Designation: ~~**E2218 – 02 (Reapproved 2008)**~~ **E2218 – 14**

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

3. Terminology

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

~~3.2 *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. See Fig. 1.~~

~~3.2.1 *Discussion*—The graduated scales on the FLD shall be in percent strain, calculated from the initial gage length.~~

~~3.2.2 *Discussion*—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.~~

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.

[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.

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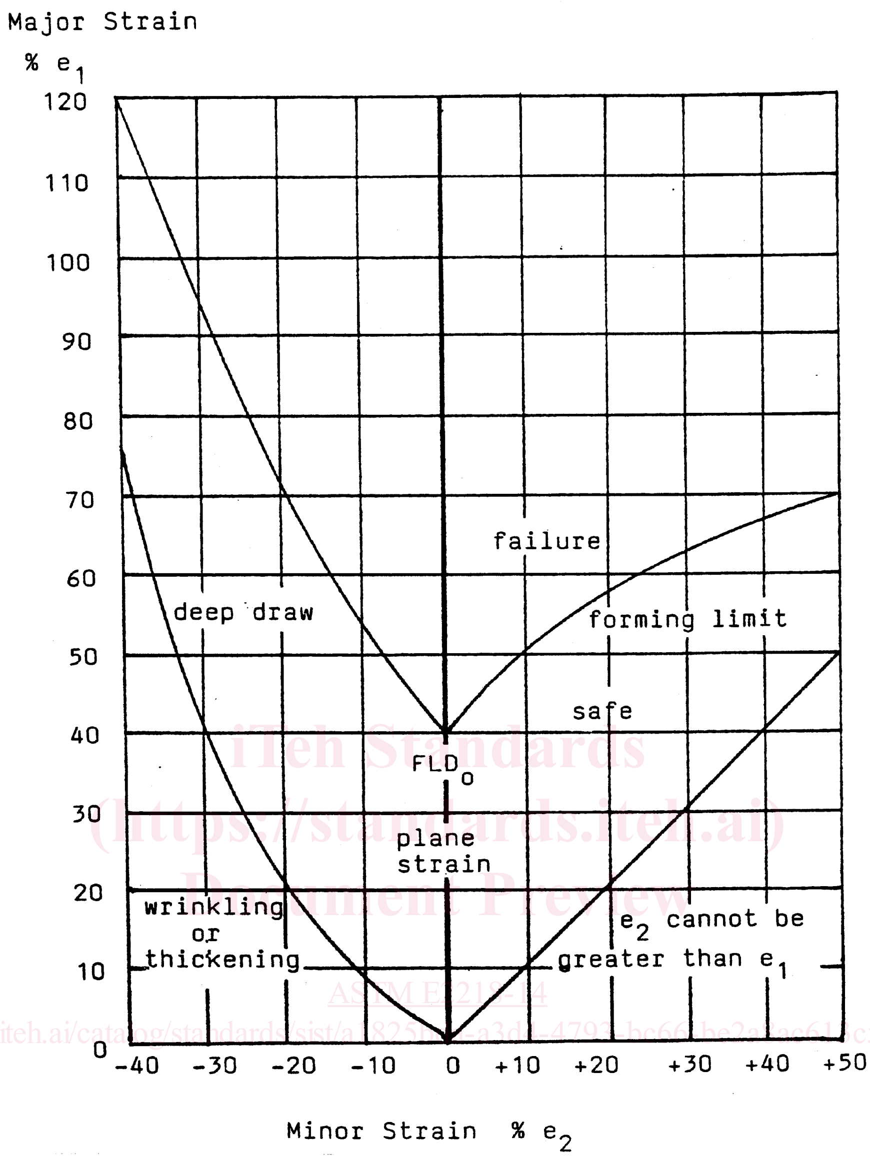
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.1.1 *Discussion—*

See Fig. 1.



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. ~~1~~2 Forming Limit Diagram

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.

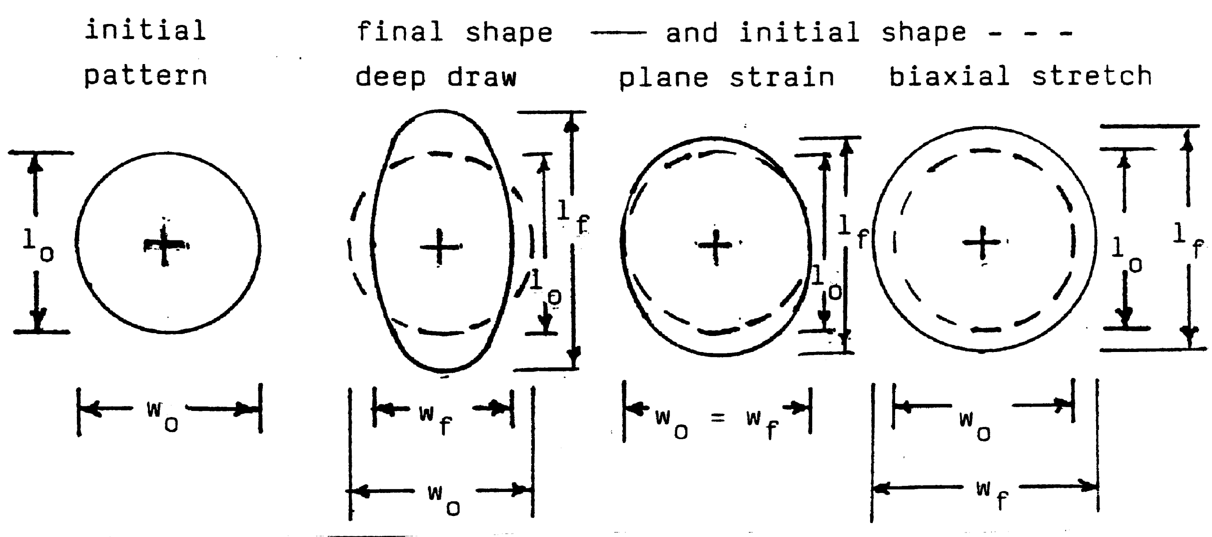


FIG. 41 Possible Changes in Shape of the Grid Pattern Caused by Forming Operations on Metallic Sheet Products

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. See Fig. 3.

3.2.4.1 *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 %.

3.2.4.2 *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.

3.2.4.3 *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 from the surrounding flange being pulled into the die cavity.

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

3.2.6.1 *Discussion—*

The major strain (e_1) is measured along the stretched line of a square pattern, or along the major axis of the ellipse resulting from deformation of a circular grid pattern.

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

3.2.7.1 *Discussion—*

The minor strain (e_2) is measured at 90° to the major strain, along the shorter dimension of the final rectangular shape of a part formed using a square pattern, or the shorter axis of the ellipse resulting from deformation of a circular grid pattern. f a square pattern becomes skewed into a parallelogram shape, it shall not be used to measure strain.

3.2.8 *plane strain*—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). It is sometimes referred to as FLD_o. See Fig. 2 and Fig. 1.

3.3 *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. See Fig. 2.

3.3.1 *Discussion*—The curve of Fig. 2 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. 2 correlates with the upper curve of Fig. 1, a generic curve representing a metallic sheet material with a FLD_o of 40 %.

3.3.2 *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 gage 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.

3.3.3 *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 %, or even greater strain levels.

3.3.4 *Discussion*—For convenience, the forming limit curve (FLC) can 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, that value shall be noted in the report.

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

3.3.2.1 *Discussion*—

The major strain (e_1) is measured along the stretched line of a square pattern, or along the major axis of the ellipse resulting from deformation of a circular grid pattern.

3.3.3 *minor strain*—the strain (e_2) 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, along the shorter dimension of the final rectangular shape of a part formed using a square pattern, or the shorter axis of the ellipse resulting from deformation of a circular grid pattern.

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.

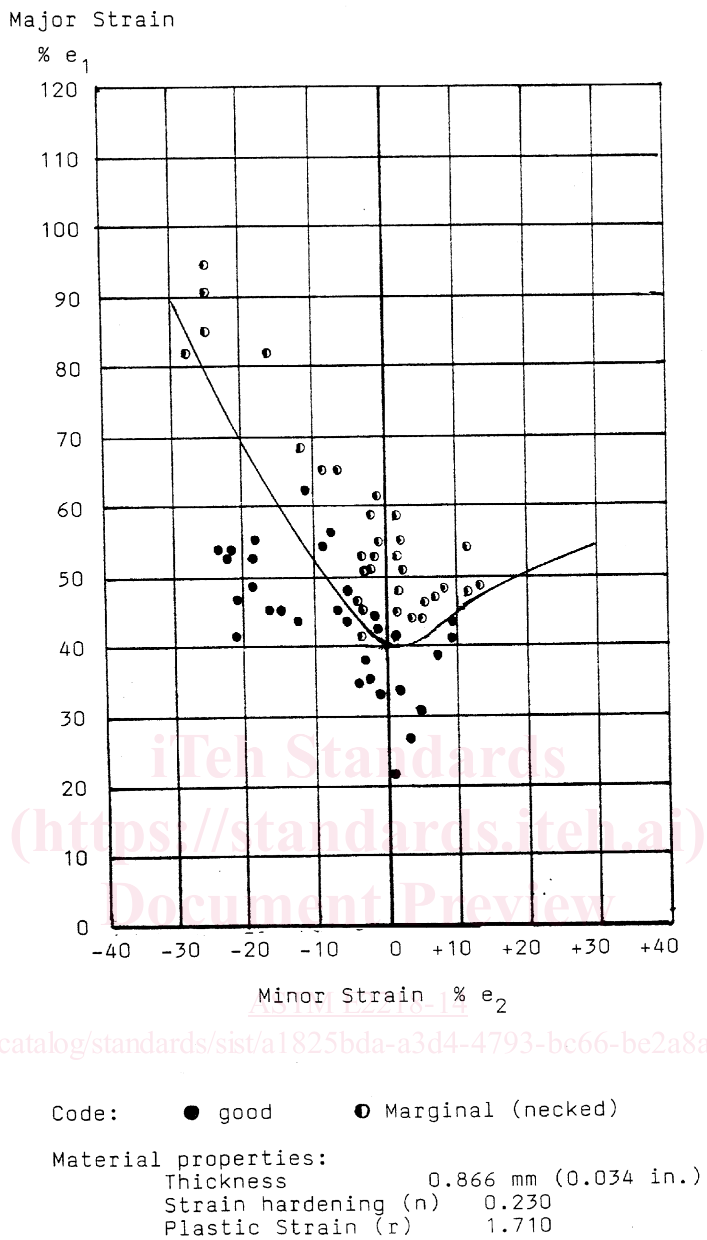
3.4 *grid pattern*—a pattern applied to the surface of a metal sheet to provide an array of precisely spaced gage points prior to forming the metal into a final shape by the application of a force.

3.4.1 *Discussion*—An array of squares, or circles, or both, is printed on the surface of the specimen. Suggested patterns are shown in Fig. 3. The pattern shall adhere to the metal so that it will not be moved on the surface or rubbed off by the forming operation. 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.

3.4.2 *Discussion*—Suggested dimensions for the gage lengths are 2.5 mm (0.100 in.) for the sides of a square pattern, or diameter of a circle pattern. After the part has been formed, critical areas are measured for the resulting gage 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. 4. The major strain (e_1) and associated minor strain (e_2) at 90° to (e_1) are calculated from these gage length changes. The strains can be either engineering strain based on the original gage length, or true strain.

3.4.3 *Discussion*—Larger patterns, of 6 mm (0.25 in.) up to 125 mm (5 in.), can be used to measure low strain levels on formed parts, but are not used in determining the FLC.

3.4.4 *Discussion*—Circles are suggested 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



Cold Rolled Drawing Quality Aluminum Killed Steel
Longitudinal Mechanical Properties

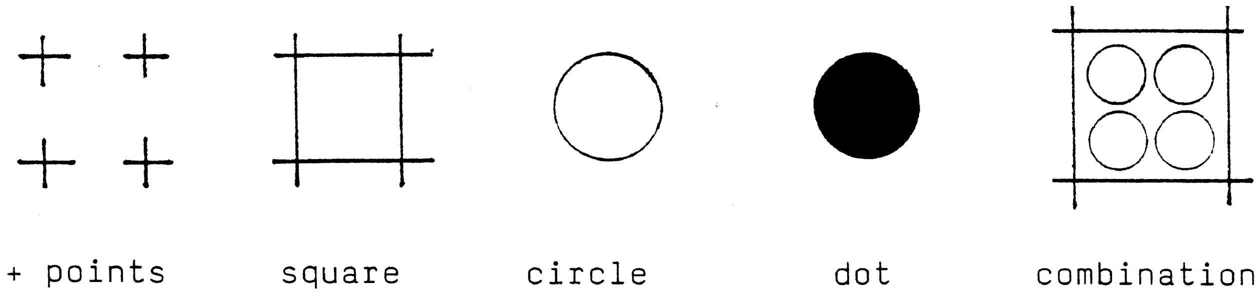
Thickness		Yield Strength		Tensile Strength		% El in 50 mm	*n* Value	*r* Value
mm	(in.)	MPa	(ksi)	MPa	(ksi)			
0.866	(0.034)	163.4	(23.7)	304.7	(44.2)	43.5	0.230	1.71

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. ~~2~~3 Forming Limit Curve (FLC) for a Cold Rolled Drawing Quality Aluminum Killed Steel Sheet.

~~commonly have diameters of 2.5 mm (0.100 in.) and can 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.~~



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

FIG. ~~3~~4 Examples of patterns for ~~Gage~~Gauge Length measurement units used in Determining Forming Limit Curves (FLC)

~~3.4.5 *Discussion*—An alternate to circles is a pattern of solid dots of precise diameter, which are measured across the diameter of the dot.~~

~~3.5 *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. See Fig. 4.~~

~~3.5.1 *Discussion*—Deep drawing 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. 1.~~

~~3.5.2 *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.~~

~~3.6 *major strain*—the largest strain (e_1) developed at a given location in the sheet specimen surface.~~

~~3.6.1 *Discussion*—The major strain (e_1) is measured along the stretched line of a square pattern, or along the major axis of the ellipse resulting from deformation of a circular grid pattern.~~

~~3.7 *minor strain*—the strain (e_2) in the sheet surface in a direction perpendicular to the major strain.~~

~~3.7.1 *Discussion*—The minor strain (e_2) is measured at 90° to the major strain, along the shorter dimension of the final rectangular shape of a part formed using a square pattern, or the shorter axis of the ellipse resulting from deformation of a circular grid pattern. f a square pattern becomes skewed into a parallelogram shape, it shall not be used to measure strain.~~

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~~3.8.1 *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. 2 and Figs. X2.1-X2.3.~~

~~3.9 *biaxial stretching*—a mode of metal sheet forming in which positive strains are observed in all directions at a given location. See Fig. 4.~~

~~3.10 *limiting dome height (LDH)*—an evaluative test for metal sheet deformation capability employing a 200 mm (4 in.) hemispherical punch and a circumferential clamping force sufficient to prevent metal from the surrounding flange being pulled into the die cavity.~~

~~3.10.1 *Discussion*—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 (4 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 (4 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.~~

4. Summary of Test Method

4.1 The procedure for determining a forming limit curve (FLC) involves the following:

4.1.1 Using a hemispherical punch testing machine (LDH tester). Sometimes called a bulge tester. The LDH test employs a 100 mm (4 in.) diameter machined surface punch.

4.1.1.1 A universal testing machine for tension load application and a sub-press for against the metal sheet surface loading with a ball punch of 75 mm (3 in.), 100 mm (4 in.), or larger diameter can be used in place of the LDH test equipment.

4.1.2 Preparing a series of grid pattern blanks with different widths and a common length suitable for being securely gripped in the test apparatus.