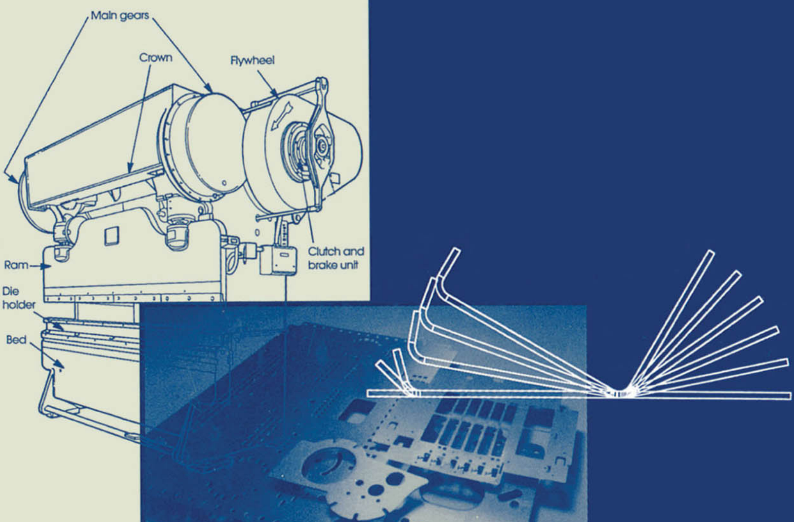
Handbook of Metalforming Processes



edited by
Henry E. Theis

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Herr-Voss Corporation
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Preface

Sheet metal fabrication has been the unsophisticated stepchild of the industrial revolution in spite of the fact that almost all products are ultimately encased in, guarded by, or held together with flat-rolled metal products.

During and after World War II, machine tool technology accelerated at a very rapid rate, with ever-tightening tolerances, increasing automation, and productivity. Sheet metal work remained an essentially little understood, mysterious, and relatively unsophisticated art. Sheet metal tolerances were measured in fractions of an inch rather than in thousandths. Precision sheet metal fabricating came of age in the last quarter of the twentieth century. As tolerances tightened, automation became more practical, and quality and repeatability improved.

It is our intention to provide the reader with a broad, interdisciplinary knowledge of the fabrication of flat-rolled metal products, otherwise known as sheet metal. This is only an overview. Bibliographies and references are given for in-depth and detailed technical explanations of many of the rapidly advancing technologies.

This handbook is written for manufacturers of formed precision metal products to add to their understanding of the available materials, equipment, tooling, and processes. It is not intended to be a technical explanation or manual on the design of the equipment. The book will be useful to those working on the shop floor as well as to nontechnical management personnel.

Henry E. Theis

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I
Mechanical Metallurgy

Chapter 1, ''Mechanical Metallurgy of Flat-Rolled Metal Products'' (Sinha), describes what goes on inside and on the surface of sheet, plate, and coil stock in the shearing and forming process. This chapter will provide a technical base for understanding various types of equipment used by the metal-forming professional.

1

Mechanical Metallurgy of Flat-Rolled Metal Products

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I. INTRODUCTION

Flat-rolled products are classified into sheet, strip, and plate according to their width as well as their width-to-thickness ratio. Sheet metal forming is defined as the plastic deformation of flat sheet metal by tensile loads into a part of desired shape, without fracture or excessive thinning. The process may be simple, such as bending, deep drawing, and stretching, or a sequence of very complex operations, such as stamping involving several basic processes. Therefore, sheet metal forming involves many different processes, equipment, and practices, using sheet materials of various dimensions and properties [1–3]. A majority of sheet-metal-forming processes is listed in Table 1 [4].

Sheet metal forming holds a key role in metalworking (or deformation processing) industry because of its versatility, cost-effectiveness, and materials savings [5–7]. The design and development of sheet metal parts in the automotive industry as well as the demand for improved sheet-forming processes on a reasonable time scale and reduced part development cost have required the use of computer simulation in the tool and die design of sheet metal pressings. The extensive use of finite-element method (FEM) has provided additional advantage in simulating and improving the design of sheet-forming processes and in optimizing the formability of metal sheet and its applications in the automotive industries [6]. In this chapter, basic forming methods, type of defects encountered in sheet metal parts, well-known material properties, forming limit curves, and various formability test methods commonly used for sheet metal forming are presented.

Table 1 Classification of Sheet-Metal-Forming Processes

Bending and straight flanging	Deep drawing and flanging
Brake bending	Spinning (and roller flanging)
Roll bending	Deep drawing
Surface contouring of sheet	Rubber-pad forming
Contour stretch forming (stretch forming)	Marform process
Androforming	Rubber-diaphragm hydroforming (fluid cell forming or fluid forming)
Age forming	Shallow recessing
Creep forming	Dimpling
Die-quench forming	Drop hammer forming
Bulging	Electromagnetic forming
Vacuum forming	Joggling
Linear contouring	
Linear stretch forming (stretch forming)	
Linear roll forming (roll forming)	

Source: Ref. 4.

II. BASIC FORMING METHODS

Many sheet metal forming operations are complex and consist of different types of basic forming operations—bending, flanging, bend-and straighten, stretching, deep drawing, ironing, coining, and embossing.

A. Bending

Bending is the most common type of deformation that occurs in almost all sheet-metal-forming operations. Two types of bends are more commonly used (Fig. 1a). The first is called by several names, such as free bend, V-bend, U-bend, and press brake bend. In each case, a punch drives the sheet blank into a long channel die as both free edges swing upward. In the second type, called a wiping bend, one edge is held securely while the punch wipes or swings the free edge downward. In the case of V-type dies, lower forces are required to bend the sheet metal because the displacement between forces is maximum. According to Huang and Gerdeen, bending should be divided into small curvature bending and large curvature bending and should be studied separately [8].

Bending around small radii or sharp corner results in a cracking or splitting (in the early stages of a forming process) because of localized strain at the bend radius and prevention of its uniform distribution throughout the part. Lubrication is avoided during bending over a sharp radius, because die friction minimizes

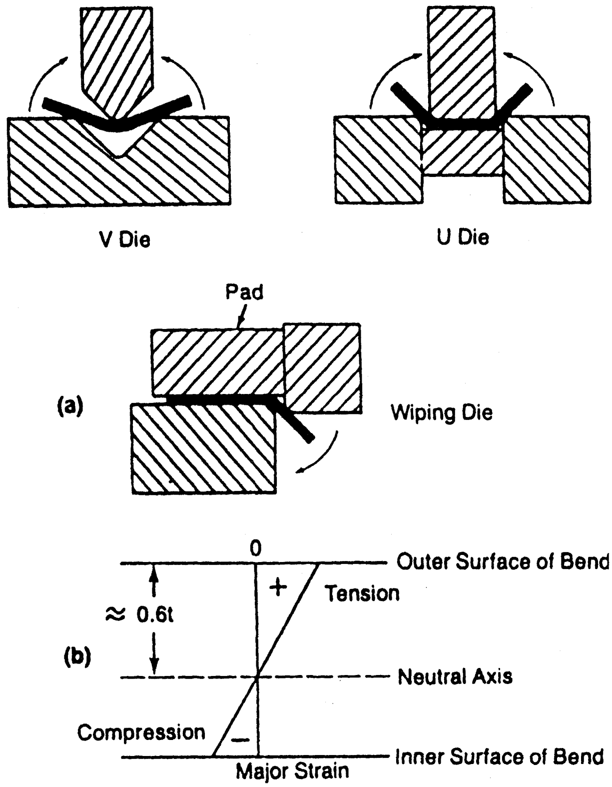

Figure 1 Schematic diagrams showing (a) the action of a V-die, U-die, and a wiping die, and (b) the strain states in bending. (From Ref. 11.)

strain localization by restricting metal movement away from the radius. When the axis of bending is in the rolling direction (where inclusions and other defects become elongated, producing a line of weakness), a greater tendency toward splitting exists along these lines of weakness. This decreases the resistance to fracture compared to when the axis is inclined to the rolling direction [1].

The bending of a sheet metal resembles the case of a beam with a high width-to-height ratio. The bending process is characterized by stretching (tensile stresses) on the outer surface of the bend radius, by the line of zero stress (known as neutral axis or line at the middle of the thickness of the sheet), and by compressive stresses on the inside surface of the bend radius (Fig. 1b). Sheet metal thins slightly in the bend area. When the degree of bending increases, the neutral axis or line shifts from the center of sheet metal thickness toward the inside or compressive side of the bend. Therefore, fracturing or necking during bending always occurs at the outside bend surface and wrinkling occurs on the inside surface of the bend.

A very simple estimate of bending force to make a good 90° bend, without an undesirable springback, can be obtained from

$$F = \frac{1.33w\ t^2 s}{W} \tag{1}$$

where w is the width of the strip (the length of the line over which bending occurs), t is the thickness of the strip, s is the ultimate tensile strength, and W is the width of the die opening [9, 10]. Variations in bending stresses can result in springback (shape distortion) after bending. The effects of springback, however, can be overcome by several methods, such as overbending, bottoming or setting, and stretch bending [11].

The outer and inner sheet metal panels of a part are often assembled by hemming and seaming (Fig. 2) in a manner similar to their use in the clothing industry. A hem is a fold at the edge of a sheet metal to get rid of the sharp edge, improve the edge appearance and wear resistance, and increase the rigidity of the edge slightly. Thus, hemming is an operation in which flanges are flattened against the workpiece in 180° bends to make a finished or reinforced edge. Seaming is the joining of two edges and involves the forming of the bent shape of two open hems, sliding the two edges together, and then pressing them flat. In the manufacture of metal drums, cans, pails, and numerous other products made of light gauge metal, several types of seams are employed [12, 13].

Plane-strain bending (i.e., bending about a straight line) is extensively used in the sheet metal industry to produce structural sheet parts and nonsymmetrical

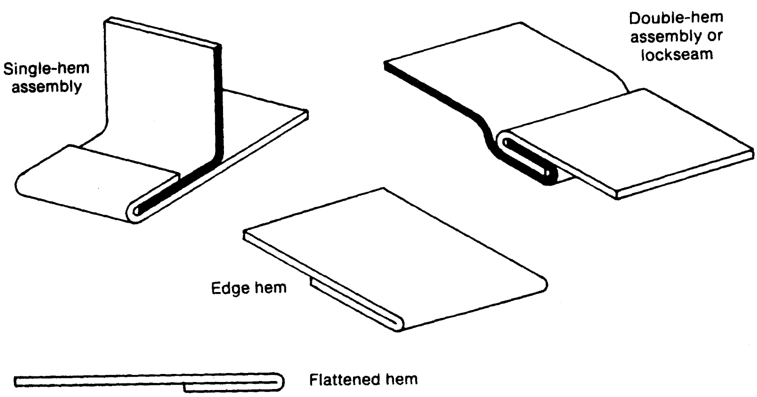

Figure 2 Assembly of sheet metal panels by hems and seams. (From Ref. 13.)

boxes. Understanding of the mechanics and metal flow in the bending process will help to assess bendability, select best possible parameters, and control springback [14].

B. Flanging

The main differences between flanging and conventional bending are that the bent-down metal during flanging is shorter than the overall part size, and the flanges and bends have clearly different functions. Flanging deformation also takes place in many stretching and deep drawing processes for cups, panels, and boxes. Flanges are used for rigidity, hidden joints, appearance, avoidance of sharp edges, and the strengthening of the edge of sheet parts such as automobile front fenders and complex panels formed by drawing or stretch forming.

Three basic types of flanges are shrink, stretch, and straight flanges as shown in Fig. 3. In shrink flanging, the flange length shrinks during forming. This produces convex flange curvature, and the metal in the flange is under compression. On the other hand, stretch flange, in which the metal is in tension,

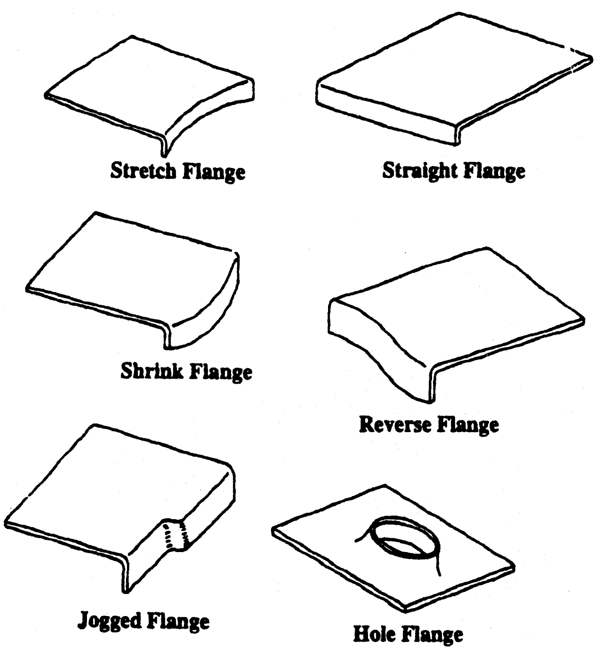

Figure 3 Types of flanges. (From Ref. 15.)

has a concave curvature (when viewed from outside the flanged surface). Excessive compression in the shrink (convex) flange causes wrinkles, whereas excessive tension in the stretch (concave) flange causes cracks and tears. Shrink and stretch flanges are usually formed adjacent to each other, producing a reverse flange. A straight flange is the same as the single curvature bend without longitudinal stresses imposed on the sheet except at the bend radius [15]. It is accomplished by bending of flanges with a wiping die.

C. Bend-and-Straighten Operation

The final shape produced by a bend-and-straighten operation is similar to a bending operation. However, the intermediate steps are quite different and, therefore, produce different characteristics in the final product (Figs. 4 and 6b). In the bend-and-straighten operation, blankholder prevents the swing of the metal. The outer (convex) surface is first placed in tension and then in compression. The inner

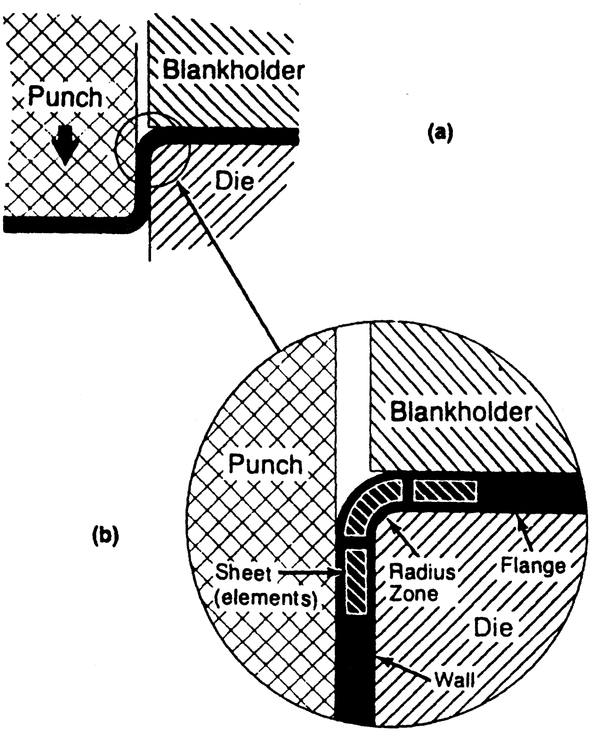

Figure 4 Schematic diagram showing bend-and-straighten operation. (From Ref. 2.)

surface undergoes the reverse sequence. On the basis of the die radius of curvature, the working sequence may be severe. Therefore, the properties of the wall are changed, in a way that makes the wall stronger and less ductile than if it were formed by bending only.

D. Stretch Forming

In stretch forming, the hold-down pressure on the flange is high enough to prevent or restrict material from being pulled into the die cavity and the sheet deforms by elongation and uniform thinning as a round punch of lesser diameter descends. The material must, therefore, be capable of withstanding large enough elongation prior to the onset of necking or plastic instability. For predicting the pressure required for stretch forming, the following equation can be used:

$$P = 1.25\sigma_Y A \tag{2}$$

where P is the stretch-forming pressure (in lbs.), σ_Y is the yield strength of metal

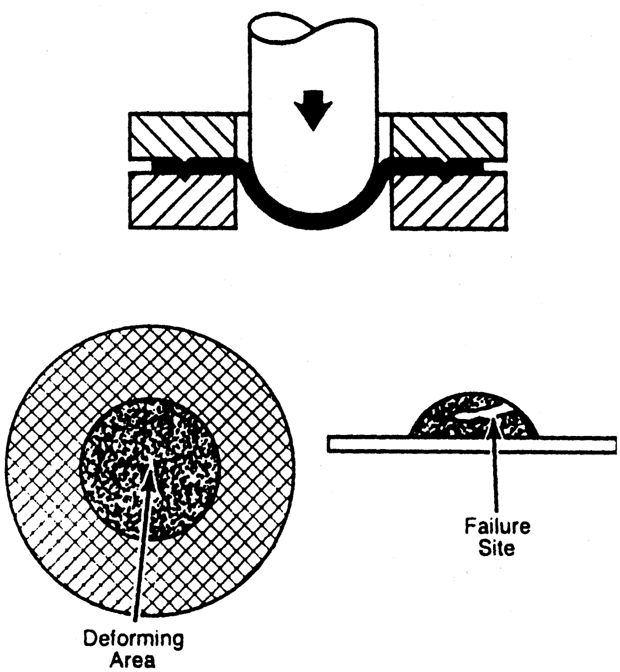

Figure 5 Stretch forming in which no deformation is allowed in the flange area and all deformation occurs in the die opening over the punch. (From Ref. 2.)

(in psi), A is cross-sectional area (in in.^{2}), and 1.25 is an empirical constant [12]. In some cases, stretching implies uniaxial stretching (i.e., application of uniform tensile stress to a sample of fixed gauge length and constant width so that the sample elongates only in the direction of applied stress); however, stretching generally refers to biaxial stretching in which tensile strains are produced in all directions in the sheet plane (Fig. 5) [1, 2]. Biaxial (stretch) strain states occur when both principal surface strains are positive (but not necessarily equal). Balanced biaxial stretching takes place when the perpendicular forces are equal. This results in a greater degree of deformation than in any other forming mode [1]. For stretching, the most important parameters are the uniform elongation of the sheet metal and the n-value (see Section III). This process is used mainly in the automotive and aerospace industries with sheet of steel, aluminum, and titanium alloys, stainless steels, and heat-resistant alloys [16]. Typical examples of parts made primarily by stretching are aircraft wing skin panels, engine cowlings, and automobile door frames, window frames, and body panels.

E. Plane-Strain Stretch

The plane-strain stretch operation is identical to a bending operation, but a tensile-strain component is added across the radius. It produces elongation in one direction and zero elongation (or strain) in the perpendicular direction (Fig. 6a). It is often found to occur when a wide, flat area of a sheet metal is stretched longitudinally and the strain in the transverse direction is prevented by the adjacent metal. Plane-strain stretching is an important type of forming (or stamping) operation because most materials fracture in stamping operations at a lower strain in the plane-strain region than in any other condition. This deformation state is usually observed when the ratio of the bend radius to sheet thickness, R/t, is > 20. This specific deformation is very sensitive to the type of die construction. It is interesting in Fig. 6 that the tip or angle of the die can cause a change in the type of deformation from (a) a plane-strain stretch without metal movement to (b) a bend-and-straighten operation.

F. Deep Drawing

Sometimes called drawing, cup drawing, or radial drawing of metal sheet, deep drawing is used to produce deep, round cups or containers by a process in which a flat sheet blank is firmly held by hold-down forces while the central portion of the sheet is impacted by a flat-bottomed punch into a desired shape, without the formation of wrinkles of the side wall (Fig. 7) [17]. This operation draws (pulls) the edges of the blank inward to form the wall of the cup (or container). The metal is stretched radially by the tensile forces produced by the punch, but it is compressed circumferentially (or in the perpendicular direction) as its diameter

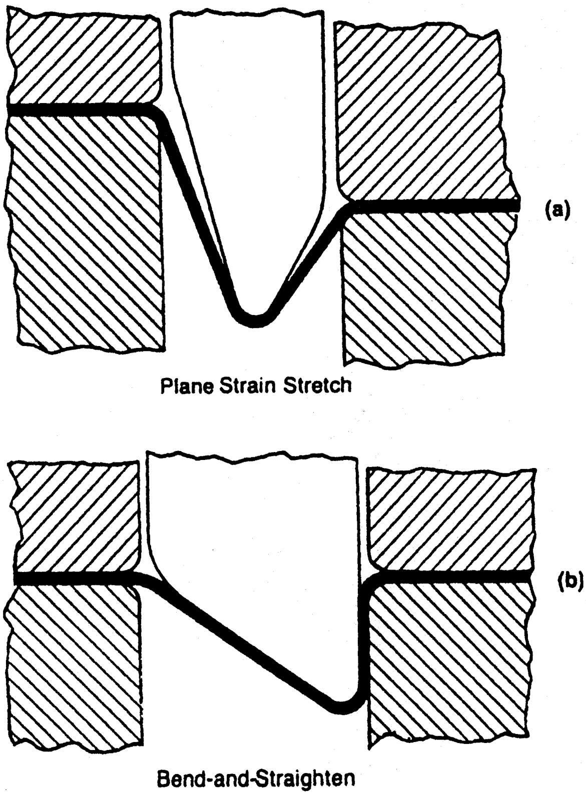

Figure 6 The die angle can change the deformation mode from (a) plane-strain stretch to (b) bend-and-straighten. (From Ref. 2.)

decreases. For drawing, it has been shown that normal or planar anisotropy as well as the product of the strain hardening coefficient and normal anisotropy is directly related to deep drawability [3]. Figure 8 is a schematic of several major strain/minor strain configurations, representing the regions of plane-strain stretching, biaxial stretching, biaxial balanced stretching, and drawing operations.

G. Ironing

Ironing is a process of smoothing and reducing the wall of a cuplike container by progressive squeezing of the metal between an inner cylindrical punch of unchanging diameter and outer dies with decreasing internal diameters (Fig. 9a and 9b). In addition to producing a thinner and more uniform wall thickness,

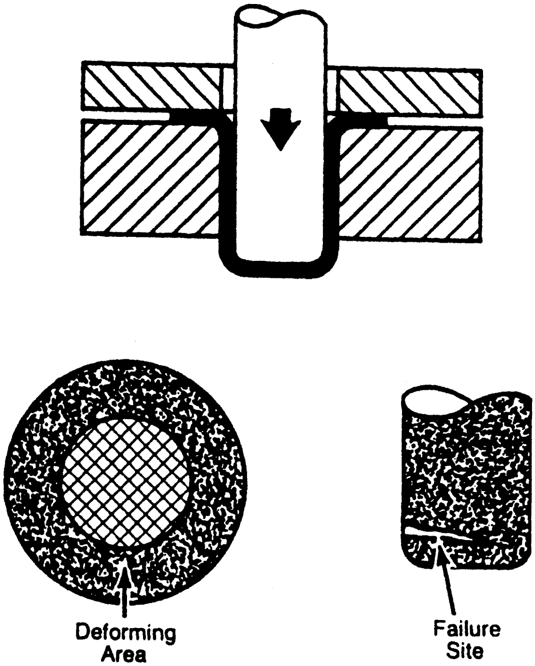

Figure 7 Deep drawing in which no deformation occurs over the bottom of the punch and all deformation is restricted to a tension–compression deformation in the flange of the blank. (From Ref. 2.)

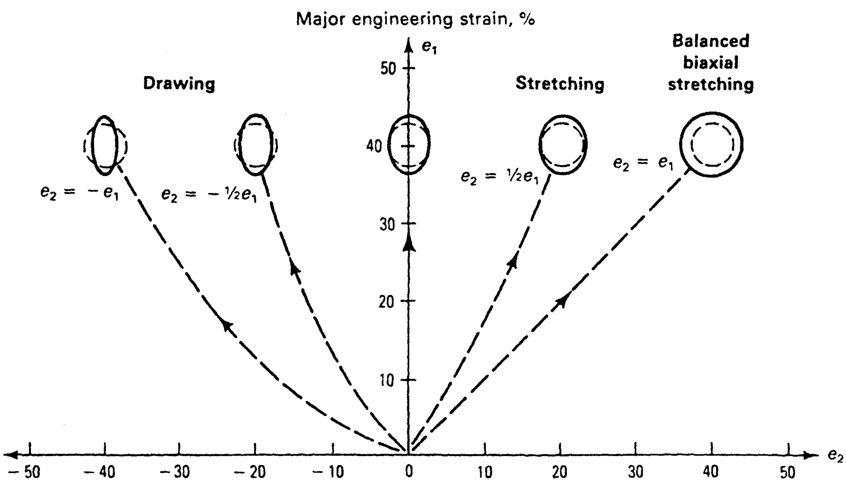

Figure 8 Schematic diagram of several major strain/minor strain combinations. (From Ref. 1.)

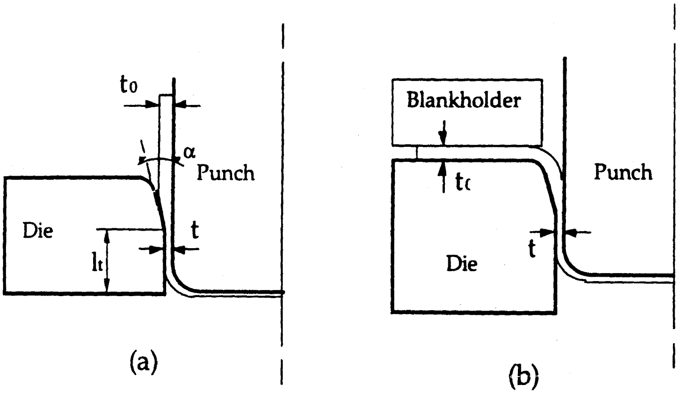

Figure 9 (a) Simple and (b) simultaneous ironing. (From Ref. 18.)

ironing reduces the degree of earing. Deep drawing and ironing are major processes used today in the manufacture of most beverage cans from aluminum alloy and steel cans for the food industry [18]. It is found that the maximum thickness reduction in the simultaneous ironing is always smaller than in the simple or single ironing stage due to the additional stretching of the sheet by the frictional resistance force at the flange region. However, as the deep drawing ratio is decreased, the maximum thickness reduction increases and becomes closer to that in the simple ironing process [18].

H. Coining

Coining occurs when metal is compressed between two closed-die surfaces, resulting in a well-defined imprint of the die on the workpiece with small thickness reductions. It provides improvements in thickness tolerances and surface quality. It is widely used for making coins and parts with similar surface features, for flattening, and for minimizing springback upon removal of parts from a die. In many stamping operations, coining is omitted because it produces restrictions of metal movement, localized strain, and surface damage [1].

I. Embossing

Embossing is more of a drawing or stretching operation and does not need the high pressure necessary for coining [12].

III. DEFECTS IN SHEET METAL FORMING

The major problems encountered in sheet metal forming are divided into seven cases: fracturing, shearing, edge cracking, buckling and wrinkling (due to large compressive stresses), springback, loose metal and oil canning (due to small strain), and undesirable surface texture or appearance. The occurrence of any one or a combination thereof can destroy the usefulness of the sheet metal parts. The effects of these problems are described below.

A. Fracturing

Fracturing occurs when a sheet metal blank is subjected to stretching, shearing, or drawing forces that exceed its ultimate tensile strength for a given strain history, strain rate, strain state, and temperature (see failure sites in Figs. 5 and 7). In stretching, uniform thinning occurs initially, at least in a local area. Finally, a point is reached when deformation concentrates and causes the formation of a thin region or localized neck that may render a part unacceptable without fracturing or which ultimately fractures. The formation of a neck is usually considered as a failure because it produces a visible defect and a structural weakness. However, in high-strength materials, necking may be so localized and short-lived that it is virtually imperceptible. In general, formability tests are associated with fractures occurring in stretching operations.

The cutting of a sheet along a straight line is called *shearing*. In shearing such as slitting, blanking, notching, parting, piercing, nibbling, perforating, and trimming, fracture can occur without prior thinning. The forces required to effect shearing depends on several factors such as metal and sharpness of cutting edges of the tools used. For example, shearing of harder, less ductile metal requires greater force than shearing of softer, more ductile metals [8]. Sharp tools reduce the force requirements because of the more effective localization of force. Dull tools create greater force requirements and result in secondary fractures in the metal and rough and irregular edges. Shearing failures are sometimes noticed in stamping operations by shearing forces in the plane of the sheet; their occurrence is, however, less common than the stretching failures [1].

The quality of the cut surface is greatly influenced by the clearance between the two shearing edges. With a very tight clearance, the cracks miss each other and the cut is accomplished by a secondary tearing process, causing a jagged edge almost at the middle of the sheet thickness. Excessive clearance allows extensive plastic deformation, a delayed separation along a fin (burr) pulled out at the upper edge. Hence, a proper choice of clearance is a very important aspect of the process. A small clearance produces more rapid tool wears and is non-economical. For practical purposes, a clearance between 4% and 12% of the sheet thickness is widely used; a smaller clearance goes with a more ductile material.

In the course of shearing a thousand parts, the tool edges become blunt and worn, and then a burr defect forms at the sheared edge even with an optimum clearance. The fine cracks existing in the burred edge can initiate large cracks in the subsequent forming operation or during the service life of the part and are, therefore, unacceptable. The jagged edge of the burr with its sharp roots acts as a stress raiser and results in a reduced elongation when measured in the tension test. Consequently, it initiates fracture during subsequent forming or in the service of the part.

B. Edge Cracking

The susceptibility to edge cracking that occurs at the sheared edges is greatly enhanced if shearing has produced a burred edge. This problem varies significantly with material; it becomes more pronounced in high-strength steels with elongated inclusions. Sharp and aligned tools eliminate this problem [19]. The sensitivity of edge cracking is often assessed by the hole-expansion test discussed below.

C. Buckling and Wrinkling

In a typical drawing or draw-forming operation, the punch strikes and stretches the blank and starts to pull it through the blankholder ring. The edges of the blank are pulled into regions with progressively decreasing perimeters. This causes high circumferential compressive stresses on the part surface. If these stresses reach a critical level corresponding to the material and thickness, they result in uneven stretching, slight undulation, or local buckle (Fig. 10) [20]. In a severe form, buckles may progress into more pronounced undulations or waves, known as

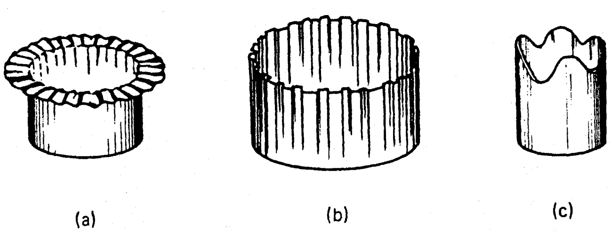

Figure 10 Defects occurring in deep-drawing operations: (a) wrinkling in the flange, (b) wrinkling in the wall, and (c) earing. (From Ref. 20.)

wrinkles, if the blankholder pressure is not high enough. Wrinkling is actually buckling of the undrawn part of the blank under compressive stresses. It may occur in the vertical walls (Fig. 10) [20]. If it occurs on the punch nose during drawing a domed cup, it is called *puckering*. Wrinkles may occur at other regions also, where there is an abrupt sectional change and where the metal is unsupported or contacted on one side only. In extreme instances, folds and double or triple metal may develop. These may produce splitting in other regions, by preventing metal flow or by locking the metal out. However, increased amount of blankholder force (BHF) or blankholder pressure (BHP), increased punch diameter, deeper drawbeads, and a smaller blank diameter often removes or reduces the formation of these defects [1]. The blankholder is sometimes called a draw ring, a pressure pad, or a holding ring [21].

The wrinkling tendency in shrink flanging increases with an increase in sheet yield strength, flange length, and flanging angle, whereas the wrinkling tendency decreases with (a) an increase in strain hardening (or stretching), elastic modulus, sheet thickness, and contour radius, (b) a reduction in the flange length, (c) providing offsets in the flange to take up excess metal, or (e) reducing the clearance between the wiper die and the male die to iron-out wrinkles [14].

In deep drawing of round and nonsymmetrical sheet metal parts, the diameter, flexural strength (thickness and Young's modulus), drawing ratio, yield stress, level of stress, strain hardening rate, and the boundary conditions determine the susceptibility of the part to wrinkling [21].

D. Springback

Springback is the dimensional change in the part shape from that of the die shape due to the elastic deformation of the part after its removal from tooling. Thus, it is an elastic recovery of the sheet metal after removal of the (bending) load.

Springback is one of the major formability concerns in sheet metal part assembly as well as in the forming of high-strength steel sheet. High strength low alloy (HSLA) steels and aluminum alloys are used widely in automotive parts in recent years. This factor is present in forming operations due to the occurrence of a relatively low amount of metal deformation. It is an inherent problem in all forming operations, but it becomes particularly severe in plane-strain (or straight line) bending operations. Springback is a complex phenomenon because its extent depends on a very complicated interaction between material properties, die friction, part geometry, tool geometry and die dimensions (die opening and radii of punch and die), and forming conditions [22, 23]. Because aluminum alloys have a lower modulus of elasticity (approximately one-third that of steel) and mechanical properties, springback from a loaded condition is greater for aluminum alloys than for steels [24, 25]. In many instances, springback

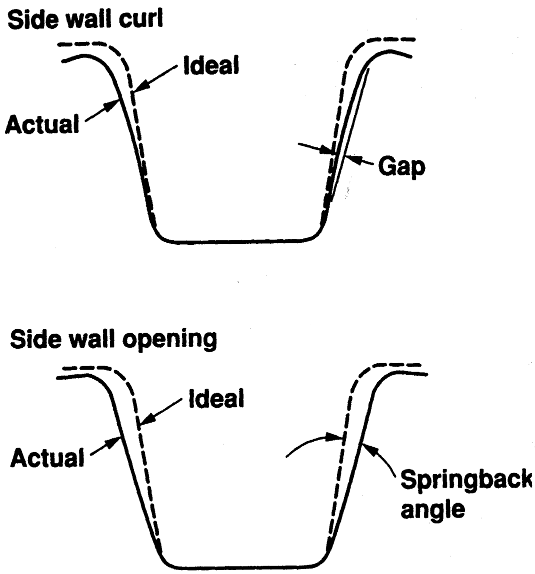

Figure 11 Modes of springback in plane-strain channel forming. (From Ref. 25.)

consists of two components: a sidewall opening and a sidewall curl as shown in Fig. 11 for the forming of a channel section [25]. There are many variables that can influence springback. An increase of Young's modulus, the friction or friction coefficient, the stretching force, the blankholder force, and the postloading force will reduce the springback. Other variables that can influence springback are deformation speed, temperature, and other geometrical parameters [26].

The springback of small radius-to-thickness bends, in the range $R/t < 10$, is larger than that predicted by any known theory [27].

E. Overcoming Springback

Several methods such as overbending, bottoming, and stretching are employed to counteract the effects of springback (Fig. 12) [11]. Overbending of the formed part is the safer approach to effect compensation. It has been widely agreed by press operators to give a 2% additional allowance to the angle of the bend to compensate for springback in steel parts. However, care must be taken in applying this allowance, because thin steel parts tend to springback more than the thicker steel parts. Flanges with curved surfaces need a higher deformation (or strain) in the metal and do not springback as much as straight-line bends.

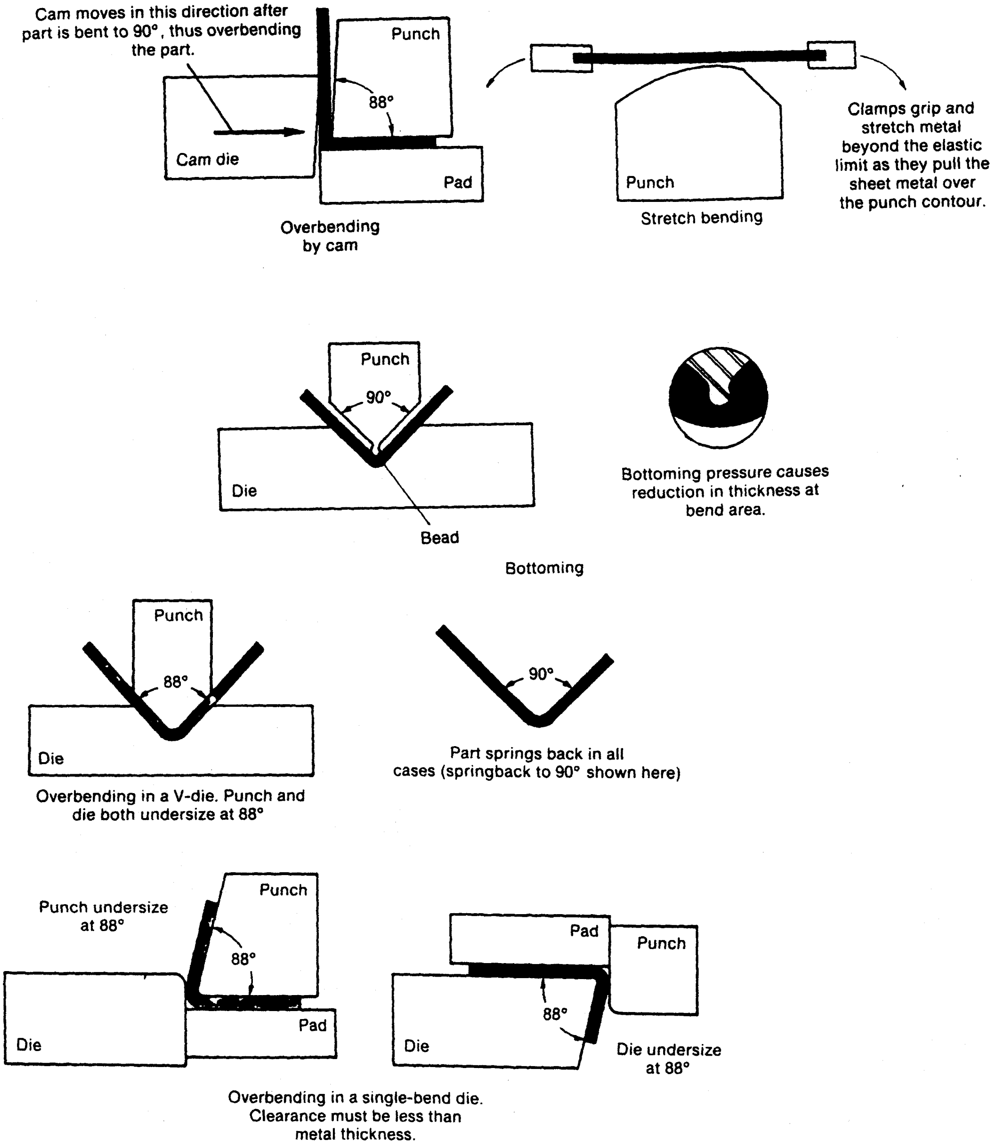

Figure 12 Methods of overcoming springback. (From Ref. 11.)

Another method of compensating for springback is to "bottom" or "strike home" with the punch in the region of the flange or bend. However, striking home, which is sometimes unavoidable, requires the application of heavy pressures by the die and press due to thick areas in the stock [11].

Stretch bending, mostly performed with a special hydraulic machine, involves stretching (or stressing) the blank beyond the yield strength. The blank is then forced over the punch to achieve the desired contour. This prestressing prior to bending causes a very slight springback. This method is used to bend only relatively large radii, because sharp radii would require prestressing of metal beyond the ultimate tensile strength.

F. Loose Metal and Oil Canning

A common defect associated with springback in large automobile body panels is called *loose metal.* This occurs in undeformed or less deformed regions and is undesirable. Because of the faulty die design or excessive yield strength of the forming metal, certain areas of the part do not receive enough plastic deformation, remain underformed, and have practically zero stiffness. These defects are undesirable because they can be easily deflected after the release of the part from the die. This causes the *loose metal* appearance. The loose metal frequently occurs toward the center of large, flat, or slightly curved parts. An increase of restraining forces on the blank edges usually improves this problem [1, 11]. *Oil canning* is a distortion in an area of stamping where little contour is present and a local area can be either concave or convex.

G. Undesirable Surface Appearance

Heavily deformed and especially coarse-grained steel sheet often develop a surface roughness of about the scale of the grain size, usually called *orange peel* and may impair the reflectivity or paintability of the surface. This rough surface appearance is an unacceptable problem particularly because it is visible in service, but it may be tolerated on unexposed regions of a panel. Orange peel is observed only when there is a free surface not in intimate contact with tools. A related surface phenomenon is the *roping* or *ridging*, found in ferritic stainless steels and some aluminum-base alloys. These wrought alloys are characterized by duplex textures. Grain sizes greater than ASTM No. 7 is usually avoided due to excessive orange peel. An ASTM No. 7 is usually recommended for general sheet forming; the finer the grain size, the smoother the surface after forming [3].

Another source of surface problems is *Luder's lines, Luder's bands*, or *stretcher strains* (see Section IV for more detail) and is associated with yield-point elongation (YPE). These defects are particularly apparent in regions where the strain or deformation is very low, and they disappear at moderate and high strain levels or by roller leveling or temper rolling (a very small reduction of ~0.5%). Aged rimmed steels and some aluminum–magnesium alloys also develop severe Lüder's bands. Stretcher strains usually occur in materials with pronounced YPE or susceptibility to strain aging (as in low-carbon steels). The use of nonaging steels or roller leveling the sheet prior to forming can remove this problem. The negative strain rate sensitivity of some nonferrous alloys also results in stretcher strains [19].

Another important defect is called *mechanical fibering*, particularly in bending. During its processing history, impurities, nonmetallic inclusions, and voids align themselves in the rolling direction and are termed stringers. If these stringers are oriented normal to the direction of bending, cracking of the outer layers will occur due to tensile stresses (Fig. 13). Mechanical fibering in a sheet material can be reduced or eliminated by promoting a spherical shape of inclusions by using various additives and/or vacuum degassing and melting.

In some instances, zinc-coated steels exhibit surface defects called *spangles*. This phenomenon occurs only in hot-dipped products and is caused by the development of a coarse grain size in the galvanic coating, which gives clear visibility of the individual grains. This problem can be overcome in the coating process. In addition to the above problems, handling damage, dents caused by dirt or slivers in the die, scratching, and scoring or galling by the breakdown of or insufficient lubrication and accumulation of debris at the die-sheet interface

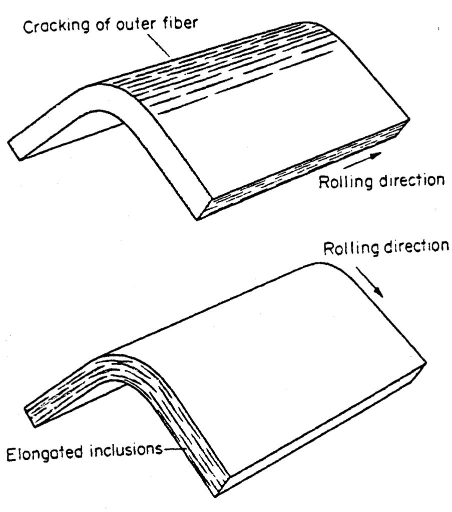

Figure 13 Mechanical fibering in sheet metal and its effect on bending of sheet. (From Ref. 3.)

sometimes produce unacceptable surfaces. Surface marks, namely draw marks, step rings, and burnish, are caused by improper punch-die clearance or poor lubrication [20].

IV. MATERIAL PROPERTIES

The material properties which are of profound significance in sheet metal formability are tensile properties and fracture properties. These properties are controlled through chemical composition of metals and alloys, casting and processing techniques such as ingot and strand castings, hot and cold rolling, heat treatment, microstructure, gage and level of cold work, and texture or anisotropy. The processing steps that increase the strength of a material usually decrease its formability. For optimum formability in a wide range of applications, the workpiece should satisfy the following conditions: (1) uniform strain distribution, (2) high strain level without necking or fracture, (3) maintenance of in-plane shear stresses without fracturing, (4) maintenance of in-plane compressive stresses without wrinkling, (5) no change in part shape after removal from the die, and (6) smooth surface without surface damage.

Some production processes can be successfully operated when the workpiece has a wide range of properties. Some processes run well with workpieces having a narrow range of properties. However, the process can be adjusted to accommodate variations in workpiece properties, although this sometimes leads to lower production and higher material waste. Generally, consistency is an important factor in generating a high productivity of closer-tolerance parts [1].

A. Tensile Properties

The most widely used intrinsic test of sheet formability is the uniaxial tension test. In the standard tensile testing, a test specimen of 2.000 in. (50.8 mm) gauge length and 0.500 in. (12.7 mm) width (Fig. 14a) is gripped in a tensile testing machine, and then the grips are pulled apart at a constant strain rate to fracture, as described in ASTM E8 [28]. The applied load and extension are measured by means of a load cell and strain gauge extensometer. The load–elongation (or extension) relation is recorded from which both the engineering (or nominal) stress (s)–engineering (or nominal) strain (e) and true stress (σ)–and true strain (ϵ) are plotted (Fig. 14b) [29] using the following equations:

$$\text{Engineering stress, } s \text{ (psi or MPa)} = \frac{F}{A_o} \tag{3}$$

where F is the applied load or force and A_o is the original cross-sectional area in gauge length;

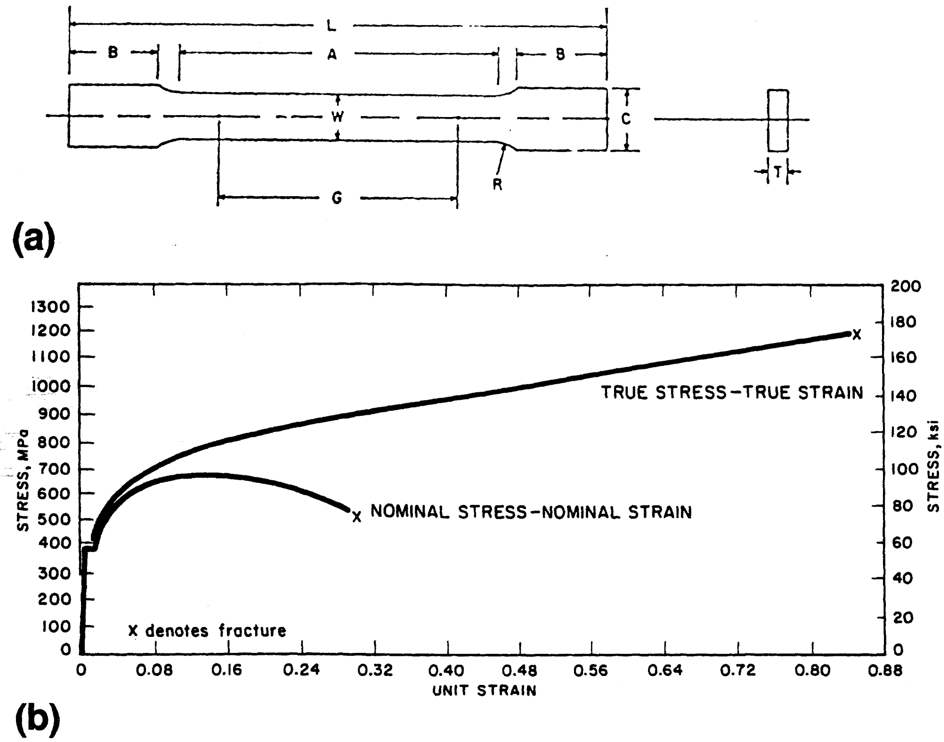

Figure 14 (a) Standard flat tensile test specimen. (b) Engineering stress–engineering strain curve and true stress–true strain curve. (From Refs. 28 and 29.)

$$\text{Engineering strain, } e = \frac{l_f - l_o}{l_o} \tag{4}$$

where l_o is the original gauge length of the specimen, l_f is the instantaneous or final gauge length after the occurrence of deformation, and Δl is the change in length. The true strain ϵ is defined as the sum of instantaneous length changes dl divided by the instantaneous length l or

$$\epsilon = \int_{l_o}^{l_f} d\epsilon = \int_{l_o}^{l_f} \frac{dl}{l} = \ln\left(\frac{l_f}{l_o}\right) = \ln\left(\frac{l_o + \Delta l}{l_o}\right) = \ln(1 + e) \tag{5}$$

During the plastic deformation, the volume of the specimen remains unchanged; that is, volume conservation is maintained:

$$A_f l_f = A_o l_o \tag{6}$$

where A_f is the true, final, or instantaneous uniform cross-sectional area in the gauge length, after the occurrence of some deformation, We can rewrite Eq. (5) as

$$\epsilon = \ln\left(\frac{A_o}{A_f}\right) \quad \text{or} \quad \frac{A_o}{A_f} = \exp(\epsilon) \quad \text{or} \quad A_f = A_o \exp(-\epsilon) \tag{7}$$

Equation (7) indicates that the cross-sectional area decreases exponentially with true strain. Now, we are able to define true stress as

$$\sigma = \frac{F}{A_f} = \frac{F}{A_o}\exp(-\epsilon) = s\,\exp(\epsilon) \tag{8}$$

It is thus obvious that the engineering stress–strain system depends on the original dimensions of the test specimen, whereas the true stress–strain system depends on the instantaneous specimen dimensions. Moreover, the true stress is always greater than the engineering stress, and the ratio of the two increases with the increase in the plastic strain. At large strains (above ~10%), the difference between the two is quite large, whereas at low strains (<1%), there is no measurable difference. The stress–strain curves remain identical for both tension and compression tests when true stress and true strain values are taken into account. On the other hand, their data differ when engineering stress and engineering strain values are inserted, which does not seem to be logical. However, engineering stress–strain data are employed for convenience, particularly for a small strain; the true stress–strain data provide a more rational approach and are successfully used in helping to understand the forming operations involving plastic deformation.

Table 2 lists typical tensile properties measured on selected thin (0.5–1.0 mm or 0.02–0.04 in.) sheet materials. The following properties, usually obtained from a tensile test, are used in specifications.

1. Modulus of Elasticity (Young's Modulus) *E*

This is the slope of the stress–strain curve in the elastic or linear region of the stress–strain curve and is expressed as

$$E\ (\text{psi or MPa}) = \frac{s}{e} \tag{9}$$

It is used to measure the deflection or stiffness of materials under load, and is an important design parameter. It is the structure-insensitive property of a material [30]. The magnitude of the elastic modulus varies widely for different metals; for example, E for low-carbon steel is approximately 30×10^6 psi and E for aluminum is 10×10^6 psi. This is only marginally affected by a small variation

Table 2 Typical Tensile Properties of Selected Sheet Metals

Material	Young's modulus, E		Yield strength		Tensile strength		Uniform elongation (%)	Total elongation (%)	Strain hardening exponent (n)	Average normal anisotropy (r_m)	Planar anisotropy (Δr)	Strain rate sensitivity (m)
	GPa	10^6 psi	MPa	ksi	MPa	ksi						
Aluminum-killed drawing quality steel	207	30	193	28	296	43	24	43	0.22	1.8	0.7	0.013
Interstitial-free steel	207	30	165	24	317	46	25	45	0.23	1.9	0.5	0.015
Rimmed steel	207	30	214	31	303	44	22	42	0.20	1.1	0.4	0.012
High-strength low-alloy steel	207	30	345	50	448	65	20	31	0.18	1.2	0.2	0.007
Dual-phase steel	207	30	414	60	621	90	14	20	0.16	1.0	0.1	0.008
301 Stainless steel	193	28	276	40	690	100	58	60	0.48	1.0	0.0	0.012
409 Stainless steel	207	30	262	38	469	68	23	30	0.20	1.2	0.1	0.012
3003-O Aluminum	69	10	48	7	110	16	23	33	0.24	0.6	0.2	0.005
6009-T4 Aluminum	69	10	131	19	234	34	21	26	0.23	0.6	0.1	−0.002
70-30 Brass	110	16	110	16	331	48	54	61	0.56	0.9	0.2	0.001

Source: Ref. 1.

in material structure such as small alloying additions or the presence of defects such as vacancies, dislocations, or grain boundaries. However, the variation becomes appreciable when the alloys either show complete solid solubility or form intermediate phases. The general rule is that the stronger the interatomic forces (curvature of the potential energy well), the higher the modulus. In addition to the variation in the elastic modulus, crystallographic dependency in the elastic modulus also occurs; that is, if we determine E along different crystallographic directions in a single crystal, we will obtain different results. The directional variation in properties is termed *anisotropy*; for example, E_{iron} varies between 41×10^6 psi (2.83×10^5 MPa) in the [111] direction and 19×10^6 psi (1.31×10^5 MPa) in the [100] direction [31].

Finally, E decreases approximately linearly as the temperature is increased up to about half the melting temperature; a rapid decrease, however, occurs with a further increase in temperature; for example, E at half the melting temperature becomes 0.8, and at near the melting temperature, it reaches 0.4 of the value near the absolute temperature [31]. The modulus is a major parameter in determining elastic springback. The lower-modulus metal has greater springback when unloaded from a given flow stress.

2. Tensile Strength (s_{ut})

This is also referred to as the *ultimate tensile strength* (UTS) and is expressed in psi or MPa. It is a maximum stress on the engineering stress–strain curve. It is an index of the quality of a material; that is, it is a good indication of defects, flaws, or harmful inclusions present in the material.

The maximum in the engineering stress–strain curve (i.e., s_{ut}) is also significant because homogeneous and stable plastic deformation is obtained at strains less than e_{ut}, leading finally to failure by ductile (cup–cone) fracture. However, the extent of the tendency toward necking is mostly governed by the strain rate sensitivity m of the material. The higher the value of n (i.e., closer to 1), the lower the tendency toward localization of strain. It should be pointed out that the amount of strain prior to the occurrence of necking is referred to as uniform strain e_u, which may be equivalent to uniform elongation with respect to the engineering strain. For steels without YPE, the ratio of UTS to YS (yield strength) is related to the n value.

3. Yield Strength (σ_y)

The applied stress required to induce the onset of plastic deformation (yield point) is called *yield stress*. This stress is the most important value for structural design because it avoids the practical difficulties encountered in measuring the exact stress for the proportional limit or elastic limit at which a material starts to deform plastically. It is extremely sensitive to the structure and prior history of a material.

It is the usual practice to use offset yield strength by a specific plastic strain because it is measurable and reproducible from one laboratory to another. Its measurement involves taking a measured stress–strain curve and drawing a line parallel to the elastic or straight-line portion of the curve that is offset in strain by 0.002 until it intersects the stress–strain curve. This intersection gives the value of yield strength, σ_y—the 0.2% offset yield strength. This 0.2% set or offset is tolerable in most cases. In some cases, however, 0.1% or 0.5% offset is required. In materials showing a sharp yield point (mild steel), the lower yield stress is considered as the yield strength.

4. Yield-Point Elongation (e_y)

Many metals, especially low-carbon steel, show a localized, heterogeneous type of transition from elastic to plastic deformation that produces a yield point. The load at which the sudden drop occurs in the load-elongation curve is called the upper yield point. The constant load is referred to as the lower yield point and the elongation or stretching that occurs for a while without any increase in its flow stress (i.e., constant load and before the load starts to increase monotonically) is called *yield point elongation* (YPE or e_y) (Fig. 15) [27]. The extent of YPE depends on the rate of deformation, with the elongation usually increasing with deformation speed [3]. This behavior is caused by the sequential trapping of dislocations by solute atoms and their subsequent breaking away from the trapped atmosphere. The plastic deformation which occurs during YPE is discontinuous, small, and localized and is oriented 55° to the tensile axis; this is called *Lüder's band, Lüder's strain*, or *stretcher strain*. Lüder's band formation does not produce strain hardening until it is complete (i.e., when YPE is complete); that is, when

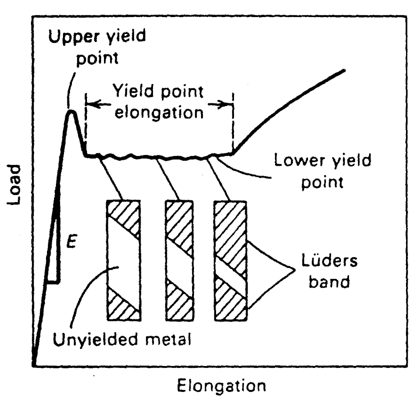

Figure 15 Schematic showing yield-point elongation. (From Ref. 32.)

YPE zone or Lüder's zone ends, work hardening is registered on the stress–strain curve. Lüder's zone occurs in steels that are prone to strain aging; that is, a strong interaction between solutes (e.g., C or N in iron and steel and Mg in Al) and dislocations that produce solute segregation to, and immobilization (pinning) of, dislocations.

Discontinuous or inhomogeneous yielding and flow by Lüder's band formation and propagation has long been a nuisance and is sometimes an unacceptable problem in the fabrication of complex shapes such as automobile doors and bumpers from low-carbon steels because of the surface appearance marred by Lüder's lines. However, discontinuous yielding has sometimes been proven to be advantageous, as in machining of low-carbon steels.

With coarsening of grain size, e_y decreases [33]:

$$e_y = \text{YPE}(\%) = \frac{k_y d^{-1/2}}{\alpha} \tag{10}$$

where d is the grain size and k_y and α are constants depending on the material and tensile testing conditions. Also, the Lüder's band front becomes less pronounced, and, finally, it becomes diffuse and difficult to observe at a very coarse grain size. Usually, both the yield stress and the YPE are increased by the presence of fine precipitates [34].

5. Ductility

Ductility is a measure of (a) engineering strain required at fracture, e_f, usually called the *elongation*, or (b) the *reduction of area* at fracture, RA(q). Both elongation e_f and reduction of cross-sectional area, RA, are expressed as a percentage:

$$\text{Elongation} = \left(\frac{l_f - l_o}{l_o}\right) \times 100 \tag{11}$$

$$\text{RA} = \left(\frac{A_o - A_f}{A_o}\right) \times 100 = q \tag{12}$$

where l_o, l_f, A_o, and A_f have the usual meanings. Percent elongation is a better indicator of quality than the tensile strength because this is drastically reduced in the presence of inclusions and porosity. Elongation $\times$ tensile strength is an index of toughness at low strain rates. The gauge length over which the percent elongation is measured must be quoted. The materials are called ductile when RA $> 50\%$, semibrittle when RA is small ($<10\%$), and notch brittle when RA is moderate in a simple tension test (say 30%) but very small or zero when a notch or crack is introduced into the tensile specimen before testing.

Ductility may, in some instances, be determined in terms of the *uniform strain* (or elongation) e_u or the *zero gauge length strain* e_0. The former, being the strain prior to the occurrence of necking, is an important value in the formability of sheet metal because its magnitude specifies the permissible strain to obtain uniform or homogeneous deformation, after which local thinning (i.e., inhomogeneous deformation) may occur. For metals that obey the power-law curve (of strain hardening), e_u is related to the strain hardening exponent, n, by the following equation:

$$n = \ln(1 + e_u) \tag{13}$$

This relationship holds good for steels; for other materials, the actual e_u measured in tension should be employed. As shown in Fig. 16, both e_u and total elongation, e_T, decrease with an increase in yield strength. The e_u, like the n value and UTS/YS ratio, is employed as a measure of maximum allowable stretchability. Zero gauge length strain, e_0 is measured from the reduction of area at fracture by the following expression:

$$e_0 = \frac{q}{1 - q} \tag{14}$$

This quantity is important in forming operations where gauge length is very short.

Aluminum alloy sheets tend to have a considerably low elongation compared to mild steel in contrast to the slightly low UTS. The uniform elongation of aluminum sheets is higher than that of steel sheets, although the local elongation of them is very small.

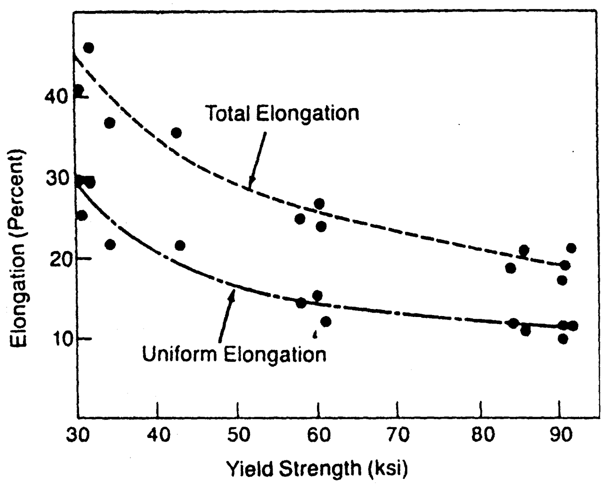

Figure 16 Effect of yield strength on both uniform elongation and total elongation. (From Ref. 2.)

The relation between the reduction in area at fracture q (in tension test) and the minimum permissible bend radius, R_m, for a given thickness of sheet can be predicted fairly accurately (for less ductile materials) by [35].

$$\frac{R_m}{t} = \frac{1}{2q} - 1 \quad \text{for } q < 0.2 \tag{15}$$

and for ductile materials (due to the shift of the neutral radius in tight bends) by

$$\frac{R_m}{t} = \frac{(1 - q)^2}{(2q - q^2)} \quad \text{for } q > 0.2 \tag{16}$$

In addition to the significance of e_u on formability, e_T (e.g., in 2-in. gauge length) at fracture is being considered as an important indicator of formability (e.g., in dual-phase steels) and is a measure of cleanliness of the material. It is noted that total elongation (e_T) = uniform elongation (e_u) + postuniform (or necking) elongation (e_{pu}); the first term is dependent on the strain hardening exponent n and the second term is dependent on the strain rate sensitivity m. These combined factors, therefore, contribute to the overall formability of the sheet material [3]. Thus, e_T is dependent on the length, width, and thickness of the gauge section employed for the measurement. More specifically, e_T is dependent on the sum of n and m variables. It also correlates well with the hole expansion, bending capacity, elongation of a blanked edge, and other forming operations.

B. Strain Hardening Exponent

Strain hardening is a phenomenon whereby, during the deformation of metals at lower temperatures, the yield stress (required to continue) increases with increasing strain. Strain hardening is caused by the storage of dislocations within a metal and the resistance they offer to the passage of other dislocations. Strain hardening influences the cold formability of sheet. As a result of strain hardening, in many instances, an annealing treatment is required after each forming operation, to enhance the formability and obtain the desired deformation [36]. In a ductile material, the strain hardening (or work hardening) characteristics up to a maximum load can be represented by

$$\sigma = \frac{d\sigma}{d\epsilon} \tag{17}$$

The flow stress is defined as the stress required to maintain deformation (or cause the metal to flow plastically) at any given strain. Flow stress of many metals in the region of uniform plastic deformation can be described by the nth-power hardening equation (Ludwick–Hollomon):

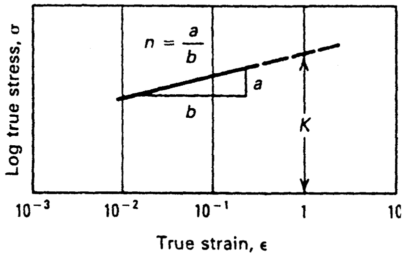

Figure 17 A log σ versus log ϵ plot for the true stress–true strain curve. (From Ref. 28.)

$$\sigma = K\epsilon^n \tag{18}$$

where K and n are the strength coefficient and strain hardening exponent, respectively; both are independent of temperature at sufficiently low temperatures. A log σ versus log ϵ plot for the true stress–true strain up to maximum load provides the n value, represented by the slope of a straight line for most polycrystalline materials as shown in Fig. 17. The n value indicates the ability of a material to be strengthened as a result of plastic deformation. It is a very significant parameter in sheet metal forming. The final strength of a cold-worked part can be determined from the n value. The amount of e_u, the level of forming limit diagram (FLD), the strain distribution, and many other forming variables are directly related to the n value. The n value is not influenced by texture, but is reduced by the addition of solid-solution elements in steel and by the refinement of ferrite grain size [37].

Table 2 lists n values for several materials [1]. Typically, the n values for most metals vary between ~0.1 and ~0.5. The n values of aluminum alloy sheets decrease sharply with an increase in the tensile strain and are lower than those of steel sheets. The n value of commercial HSLA steels decreases with increasing strength and its low n value makes it less formable than mild steel [38]. There are different strain hardening behaviors for mild steels and high-strength steels. The strain distribution ability of steels increases with the increase in overall n value. The peak n value at a low strain level increases the strain distribution ability of the steel. Aging of rimmed steels causes the n value to decrease with time. Additionally, excessive temper rolling beyond that required to eliminate YPE (e_y) will also reduce the n value.

For some materials such as dual-phase steels, some aluminum alloys, and so forth, the n value is not constant, as given by Eq. (18). In such cases, two or three n values may be required to be determined for initial (low), intermediate, and terminal (high) strain regions. The initial n value relates to the low-deformation region, where springback is often a problem. The terminal n value relates to the high-deformation region, where fracture may occur [1].

Recrystallized structures produce low yield strength and high hardening capacities and are ideal candidates for forming applications. In addition, low stacking fault energy such as in brass is advantageous because the difficulty of cross-slip leads to a high hardening rate. In certain stainless and high-strength steels, the decomposition of metastable austenite to martensite during deformation results in a very high n value.

Because most engineering materials need high strength and good formability, a desirable means of strengthening them is by dispersion of hard, spheroidal phases in a soft, ductile matrix. This is also the basis for the dual-phase, ferrite–martensite (high-strength) steels used in the automotive industry. This type of microstructure provides a high initial hardening rate and allows improved shape fixability and less springback compared to high-yield-strength steels [17].

C. Strain Rate Sensitivity

The flow stress of most metals is dependent on the speed of testing. The strain rate sensitivity m of the yield strength (or flow stress) can be described by a parabolic law:

$$\sigma = K\,\dot{\epsilon}^{m} \tag{19}$$

where σ is the flow stress, K is a constant, $\dot{\epsilon}$ is the strain rate, and m is the strain rate sensitivity exponent; both K and m are functions of material and deformation temperature. Whether or not necking is localized or diffuse depends on the value of m, which is defined as

$$m = \frac{d \ln \sigma}{d \ln \dot{\epsilon}} \tag{20}$$

A positive m value suggests that the flow stress increases with the rate of deformation. This has two outcomes: (1) higher stresses are required to form parts at higher rates and (2) at a given forming rate, the material resists further deformation in areas that are being strained more rapidly than nearby areas by increasing the flow stress in those areas. This produces a more uniform strain distribution. This is of special significance in the postuniform elongation region, where necking and high strain concentrations occur. An approximately linear relationship has been found between the m value and postuniform elongation for various steels and nonferrous alloys [17]. Postuniform elongation increases from 2% to 40% with the increase of m value from -0.01 to $+0.06$. It is noted that when m is >0, the stress increases with strain rate; when m is <0, the stress decreases.

In general, the m values of commercial superplastic materials range between 0.4 and 0.9. At ambient temperatures, some metals such as aluminum alloys and brass have low or slightly negative values, thereby indicating their low postuniform elongation [1].

Because m is related to the capability of the material to resist plastic instability or necking, the higher value of m for superplastic materials implies the greater resistance to catastrophic necking [39] and its forming capability into deep shells [3]. It should be noted that m value does not precisely determine elongation nor does the maximum m value always imply maximum elongation. Other factors such as strain, strain rate, grain size, initial homogeneity, and strain rate path have important bearings on the value of m. The m value is temperature dependent. Some metals have negative m values at room temperature and positive values when heated to 400°F. Thus, warm forming could be very beneficial for these metals.

Where stretching operations predominate, good formability depends on high n and m values. On the other hand, if the drawing operation predominates, the average strain ratio, r, is very important, as discussed in Section IV.D. Table 2 lists m values for a number of engineering metals and alloys. The m values for aluminum alloy sheets are extremely low, particularly the 5xxx series, and aluminum alloy sheets show a negative value [40]. The higher m values for steel often causes a much better performance compared to that of aluminum alloys [19].

D. Plastic Anisotropy

When a polycrystalline metal is severely deformed by rolling, deep drawing, swaging, or wire drawing, certain crystallographic directions or planes of the majority of individual crystallites or grains tend to rotate themselves in a nonrandom preferred orientation with respect to the direction of deformation. This preferred (grain or cyrstal) orientation is usually called the *deformation texture* or *cold-worked texture.* Thus, texture, denoting preferred orientation of crystallites (grains), introduces anisotropy in mechanical properties of metals and alloys sheet materials [28, 41]. It produces peaking or earing (Fig. 10) and nonuniform wall thickness during deep drawing of aluminum alloy and steel sheets. The development of such structures is most conveniently characterized by the measurement of the plastic strain ratio or plastic anisotropy factor, r, which is defined as the ratio of the true width (or lateral) strain, ϵ_w, to the true thickness strain, ϵ_t (i.e., $r = \epsilon_w/\epsilon_t$) in a tensile test on the sheet metal specimen. For isotropic sheet material tested in tension, $r = 1$; for plastic anisotropy, $r > 1$. The r is a measure of capacity of a sheet to resist thinning. The higher the r value, the greater the resistance to thinning during deep drawing [37]. This behavior, due to plastic anisotropy in the rolling plane, is undesirable because it leads to frequent interruptions of production runs and causes materials wastage. It is, therefore, necessary to control earing to a tolerable minimum by introducing an appropriate production schedule [42]. In contrast, plastic anisotropy producing a high deformation resistance in thickness direction and less in the rolling plane is said to have a larger limiting draw ratio (LDR) and can be used advantageously in various aspects of formability [43]. Thus, LDR is defined as the largest ratio of blank-to-cup diameters that may be drawn successfully. The LDR has been reported to vary linearly with the r_m value [44].

In sheet-metal-forming technology, the drawability of the deep-drawn containers (e.g., oil filters and compressor housings) [37] can be predicted from the average normal anisotropy, r_m, in the sheet, given by

$$r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{21}$$

The planar anisotropy which is responsible for the magnitude and position of ears in a deep-drawn cylindrical cup and to undesirable metal flow in the blank holder, in the general case, is usually defined by

$$\Delta r = \frac{r_0 + r_{90} - 2r_{45}}{2} \tag{22}$$

where r_0, r_{45}, and r_{90} are the experimentally measured plastic strain ratios in the rolling (0°), 45°, and transverse 90° directions in the sheet, respectively. When Δr is positive, the earing occurs in the 0° and 90° directions; when Δr is negative, the earing (i.e., uneven edges on cylindrical cups drawn from circular blanks) [37] occurs in the 45° direction. When $\Delta r = 0°$, the earing disappears. Thus, planar anisotropy, Δr, is bad for earing.

An r_m value of 1 denotes complete isotropy or equal flow strength in the plane of the sheet and in the thickness direction. A large r_m value improves LDR, which indicates the high average depth (or wall height) and a high-through-thickness strength relative to the strength in the plane of the sheet [28]. A high r_m value also improves the dent-resistance property of formed panels [45–47]. Rimmed and semikilled steels have r_m values close to unity (1.0–1.3) due to their weak texture and are, therefore, not suited for the most demanding deep-drawing applications. On the other hand, aluminum-killed steels with strong $\{111\}\langle 100\rangle$ textures have r_m values in the range 1.5–1.8. The Ti- or Nb-stabilized steels with strong $\{111\}$ and $\{554\}$ orientations have r_m values approaching or exceeding 2.0. There is a direct relationship between r_m value and the grain size of steel, as shown in Fig. 18.

It is important to point out that the press-forming processes used in the industry to form automobile bodies, domestic consumer durables, beverage cans, and so forth can be considered as specific forms of deep drawing; therefore, a close control of r values affects a large sector of manufacturing industry. A combination of a high r_m value and a low Δr values gives optimum drawability.

E. Annealing or Recrystallization Texture

The recrystallization of a cold-worked metal having preferred orientation or texture also produces a preferred orientation of recrystallized grains that are generally

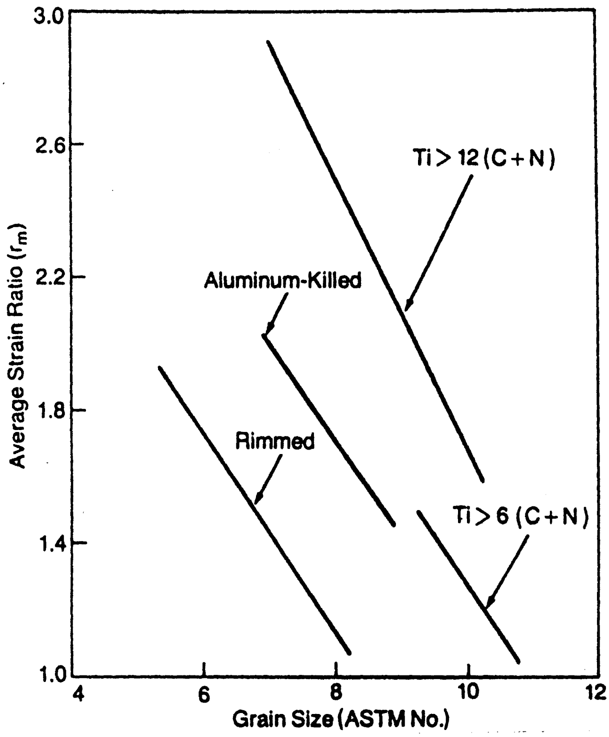

Figure 18 A relationship between the r_m value and grain size of steel. The normal range of conventional rimmed and killed steels is shown. In addition to chemical composition, the value is determined by the coil processing. Two titanium-treated aluminum-killed steels are also shown. To produce an interstitial-free steel with a high r_m value, the amount of titanium present must exceed six times the amount of carbon plus nitrogen. (From Ref. 2.)

different and more pronounced than that of the deformation textures. This is called *annealing texture* or *recrystallization texture* [28]. A great amount of work has been done in the study of recrystallization textures of aluminum alloys and low-alloy steels because of their industrial importance. In general, a well-defined recrystallization texture will be produced, provided the deformation texture is sharp. An outstanding example of a sharp recrystallization texture is the production of {100} ⟨001⟩ in many face-centered-cubic (fcc) metals (notably Fe–Ni as well as copper, gold, and aluminum) after cold rolling and subsequent recrystallization of sheet material [48]. A strong recrystallized cube texture found in Al–Mg and Al–Mg–Mn–Fe–Si (3004) alloy rolled product has important influence on both plastic and surface properties of the products. This affects both normal and planar anisotropy, which, in turn, determines deep drawability and earing behavior, respectively [49]. To minimize earing in 3004 alloy in its final state, it is essential to generate a strong cube texture at the hot-rolling stage; on subsequent cold rolling, the 0°/90° earing tendency related to cube texture gradually transforms to a 45° tendency arising from the deformation-induced reorientation of texture and if the two are correctly played off against each other, earing almost completely vanishes. To ensure the formation of cube texture in the hot-rolling stage, second-phase particles must be precisely controlled [50].

The important process variables that affect the annealing texture are grain boundary mobility and major deformation texture (or degree of cold work), preferred orientation of nuclei of the recrystallized grains, composition, initial grain size, and annealing temperature and time.

In steels, moderate plastic deformation and low annealing temperature are beneficial in developing the recrystallization texture. Planar anisotropy increases with increasing deformation and higher annealing temperature in copper sheets, whereas the inverse is found in brass sheets [28].

An ideal annealing texture for improving deep drawing in low-carbon steels is the strong cube-on-corner $\{111\}\langle 110\rangle$ texture (i.e., one with textural component in the plane of sheet which increases with the r_m value), which, in turn, increases with increasing purity of steel and decreasing initial grain size before cold rolling begins [34].

In low-carbon steels, the annealing texture depends significantly on the hot-band texture, grain size, alloy chemistry, coiling temperature, and cold reduction. In aluminum-killed steels, the precipitation of AlN changes the recrystallization behavior to promote the formation of a strong $\{111\}\langle 110\rangle$ orientation. One practice used in the steel mill is to finish hot, above 900°C, and coil cold, below 600° C, on the hot strip mill to keep the Al and N in solution. After subsequent cold rolling, AlN precipitates form during the heating cycle in box or continuous annealing [37].

F. Surface Topography (or Surface Finish and Roughness)

In sheet metal forming, the surface topography of sheet is an important consideration. Typical metal surfaces produced by rolls textured by conventional grinding (mill finish) have bidirectional surface topography, In contrast, shot blasting, laser [51], electron beam [52], and electrodischarge machining (EDT) [53] processes have been used to produce a beneficial textured surface of the rolling mill stands used in the production of sheet steel. These topographies that are more isotropic in roughness are imprinted on (or transferred the pattern) to the sheet during low-reduction final rolling passes. As these rolls are used, their finish tends to become smoother. Among these roll texturing processes, the laser and

EDT may provide a balanced surface topography leading to improved formability, ease in handling, and image clarity of painted surface during manufacturing and processing of steel sheets as compared to mill finish, where the painted appearance and reproducibility are unacceptable [54, 55].

A surface roughness of 0.8–1.5 μm (30–60 μin.) for average peak height and 2–6 peaks/mm (50–150 peaks/in.) is regarded as the standard for a cold-rolled steel sheet. A rougher sheet surface has the tendency to hold lubricant better and resist galling and cold welding to die surfaces during forming. For parts that are subjected to little forming, a minimum roughness is used in order to attain a smoother and often preferred surface finish.

G. Surface Friction

Surface or interface friction is an important characteristic that affects the formability of sheet metal products. Sheets and tooling surface characteristics, deformation behavior, and the lubricant are reported to play important roles affecting the surface friction conditions [49]. Recently, increased attention has been given on reducing the surface friction for enhancement in formability of sheet steel products through the application of solid-film lubricants or special posttreatments such as phosphates, Cr/CrOx, and so forth on top of electrodeposited zinc or galvannealed Zn–Fe-alloy-coated surfaces [56].

The surface friction is represented by the coefficient of friction, which, in turn, represents the cumulative effects of surface coating, surface finish and surface roughness, surface hardness of both tooling and workpiece, as well as lubricant at the interface [38, 57].

The effect of friction on deep drawing or cupping is twofold. Lubrication of the flange is advantageous due to the reduction of work expended to overcome friction. On the other hand, high friction on the cylindrical surface of the punch increases drawability.

H. Effect of Microstructures on Formability

The formability of a steel sheet depends on various microstructural features such as grain size and shape, grain orientation relative to the rolling direction, and microstructural constituents present in the steel. Fine-grained steels have low n values and limited formability. Although coarse-grained steels have better formability, they exhibit roughened surface (called *orange peel*) by stretching steel with a grain size below ASTM 5, which is unacceptable for many applications (see Fig. 18). Rimmed and hot-rolled aluminum-killed steels usually have equiaxed grains. Cold-rolled aluminum-killed steels, when properly processed, usually exhibit pancake-shape ferrite grains, resulting in preferred grain orientation, which is responsible for excellent formability. Steels with spheroidized microstructure have better formability and low edge retention characteristics, whereas those with the pearlitic microstructure have reduced formability and better edge retention characteristics. The microconstituents present in low-carbon steels such as iron carbides, various nonmetallic inclusions (e.g., sulfide, silicate, and oxides), and submicroscopic particles of AlN in in aluminum-killed steels influence formability by changing its strength. Alloying elements that dissolve in ferrite strengthens the steel considerably, thereby reducing its formability [1].

Low-carbon steels, coated and uncoated, are generally available as commercial quality (CQ), drawing quality (DQ), and drawing-quality special-killed (DQSK) grades. Some steel mills also provide specialized grades, such as interstitial-free deep-drawing steels, baking steels, and high-strength steels, notably dual-phase steels for better formability [1].

Dual-phase steel composed of ferrite and martensite show good stretchability and low yield stress (the YS/UTS ratio being ~0.5), but reduced stretch flangeability. The effects of microstructures on formability were studied on steels strengthened by bainite and/or martensite. In steels, martensite was substituted with bainite and an increased volume fraction of retained austenite. Stretch flangeability and stretchability were evaluated by the punched hole-expansion ratio and elongation, respectively. Based on these results the following conclusions were established:

1. The stretch flangeability of multiphase steels is lower than that of single-phase steels at a particular tensile strength level, although stretchability of the former is superior to that of the latter.
2. In multiphase steel, stretch flangeability decreases as the hardness ratio of hard phase to ferrite increases, which leads to strain concentration at the hard phase–ferrite interface. The stretchability of multiphase steels increases considerably with an increase in the volume fraction of ferrite and retained austenite. However, stretch flangeability of the steel containing retained austenite is low due to the presence of its hard phase.

According to the above findings, several types of high-strength hot-rolled steel sheets with excellent formability were developed. Low-carbon bainite steels have excellent stretch flangeability. The steel comprising ferrite and low-carbon bainite exhibits a good combination of high stretchability and stretch flangeability. The steel containing ferrite, high-carbon bainite, and retained austenite shows excellent stretchability [28, 58].

V. FORMABILITY TESTING METHODS

There are two types of formability tests: intrinsic and simulative. Intrinsic tests measure the basic material properties. They provide comprehensive data that are insensitive to thickness and surface conditions of the material. Important intrinsic tests include uniaxial tensile test, plane-strain tensile test, the Marciniak stretching and sheet torsion tests, the hydraulic bulge test, the Miauchi shear test, and hardness tests.

Simulative tests determine the suitability of sheet metal for a specific deformation or forming process. They provide limited and particular information that is sensitive to thickness, surface condition, lubrication, and type and geometry of tooling. They can be classified according to the predominant forming operations involved, such as bending, stretching, and stretch drawing. In addition, tests to measure wrinkling and springback found after the forming operation have also been developed. They are only described in this section.

A. Bending Tests

There are two types of bending tests: simple bending and stretch–bending tests. Simple bending tests relate to bending the sheet metal without tension, as in a hemming operation. Stretch–bending tests are used to predict how the sheet metal will perform in a combined bending and stretching condition when sheet metal is pulled over a punch or die radius.

Simple bending tests can be accomplished in various ways (ASTM E290). The simplest method for thin sheet material is to clamp one end of the specimen in a bend die in a vise, as shown in Fig. 19, and to bend the specimen over the die manually or with a nonmetallic mallet.

If the specimen bends through 180° without exhibiting fracture or crack, the experiment is repeated with a bend die of smaller radius until failure or cracking occurs on the convex surface. A modified test uses extremely small

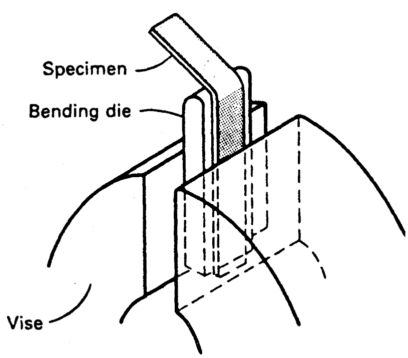

Figure 19 Schematic of a simple bending test. (From ASTM E290.)

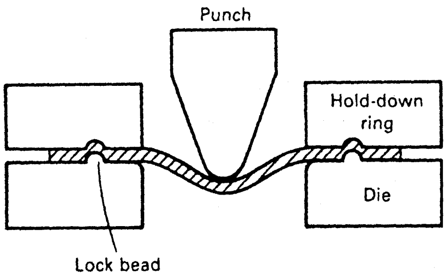

Figure 20 Schematic of a stretch–bending test. (From Ref. 1.)

bend radii for highly ductile metals. The specimen is first bent at its midlength, through less than 90°, over a small radius. The test is then completed by pressing the ends of the specimen together between flat platens without a bend die placed between the platens. Specimens are examined for cracking at the apex of the bend with the magnification of up to 20×.

The ratio of the width to thickness of the specimen should be >8 : 1, and sheared edges should be machined, filed, or sanded to remove heavily cold-worked metal present. In a longitudinal bend test, the length of the specimen is parallel to the rolling direction, and the axis of the bend is perpendicular to the rolling direction. In a transverse bend test, the length of the specimen is perpendicular to the rolling direction, and the axis of the bend is parallel to the rolling direction.

Stretch–bending tests involve clamping the edges of a sheet metal and pressing in the center by a series of punches (see Fig. 20) with hemispherical or angular (V-shaped) configuration. The former test uses a hemispherical tipped punch and concentric circular lock bead and involves a range of strain states. The latter test uses a wedge-shaped punch and straight parallel lock beads and produces plane-strain state.

The punch height at fracture (H) which is influenced by limit strain and strain distribution of a material has been used as a measure of stretch–bend formability. The conditions are selected in such a manner that the fracture takes place in the region of punch contact. All the testings are performed in the dry condition [59].

B. Stretching Tests

Ball punch tests, such as Olsen and Erichsen cup tests, are employed to measure the properties of sheet metals in stretching. These tests involve stretching a specimen over a hardened steel ball and measuring the height of the cup products. More recently, tests involving stretching the specimen over a much larger hemispherical dome have been developed, including the limiting dome height (LDH) test which uses specimens of different widths to control the strain ratio at fracture. Another test is known as the hole-expansion (HE) test, in which a cylindrical, hemispherical, or conical punch is pushed through a circular hole of smaller diameter in the specimen. This initially increases the diameter of the hole and eventually forms a rim of stretched metal. The edge ductility of the metal is measured by the amount of hole expansion that occurs without edge cracking.

1. Ball Punch Tests

The Olsen and Erichsen cup tests are similar, differing primarily in the dimensions of the tooling used. The Olsen test (ASTM E643) uses a 22.2-mm (0.875-in.)-diameter hardened steel ball and a bottom die with a 25.4-mm (1-in.) internal diameter [28.6 mm (1.25 in.) for gages over 1.5 mm (0.06 in.)] and a 0.81-mm (0.032-in.) corner radius of the exterior of the bottom and top dies as shown in Fig. 21. The Erichsen test, which is widely used in Europe, uses a 20-mm (0.79-in.)-diameter ball and a die with a 27-mm (1.06 in.) internal diameter and a 0.75-mm (0.03-in.) die profile radius.

In both tests, the cup height at fracture (or, preferably, maximum load or punch force) is employed as the measure of stretchability or formability index. The preferred criterion for measuring this point is the maximum load. When this is not possible, the onset of a visible neck or fracture can be used, but this yields a slightly different value [1, 2].

These tests, as indicators of stretchability, should correlate with the n value, but the correlation is unsatisfactory. A better correlation with the total elongation and reduction in area can be obtained. These tests have the drawbacks of poor reproducibility of results and poor correlation with other properties or service/

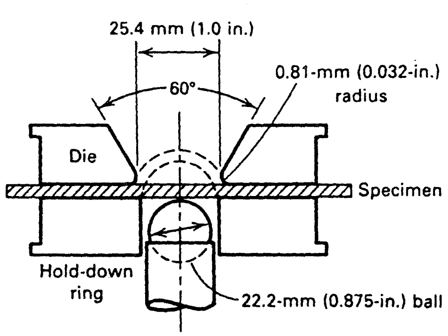

Figure 21 Schematic of Olsen cup test. (From ASTM E290.)

production experience. However, in the case of closely controlled experimental conditions, satisfactory reproducibility and correlation have been observed.

The problems with the Olsen and Erichsen tests are their inability to address formability in the plane-strain conditions, where approximately 85% of all fractures in automotive panels occur. This resulted in the development of stretchability tests that uses a much larger-diameter punch, a lock bead to prevent drawing-in, plane-strain stretch condition, and more rigorously defined test conditions.

2. Hemispherical Dome Test

This test uses 50.8-, 76.2-, and 101.6-mm (2.0-, 3.0-, and 4.0-in.) punches. However, a 101.6-mm (4.0-in.) diameter punch is the most widely used. Figure 22 [57] shows the typical tooling used for this test. The lock bead together with a hold-down force (HDF) of about 222 kN (25 ton) totally prevents drawing-in of the flanges.

The specimen fractures circumferentially at a distance (for lightly lubricated low-carbon steel) of 35–40 mm (1.38–1.57 in.) from the hole, where radial strain peaks sharply. The circumferential strain varies gradually from a maximum of 10–20% at the pole to flange or zero at the lock bead.

The hemispherical dome (HD) test provides more reproducibility of results than the Olsen and Erichsen cup tests. For low-carbon steels, the dome height, which is determined at the point of maximum load, increases linearly with the n value. For other materials such as brass, aluminum alloys, and zinc, optimum correlation has been found between the dome height and the total elongation, which includes the effects of strain rate hardening and limiting strains.

The use of a thin layer of standard lubricant in a consistent fashion reduces scatter in test results, simulates production conditions more closely, reduces tooling damage, and simplifies specimen preparation. However, the use of lubrication makes the strain ratio at fracture more biaxial. This is undesirable for production simulation because production failures mostly occur in the plane-strain region or in a less biaxial manner. Specimens of different widths are used to control the strain ratio at fracture. This method has been modified further into the limiting dome height (LDH) test.

3. Limiting Dome Height Test

Figure 22 shows the tooling and a typical sheet specimen after fracture. The height of the dome at maximum load (near failure), which combines the effect of forming limit with requisite strain distribution for that strain rate, is employed as a measure of stretchability. The LDH test uses a 4-in. ball to stretch to fracture a rectangular sheet. The width of the specimen is varied to provide a minimum dome height, known as the limiting dome height. In order to determine the LDH minimum, strip specimens of different widths are used. This test assesses the

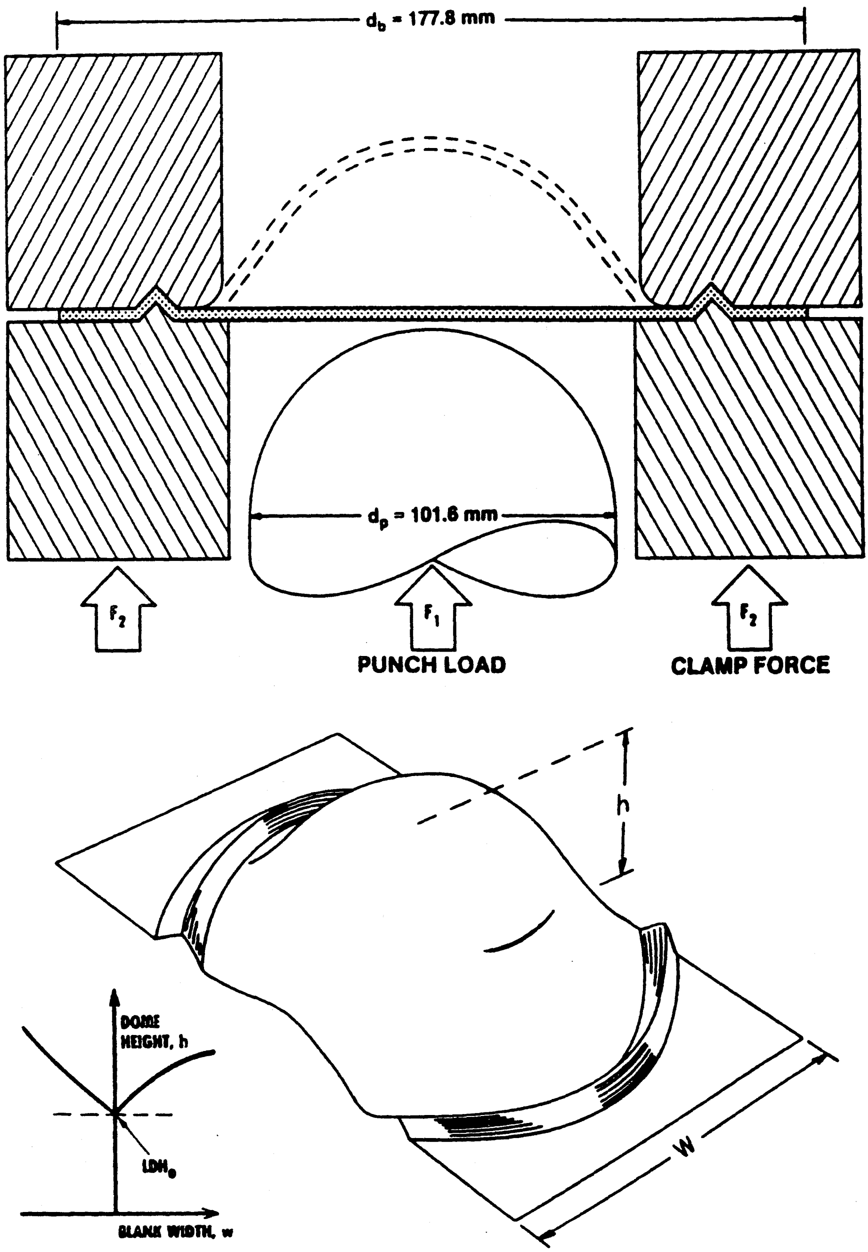

Figure 22 Dome test and limiting dome height test. Punch diameter: 101.6 mm; punch rate: 4.2 mm/s; clamp force: 1000 kN, no. of replicates: 5. (From Refs. 57 and 61.)

formability performance of a material in or near plane-strain stretching condition, which is the most detrimental condition in stampings. This test is very sensitive to punch conditioning and punch temperature effects. Although the test fails to distinguish among different contributions to the materials formability such as base metal, coating, and lubricant properties, it is capable of detecting overall changes in formability [57, 60, 61].

4. Hole-Expansion Test

This test uses a flat sheet specimen with a circular hole in the center which is clamped between annular die plates and deformed by a punch, thereby expanding and ultimately cracking the edge of the hole. Flat-bottomed hemispherical and conical punches have been used, and in some cases, die plates have been equipped with lock beads to prevent drawing-in of the flange. The punch should be well lubricated and should have a large profile radius. A spacer can be used between the punch and the specimen. Figure 23 shows the hole-expansion test using a flat-bottomed punch. The hole-expansion test is terminated when a visible edge crack or fractured hole diameter is noticed. The hole expansion ratio is expressed as

$$\text{Hole expansion ratio (\%)} = \frac{D_f - D_o}{D_o} \times 100 \qquad (23)$$

where D_o and D_f are the original and final hole diameters, respectively.

In most cases, the removal of burr and cold-worked metal from the edge of the punched hole increases the hole expansion considerably. The hole expansion also increases with the increase in e_T and r_m values and decreases with the increase in tensile strength. Inclusion shape control also improves hole-expansion performance.

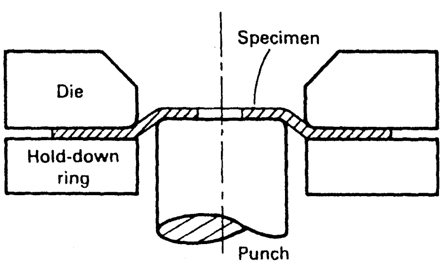

Figure 23 Schematic of the hole-expansion test with a flat-bottomed punch. (From Ref. 1.)

This test is normally used to evaluate the edge or flange stretchability of the material. The stretch flange formability in high-strength hot-rolled steel sheets is a very important property for automobile applications and is normally evaluated by a hole-expansion ratio. The hole-expansion ratio has a strong relationship with the $n\,(1 + r)$ values as derived by Hill's theory. It is possible to produce excellent stretch-flange formability in Ti- or Nb-free, Cu- and/or P-added ultralow-carbon hot-rolled steel sheet with a strength of 370–590 MPa because of a reduction of the anisotropy of (or improvement of the minimum) the r value, thereby a reduction of earing [56, 62].

C. Drawability Tests

1. Swift Cup Test

This test determines the limiting draw ratio (LDR) of a material and is the most extensively used simulative test to evaluate deep drawability. In cup drawing, circular blanks with progressively larger diameters are clamped in a die ring and deep drawn into cups using a flat-bottomed [50.8-mm (2.0-in.) diameter] cylindrical punch. In this test, the sheet metal experiences a large deformation in the flange and substantial sliding is involved at the die radius [57]. Figure 24 illustrates the standard tooling geometry for this test. A similar test apparatus with a 32-mm punch has been used in Europe. The drawability is expressed as either the limiting draw ratio (LDR) or the percentage of reduction. The LDR is defined as the ratio of the maximum blank diameter D that can be successfully

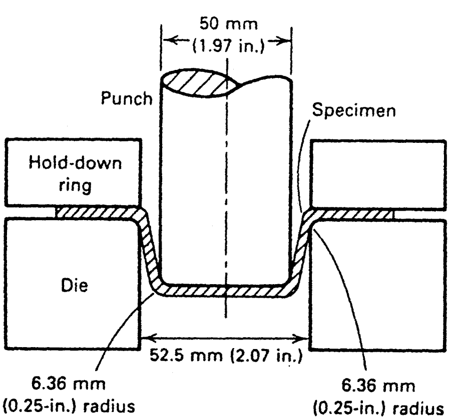

Figure 24 Standard tooling for the Swift flat-bottomed cup test. (From Ref. 1.)

drawn into a cup of diameter d or to the punch diameter d, or as the ratio of the diameters of the cup before and after the draw operation [63]. Thus,

$$\mathrm{LDR} = \frac{\mathrm{D}}{\mathrm{d}} \tag{24}$$

$$\%\ \text{Reduction} = \left(\frac{\mathrm{D} - \mathrm{d}}{\mathrm{d}}\right) \times 100 \tag{25}$$

The cup height is approximately given by

$$h = \frac{D^2 - d^2}{4d} \tag{26}$$

An alternative method for measuring the LDR uses blanks of single diameter, which is smaller than the critical diameter in the standard test [64]. The blanks are drawn to the maximum load, which normally occurs prior to the occurrence of 50% of draw. The clamping force is then increased to prevent further drawing-in of the flange, and the load is increased to the point of fracture. The limiting blank diameter (LBD) is defined by

$$\mathrm{LBD} = \left[\frac{\text{Fracture load} - (\text{Blank diameter} - \text{Die diameter})}{\text{Maximum drawing load}}\right] + \text{Die diameter} \tag{27}$$

The limiting draw ratio is given by

$$\mathrm{LDR} = \frac{\mathrm{LBD}}{\text{Punch diameter}} \tag{28}$$

This method has been shown to correlate well with the standard test for a range of materials of widely different drawability [64].

The LDR increases with r_m and the thickness t, specifically at the low ends of the ranges of variables, but it is insensitive to the n value [65]. The LDR also increases with the increase of punch profile radius up to about 8 times the sheet metal thickness, with the die profile radius up to about 12 times the metal thickness and with the increase of punch speed. The height of the ears formed in this test linearly varies with the Δr value.

A small BHF may cause wrinkling, whereas a very high BHF may result in fracture at the punch profile radius. The die rings should be well lubricated, but the punch should not be lubricated. By not lubricating the punch, the extent of stretching that occurs over the punch profile radius and the tendency for splitting to occur at this location are reduced.

The BHF or BHP must be sufficient to prevent wrinkling for a particular thickness and size of blank; for example, a BHF of $\sim$ 6 kN force is applied to prevent wrinkling in sheet steel products. Typically, five blanks are drawn at 2.54-mm (0.1-in.) intervals, starting from an initial blank diameter of 101.6 mm

(4 in.). A normal criterion for defining LDR is based on the maximum blank diameter at which at least four out of five specimens are successfully drawn [56, 57].

D. Stretch–Drawing Tests

Many drawing operations comprise both stretching and drawing. The ratio of stretching to drawing in an actual component can be measured by a shape-analysis method [66]. A line is drawn from a reference point (e.g., the center of the blank) to the edge of the blank, through the critical forming area. After forming, the ratio of the increases in length of this line inside and outside the initial die contact line is taken as the ratio of stretching to drawing. There are two types of stretch–drawing tests: the Swift round-bottomed cup test and the Fukui conical cup test.

1. Swift Round-Bottomed Cup Test

This test is similar to the Swift flat-bottomed cup test discussed earlier. However, the top of the punch is hemispherical, which results in stretching in the center of the specimen and the drawing-in of the flange to produce the cup wall.

This test was employed to evaluate 50 different steels with a 50-mm (1.97-in.)-diameter punch and 127-mm (5.0-in.)-diameter specimens, and with a 65-mm (2.56-in.)-diameter punch and 165-mm (6.5-in.)-diameter specimens [67]. Hold-down forces of 490 and 981 N (110 and 220 lbf), respectively, were employed at a test speed of 1 mm/s (0.04 in./s). Both sides of the specimens were lubricated with a thin polyethylene sheet.

The endpoint of the test is known by detecting fracture visually or a drop in the punch load. Multiple-regression analysis of the test results showed that the cup height at fracture increases linearly with the increases in the n value, the r_m value, and metal thickness.

To determine the correlation between performance of the steels in the stretch–drawing test and in actual parts production, 4 automotive stampings were made using 12 different steels for each. The stampings had stretch-to-draw ratios ranging between approximately 1:5 and 2:1, and minor-to-major strain ratios in critical areas ranging between -0.3 and $+0.45$. The correlation coefficients between the test and the stamping results had an average value of 0.92 and ranged between 0.89 and 0.94 (a value of 1.00 suggests perfect correlation). In another trial on a stamping with a stretch-to-draw ratio of 4.5:1, the test results did not correlate. These tests suggest that for parts involving both (moderate) stretching and drawing, the Swift flat-bottomed cup test will serve as a useful quality-control tool [1].

2. Fukui Conical Cup Test

This test involves the deformation of circular, punched sheet metal specimens into conical cups by means of a 12.5–27-mm (0.5–1.1-in.)-diameter ball and tooling of the type shown in Fig. 25 [65]. The ball size selected depends on the sheet thickness. Lubrication is provided on the specimens facing the die side only, because lubrication on the punch side leads to tilting of the specimens. Specimens are centered and clamped by the hold-down ring and deformed to fracture by the punch.

The diameter of the base of the conical cup formed is determined and divided by the diameter of the original specimen to provide the Fukui conical cup value. The endpoint of the test is not critical, because the diameter of the cone remains the same even after fracture. A constant punch height is usually employed. When the test specimen has a greater amount of planar anisotropy (a high Δr value), the conical cup is asymmetric, and an average diameter must be measured. A high correlation between the Fukui conical cup value and the product of the average n value and the average r value has been observed for low-carbon steels [65].

An alternative method of this test has been developed. The punch travel between the initial contact with the specimen and the onset of a drop in the punch load, which is associated with the formation of a visible crack, is determined and used instead of the ratio of diameters. This value, termed the formability index, correlates with the uniform elongation and, thus, with the n value for low-carbon steels.

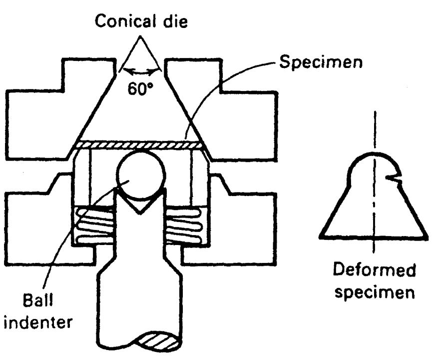

Figure 25 Schematic of the Fukui conical cup test. (From Ref. 65.)

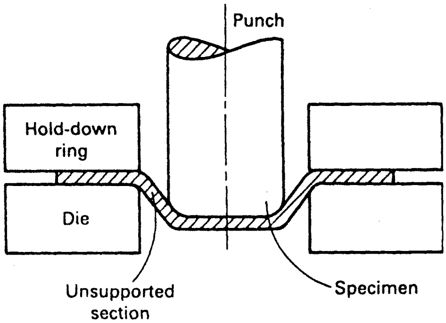

Figure 26 Schematic of the conical cup wrinkling test. (From Ref. 1.)

E. Wrinkling and Buckling Tests

1. Conical Cup Wrinkling Test

This test is similar to the Swift flat-bottomed cup test but uses a much smaller-diameter punch than that of the die opening. As a result, the cup wall is conical and is not in contact with the punch. In this test, a circular blank is held down between annular dies and deformed by a flat-bottomed punch with a diameter normally about 75% of the internal diameter of the die. Figure 26 shows a schematic of the test procedure. At a very low hold-down force, wrinkling occurs in the flange. At a high hold-down force, wrinkling occurs in the unsupported wall and is suppressed in the flange.

At a high hold-down force, tensile stresses in the radial direction in the wall hinder the formation of wrinkles, and fracture at the punch or die radius becomes the limiting factor. The maximum cup height takes place at the junction of wall wrinkle and fracture, as illustrated in Fig. 27 [68].

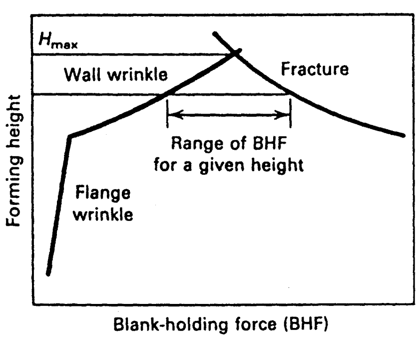

Figure 27 Wrinkling and fracture limits in conical cup drawing test. (From Ref. 68.)

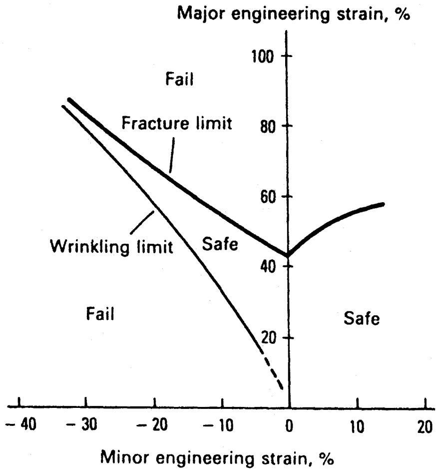

Figure 28 Combined forming and wrinkling limit diagram. (From Ref. 69.)

The results of experiments on several types of sheet steels with different thickness and tooling of varying dimensions have been studied [69, 70]. Wrinkling was found to prevail in the unsupported wall when the true compressive hoop strain increased beyond a specific value for each level of the tensile radial strain for all tooling geometries and forming conditions. The critical wrinkling strains were plotted on the forming limit diagram, as shown in Fig. 28.

A critical wrinkling strain depends on the dimensions of the specimen and tooling, hold-down force, and lubrication. Any change in these factors that diminishes the radial stress (i.e., an increase in the die radius, improved lubrication, or a reduction in the blank diameter or the hold-down force) increases the risk of the formation of wrinkles.

Material properties that influence wrinkling in the conical cup test include the r_m, Δr, and n values and the ratio of flow stress to the modulus of elasticity. A high r_m value and a low Δr value reduce wrinkling, which begins in the direction of the lowest r value. A high n value requires an increase of the hold-down force, which, in turn, increases the radial force and reduces wrinkling. A low flow stress/elastic modulus ratio also diminishes wrinkling.

2. Yoshida Buckling Test

A flat, square sheet metal specimen is clamped at opposite corners and pulled in a tensile test frame in the diagonal direction, as shown in Fig 29 [68, 71]. The standard specimen is 100 mm (3.94 in.) square with 41-mm (1.6-in.)-wide grips

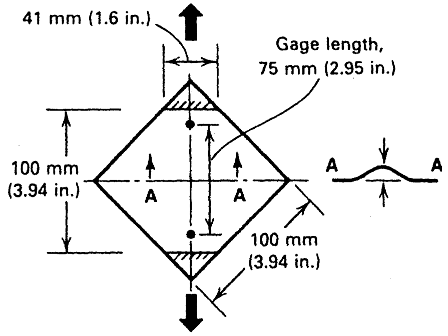

Figure 29 Schematic of the Yoshida buckling test. (From Ref. 68.)

and a gauge length of 75 mm (2.95 in.). The buckled height is measured over a 25.4-mm (1.0-in.) width at the center of the specimen.

Nonuniform stresses are produced in the specimen, and these stresses result in the formation of a buckle in the center along the direction of loading. The height of the buckle at a specific elongation, say 2%, is employed as a measure of buckling.

Several investigations have been conducted on the correlation between the buckle height and test material properties. The Yoshida buckling test and a conical cone wrinkling test (using a hemispherical punch) were conducted on various ferrous and nonferrous materials in different tempers [72]. A direct correlation for both tests between the buckling or wrinkling height and the yield strength, an inverse correlation with the n value, and a lack of correlation with the r_m value were reported. The Yoshida test was unsuccessful for aluminum sheets due to the fracture of the specimen prior to buckling.

The Yoshida test was conducted on 31 steels of various types and thicknesses, and correlations between the slope of the buckle height elongation curve, which is simple to determine compared to the height at a specific elongation, and the yield strength and the ratio of YS/UTS were found [73]. An inverse correlation with the instantaneous (2%) n value and a lack of correlation with the e_u and r_m values were also observed [1, 2].

F. Springback Tests

A springback test that bends a specimen about a 12.5-mm (0.5-in.)-radius mandrel and determines the change in the angle of bending after the removal of the bending load was developed as a quality control tool with sheet thicknesses in the range

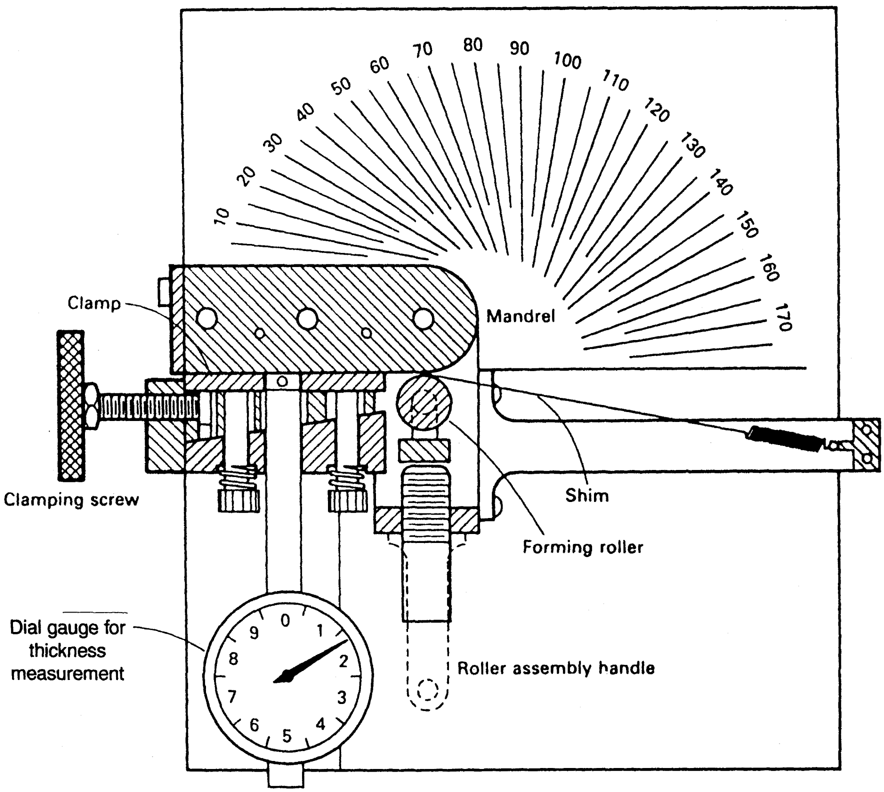

Figure 30 Springback tester for determining yield strength. (From Ref. 74.)

0.15–0.38 mm (0.006–0.015 in.) (Fig. 30) [74]. The test involves bending the specimen through 180° and releasing the load, and reading the angle of springback on the scale. The yield strength can then be determined from the springback angle and material thickness using a previously determined nomograph. Springback depends on the elastic modulus that requires different nomographs for materials with different modulii. The test is very accurate in the range of springback angles of 60°–120° and should be modified by changing the mandrel if the angle is less than 30° or greater than 150°.

The nomograph was calculated assuming an elastic/perfectly plastic stress–strain relationship, which remains unchanged in both tension and compression (i.e., zero strain hardening and no Bauschinger effect). This calculation has been refined by using an average of experimentally measured tensile and compressive stress–strain curves, including strain hardening [75]. This gives a better average ratio of the yield strength predicted using springback measurements to the tensile test yield strength from 0.80 to 0.91. Recently, a similar test with a large-radius mandrel [19 mm (0.75 in.)] was developed [76].

VI. FORMABILITY LIMIT CURVES

The forming limit diagram, also called formability limit curve, shows the localization (called forming limit) and failure strains by relating the maximum (major) to minimum (minor) strains in the two-dimensional strain space. The formability performance of a material depends on the forming limit and the strain distribution ability. For materials with the same forming limit, the formability performance is governed by their strain distribution ability. There are two types of laboratory test to determine the limiting strains. The first type of test involves stretching test specimens over a punch or uses hydraulic pressure (e.g., the hemispherical punch method). This test is used more widely than the second test; the latter produces only in-plane deformation and does not comprise any contact with the specimen within the gauge length.

The formability limits of a sheet metal were described by Keeler in the form of a forming limit diagram (FLD) [77]. FLDs are dependent on bulk material properties, geometry of deformation, strain history (or strain path), sheet thickness, and the characteristics of the tool–sheet interface. Thus, the FLD acts only as an indicator of formability and cannot be regarded as a material property [78].

The FLD is a map of combinations of surface strains leading to success and failure in a sheet-stamping operation. These were experimentally determined boundaries of safe and failure regions of strain that represent all situations in biaxially stressed parts. The abscissa indicates the minor (tensile or compressive) strain and the ordinate indicates the major (tensile) strain. The technique involves imprinting or marking a sheet metal blank with a circular or square grid pattern by photoprinting, photoetching, or electroetching processes prior to forming. The gridded blank specimens of various widths are then deformed or stretched by punches of various shapes to develop a wide range of surface–strain combinations using different frictional conditions. The common method involves stretching over a hemispherical punch until the sheet starts to fail or tear. When a circle, after deformation, becomes distorted, its major and minor engineering strains are measured manually using dividers and rulers, graduated transparent tapes, or a low-power microscope with a graduated stage or automatic grid circle analyzers and plotted on the FLD. For improved accuracy of measurement, the circles in the grid are marked as small as is practicable. Measurements are made on circles containing localized necks or tears (or failures) and on neighboring circles that are defects-free (i.e., safe). The boundary between the failure and safe regions