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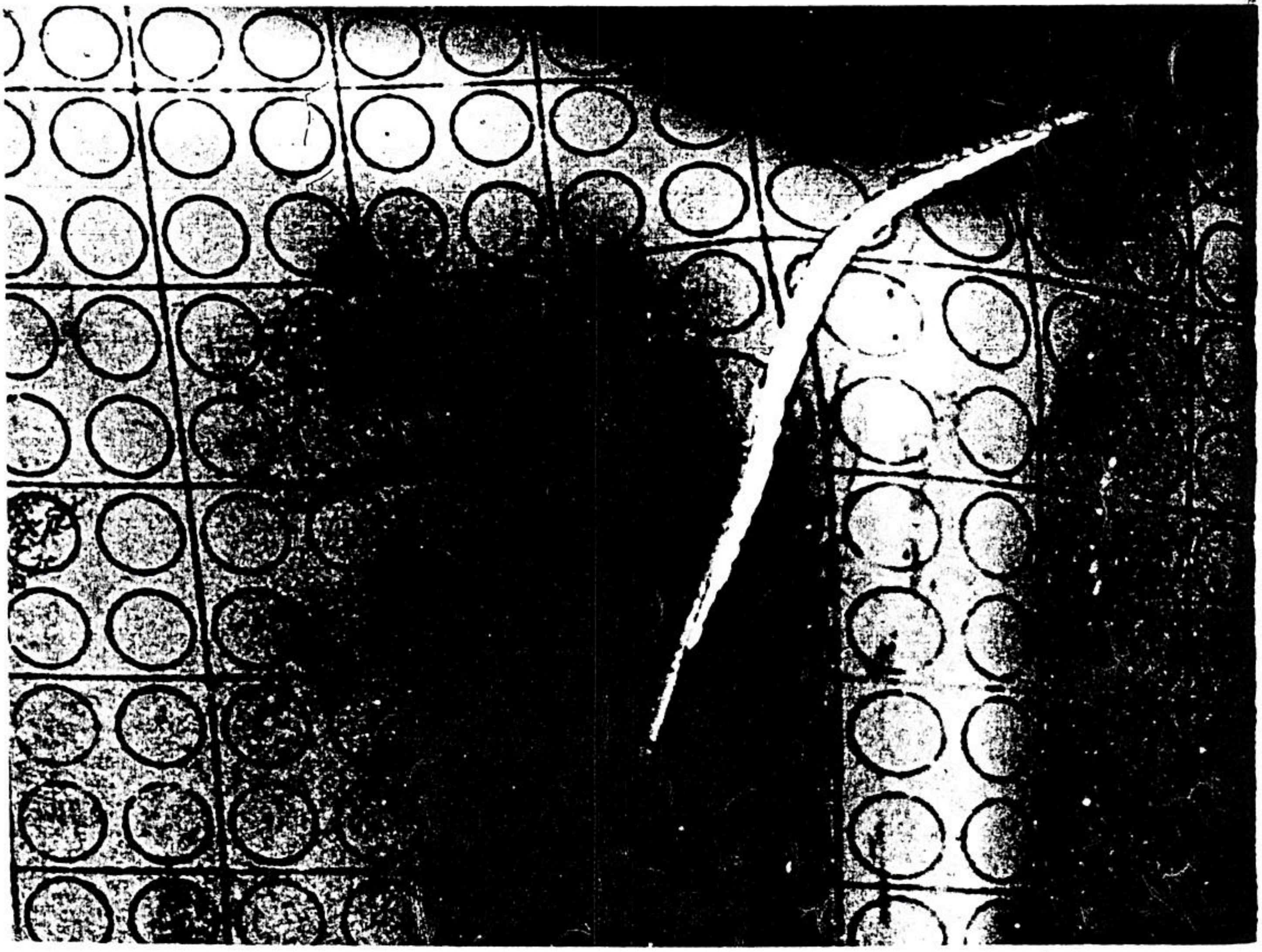
Part 2 — Visible Strain Patterns

Understanding Sheet Metal Formability

When a grid of small-diameter circles is etched on a sheet metal blank before forming, strain patterns caused by forming are made visible. This makes it possible to locate and eliminate causes of breakage.



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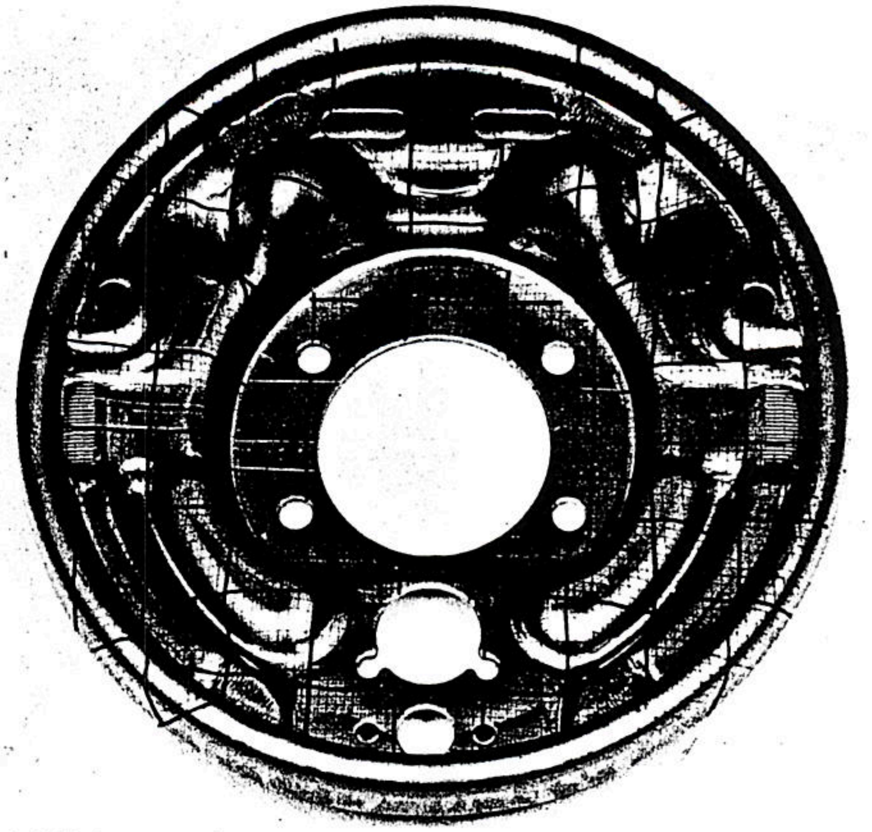
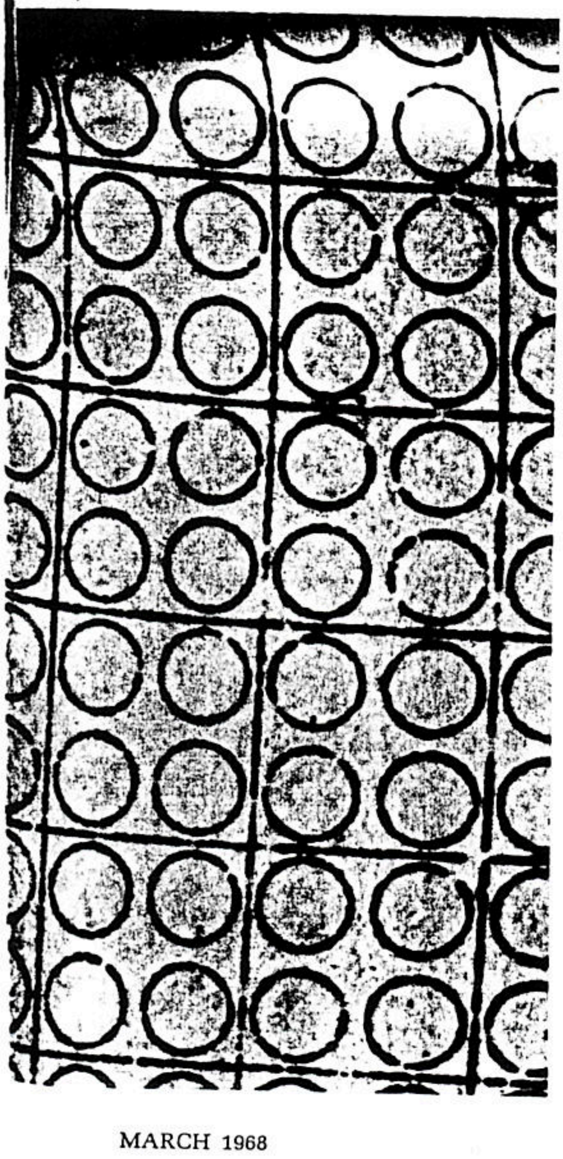


2. LARGE GRID (heavy lines) often encompasses critical areas. Because of the distance between lines, detailed information about the distribution of strains cannot be obtained. The smaller grid within the larger grid gives more information but the squares are not oriented to indicate the maximum strain.



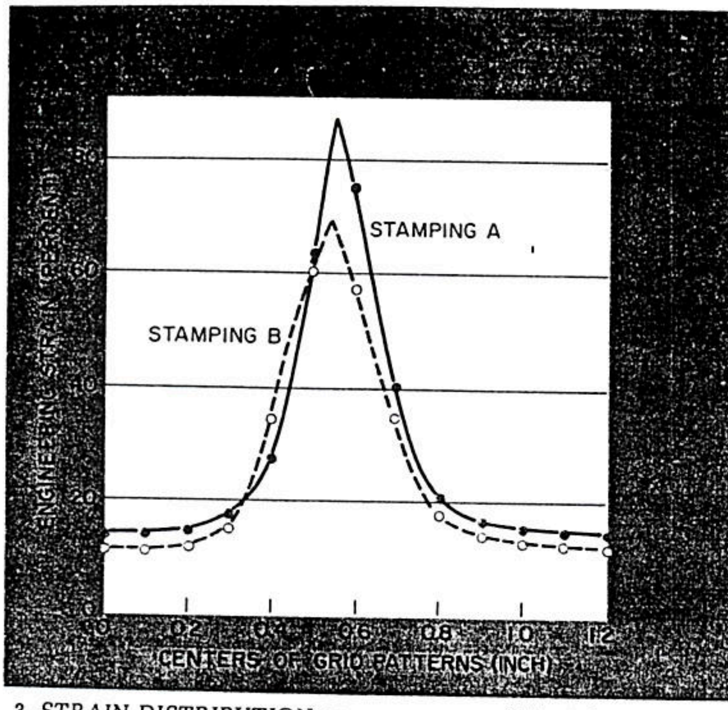
1. STRAIN PATTERNS in a formed sheet metal part are made visible by etching 0.2-inch-diameter circles on the blank. During forming, the circles are deformed into ellipses where strain is high. The major axes of the ellipses indicate the direction of maximum strain. Here excessive strain tore the blank.

Whether or not a particular sheet of metal can be formed without breakage depends on material properties, surface conditions, blank size and shape, lubrication, press speed, blankholder pressure, punch and die design, and many other known and unknown factors.

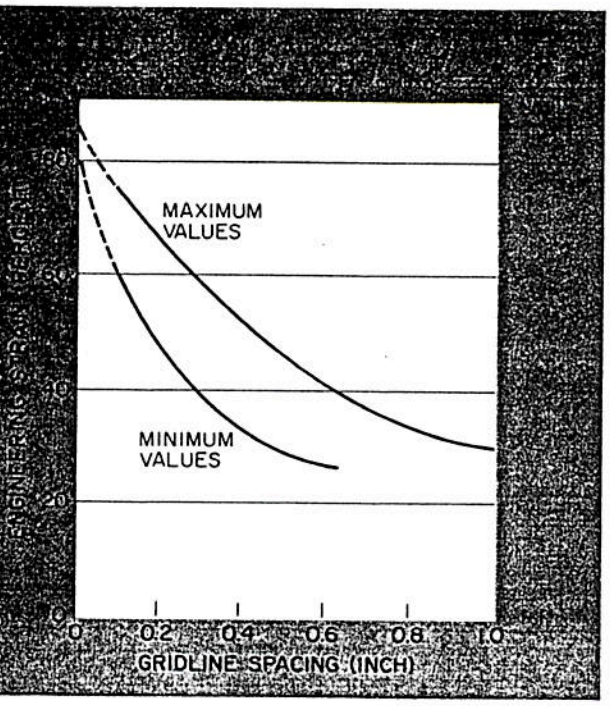
The amount of deformation determines when sheet metal will fail. The areas of the sheet that are subject to the greatest deformation—hence are the most likely areas of breakage—are made visible by scribing, printing or etching patterns of straight lines or circles on the blank, then forming the part. Strain patterns are clearly visible after forming, *Figure* 1. If the sheet is thin, they indicate the strain through the thickness of the sheet.

In an early form of this test, parallel lines are hand-scribed or machine-scribed longitudinally and transversely on the blank at 1-inch intervals, making 1-inch squares, *Figure* 2. After the blank is formed, the square showing critical increase in area is measured and the increase in area is calculated. If the areas of high strain are smaller than 1 square inch, or if the square has been distorted irregularly, the sheet is cut into sections and the decrease in thickness of each section is measured. This can be translated into increase in area. Where a minor increase in area is accompanied by a large elongation in one direction, the percent elongation is measured.

The maximum percent increase in area, or percent elongation in any one direction, is then related to a severity rating, which in turn determines the class or grade of steel required to successfully form the stamping.



3. *STRAIN DISTRIBUTION across an area of biaxial stretch in a production automotive bumper. The strains were determined from an electrochemically marked grid with 0.1 inch spacing. Stamping A was produced by the usual method; Stamping B was produced with emery tape on the punch to restrict metal flow at the high strain region. The peaking of strain is severe in Stamping A; less severe in Stamping B.*



4. *AVERAGE STRAIN VALUES for various gridline spacings. Maximum values were calculated with peak strain centered in the spaces between gridlines. Minimum values were calculated with peak strain located on gridlines. Sensitivity of strain measurement increases as space between gridlines is made smaller. Values are for Stamping A at left.*

SHEET METAL FORMABILITY

The 1-inch scribed-square test can be successfully applied to many large stampings that have large forming radii. The correct grade of steel for these stampings can usually be determined visually without the aid of a scribed grid, however. In addition, these stampings often are exposed automotive panels, and finishing and processing requirements, more than forming requirements, determine the grade of steel used.

Long experience and critical judgment are necessary to interpret measurements and apply them in a useful manner when stampings have sharp radii and character lines.

When this test is used, steel suppliers cannot determine the correct grade of material on the basis of the maximum increase in area. Each supplier has to look at the stamping on which the grid was applied, and apply his own judgment or correction factor in interpreting the numbers.

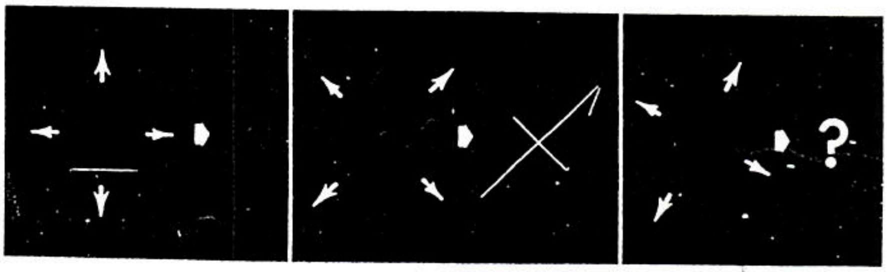
The reason for this is that the apparent strain breakage varies from one part design to another. A panel of one configuration may break when the maximum increase in area is 20 percent. A panel of another configuration, formed from the same material, may be successfully produced when the increase in area is 35 percent. And breakage has been known to occur when the percent increase in area is almost zero.

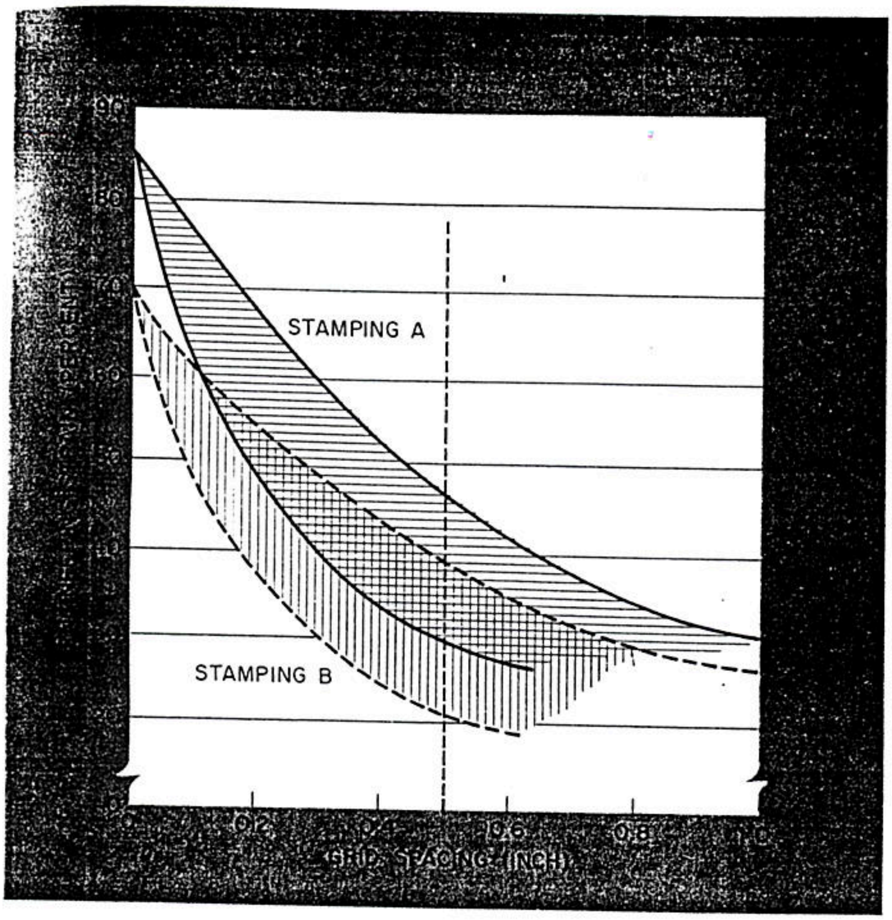
Although the 1-inch scribed-square test is not sensitive enough to allow the strain patterns in complex stampings to be satisfactorily evaluated, the basic concept of this test is excellent. Useful strain measurements can be made on more complex stampings with advanced tests based on the same concept.

The most important requirement of any grid system is proper spacing between lines. Since all material between adjacent lines is considered as one unit, any variation in strain from point to point between the lines is undetectable. Only an average strain value is obtained. Therefore, the lines must be sufficiently close to each other so that very localized differences in strain can be detected.

The problem encountered with a 1-inch grid system is illustrated in *Figure* 2. A blank was imprinted with 1-inch squares, each subdivided into one hundred 1/10-inch squares. Variations in strain are great within each 1-inch square. These variations are undetected by the large squares, which only average the strains.

Variation of strain in a small area is illustrated quantitatively in *Figure* 3, which shows a strain distribution across a character line of an automotive bumper. The strain was measured from a 1/10-inch grid spacing. Strain rises rapidly from a low-level plateau





5. RANGE OF STRAIN VALUES for Stampings A and B (Figure 3). Maximum and minimum values are calculated for extremes in grid orientation. For gridline spacings greater than 0.1 inch, actual measurements of strain values for Stamping B could be less than, equal to or greater than those for Stamping A, depending on where the grid was placed on the blank.

to a substantial peak and then drops again over a total distance of not more than 1 inch. This type of strain distribution is common.

Two different conditions are shown. Stamping A was produced normally. Stamping B was produced with a piece of emery tape over the character line to increase friction. The tape reduced the amount of localized peak strain on the character line. Using these curves, the effects of different gridline spacings are shown in *Figure* 4. This curve was obtained by calculating the maximum strain that would have been measured for Stamping A in *Figure* 3 for larger and larger spacings between lines.

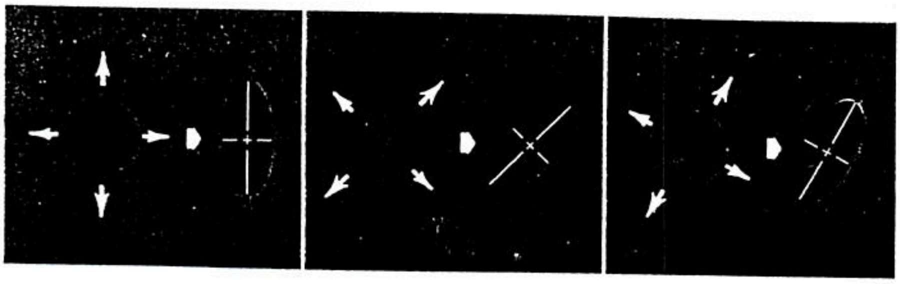
The calculations have been made in two ways. In the upper curve, the grid is assumed to be centered over the peak strain. In this manner, the maximum average strain value is obtained. In calculating the lower curve, a gridline is assumed to be located at the peak strain. In this case, only half the peak strain is averaged within a given gridline spacing, which results in a lower measured strain.

Measured strain, then, is very dependent on gridline spacing (gage length). The longer the gage length, the more the peak strain is averaged with lower strains. In the case of the maximum strain measurements, a 1-inch gridline spacing would have indicated a maximum strain of about 33 percent. In reality, however, a 1/10-inch-long segment of material has strained 75 percent.

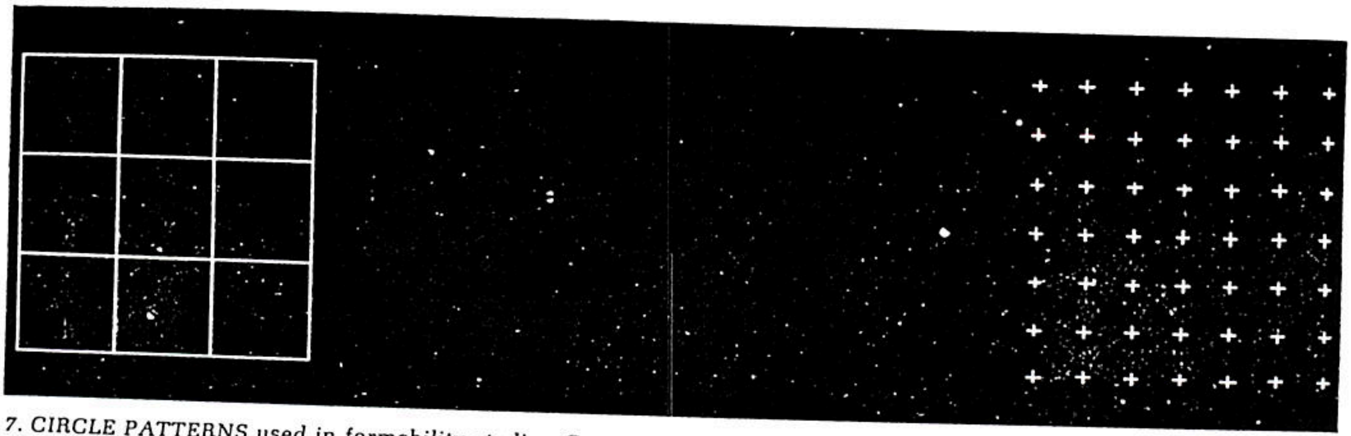
Maximum and minimum curves representing the possible range of measured values for Stampings A and B are shown in *Figure* 5. If a 1/2-inch grid system were used, the strain value for Stamping A could be less than, equal to, or greater than that for Stamping B, depending on chance measurements. Even though the condition for Stamping B is better than that for Stamping A, the two curves are not separated until the gridline spacing is reduced to 1/10 inch.

Like the gridline spacing, the configuration and orientation of the grid also influence the measured strain values. In the past, squares were commonly used because they can be conveniently scribed by intersecting sets of parallel lines. Squares, however, are seldom oriented correctly to permit direct measurement of maximum strain, as is shown in the left portion of *Figure* 6. When the sides of the square are oriented parallel to the direction of maximum elongation, the square will elongate into a rectangle. Simple measurements of the old and new dimensions permit strain to be calculated. If the diagonals of the square are oriented in the direction of maximum elongation, the diagonal lengths of the old and new dimensions can be used to calculate strain.

The direction of maximum elongation is usually unknown. It may vary from point to point in the stamping, while the direction of the grid system remains fixed. This necessitates complex measurements of square dimensions and shear angle before maximum strains are calculated. And the direction of maximum strain is not readily observed from the specimen.



6. SQUARES VERSUS CIRCLES. When the sides or diagonals of a square are oriented parallel to the direction of maximum elongation, maximum strain is readily calculated. Normally, the sides and diagonals are oriented in other directions. An advantage of circles is that they elongate into ellipses. The major axes of the ellipses are parallel to the direction of elongation.



7. CIRCLE PATTERNS used in formability studies. Greatest accuracy of strain measurement is possible with pattern at left, although strain is not measured in areas between circles. The tangent points at right center reduce accuracy. Patterns of overlapping circles (left center and right) are overly complex, making it hard to visualize strain.

An ideal grid system is nondirectional. A circle—the simplest pattern—is always correctly oriented to furnish the maximum strains directly. When the material is strained, the circle becomes an ellipse. The two principal strain directions are vividly indicated by the major and minor axes of the ellipse, as shown in the right portion of *Figure* 6.

Strain is calculated from the formula: Percent strain = $100\,(l_u - d_o)/d_o$, where l_u is the length of the axis of the ellipse and d_o is the diameter of the initial circle.

Several patterns of circles being used by different groups are shown in *Figure* 7. The pattern shown at the upper left consists of circles and parallel lines. The parallel lines are not used in strain measurements. They are aids in identifying a particular row of circles and in evaluating flow lines throughout the stamping. No strain measurements are made in the spaces between the circles. Since each circle is separate, the strain pattern from point to point is easily seen.

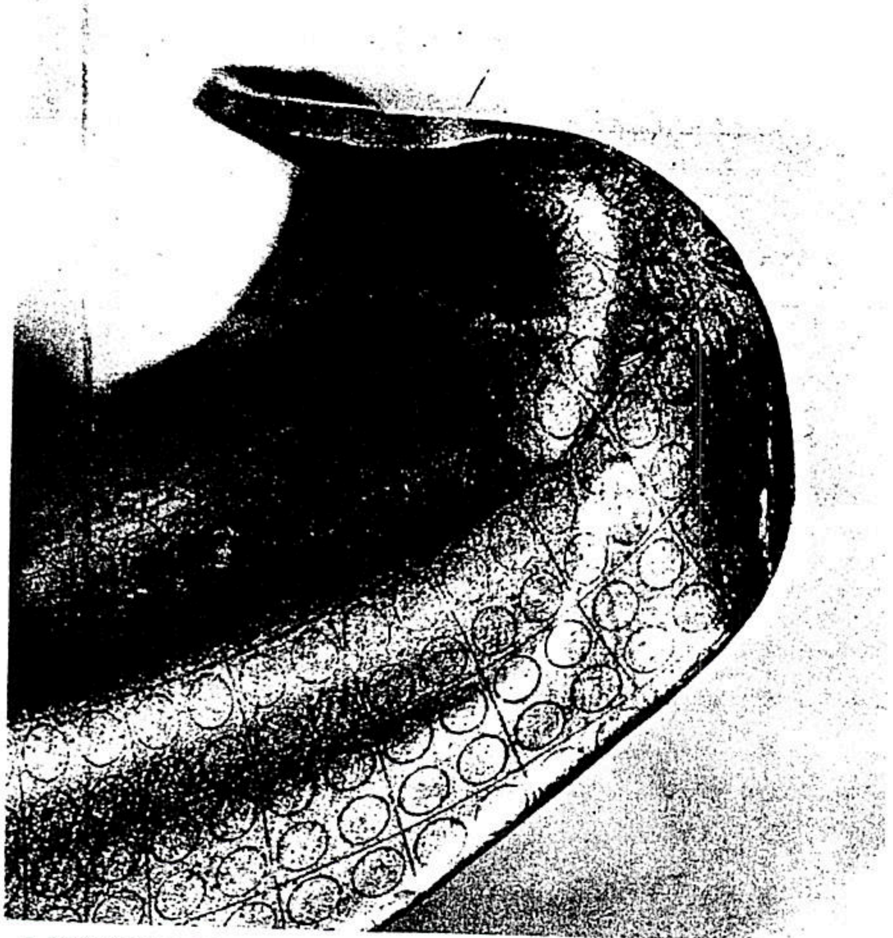
The circles in the pattern shown at right center in *Figure* 7 are tangent, so there is less space where no strain measurements are made. The tangent points reduce the accuracy of measurement, however.

Two sets of overlapping circles are used in the patterns shown at left center and right in *Figure* 7. These patterns are designed so that all surface areas are within at least one circle. Strain is measured twice in some areas, which is probably as bad as having areas where strain is not measured. The complexity of these patterns makes strain distribution hard to see.

Hand scribing methods are no longer feasible when patterns of small circles are used. A typical 9-inch-square area might require five thousand circles 1/10 inch in diameter, accurate to within ±1 percent. Six of these blanks could be required for a test, with preparation time limited to a few minutes.

Hand scribing of patterns has another disadvantage—deep-scribed lines can act as stress concentrators. Failure then takes place along a line, rather than in the area where strain normally is at a maximum. Consequently, the strain pattern is inaccurate.

A faster, more accurate method of imprinting complex grid patterns is required. One solution attempted was imprinting with a rubber stamp. A dis-



8. LOCALIZED STRAIN is visible in the hook area of this automotive bumper jack hook. Circles are 1/10 inch in diameter. Circle just under edge of lip at top of part is greatly elongated. Most deformation is restricted to one circle.

advantage is that inks are easily rubbed off the blank or are dissolved in oil. The ink can be replaced by copper plating or by acid etchants. These produce broad lines so measuring accuracy is poor.

Fine lines can be applied through silk screen masters. Imprinting and drying are slow and the inks are easily rubbed off or dissolved.

For laboratory tests, photoprinting gives good results. The blank is coated with a photosensitive emulsion. Then the emulsion is covered with a photographic negative and exposed to strong ultraviolet radiation. The latent image is developed like a photographic print. Very fine, sharp lines can be printed on the blank in this way. Grids having 100 to 200 lines per inch are produced on a routine basis.

Since processing time is 30 minutes or longer, and special darkroom and whirling equipment are required, it's not practical to make photogrids in the average pressworking shop. The photogrid is removed by chemicals and rubbing, which also limits its use for formability tests in the average production shop.

Electrochemical marking has made the use of small-diameter circle test patterns feasible for shop formability tests. In this process, an "electrical stencil" is placed on a cleaned blank. A felt pad, soaked with electrolyte, is placed on top of the blank. The pad is covered by an electrode. Leads are attached to the electrode and the blank, and current from a 14-volt power source is applied for 5 to 7 seconds. Depth of the mark is 1/2 mil or less, depending on the etching time. After etching, the solution on the blank is neutralized and a polarized oil is applied to prevent rusting.

The grid is accurate and several hundred grids can be made with each stencil. Since the pattern is etched, it cannot be removed by oil, chemicals or ordinary rubbing of the material over the dies. It can be applied through a phosphate coating.

Depending on the desired accuracy, several different techniques can be used to measure grid patterns after forming. For rough measurements, simple flexible rules or calibrated plastic strips are satisfactory. Higher accuracy is provided by using dividers with sharp points and a rule calibrated in hundredths of an inch. A magnifying glass is helpful. For the exact measurements needed in research or laboratory work, an optical magnifier with a calibrated reticle is used.

An electrochemically marked stamping is seen in *Figure* 1. The circles on the specimen are 2/10 inch in diameter. The relative amounts of strain can be estimated visually for each area within the stamping from the deformation of the circles. The direction of the maximum strain also changes, especially along the character lines and buckles.

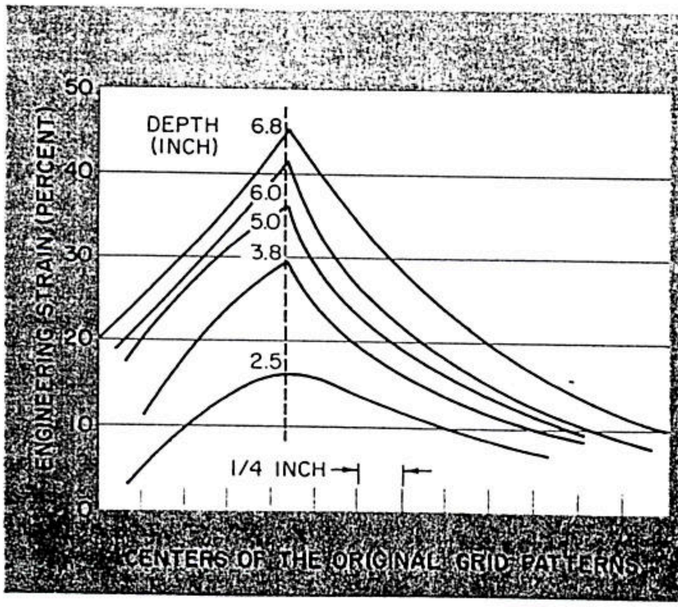
A magnified view of a bumper jack hook, *Figure* 8, shows very severe localization of strain in the hook area. Almost all deformation is restricted to one circle. The design of this stamping was subsequently modified to change the strain distribution.

Strain patterns in finished stampings can yield much useful information. To solve some forming problems, however, the strain history in different areas of the stamping must be known. Strain histories often reveal the cause of high strain values.

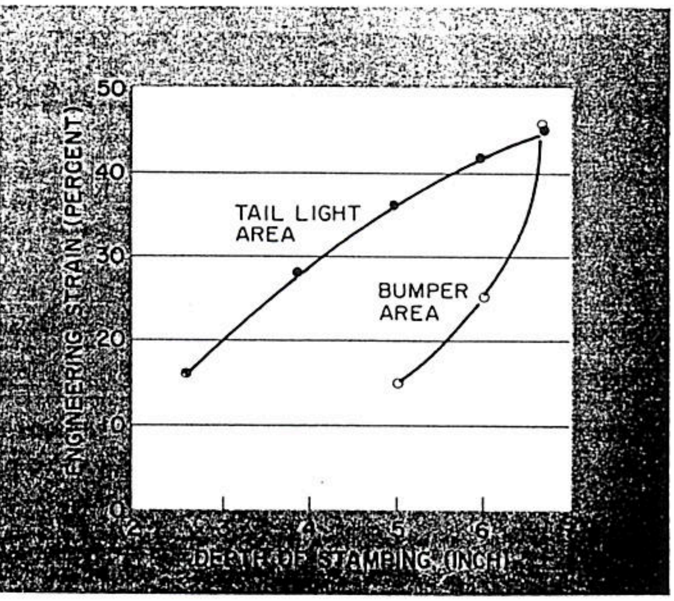
The easiest method of obtaining strain histories is to form a series of stampings, each of which represents a progressive stage in forming. These are often called "incremental hits." A separate, gridded blank is normally used for each stage.

The amount of punch travel is the most convenient means of determining when to stop the forming of each stage. If total punch travel is 7 inches, partially formed stampings might be obtained at every inch of travel. Most deformation of interest usually occurs during the final 20 percent of punch travel. Therefore the last 2 inches of punch travel should be divided into even smaller increments—say 1/2 inch or 1/4 inch of travel.

The strain histories must be obtained under conditions that approximate actual forming conditions as closely as possible. Since material properties and the effectiveness of lubrication are sensitive to deformation speed, inching the ram down to the desired depth is unsatisfactory.



9. STRAIN DISTRIBUTIONS across an area of biaxial stretch in the tail light area of an automotive quarter panel. Distributions at different stages of forming were obtained by varying lengths of punch travel. Most deformation is in final stages.

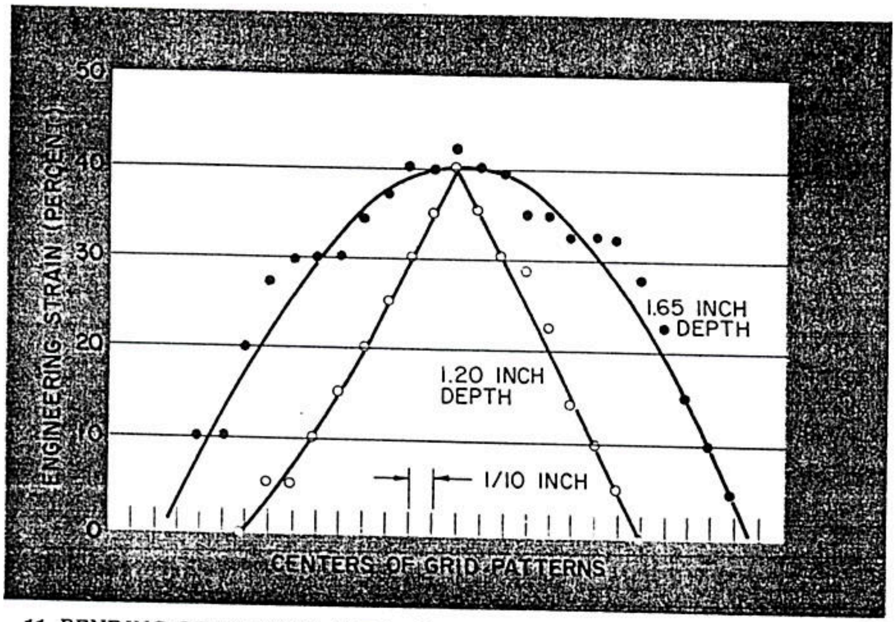


10. STRAIN HISTORIES for the the tail light and bumper areas of an automotive quarter panel. Principal strain increases with depth of stamping. Last value shown is for the completed stamping.

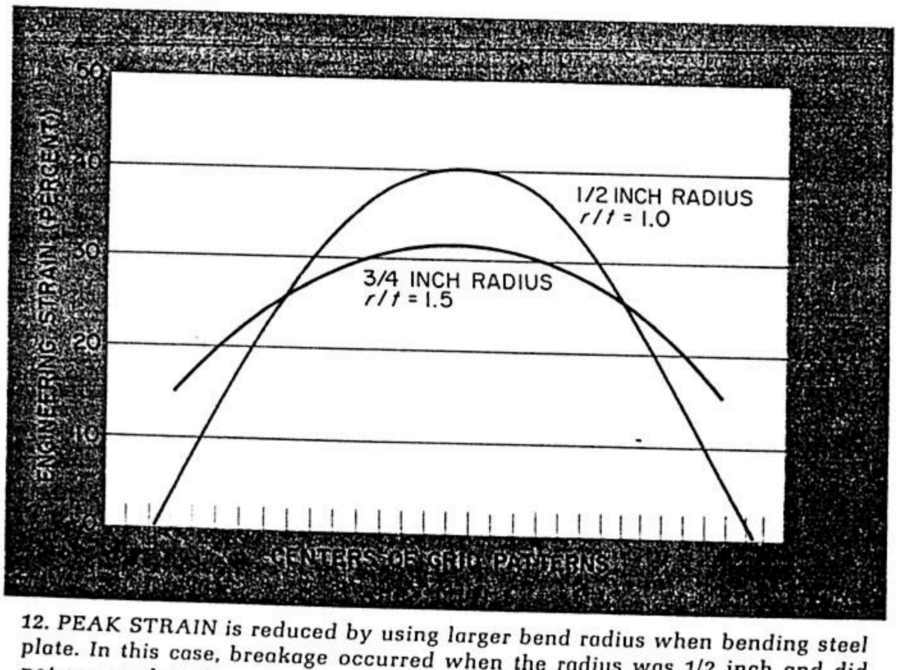
The correct method for obtaining partially formed stampings is to raise the punch by adjusting the pitman arm. The press is then operated at normal speed. The stamping will be deformed at approximately the correct forming speed, stopping short of the finished position by the amount the punch was raised. By raising the punch in additional increments, a series of partially formed stampings is obtained.

All blanks used in the sequence should have identical properties. If only one blank is available, it can be partially formed, removed from the press for strain measurements, returned to the press for forming of an additional increment and so on until the entire sequence of partial forming steps has been completed. This procedure is not recommended because it is slow, and because speed effects cause different strain patterns.

Partially formed stampings are measured in the same way as completed stampings. Strain values are plotted as a function of the original centers of the pattern of circles. Such a distribution appears in *Figure* 9. This strain distribution shows a characteristic small amount of nonuniformity at 2.5 inches. As the stamping is progressively formed, the general strain level increases. The degree of nonuniformity or amount of peaking increases with increasing depth. The completed depth is 6.8 inches.



11. BENDING OF STEEL PLATE is illustrated in this strain history. The peak strain is not increased as depth increases from 1.20 to 1.65 inches. Instead, the previous strain distribution is broadened. The material is 1020 steel.



12. PEAK STRAIN is reduced by using larger bend radius when bending steel plate. In this case, breakage occurred when the radius was 1/2 inch and did not occur when the radius was increased to distribute strain more uniformly.

The critical element is usually the failure element—the one with the highest strain value. An element is a small volume of metal in the blank. Its location with respect to the punch and die may change as the stamping is formed.

The element is specified by the circle that occupies the identical location in the blank. A vertical line is drawn on the graph for that element. The intersection of the line with the strain distribution curves gives the strain values for that element at each forming depth. Using punch travel as the reference base, the strain history is obtained by cross-plotting the strains as a function of stamping depth.

The strain history of this tail light area, as well as the bumper area of the same quarter panel, is shown in *Figure* 10. The final strain is the same for both areas but their strain histories are quite different. Examination of the two curves indicates that a small additional increment of depth (or a change of material or die conditions) will generate a much higher strain in the bumper area than in the tail light area. For this reason, the bumper area is considered to be more critical, even though the maximum or final strains are identical. This was determined through the strain histories. Locking beads opposite the tail light area were found to restrict the flow of metal moving in from the flange so there was early and continued straining over the punch area. The bumper area had no locking beads. Metal moving in from the flange at this location reduced the amount of stretching required in the punch area. The sharp point configuration caused the metal to lock between the punch and die just prior to completion of the stamping. All deformation was now confined to a very small area. Consequently, at the end of punch travel the amount or rate of straining in the bumper area was very large.

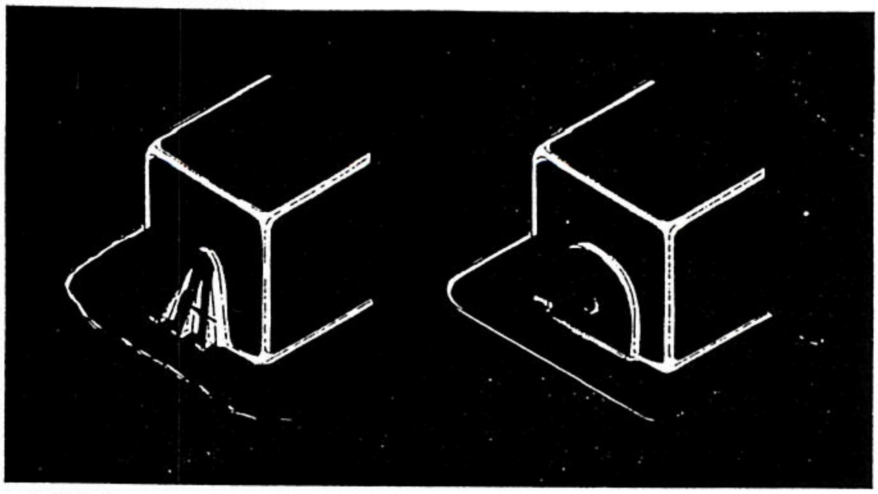
Strain histories are useful in understanding the breakage of steel plate in bending. For example, measurements were obtained on spacers made from

1/2-inch-thick x 4 1/2-inch-wide bars of 1020 steel. A 1/10-inch grid was used. As shown in *Figure* 11, the strain distribution and the peak strain increased until a depth of 1.2 inches was reached. (As the depth increased, the angle of bend increased.) Increasing the depth beyond 1.2 inches (and increasing the angle) did not cause an increase in the peak strain—it merely broadened the previous strain distribution. If a piece of material cannot withstand the peak strain, fracture will occur at about three-fourths the desired depth. This is quite different from most stretching operations.

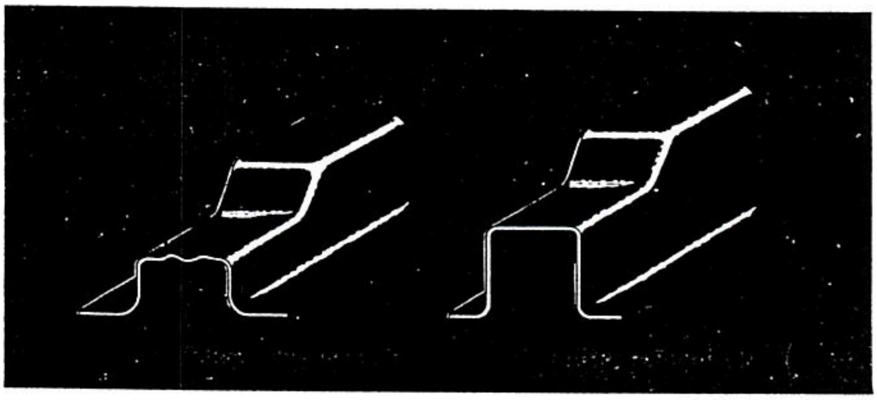
The r/t ratio (ratio of bend radius to plate thickness) has a strong influence on breakage. The reasons for this are apparent from the strain distribution, *Figure* 12. With 1/2 inch plate and a 1/2 inch bend radius ($r/t = 1$), the plate had a peak strain of 40 percent and end splits resulted. When the bend radius was increased to 3/4 inch ($r/t = 1.5$), no breakage occurred. The strain became more uniformly distributed, reducing peak strain to 32 percent. This is characteristic of bending and stretching types of deformation. A sharper radius concentrates the strain in a smaller area, thereby producing higher peak strain.

Strain measurements made on the final stamping can be extremely deceiving. For example, a formed oil pan showed breakage at a compressive strain of 4 percent. Fracture does not normally occur in compression. The oil pan, *Figure* 13, had been made in two operations. The basic shape of the oil pan was drawn in the first operation. In drawing, metal is forced into a compressive strain; buckles or wrinkles sometimes form. In this case, the circle in the critical area was highly elongated in one direction and compressed in the other direction.

The oil seal flange was formed by stretching in the second operation. In so doing, approximately 30 percent tensile elongation was required. The circle was now pulled back to nearly its original size and shape. Although the final measurement showed only 4 percent compression, the metal had actually been first worked in compression, which had consumed much of its original ductility. When the metal was reworked in tension in the second operation, the 30 percent elongation exceeded the amount of ductility remaining. If the sequence had been reversed, with the stamping being worked in tension before being worked in compression, no failure would have occurred.



13. OIL PAN IS FORMED in two operations. The first operation generates a severe compression strain, as indicated by long, narrow ellipse. Second operation forms an oil seal flange in this area, subjecting the critical area to a tensile strain. The sum of the two strains indicates a 4 percent compression.



14. BUCKLES ARE CREATED in the first operation on this stamping. Buckles provide extra metal so that failure is avoided in a subsequent operation.

The problem was solved by placing a partial oil seal flange preform into the first operation. This prevented the material from being worked so much in compression and also reduced the amount of elongation required in final forming.

Partially formed stampings are also used to trace the formation of buckles or wrinkles. Buckles often end up at a substantial distance from the point where they start, so an examination of the final stamping may not give clues as to the conditions that generated the buckle.

Buckles generated during early stages of forming can provide metal necessary to prevent breakage at a later forming stage. One example was the automotive frame channel shown in *Figure* 14. Here buckles are created in the first operation, providing sufficient metal over the radius to prevent failure in a subsequent operation.

It's evident that measurements and visualization of strain patterns make it possible to locate and eliminate the causes of many breakage problems. In Part 3 of this article, which will appear in the April 1968 issue, it will be shown how two "new" material properties—the work hardening coefficient n and the anisotropy coefficient r—affect stretchability and drawability of sheet metals. ▲▲

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