.

X3.3.4.3 The use of averaging and multiple neighboring displacement points to measure a single value of strain makes assessment of a specific gauge length difficult.

(1) A uniform method of effective gauge length assessment should be used (a suggested gauge length is given in 7.1.1).

(2) An effective gauge length for DIC should include all of the pixels that are used in calculating a single measurement of forming limit strain. This should include all the subsets averaged during any strain calculation or smoothing process.

(3) If the size of the total area used in each average strain measurement is in pixels, it is suggested to use the average magnification to convert the effective gauge length into physical units.

X3.3.5 The appropriate locations of the measurements are defined in 13.1.3 and 13.1.4.

X3.3.5.1 Each strain measurement location should include the entire effective gauge length (see 7.5).

X3.3.5.2 The assessment of a measured strain point as good, marginal, or fracture/fail is described in 13.2.

X3.4 DIC Calibration & Accuracy

X3.4.1 DIC system calibration should be performed based on the system manufacturer's requirements.

X3.4.1.1 Some DIC systems may be calibrated for strain measurement without the need for the spatial measurement to be converted into physical units (for example, mm). If the results are to meet 7.1.1 to have a specific dimension of gauge length, then the system should be calibrated to spatial physical units for comparison.

X3.4.2 Requirements on the accuracy of the major strains are given in 10.3, 13.3.1, and 15.2.

X3.4.2.1 Guide E2208 Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems describes methods to assist users in understanding the issues related to the accuracy of non-contacting optical strain measurement systems, including DIC systems.

X3.4.3 Frequently, DIC system manufacturers recommend assessment of the noise floor before a series of tests.

X3.4.3.1 The noise floor assessment uses image pairs of a patterned sample that has been slightly translated, but not strained (that is, rigid body motion). The measured strains in this case should be zero, and the deviation is seen as the noise floor for the subsequent measurements.

X3.4.3.2 The noise floor assessment should use the same equipment, camera and lens, set-up, acquisition, DIC analysis parameters, grid pattern quality, calibration, and physical environment, as the measured test piece, since these variables can affect this assessment.

X3.4.3.3 If a random grid pattern is used, then the pattern quality can vary with each test piece. To account for this variation, the noise floor assessment may be made for each sample tested using one image pair of the shifted test piece before each test.