ordered to a specified nominal thickness, with the tolerances being plus and minus as shown in the ASTM A568, Table 23 (Cold Rolled Sheet—thickness tolerances). An example of this method is shown below.

0.034 in (8.6 mm) x 36.5 in (930 mm)

Tolerance would be plus and minus 0.003 in (0.08 mm).

3. Defining Profile

3.1 Feather Edge[1]—Feather edge is generally understood to be the thickness deviation between a location 3/8 in (9.5 mm) from the mill trimmed edge of sheet steel and a position 1 in (25 mm) to 2 in (50 mm) in from the mill trimmed edge.

3.2 Crown[1]—Crown is generally understood to be the difference in thickness between a point 3/8 in (9.5 mm) in from the mill trimmed edge and the center area of the sheet across the width as rolled. A more correct interpretation of crown would be the difference in thickness 1 in (25 mm) to 2 in (50 mm) in from the mill trimmed edge and the thickness at the center of the sheet width as rolled.

[1] To illustrate the phenomenon of feather edge and crown, profiles of typical hot rolled and cold rolled sheet are illustrated on preceding page. Actually, however, no such "classic profile" exists.

ϕ PROPERTIES OF LOW CARBON SHEET STEEL AND THEIR RELATIONSHIP TO FORMABILITY—SAE J877 JUN84

SAE Information Report

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1. Introduction—Problems associated with the evaluation of formability or deep drawability of sheet metals are complex and may be difficult to solve due to the number of variables involved. As long ago as 1940, the AISI Technical Committee on Sheet Steel reviewed this problem. More recently, Volume 1 of the Ninth Edition of the ASM Metals Handbook contains sections on "Low Carbon Steel Sheet and Strip" and "Formability of Steel Sheet" that provide suggestions to help evaluate parts and select materials. The purpose of this information report is to summarize the sheet metal characteristics that are commonly used when attempting to predict the formability of sheet metal.

2. Traditional Tests of Formability—The Rockwell Hardness and the Ball Punch Deformation Test (sometimes referred to as the Olsen or Erichsen Cup Test) have historically been the primary mechanical tests made by the fabricator to indicate formability. These tests are easily and quickly made, and require a minimum quantity of material. Unfortunately, they are not exact measures of formability, and can be used only as a guide in determining if trouble in a press operation is due to the sheet metal.

2.1 Ball Punch Deformation Test—This test consists of forcing a ball-type punch against the surface of a securely clamped sheet specimen until the metal fails. A deeper cup indicates better ductility. Details for conducting this test can be found in ASTM E643, "Standard Method for Conducting Ball Punch Deformation Test for Metallic Sheet Material." The test can also be used to predict surface coarsening after forming. For example, with material exhibiting an ASTM grain size of 8 or finer, the outer surface of the cup will be smooth, however, with a grain size of 7 or larger there will possibly be moderate to heavy surface coarsening. In addition, directionality problems within the sheet, and any tendency for brittle fracture, may be detected by examination of the fracture line.

2.2 Rockwell Hardness Test—Indentation hardness is one of the common controls in sheet steel production. However, it is not an exact indicator of formability and should not be used to establish rigid inspection limits. Details for conducting the test are given in ASTM E18 "Methods of Test for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials." As explained in E18, there are minimum sheet thickness limits for various hardness scales. Normally, the hardness of a low carbon steel is reported as an HRB value; but for thin sheets, such as less than 0.040 in (1 mm), the test should be made using the F scale. The HRB value can then be obtained from a conversion table and included in parentheses. Surfaces of the sheet to be tested may be prepared by lightly pre-polishing with 180 grit paper to provide a smooth flat surface. Results are more repeatable with this type of surface preparation than when the as-rolled surface is used. For comparison purposes, any change in the as-received surface should be noted.

3. Tension Test—Data from tension tests can give a more complete measurement of formability, ASTM A370, "Mechanical Testing of Steel Products," and E8, "Tension Testing of Metallic Materials," describe testing procedures.

NOTE: Any taper in the width of the bar between the gage marks could affect the total elongation adversely.

3.1 Yield Strength—The measured strength depends on both the steel and the conditions under which the prepared specimen is loaded. This term is applicable to those materials having an engineering stress-strain diagram in the transition from elastic to plastic strain which is a smooth curve as well as to those which exhibit an upper yield point or sharp knee. The upper yield point may be reported as well as the lower yield point. If only a single yield point value is reported it should be indicated whether it is the lower or upper yield point. In reporting yield strength, the method by which it was determined should be stated (0.2% offset method, 0.5% extension underload method, halt of the pointer or from a stress-strain diagram). See ASTM E8 for a description of these methods.

In forming sheet metal, the upper yield point has to be overcome before any deformation occurs in the flat blank. Experience has indicated that when the upper yield point is high in relation to the lower yield and approaches the ultimate strength, the material will have a greater tendency to split than material which has an upper yield point only slightly higher than the lower yield point. A low yield strength is preferred when formability is the major consideration.

3.2 Tensile Strength—The strength at the highest load reached during the tension test is the tensile strength. It is calculated in psi or MPa units using the specimen cross sectional area measured before testing.

3.3 Elastic Ratio—The yield strength divided by the tensile strength expressed as a decimal value is the elastic ratio. Steels with low elastic ratios have a greater capacity for being formed due to the greater separation between the yield load and the ultimate load during which forming can take place.

3.4 Total Elongation—The total elongation is the percent increase of a gage length on the tension test specimen. For low carbon sheet steel, a 2 in (50 mm) gage length and a 0.5 in (13 mm) gage width is normally used. Steels with a higher percent elongation will stretch further before failure. This elongation is a direct measure of ductility and represents an important consideration in evaluating formability. Caution must be used, however, in comparing elongation values since they depend on specimen preparation and testing procedure. Total elongation also may vary with sample orientation in relation to the sheet rolling direction.

3.5 Uniform Elongation—The amount of deformation that can occur before any measurable localized necking of the tension specimen starts, is known as uniform elongation. This is designated as e_u and will usually vary between 20 and 28% for low carbon steel.

3.6 Yield Point Elongation—The yield point elongation indicates the intensity of stretcher strains that can develop in certain low carbon steels in lightly formed areas. It is caused by interstitial elements such as carbon and nitrogen, or in the case of certain high strength steels, a very fine grain size. The tendency to strain can be minimized by temper rolling at the producing mill. However, in grades subject to aging, the effect of temper rolling is only temporary and it is necessary for the user to properly roller level the sheet immediately before forming a shape. Sheet steels are available that will not exhibit yield point elongation.

3.7 Typical Mechanical Properties—Table 1 lists typical mechanical properties of hot rolled and cold rolled sheet steel. Metallic coated products generally exhibit higher yield strength and hardness and lower elongation due to the type of processing associated with the coating operations. The properties listed are intended for information only, and the values are not to be used as criteria for acceptance or rejection. Mechanical properties are not normally used in specifications unless special structural properties are required in the part. Due to the range of properties possible, the expected distribution can overlap among the various qualities. The ranges are broader for hot rolled sheets than for cold rolled. Also, rimmed steels may exhibit a broader range of properties than killed steels, due to the segregation of carbon, phosphorous, and sulfur that occurs during solidification in the steel making process.

TABLE 1—MECHANICAL PROPERTIES OF HOT ROLLED AND COLD ROLLED SHEET STEEL

Sheet Quality	Typical Properties[b]						Strain Aging Potential	Strain or Flute Potential[a]
	Yield Strength		Tensile Strength		Elongation, % Gage (1/2 × 2 in) (13 × 50 mm)	RB Hard-ness		
	psi	MPa	psi	MPa				
Hot Rolled and Hot Rolled Pickled,								
Commercial Quality	38 000	260	52 000	360	30	50 – 75	Yes	Yes
Drawing Quality	35 000	240	50 000	340	36	45 – 65	Yes	Yes
Drawing Quality Special Killed	35 000	240	50 000	340	40	48 – 68	No	Yes
Cold Rolled								
Commercial Quality, Annealed Last	34 000	230	46 000	320	37	35 – 60	No	Yes
Commercial Quality, Temper Rolled	32 000	230	46 000	320	35	38 – 60	Yes	No[c]
Drawing Quality, Annealed Last	32 000	220	45 000	310	41	35 – 50	No	Yes
Drawing Quality, Temper Rolled	29 000	200	45 000	310	40	35 – 55	Yes	No[c]
Drawing Quality Special Killed, Annealed Last	30 000	210	43 000	300	42	35 – 48	No	Yes
Drawing Quality Special Killed, Temper Rolled	25 000	170	43 000	300	41	35 – 48	No	No

[a] Cold Rolled Sheets are usually ordered temper rolled to minimize strain and fluting hazards, but for unexposed parts they may be ordered annealed last. If the consumer needs to avoid strain and fluting and does not have effective roller leveling equipment, he should order Special Killed Steel. (Strain and fluting are illustrated in SAE J810.)
[b] These values are given as information only and are not intended as criteria for acceptance or rejection.
[c] This only applies to freshly tempered rolled material.
1 ksi = 1000 psi = 6.89 MPa

3.8 Test Specimen—The location and orientation of the test specimen relative to the processed coil from which it was taken is important. Samples should be secured from the center three-fourths of the width and after uncoiling 50—100 ft (15—30 m) to avoid coil edge and end variability, if the tests are to be representative of the bulk of the product.

4. *Special Tests of Formability*—During the late 1960's, new test methods more directly related to the actual mechanism of deformation began to be developed and accepted. These tests are used to obtain a more complete characterization of sheet steel formability.

4.1 Plastic Strain Ratio—This is a measure of a sheet metal's resistance to thinning as controlled by the crystallographic orientation of its structure, which is dependent on the chemistry and processing of the material. When a tensile test specimen from a sheet of ductile metal having isotropic mechanical properties is stretched 20%, the width and thickness will each contract 10%. This is essentially true for steel in the as-hot-rolled condition, or for a normalized low carbon sheet steel. If the sheet has been cold reduced and annealed subcritically by conventional methods, it will have a degree of anisotropic mechanical properties. In that case, a tensile test specimen stretched 20% will exhibit a different amount of contraction in the thickness than in the width. The degree of anisotropy is measured by the plastic strain ratio, r. The procedure for determining r can be found in ASTM E517, "Standard Test Method for Plastic Strain Ratio r for Sheet Metal." For anisotropic materials, the r value changes with test direction, and for convenience it is measured in directions longitudinal (0 deg), diagonal (45 deg), and transverse (90 deg) to the rolling direction. An average value, r_m, is usually reported $r_m = \frac{r_0 + 2\,r_{45} + r_{90}}{4}$.

Higher r values indicate greater resistance to thinning, and are directly related to an increased ability of the sheet to be formed by deep drawing. Typical r_m values for several selected steels are shown in Table 2.

4.2 Strain Hardening Exponent—The strain hardening exponent, known as the n value, is defined as the exponent of the power law relationship of true stress (σ) to true strain (ϵ), $\sigma = K\epsilon^n$, where K is a strength coefficient. True stress and true strain are based on the instantaneous cross section area, rather than the initial area used for engineering stress and strain. Determination of n from load elongation curves is described in ASTM E646, "Tensile Strain Hardening Exponents (n values) of Metallic Sheet Materials." A higher n value indicates a capability for the metal to strain harden in areas that have been cold worked by deformation processes, and in turn cause further straining to occur in less cold worked areas. This capacity to transfer strain contributes to a better response to biaxial stretch deformation modes. Typical n values for selected sheet steels are shown in Table 2.

TABLE 2—TYPICAL PLASTIC STRAIN RATIO AND STRAIN HARDENING EXPONENT FOR SELECTED STEELS

Sheet Quality	r_m	n
Hot Rolled Drawing Quality	1.0	0.20
Cold Rolled Drawing Quality	1.2	0.24
Cold Rolled Drawing Quality Special Killed	1.6	0.24

4.3 Strain Rate Hardening—The m value is a measure of the change of the flow stress as the rate of strain is changed. It becomes important beyond uniform elongation, when a tension test specimen necks-down by a diffuse, and finally localized reduction of cross section prior to fracture. It is the strain rate sensitivity of the flow stress ($\dot{\epsilon}$) in the modified power law equation, $\sigma = K\epsilon^n \cdot \dot{\epsilon}^m$. Since the m value is strain rate dependent, its determination requires loading control based on changes in the strain. In general, higher positive m values are desired. For low carbon steels, the m value is positive and generally in the range of 0.006 to 0.012. Its significance is apparent in that it accounts for the total elongation being on the order of two times the uniform elongation for most low carbon high ductility sheet steels.

4.4 Cup Drawing Tests—Deep draw biaxial deformation cupping tests, in which metal is allowed to be drawn-in from the flange area of the test blank, are considered distinct from clamped flange stretch tests such as the previously described Ball Punch Deformation Test. Referring to the severity curve of J863 DEC81, these tests generally develop negative e_2 strains in the cup side wall near the flange.

4.4.1 Swift Cup—Either a flat bottomed or a round bottomed punch is used to draw a suitably lubricated circular blank into a straight walled cup shape of 2 in outside (50 mm) diameter over an approach radiused hold-down die. The punch diameter, die radius, and pressure are optimized for the gage and strength level of the sheet metal under test. Blanks of increasing diameter are tested until a diameter is reached with which the cup bottom is punched out rather than forming a straight walled cylindrical cup shape. The reported value is the limiting draw ratio (LDR) determined by dividing the largest blank diameter that will make a straight-walled shape by the punch diameter. A value of 2 to 2.5 is generally expected for low carbon sheet steel. The LDR has been found to correlate with the r value in that material with a higher r_m will form a cup from a larger blank. The round bottom swift cup is considered a combination stretch and deep-draw test.

4.4.2 Fukui Conical Cup—The Fukui test does not employ a hold down force on the flange. This eliminates a difficult to control variable. A 60 deg approach angle conical die is used to form a cup shape by a ball punch forcing a suitably lubricated circular blank into the die until the ball ruptures the conical form. The ball diameter and blank diameter depend on the thickness of the sheet metal being tested. For low carbon steel, a 60 mm (2.362 in) diameter blank is frequently used. A larger diameter tends to collapse in the circumference rather than form a cup. The base diameter of the formed cup is measured in as many directions as necessary to determine the average, usually longitudinal, diagonal, and transverse to the rolling direction. This value may be reported, or a reduction of blank diameter can be calculated for a percent diameter reduction value. Other modifications are possible, but the test has limited usefulness due to the small amount of material being tested. It has been found to relate to both r and n of low carbon steel. Some of the more recently developed steels, such as the interstitial-free with extremely high r_m values, do not rupture in the Fukui cup test.

4.4.3 Hole Expansion Test—There are several versions of this test. In one, a cup is made using a blank with a punched or machined hole in the center which is stretched to failure as the flange is securely clamped. The test is useful in evaluating edge tearing tendencies, as well as the