Sheet metal is widely used for industrial and consumer parts because of its capacity for being bent and formed into intricate shapes. Sheet-metal parts comprise a large fraction of automotive, agricultural, and aircraft components. Successful sheet-metal forming depends on the selection of a material with adequate formability, the proper design of the part and the tooling, the surface condition of the sheet, the selection and application of lubricants, and the speed of the forming press.

Sheet-Metal Stamping and Bending

The cold stamping of a strip or sheet of metal with dies can be classified as either a cutting or a forming operation. Cutting operations are designed to punch holes in sheets or to separate entire parts from sheets by blanking. Cutting is a shearing operation that culminates in controlled fracture. A blanked shape may be either a finished part or the first stage in a forming operation in which the final shape is created by plastic deformation, often a bending operation. Individual sheet-metal parts are often joined into a structure by spot or laser welding. See custompartnet.com for descriptions of stamping and bending operations as well as discussion of bend allowance and springback allowance. The great variety of sheet-forming operations is shown in Figure 1.

When holes are punched in metal sheet, only part of the metal thickness is sheared cleanly; that is, a hole with partially tapered sides is created. If the hole is to be used as a bearing surface, then a subsequent operation will be required to obtain parallel walls. Diameters of punched holes should not be less than the thickness of the sheet or a minimum of 0.025 in. Smaller holes result in excessive punch breakage and should be drilled. The minimum distance between holes, or between a hole and the edge of the sheet, should be at least equal to the sheet thickness. If holes are to be threaded, the sheet thickness must be at least one-half the thread diameter.

The ability to bend a metal without cracking at the bend improves when the bend is made across the “metal grain” (i.e., the line of the bend is perpendicular to the rolling direction of the sheet). The largest possible bend radius should be used in design to prevent cracking, and the bend radius should not be less than the sheet thickness $t$. The formability of sheet in bending is expressed in multiples of the sheet thickness; thus a $2t$ material has a greater formability than a sheet metal whose minimum bend radius is $4t$.

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FIGURE 1
Classification of sheet-metalworking processes. (After J.A. Schey)

Stretching and Deep Drawing

Metal sheets are often formed into large contoured shapes such as the roof or fender of an automobile. To form such shapes requires a combination of stretching and deep drawing. In stretching, the sheet is clamped around its periphery and subjected to tension forces that elongate it and thin the sheet at the same time. The limit of deformation is the formation of a localized region of thinning (necking) in the sheet. This behavior is governed by the uniform elongation of the material in a tension test. The greater the capacity of the material to undergo strain hardening, the greater its resistance to necking in stretching.

The classic example of sheet drawing is deep drawing, as in the formation of a cup. In deep drawing, the blank is “drawn” with a punch into a die (Figure 2). In deep drawing the circumference of the blank is decreased when the blank is forced to conform to the smaller diameter of the punch. The resulting circumferential compressive stresses cause the blank to thicken and also to wrinkle at its outer circumference unless sufficient pressure is provided by the holddown ring or binder. However, as the metal is drawn into the die over the die radius, it is bent and then

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1. See animation of deep drawing at aluminium.matter.com under Sheet Forming.

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straightened while being subjected to tension. That results in substantial thinning of the sheet in the region between the punch and the die wall. The deformation conditions in deep drawing are substantially different from those in stretching. Success in deep drawing is enhanced by factors that restrict sheet thinning: a die radius about 10 times the sheet thickness, a liberal punch radius, $R_p$, and adequate clearance between the punch and die. Of considerable importance is the crystallographic texture or orientation of the grains relative to the sheet rolling direction. If the texture is such that the slip mechanisms favor deformation in the width direction over slip in the thickness direction of the sheet, then deep drawing is facilitated. This property of the material can be measured with a tension test on the sheet from the plastic strain ratio $r$.

$$r = \frac{\text{strain in width direction of tension specimen}}{\text{strain in thickness direction}} = \frac{\varepsilon_w}{\varepsilon_t}$$  \hspace{1cm} (1)

The best deep-drawing sheet steels have an $r$ of about 2.0.

An important tool in developing sheet-forming operations is the Keeler-Goodman forming limit diagram (Figure 3). It is experimentally determined for each sheet material by placing a grid of circles on the sheet before deformation. When the sheet is deformed, the circles distort into ellipses. The major and minor axes of an ellipse represent the two principal strain directions in the stamping. Strains at points where the sheet just begins to crack are measured. The largest strain, $\varepsilon_1$, is plotted on the $y$-axis and the smaller strain, $\varepsilon_2$, is plotted along the $x$-axis. The strains are measured at points of failure for different stampings with different geometries to fill out the diagram. Strain states above the curve cause failure, and those below do not cause failure. The tension-tension sector is essentially stretching, whereas the tension-compression sector is closer to deep drawing. As an example of how to use the diagram, suppose point A represents the critical strains in a particular sheet-metal stamping. This failure could be eliminated by changing the metal flow by either

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FIGURE 2
Deep drawing of a cylindrical cup (a) before drawing; (b) after drawing.
design changes to the die or the part to move the strain state to $B$. Alternatively, a material of greater formability in which the forming limit diagram was at higher values could be substituted.

**Computer-Aided Sheet-Metal Design**

Several computer-aided design tools for designing dies for parts to be made by sheet-metal forming\(^1\) are used extensively by the automotive industry.\(^2\) Another software,\(^3\) PAM-STAMP 2G, provides a completely integrated sheet-metal-forming simulation for a wide range of applications. The simulation can show the location of defects such as splits and wrinkles and shows where **drawbeads** should be placed to alter metal deformation flow. Operating parameters such as the die holddown force and sheet lubrication can be changed to observe their effects on formability. Built-in springback prediction enables the designer to make changes in tooling geometry before any expensive tooling has been built. This software, and the others mentioned previously, allow the development of tooling in a few days, whereas with conventional “cut and try” methods it may take several months.

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2. www.autoform.com; www.eta.com/DYNAFORM
3. www.csi-group.com