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Author(s): S. S. Hecker and A. K. Ghosh

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The Forming of Sheet Metal

How a metal behaves when it is stamped is a matter of large practical importance. Modern knowledge of the solid state is making the process less of an art and more of a science

by S. S. Hecker and A. K. Ghosh

A visitor to a factory where sheet metal is being formed, with presses rapidly stamping out identical parts from metal blanks, might well think he is witnessing an advanced technology in action. Actually the forming of sheet metal is more of an advanced art. The industry relies heavily on the judgment and experience of master craftsmen. Only recently have advances in analysis and in knowledge of the atomic structure of metals begun to fortify the art with science, putting the technology on a firmer footing and pointing the way to better performance and lower cost for the thousands of metal parts that are made daily on a mass-production basis.

Although sheet metal was worked for thousands of years in the production of coins, utensils and objects of art, it was only a century ago that the process was mechanized and began to resemble the metal-stamping lines of today. The mechanization of sheet forming was in turn a major step toward mass production. Today the forming of sheet metal touches the life of almost everyone as stamping machines produce a vast variety of parts ranging from eyelets for shoes to fenders for automobiles. The industry is a major component in the economy of every modern industrialized country.

Early in the 16th century a French inventor who appears in the annals of metalworking only as Bruiler developed a technique for rolling metal to a uniform thickness. The development made it possible to form metal parts by stamping flat pieces of metal between dies. Nevertheless, iron and steel continued for 300 years to be shaped predominantly by rolling, forging, casting and drawing, because the presses employed to stamp parts were hand-powered until the German engineers Ludwig Keserstein and Johann Luber developed the first water-driven press about 1800. When the American inventor Elisha Root introduced the first crank-powered drop press about 1850, the way was opened for a revolution in manufacturing techniques.

The rise of mass production in the second half of the 19th century was a particular stimulus to the development of sheet-metal forming, which in turn made mass production feasible. Sheet-metal parts offered several advantages over cast and forged ones, including lower weight, greater interchangeability and lower cost. About 1850 the practice of stamping tin-plated sheets of iron or steel to form food containers laid the foundation of the sheet-metalworking industry as it is known today.

Although metal stamping was well established by 1900, the main growth of the industry came when mass production became a feature of the automobile industry. Another impetus was provided by the rapid expansion of the home-appliance industry after World War I with such items as vacuum cleaners, washing machines, refrigerators and toasters. All these developments created a large requirement for sheet metal. The requirement was met by low-carbon steel, which offered the advantages of uniform thickness, good surface finish and again low cost. Low-carbon steel quickly became the universal sheet material, and it retains that role today.

Stamping is by no means the only method of forming parts from sheet metal, but it is economically the most important one, and so we shall focus our discussion on it. In the commonest form of stamping, a precut metal blank is formed in a mechanical press between a set of dies that have been carefully shaped to yield the desired part. The process begins with a blanking operation in which the sheet metal, which is stored in coils (some weighing as much as 30 tons), is automatically unrolled and cut to the proper size by shearing dies. The proper size is usually somewhat larger than the finished part because of the need for edges that can be held tightly while the blank is stamped. After stamping, the edges are trimmed off. On a large stamping the trim loss can be as much as 30 percent; the trimmed metal can only be sold as scrap for a fraction of its cost.

The next step is usually flanging, which is essentially a bending operation. A flange is ordinarily needed if the part is designed to be attached to another part, as a fender is attached to the body of an automobile. After flanging, the part may be stamped a second time in a different set of dies; this step is sometimes needed to sharpen contours and corners that do not attain their specified dimensions in the first stamping.

A typical stamping plant employs a variety of dies and presses. The pressing force can be applied by a hydraulic system or a mechanical one, with mechanical systems being generally favored because they are faster. Double-action presses that involve the motion of two rams, one for the blank holder and one for the main die, are commonest. The modern stamping line is highly or fully automatic, with mechanical fingers for feeding and transferring parts, lubricant sprayers synchronized with the motion of the press, conveyor systems based on magnetic or vacuum devices, photocells that actuate the drive systems and an inspection system that functions without stopping the production line for the removal of a part. As a result extremely high rates of production (for example 100,000 oil-filter cans per day from a single plant) can be achieved.

Automatic stamping lines were in operation long before anyone understood what kind of flow takes place in a piece of metal as it is being stamped. That knowledge is quite recent. The processes involved are drawing and (usually) stretching. One can follow them by visualizing a press that is about to stamp a metal blank. Above the blank are the main ram, which carries the punch, and the blank holder, which clamps down the edges of the blank. Below the blank is the main die.

The first action of the press pushes down the blank holder, causing the

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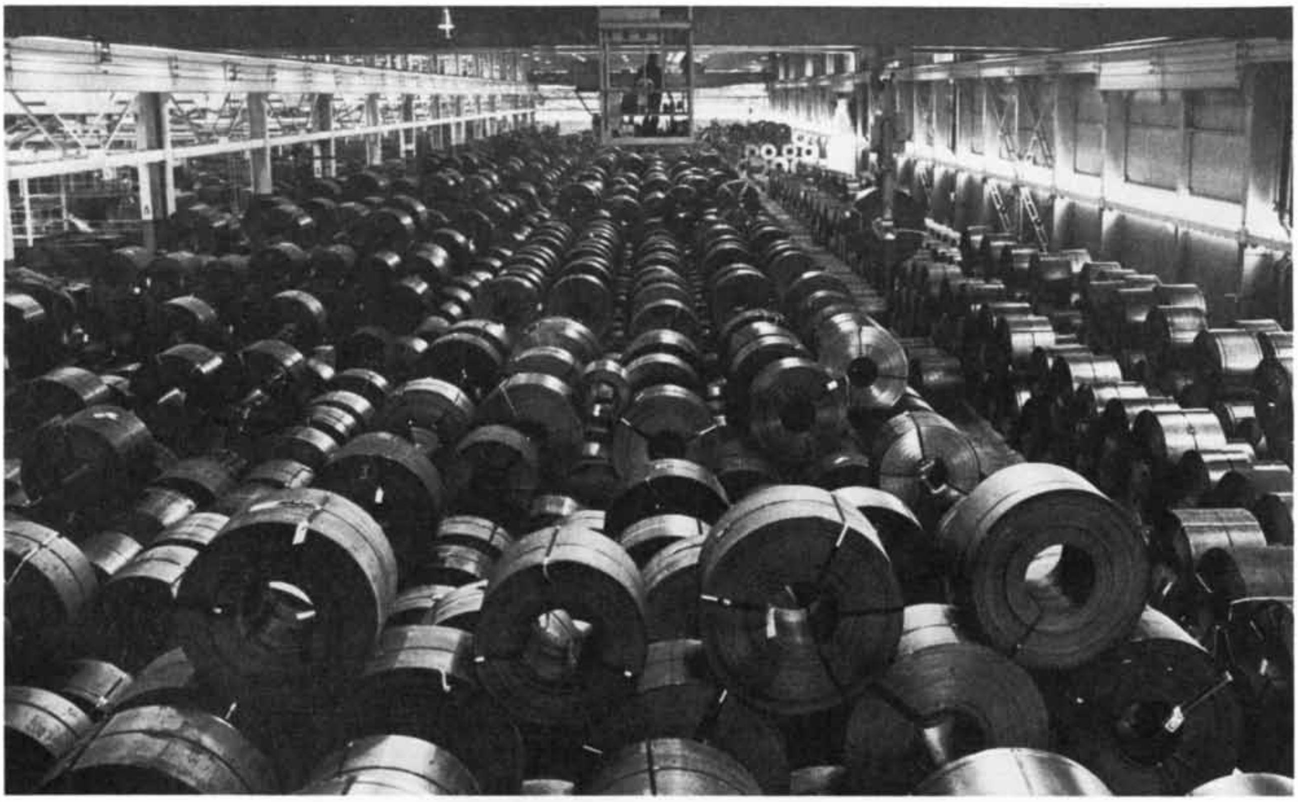
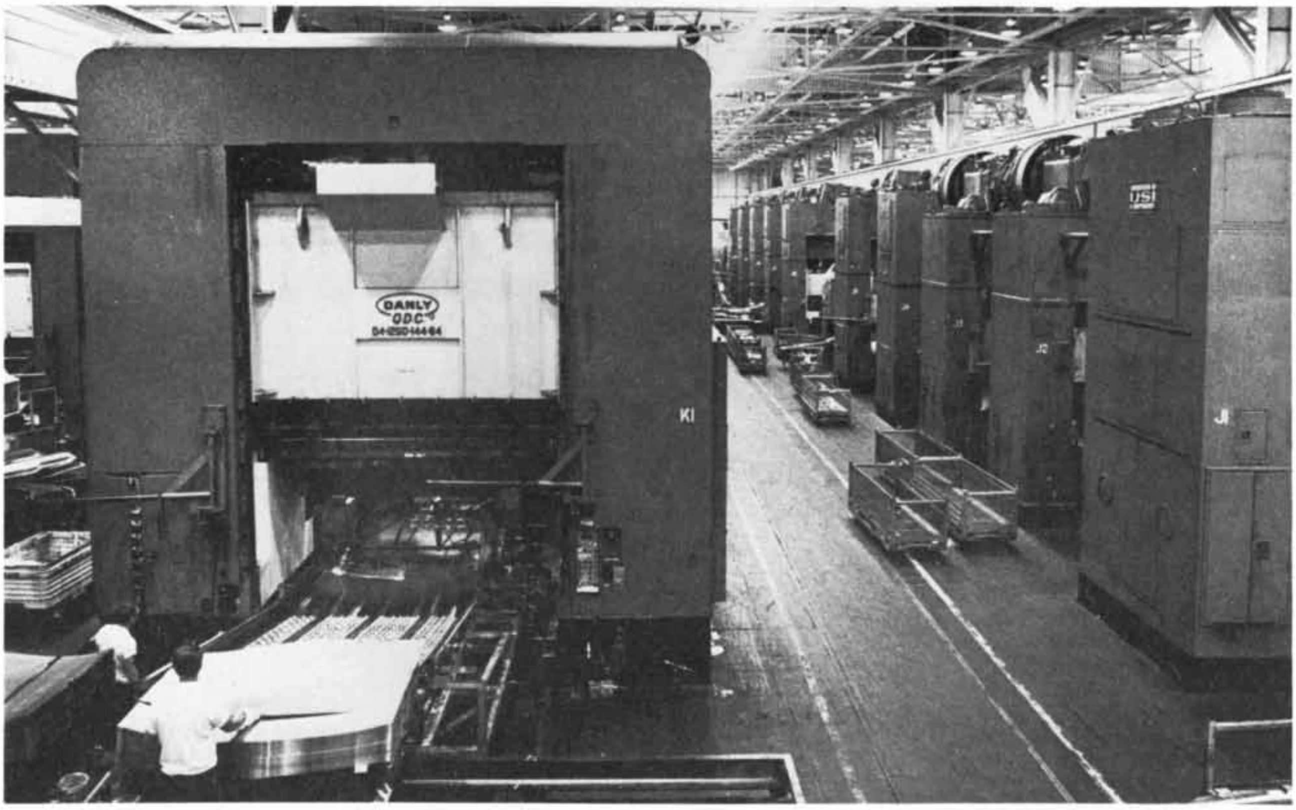


COILS OF SHEET METAL that will be formed into parts for automobiles are stored at a plant of the General Motors Corporation. The metal is low-carbon steel. Coils are transported to an adjacent stamping room, which appears in the photograph at the bottom of the page. There they are uncoiled and cut into blanks of appropriate size, which are fed into large presses that stamp out the parts.



STAMPING PRESS forms a door panel in the General Motors plant. The metal is handled automatically once the operator in the left foreground has fed the blanks individually onto the rollers that pull them into the press. The machines at the right also stamp parts.

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blank to be held fast at its edges. The second action pushes down the main ram with its punch. The metal is wrapped around the punch as the punch descends into the die cavity. Essentially the metal is drawn, or pulled, from the edges into the cavity.

Since the blank is forced to contract circumferentially as it is drawn radially inward, it tends to buckle or wrinkle. A proper flow of the metal, counteracting this tendency, is achieved by inclining the punch and die assembly, by applying heavy pressure with the holder and (sometimes) by having draw beads on the surface of the die below the blank holder. A die may incorporate several of these rodlike beads, each with a diameter of from half to three-quarters of an inch. They control the flow of metal by forcing the sheet to bend and unbend as it passes over the beads before entering the die cavity.

Unless the part being formed has a very simple shape, portions of the blank are not only drawn but also stretched as the blank is pressed into the die cavity by the punch. Stretching is defined as an extension of the surface of the sheet in all directions. The material requirements for drawing and stretching differ considerably. Progress toward understanding the influence of material properties on the flow of metal has been made chiefly through laboratory tests that treat drawing and stretching separately.

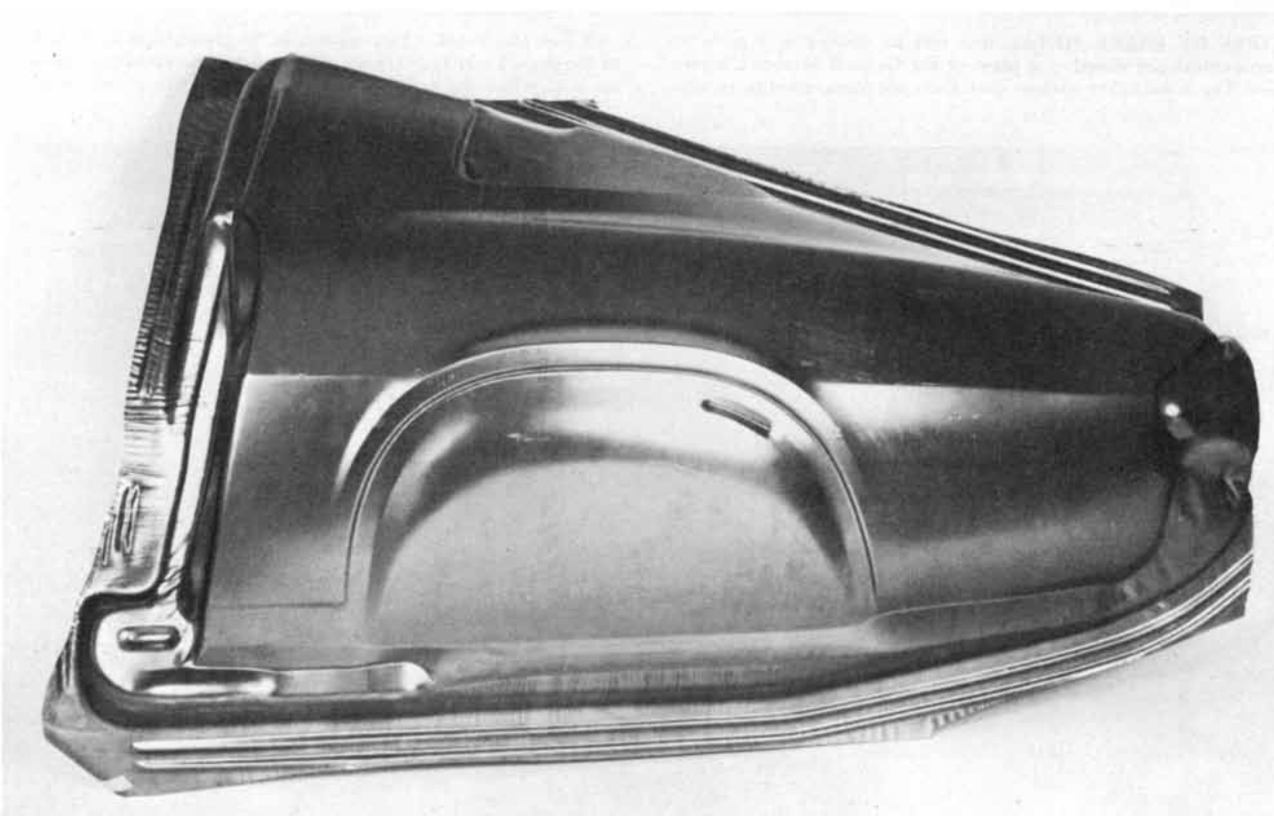
The events in drawing can be demonstrated by depicting the formation of a cylindrical cup with a flat bottom [*see bottom illustration on opposite page*]. The process is often called deep drawing. Most of the deformation in deep drawing occurs in the flange; very little takes place in the part of the blank that touches the punch. The process causes little change in the final thickness or surface area.

Circumferential contraction in the flange will cause wrinkling unless sufficient hold-down pressure is applied. The load required to deform the flange is transmitted from the bottom of the cup to the flange by way of the cup wall. If this load goes beyond what the wall can support, the metal tears near the bottom of the cup.

Thus for good drawing one needs a material that resists thinning in the cup wall. In other words, the material should have less strength (so that it will deform more easily) in the plane of the sheet than in the thickness. This directional differential in strength is termed plastic anisotropy. The property is easily measured by a simple test in the laboratory. A long, thin strip is cut from the sheet and stretched. The plastic anisotropy is determined by comparing the contraction of the sheet in width and in thickness. If the width contracts more than the thickness, the metal will resist thinning in the course of drawing and so will make deeper cups.

Plastic anisotropy is developed during primary metalworking, such as in rolling, and reflects the crystalline nature of metals. A metal consists of innumerable small grains, or crystals, all bonded together in different orientations. In each crystalline grain the atoms are arranged in a highly regular three-dimensional lattice. The crystallinity is the result of the atomic binding peculiar to metals, which favors highly symmetrical and closely packed structures.

Closely packed crystal structures strongly resist forces that tend to change their volume, but they can easily shear



STAMPED PART appears as it comes from the stamping press. The part is a "quarter panel" for the left rear side of an automobile; the arched area at the center, which will be over the wheel, will be removed in a trimming operation, as will much of material around the edges and at the right end, where the tail light will be. The material at the edges was for holding the blank in the press as it was stamped. The wrinkling and puckering resulted from the metal's being drawn in during the stamping operation. Barely visible in the formed corner above the wheel area is a dark rectangle; it is made up of a grid of circles that was put on the blank so that the deformation caused by the stamping could be studied. Two photographs showing how the circle-grid method reveals details of deformation appear on page 108.

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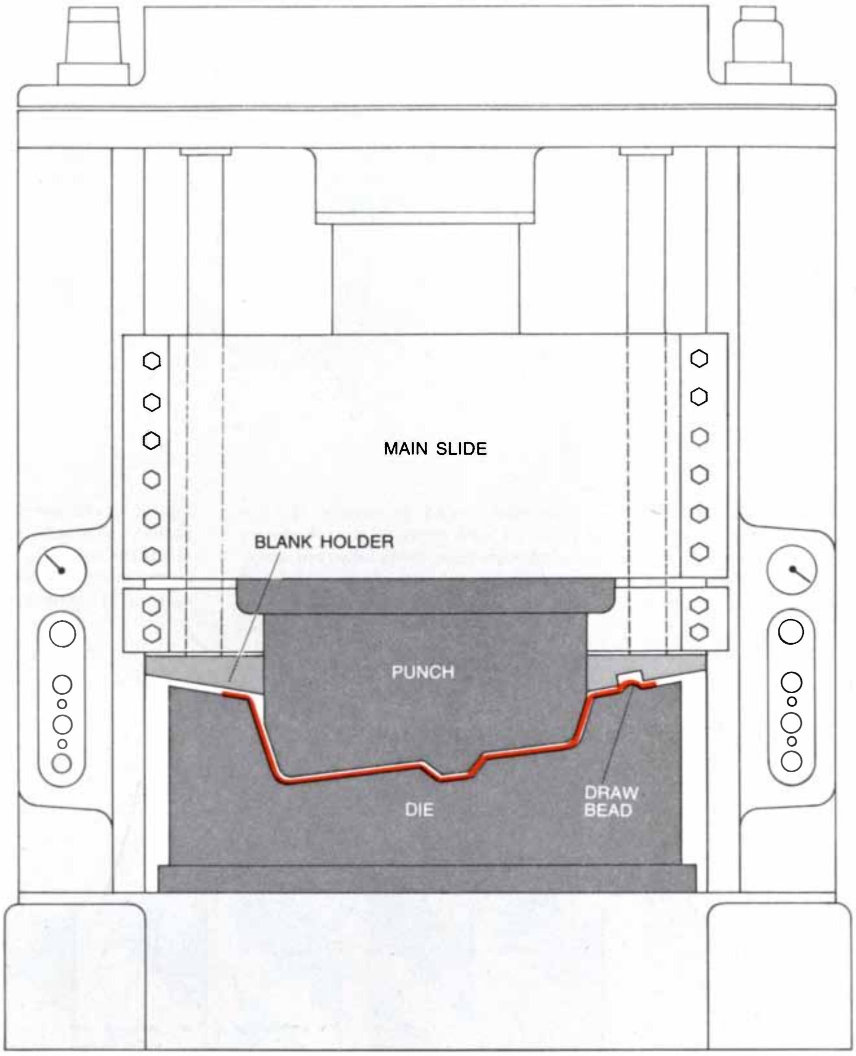
and change shape when layers of atoms slip over one another. The layers slip most easily along closely packed crystal planes in closely packed directions. Simple crystal structures have a high degree of symmetry and hence many closely packed planes and directions, so that plastic flow is easy.

Slip is made still easier by the crystalline imperfections called dislocations. They are small departures from the regular arrangement of the atoms in a grain, and they enable atoms to slip in tiny steps instead of in entire rows at a time. Indeed, the motion of dislocations is the only mechanism for slip. In the simple crystalline structure of many metals such dislocations are easily introduced; they move freely and they multiply readily during deformation, and so they account for the high ductility of such metals.

During the enormous reductions (as large as 1,000 to one) involved in rolling sheets for automobile bodies from steel ingots the individual metal grains line up in certain preferred directions. The properties of crystals vary with direction, because of the directional regularity with which their atoms are stacked, and the bulk properties of the sheet take on a similar directionality. For the best resistance to thinning, and hence the best property for drawing, as many crystals as possible should be aligned so that the direction in which they are strongest is parallel to the direction of the thickness of the material.

In crystals with a cubic symmetry, which is common in metals, this direction is along the body diagonal of the cube. In metals such as steel, which has a body-centered-cubic crystal lattice (an atom at each corner of the cube and one in its center), the preferred alignment of crystals can be achieved fairly easily. In metals such as copper, brass and aluminum, which have a face-centered-cubic lattice (an atom at each corner and one at the center of each face of the cube), the alignment is difficult to achieve because of the multiplicity of directions in which crystals can slip during deformation. In metals with other crystal structures the direction of slip is highly limited, and so the opportunity of obtaining directionality exists, although it does not necessarily give rise to a favorable alignment. For example, both titanium and zinc have a hexagonal-close-packed crystal structure, but in titanium the alignment is favorable for deep drawing whereas in zinc it is not.

The importance of plastic anisotropy in deep drawing has been recognized only in the past 15 years. Before that the trait was considered undesirable; a metal that did not deform in the same way in all directions was thought to be difficult to shape. Steel producers have made great progress in developing deep-draw-



STAMPING OF PART in a double-action mechanical press is depicted. The double action involves the motion of two rams: the main slide, which holds the punch, or upper die, and the ram that constitutes the blank holder. The first action of the press pushes down the blank holder, which clamps the precut blank around its edges. The next action pushes down the main slide, so that the part (*color*) is formed between the punch and the lower die. Draw bead helps to control the flow of the metal by making it bend and unbend on the way into the die cavity.

DRAWING, one of the two major modes of forming metal by stamping, is illustrated by the deep drawing of a cylindrical cup. The circular blank is drawn into the cup-shaped die by the flat-headed punch. The wall of the cup supports the major part of the load and tends to undergo thinning. Best material for drawing is therefore a material that is resistant to thinning.

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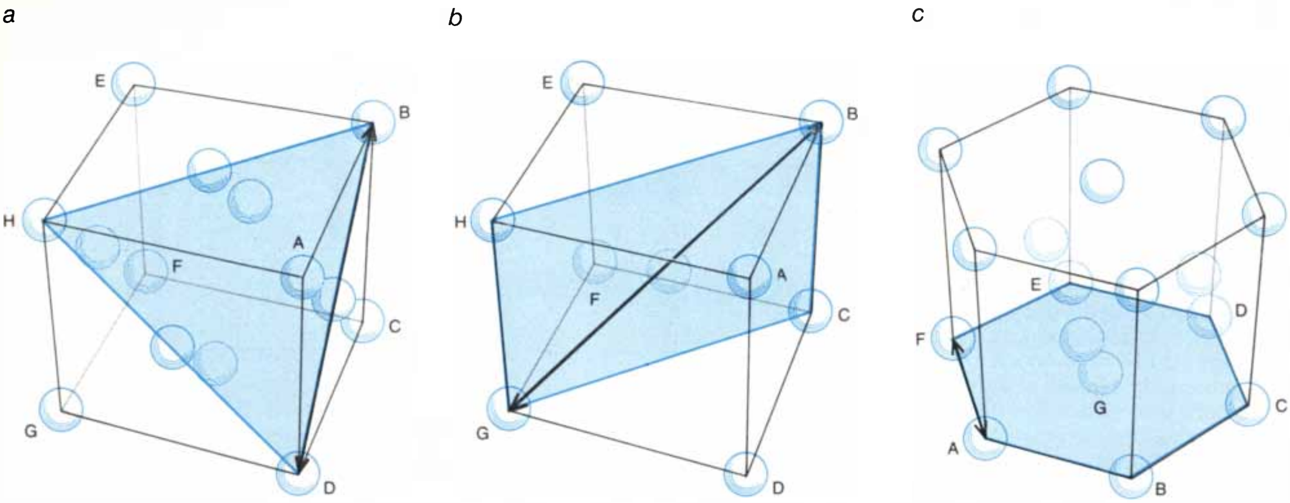
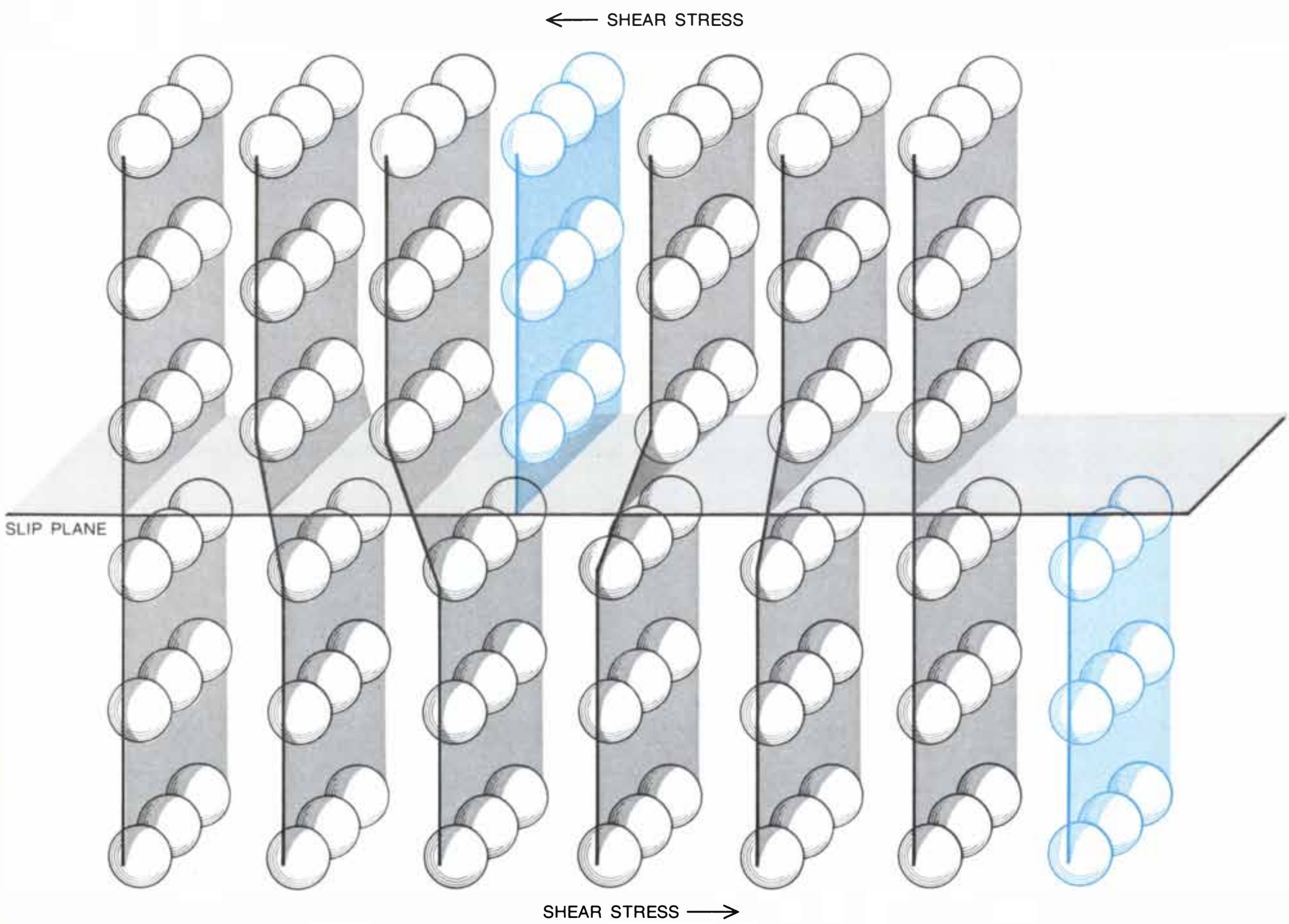


CRYSTAL STRUCTURES commonly found in metals are depicted. They are face-centered cubic (*a*), with an atom at each corner of the cube and one at the center of each face; body-centered cubic (*b*), with an atom at each corner and one in the center of the cube, and hexagonal close-packed (*c*). The structure affects the ability of a crystal to change shape by the mechanism of slip, or change in the position of atoms, and so is an important consideration in choosing a metal for forming. Slip is easiest along closely packed planes (*color*) in the most closely packed directions (*arrows*). Equivalent planes, such as HFD in *a*, are also favorable to change of shape by slip.



ROLE OF DISLOCATIONS in the mechanism of slip is portrayed. The dislocation shown is an extra half plane of atoms (*dark color*) in the crystal lattice. Deformation occurs by shearing along a slip plane that is perpendicular to the extra half plane of atoms. If shear stress is applied as indicated by the black arrows at the top and bottom, atoms are displaced in a movement that resembles the shifting of a wrinkle in a rug, resulting in a change of shape of the crystal as is suggested here by the half plane of atoms portrayed in the light color.

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ing steels; titanium producers have also taken advantage of preferred anisotropy. Face-centered-cubic metals, however, still perform poorly in drawing operations.

During stretching, as opposed to drawing, all loads are tensile. There is no beneficial squeezing action. The property a metal needs most in order to stretch well is the ability to become stronger while it is being strained, or deformed. It is this intrinsic hardening process, which is known as strain hardening, that makes it progressively more difficult to bend a wire when the wire is being bent repeatedly (until, of course, the wire breaks). Strain hardening helps to prevent the localization of strain by causing the deformation to shift to less deformed areas. Hence the process facilitates a more uniform deformation.

Strain hardening in metals is best demonstrated in a tensile test. A long strip of metal is pulled in one direction as the load required to pull the strip and the extension that results are measured and recorded. The load required to extend the metal continues to increase even after the point where permanent deformation begins. The greater the increase in load with extension, the greater the strain hardening.

With stretching the metal becomes steadily thinner and thus loses its ability to carry a load. This geometric weakening competes against strain hardening and eventually dominates it. At the point where the two are in balance the load reaches a maximum. Thereafter deformation becomes unstable because it continues with ever decreasing loads. It gradually concentrates around a weak spot in the material, a process termed diffuse necking. Eventually the deformation becomes totally localized in a neck (a "thickness trough") and the metal tears.

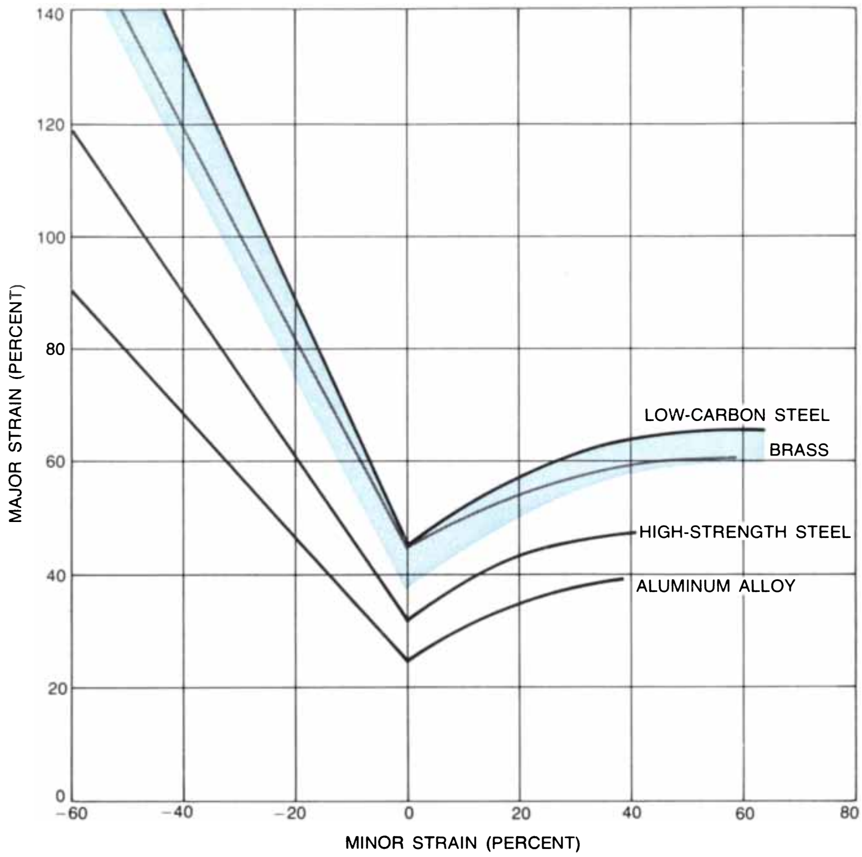
Once diffuse necking begins, a gradient in the rate of deformation also develops along the length of the specimen. The strength of many metals is sensitive to the rate of deformation. During necking a metal that hardens as the rate is increased ("strain-rate hardening") will resist the localization of deformation and delay the onset of local thinning. Both strain hardening and strain-rate hardening are influenced by the temperature of deformation. When a sheet of metal is being shaped by dies, gradients in deformation and the rate of deformation build up quickly because of the complex geometry of the shape and the friction resulting from the contact between the metal and the punch. Both strain hardening and strain-rate hardening are therefore vital in promoting a uniform deformation.

Strain hardening and strain-rate hardening can be explained in terms of the behavior of atoms during the deformation of metal. A change of shape requires slip within the metal crystals. Slip results from the motion of dislocations. Hardening depends on how much resistance dislocations experience as they glide through a crystal. Resistance is due to obstacles such as crystal boundaries, foreign atoms and faults in the stacking of the atoms in the crystal. The amount of resistance depends on the type of crystal structure. In brass, bronze and certain stainless steels, for example, stacking faults extend over distances equivalent to many atomic diameters; the faults therefore can be very strong obstacles, so that the metal resists the cross-glide of dislocations from one slip plane to another. As a result the dislocations start piling up in two-dimensional arrays, much like automobiles at a traffic light, and their continued packing leads to rapid hardening. At the other extreme of hardening behavior aluminum and iron exhibit ease of cross-gliding and so harden at a lower rate.

Obstacles can give rise to either local or long-range disturbances in a crystal. If the disturbance is long-range (perhaps greater than 10 atomic diameters), such as large foreign particles or piled-up dislocations on parallel slip planes in brass, the rate of deformation will not influence plastic flow or hardening. If the disturbance is local, such as the discontinuity due to foreign atoms or other individual dislocations, the thermal vibrations of the atoms in the crystal lattice can assist in the plastic flow. If the rate of deformation is high, there is little assistance, and the result is greater hardening than takes place at low rates.

The importance of these microscopic processes of strain hardening and strain-rate hardening in the uniformity of large-scale deformation is best assessed in the laboratory with a punch-stretch test. A metal blank is marked with a precise grid of circles of small diameter, which provide a means of measuring deformation. It is then clamped firmly to avoid any drawing in at the edges and is deformed over an unlubricated hemispherical steel punch. For good stretchability the property desired is uniform deformation over the punch.

Another important factor in stretching is the total strain the material experiences before it fails, or tears. Stuart P.



FORMING-LIMIT DIAGRAM, obtained by deforming metals in tests, indicates whether a metal can be shaped without risk of failure, or tearing. The broad colored band represents steel; under strains in the region below the band steel can be expected to undergo forming successfully, whereas above the band the strains probably will cause the metal to fail during forming. The curves for other metals are less firmly established by experience than the steel curve is.

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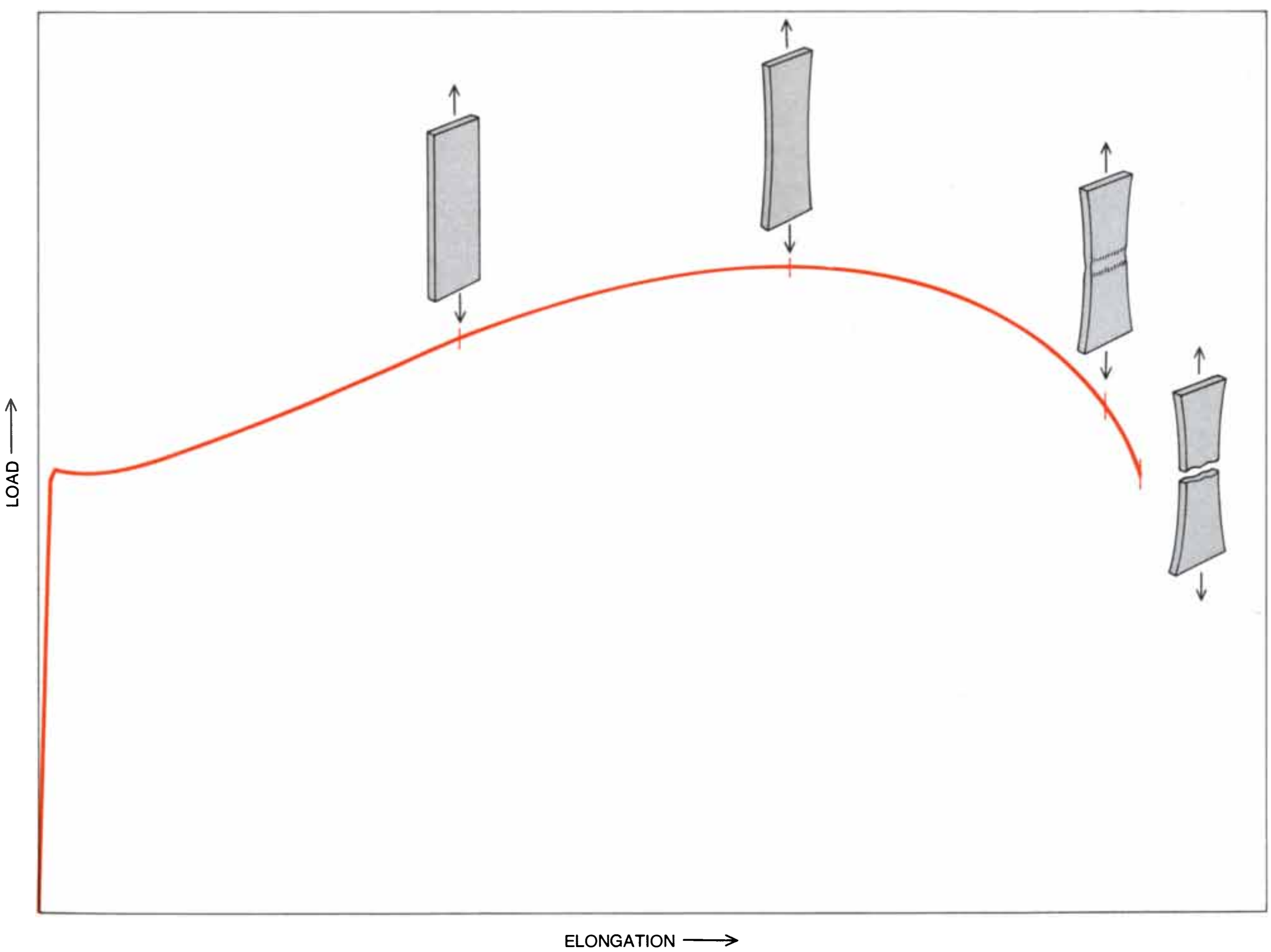
Keeler of the National Steel Corporation and Gorton M. Goodwin of the Chrysler Corporation have developed the concept of an empirical forming-limit diagram. By making many tests in the laboratory and examining hundreds of stampings from the production line they found that there is a unique failure band in the diagram for low-carbon steels. The band is determined by plotting the largest surface strain in the sheet (the major strain) against the strain perpendicular to it (the minor strain). The failure band then separates the combinations of strains that are acceptable (below the band) from the ones that cause failure (above the band). Such curves can now be determined entirely from measurements made in punch-stretch tests. For most stamping operations forming-limit diagrams have given excellent predictions of failure and have become highly useful in predicting stretchability [*see illustration on preceding page*].

The best measure of stretchability is given by the greatest height a dome achieves before failure during the punch-stretch test. The measure combines the importance of strain uniformity and strain to failure and reveals the superiority of brass (high strain hardening) and steel (moderately high strain hardening and strain-rate hardening) and the poor performance of certain alloys of aluminum (moderate strain hardening but strain-rate softening).

The properties of the material are not the only important factor in forming; another one is lubrication. Although little is known about the mechanisms of lubrication in the forming of sheet metal, the beneficial effects are well documented. Lubrication always helps to distribute strain more uniformly. Indeed, it is often more effective than an improvement in the properties of the material.

Bending operations are an integral part of all complex stampings. In bending, in contrast to most stretching operations, there is a severe gradient of stress throughout the thickness of the material. On the outside of the bend the stress is tension; on the inside it is either compression or a reduced level of tension. The severity of the tensile strains depends on the bend's radius, angle and length. Failure occurs on the tensile side by thinning and fracture. Strain hardening, strain-rate hardening and strain to fracture are important factors in the suitability of a metal for bending.

The most significant difference between bending and stretching is the role of microscopic impurities or inclusions that are not metallic. They are introduced during the solidification of the metal as it is made in bulk form at the mill. During hot-rolling they become elongated into "stringers." In bending the stringers cause premature failure if they are oriented perpendicularly to the direction of the bend. If the material is



ELONGATION UNDER LOAD is tested by pulling a piece of sheet metal to failure in tension. The point where the colored curve turns to the right is the yield point; thereafter the shape of the metal changes permanently. Beyond that point the metal continues to harden as it elongates, so that it is able to carry an increasing load. This intrinsic hardening, termed strain hardening, counteracts the decrease in the metal's load-bearing capacity due to thinning. At maximum load (*peak of curve*) the two forces balance and a process of localization of strain begins, leading eventually to the failure of the metal. The appearance of the metal at various stages is depicted above the curve. At maximum load a diffuse neck appears; near failure one sees a localized neck, where at failure the metal breaks.

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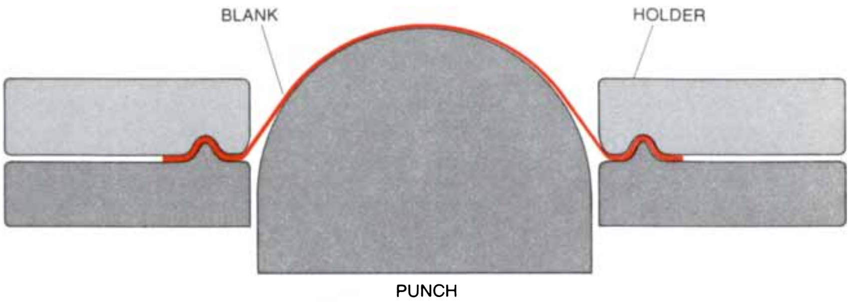
bent with the stringers oriented along the direction of the bend, its normal ductility is maintained [*see bottom illustration at right*].

This difference between longitudinal and transverse bendability is not always revealed by tensile tests. In the recently developed high-strength low-alloy steels the shape of inclusions has been controlled by adding during casting minute amounts of rare-earth elements such as cerium. Cerium combines with the inclusions of manganese sulfide that are usually present and makes them strong at the temperatures at which the steel is rolled. Hence the inclusions are not deformed with the rolling of the ingot. They remain spherical and therefore do not impart the undesirable transverse-bending properties.

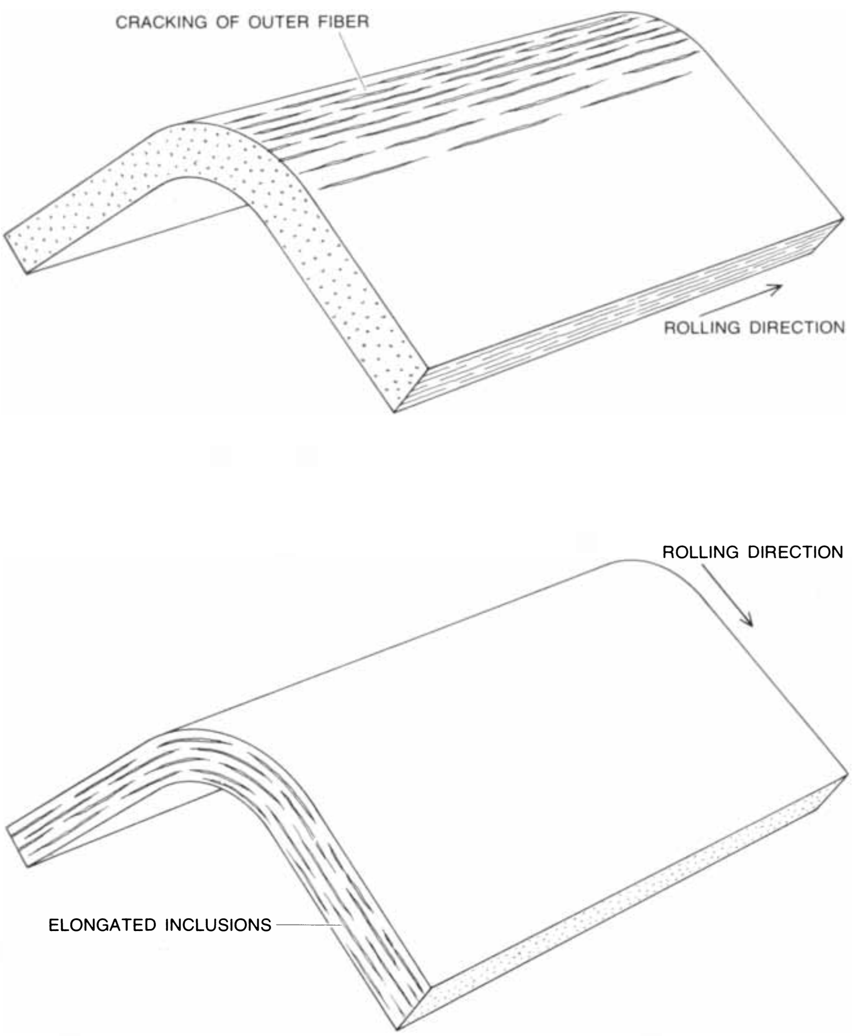
For many years low-carbon steels have satisfied almost all the requirements for the forming of sheet metal. They can withstand well the deformation inherent in forming. Steels can be produced with favorable plastic anisotropy, respectable strain hardening and strain-rate hardening and a high forming-limit curve. Enormous quantities are produced at low cost. Moreover, low-carbon steel possesses excellent stiffness and good strength, so that it meets many structural requirements, and it has a good surface finish.

Recent trends in the automobile industry, however, have emphasized reducing the weight of the vehicle to keep down the consumption of fuel while at the same time employing material that has a high strength and can absorb energy well in collisions. As a result materials such as aluminum alloys and high-strength steels, which have higher ratios of strength to weight than low-carbon steels, are being introduced in automobiles. Such materials are much more difficult to form than the conventional low-carbon steels, and production experience is lacking. The selection of metals for stamping has been greatly facilitated by laboratory studies of the simple forming processes we have described. It is now realized that the choice of the proper laboratory test depends on the shape of the stamping and the mode of forming. If the critical mode of stamping can be identified, that is, if it can be ascertained whether the part will be mainly drawn or mainly stretched, then selecting the proper material is easier.

The major problem in studying sheet forming analytically is to predict the patterns of deformation. Since the deformation occurs in various ways and in various places, mathematical calculations based on assumptions of simplified stress states and idealized properties of materials have not yielded acceptable results. More success, at least in predicting the patterns of deformation in simple and symmetrical drawing and



STRETCHING is the second major mode of forming sheet metal by stamping. It is illustrated here by a punch-stretch test that is employed in the laboratory to assess the deformation of a piece of sheet metal during stretching. A metal blank (*color*) is clamped firmly at the edges and then stretched over a hemispherical punch. The groove in the upper die and the bead in the lower one ensure that there is no drawing in of metal, so that the test assesses only stretching.



BENDING OPERATION is often an integral part of sheet-metal forming, particularly in making flanges so that the part can be attached to another part. During bending the fibers of the sheet on the outside of the bend are under tension and the inside ones are under compression. Impurities introduced in the metal as it was made become elongated into "stringers" when the metal is rolled into sheet form. During bending the stringers can cause the sheet to fail by cracking if they are oriented perpendicularly to the direction of bending (*top*). If they are oriented in the direction of the bend (*bottom*), the ductility of the metal remains normal.

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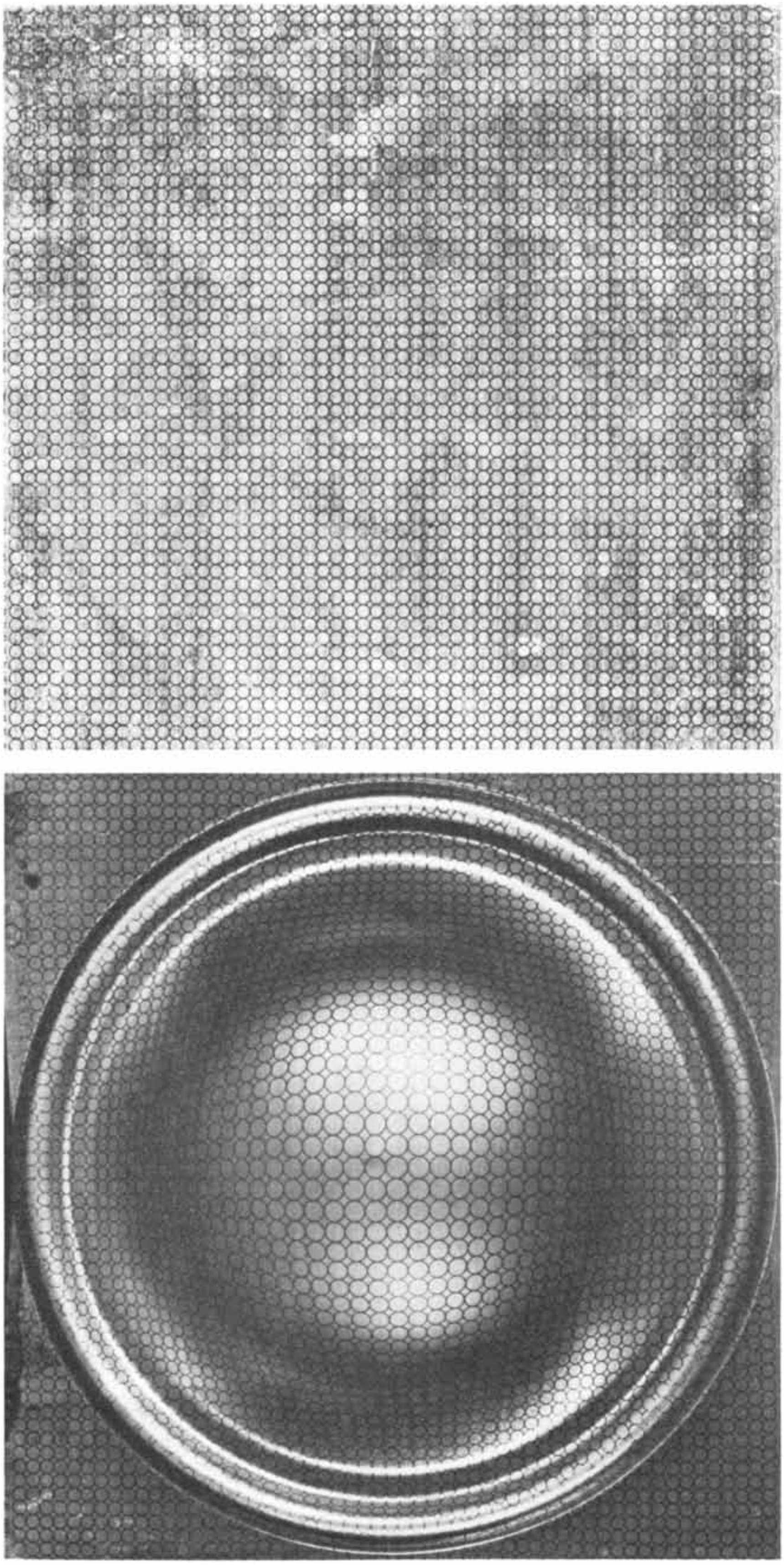

CIRCLE-GRID METHOD of testing a stamping is depicted. At the top is a metal blank of steel on which a grid of 2.5-millimeter circles has been imprinted. At the bottom is a domelike form made by stamping a blank in the laboratory apparatus that makes a punch-stretch test. Alteration of circles after stamping reveals the concentrations and amounts of deformation.

stretching, has been achieved with the finite-element method of stress analysis, in which a shape is divided into many small elements and the appropriate equations of stress analysis are solved for each of them. Such an approach is possible only with a modern high-speed computer. Even so, solutions for complex shapes and loading are currently out of reach. Therefore advances in the forming of sheet metal will continue to be partly empirical.

In this context the circle-grid method, which we have mentioned in connection with stretching, has proved to be helpful in the analysis of stampings from the production line. The method was introduced by Keeler as a replacement for the 25.4-millimeter (one inch) squares that were used previously. A quick electrochemical process puts a grid of circles (2.5 or five millimeters in diameter) on blanks of sheet metal. After the blank has been stamped the circles reveal the pattern of deformation. Areas of severe deformation are spotted by inspection. A row of circles in such a critical area can be measured and plotted to indicate how severely the deformation is concentrated. Changes in such variables of the stamping process as lubrication, hold-down pressure, draw beads and the size and shape of the blank can now be monitored to see if they really improve the uniformity of strain. In extremely troublesome cases one can measure the strains at various stages of stamping to determine the strain history. Knowing that history, one can hope to avoid such objectionable concentrations of strain.

Circle-grid analysis also serves, in conjunction with the concept of the forming-limit curve, to assess how much a stamping can be deformed without regularly failing. It is valuable also in the preproduction stage, when final changes in dies and in the selection of material are made. The method helps to determine whether the die, the lubrication and the material will result in a satisfactory stamping. Moreover, monitoring the degree of deformation during production runs will indicate whether a less formable (and probably less expensive) material might do the job satisfactorily.

Occasionally difficulties are encountered after long production runs. Stamping a few standard blanks that were set aside previously will indicate whether the trouble results from wear of the die, faulty lubrication or changes in the material. The art of troubleshooting has also been much refined, because the effectiveness of any change made in the production line can be monitored by stamping gridded blanks. Circle-grid analysis has replaced the craftsman's "feel" for the proper flow of the metal, and the forming-limit concept has provided a diagnostic tool for the analysis of failure.

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