Part 4—Predicting Forming Limits

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Understanding Sheet Metal Formability

When stampings tear during forming, the metal has been worked beyond its formability limit. Recent research makes it possible to predict this failure and avoid forming problems.

When a stamping tears during forming, the tear is a visible indication that the metal has been worked beyond its prevailing formability limit. A more formable material, different lubricants or reworked tools are needed. Many stampings can be found that are close to failure but have not yet torn. These are called "critical stampings." During die tryout, conditions may permit critical stampings to be successfully formed. In production, conditions may be less than the optimum and breakage results.

Breakage of production stampings is costly. Changing materials, lubricants or tools can be time consuming. The ability to predict failure—to identify critical stampings—would be very desirable. Recent research in sheet metal forming has provided at least a partial solution to this problem.

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Laboratory stretch forming tests have been made on a number of metals commonly used by the forming industry—annealed 70/30 brass, tough-pitch copper, 1100 aluminum and aluminum-killed steel. In the tests, 8-inch-diameter disks were securely clamped and stretched with rigid punches of various configurations and with various lubricants. The test setup is shown in *Figure* 1.

Deformation of the disks continued until the stretching limit was reached and the specimens tore. Before tearing, a trough of very localized deformation or shearing became evident on the surface of the sheet. This narrow band of localized strain is sufficient to cause rejection of the stamping if a smooth appearance is desired. Fracture is more realistically identified with this event than with the actual separation or tearing.

In the tests, strain distributions were measured for various increments of deformation from grids placed on the dome. Strain distributions for three of the materials at the onset of fracture are shown in *Figure* 2. The measured strain or percent stretch is plotted as a function of location in the initial blank.

Experience has shown that the strain distribution normally contains a peak (nonuniformity) caused by a stress gradient. Comparison of the three strain distributions reveals, however, that approximately the same maximum strain was reached in all three materials. Since the depth of the stamping is proportional to the area under the curve, greater depth before failure was achieved in the material having the most nearly uniform strain distribution.

Many experiments have been conducted with various materials, lubricants and punch configurations. The strains measured at the onset of fracture in these laboratory specimens (such as the peak strains in *Figure* 2) are shown as closed circles in *Figure* 3. Here the two principal strains for the failure element in each of the laboratory tests is plotted. The vertical axis is the largest principal strain. When circular grids are used, this strain is calculated from the major axis of the resulting ellipse. The cross strain, or surface strain perpendicular to the largest surface strain, is plotted on the horizontal axis. It is calculated from the minor axis of the ellipse. The formula for calculating the strain is percent $\epsilon = 100$ (axis of deformed ellipse-circle diameter)/circle diameter.

The curve drawn through these points, called the critical strain level, separates failure and nonfailure conditions. By measuring the strains on any given stamping and relating them to *Figure* 3, the proximity to failure can be determined for each region of the stamping. Using this curve, comparisons can also be made among different

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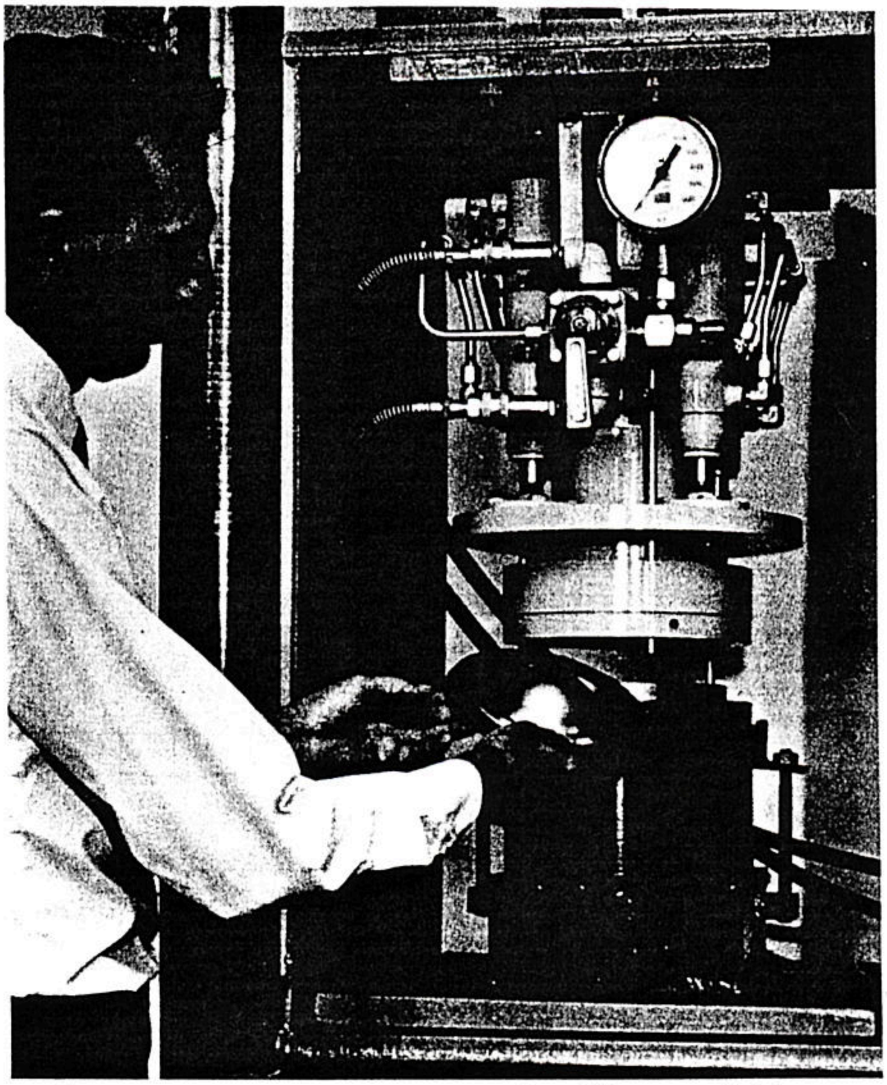
stampings, materials, tool modifications and the like.

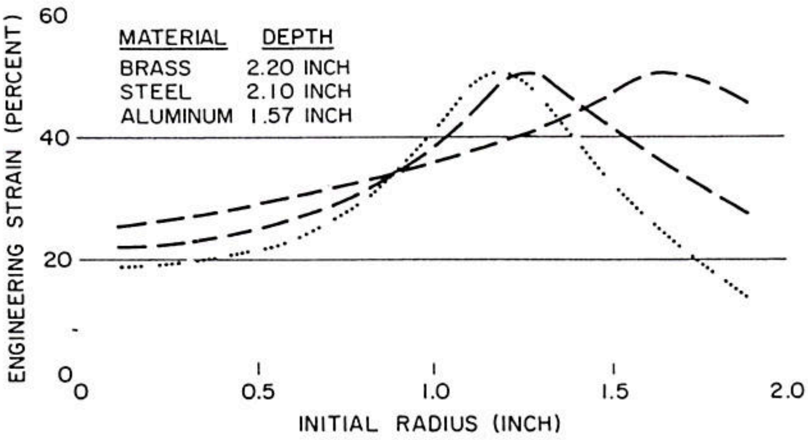
To verify the applicability of this laboratory curve to complex production stampings, blanks from a variety of critical stampings with records of high breakage were imprinted with grids and formed. Even though other variables (binder lines, draw beads and blank configuration, for example) exercise considerable control over the forming process, most failures occurred in a region of biaxial stretch located over the nose of the punch. Strain measurements made at the onset of fracture in these production stampings are plotted as open circles in *Figure* 3.

Excellent agreement was obtained between laboratory and production experiments. It should be possible to establish the proximity to failure in biaxial stretching with considerable confidence by use of *Figure* 3. If the measured strain lies well below the critical line, no failure is anticipated. If the measured strain approaches the critical line, the stamping is considered critical. Failure may be caused by small adverse changes in material properties, lubrication or die adjustment.

A current method of classifying stretching severity is to scribe a blank with 1 inch squares. After forming, the largest percentage increase in area of a 1 inch square is used to rate the severity of the forming operation. The prob-



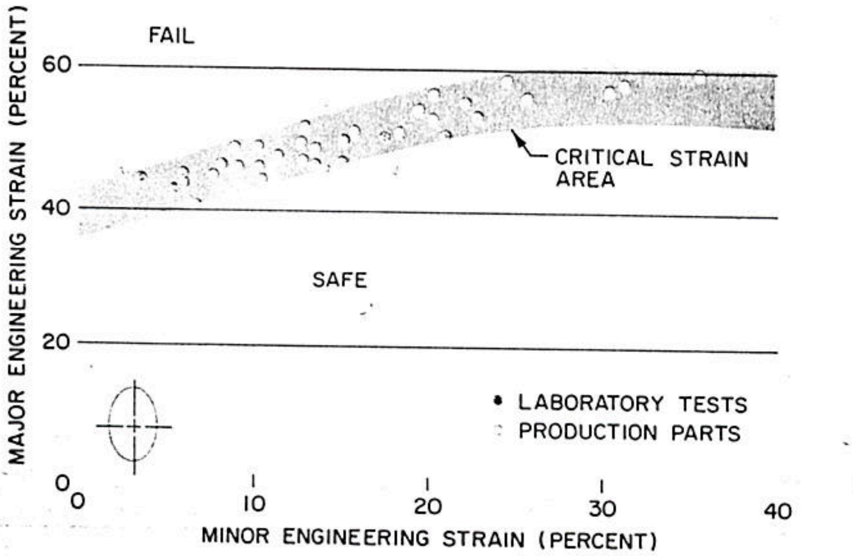
1. STRETCH FORMING TEST SETUP in a formability research laboratory. Here 8-inch-diameter disks are securely clamped and stretched with rigid punches into hemispherical, conical or elliptical configurations. Tests like this help formability researchers to evaluate the formability of sheet metals.



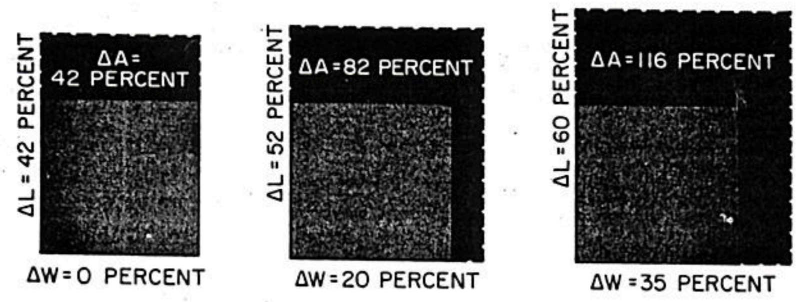
2. DISTRIBUTIONS OF PRINCIPAL STRAIN at maximum (failure) depth for Teflon-lubricated, annealed materials securely clamped and stretched over a 4-inch-diameter punch. A 20-line-per-inch grid was used. Peak strain is approximately constant for all three materials. The depth is proportional to the area under the curve. All measurements are plotted as radial distances from the centers of the undeformed specimens. Tests were made in a laboratory.

lems created by this system are illustrated in *Figure* 4. Shown here are three different critical strain conditions. For example, a maximum surface strain of 52 percent with a perpendicular surface strain of 20 percent is on the critical strain level curve. These strains would create an increase in area of 82 percent. As can be seen in this figure, there is no unique percentage increase in area at failure. Therefore, such measurements do not yield sufficient information to predict proximity to failure.

Another method of classifying forming severity involves the measurement of thickness strains. Thickness strains are proportional to the increase in the surface area. The advantage of this method is the infinitely small dimensions of the grid spacing. Variations in strain distribution are readily detected. As in the method discussed in the preceeding paragraph, no unique thickness strain exists at failure. Proximity to the critical strain level cannot be determined unless the strain components in the plane of the sheet are known.



3. *CRITICAL STRAIN LEVEL for laboratory and production stampings was obtained by marking the blank with circles. During forming, the circles are stretched into ellipses. Here the major principal strain has been calculated from the major axis of an ellipse and the minor engineering strain calculated from the minor axis of the ellipse. Above the critical strain level, stampings tear; below it they do not tear. At the critical strain level, stampings may tear. Laboratory values were obtained from biaxial stretching experiments for various annealed materials, punch geometries and lubrication. Production values were derived from measurements of automotive steel stampings.*



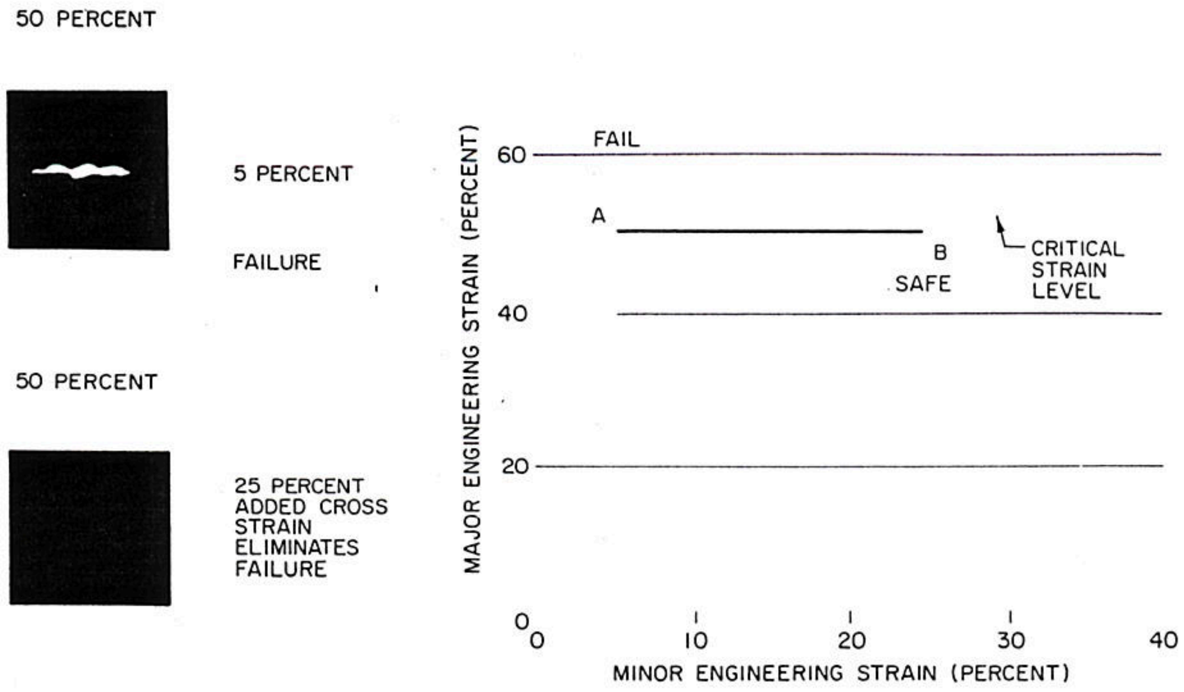
4. *STRETCHING SEVERITY is classified by scribing a blank with 1 inch squares. After forming, the largest percentage increase in area of the 1 inch square is used to rate the severity of the forming operation. No unique value of increase in area exists at failure, as seen in these three representations of critical strain conditions. Accordingly, proximity to failure can't be predicted.*

The first important aspect of the critical strain level curve is that the failure strain is fixed for annealed and lightly skin-passed materials. The curve drops to lower strain values as the material is cold worked. It is relatively insensitive to variations in cleanliness, gauge and material properties. This would not be anticipated for conditions related to the onset of fracture.

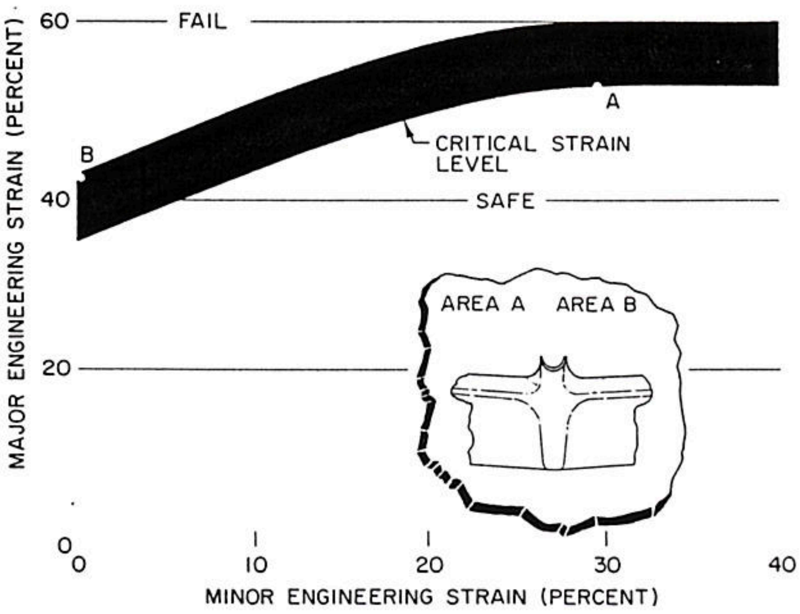
By changing the strain state, the curve can be crossed from failure to safe without changing the maximum strain level, *Figure* 5. The stamping shown in the drawing at the upper left in *Figure* 5 splits at a maximum (major) strain level of 50 percent. Very little minor strain is present (Point A). To correct this condition, die engineers normally rework the dies to allow more metal to pull in from the flange parallel to the tear. Failure of the part was avoided in this case, however, by restricting the flow of metal in from the flange and creating a greater minor strain, as shown in the drawing at the lower left in *Figure* 5. The strain state now changed from A to B, moving across the critical strain curve. While the stamping was still considered critical by virtue of its proximity to the critical level, consistent failures were avoided.

The critical strain level also suggests that the highest strain location may not be the failure site. Such a case was observed in a front bumper, *Figure* 6. The highest strain was measured in the nose or central portion of the bumper (A). Here the strain state was highly biaxial. A major strain of over 54 percent and a minor strain of 30 percent were observed. Somewhat removed from the nose was a rather sharp character line (B). Here the strain was all in one direction—across the sharp radius—with no strain along the character line. The major strain at this location was 42 percent; minor strain was zero. Failure occurred along this character line at B. Because of the upward slope of the critical-strain curve, the strain value at B was above the critical strain curve, causing failure, while the higher-strain location at A was still below the failure curve and there was no fracture.

Recent work by Gorton Goodwin at Chrysler has extended the range of the critical strain level. The curve shown in *Figure* 3 is for tension-tension



5. CHANGING THE STRAIN STATE of a stamping can eliminate tearing. Here an added cross strain moved the strain from the failure side to the safe side of the critical strain level. In this way, consistent failure was avoided.



6. MAXIMUM STRAIN may not coincide with the failure site in a formed part. This automotive bumper failed in Area B, where strain was only 42 percent in one direction, while the dome in Area A was stretched 54 percent in one direction and 30 percent in another without any tearing during forming.

strains. These most commonly occur over the head of a punch, or under conditions of stretching where the blank is clamped and the punch is pushed into the sheet. For deep-drawn stampings, it should be noted that the strain state is tension-compression. The major axis elongates and the minor axis is shortened or compressed. The preliminary critical strain level for steel in deep-drawn configurations is given in *Figure 7*.

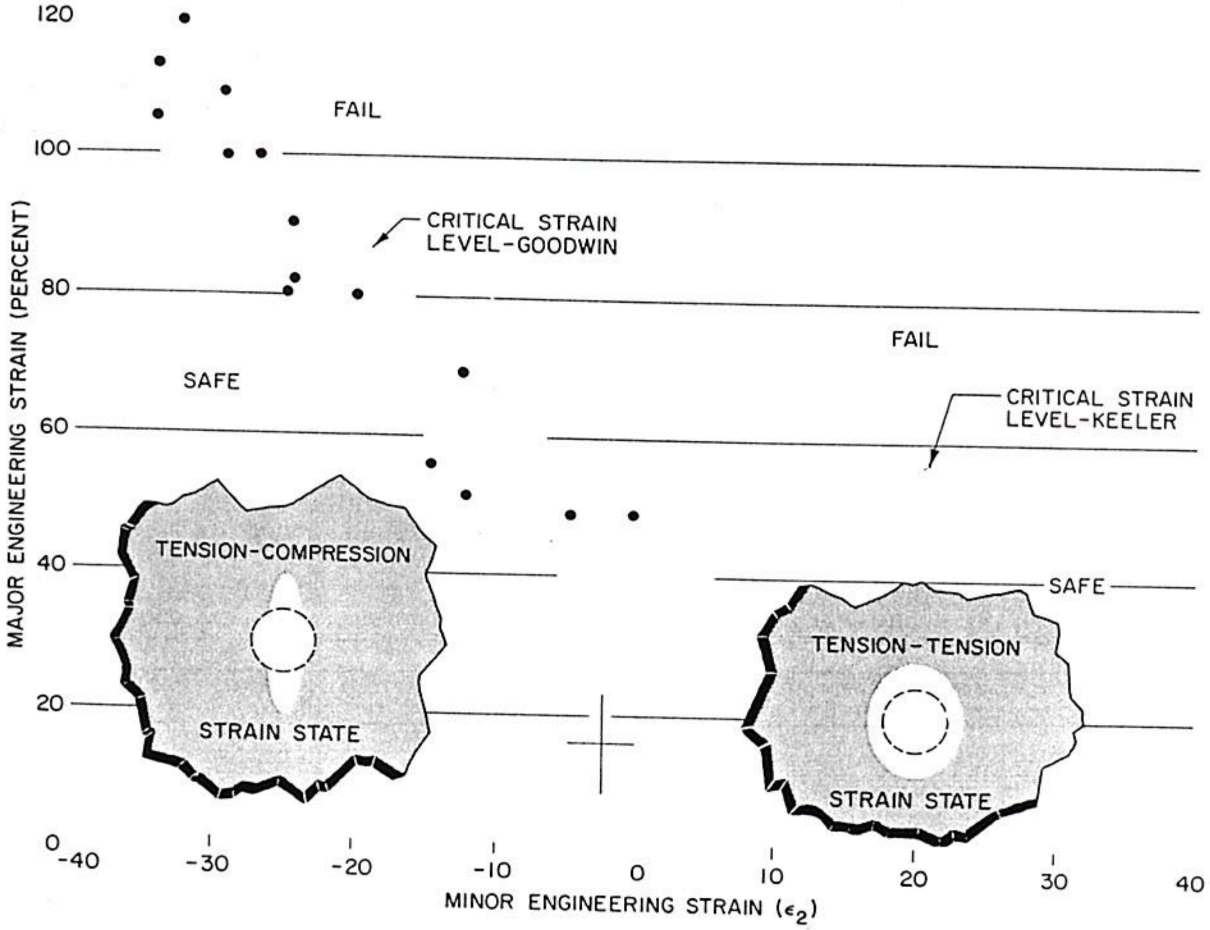
In the tension-compression regions, very high strains are possible. The reason for this—in part—is simply that metal (represented by a circle) is compressed from the sides, causing a natural elongation in the other direction without any tensile force being applied. In this type of deformation, metal can withstand very high strains under compressive stresses without failure. This type of strain is found in rolling or extrusion.

The difference between stress state and strain state is important. An identical strain state can be produced by two widely different stress states, one of which can cause failure or necking while the other will not.

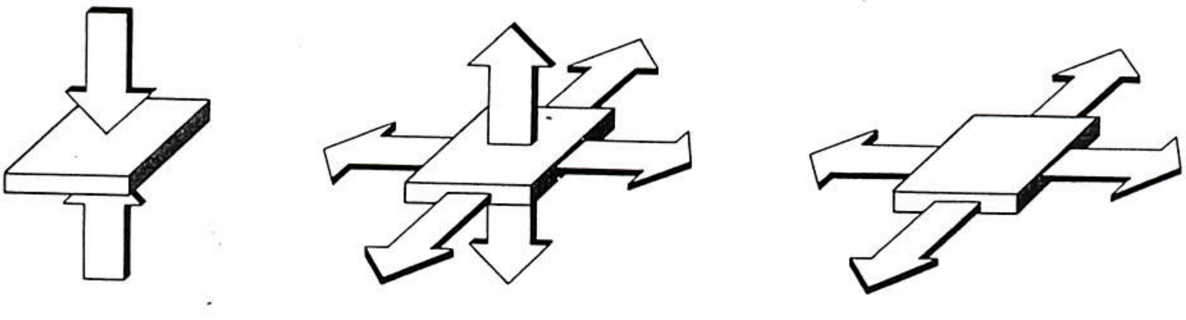
This is illustrated in balanced biaxial stretching of a sheet of metal, *Figure* 8 (right sketch). The sheet of metal can be elongated by equal stresses causing elongation along both axes of the sheet. The same deformation can be obtained by compressing the sheet of metal through its thickness (left sketch). The two stress states can be shown to be equivalent simply by adding or subtracting a hydrostatic stress component (center sketch). A hydrostatic stress state has equal stresses in all directions. A compressive hydrostatic stress can be obtained by submerging a cube of the material in pressurized water. A hydrostatic stress does not change the yielding conditions of the material.

In the case of the tensile stresses, certain types of necking and fracture localize and terminate the deformation very early in the strain history. The compressive stress, on the other hand, can cause very large amounts of deformation. A similar analysis applies to wire drawing versus extrusion. The strain states can be similar but the stress states completely opposite. If there is a choice, a compressive stress state is better than a tensile stress state.

Two concepts have evolved from the critical strain curve. First, a predictable critical or limiting strain level exists. Utilization of this phenomenon will be discussed in Part 6, to appear in July. The second concept is that the critical or limiting strain acts as a strain ceiling or barrier, and is quite fixed for



7. TENSION-COMPRESSION strain state (left) is commonly found in walls of deep-drawn parts. The vertical axis is the largest principal strain found in the surface of the stamping (major axis of the ellipse). The horizontal axis is the principal surface strain perpendicular to the largest strain (minor axis of the ellipse). Data points were obtained from Gorton Goodwin of Chrysler Corporation. Tension-tension strain state (right) is type shown in Figure 3 of this article.



8. DIFFERENT STRESS STATES can produce an identical strain state. Deformation obtained by compressing the sheet through its thickness (left) can also be obtained by balanced biaxial tension in the plane of the sheet, as explained in text.

annealed and lightly skin-passed materials, especially steel. The requirement now for a satisfactory stamping is to obtain as uniform a strain distribution as possible under this ceiling, *Figure* 9. Since the depth of the stamping is directly proportional to the area under the strain curve (which is a measure of average strain value), the more uniform the strain distribution, the deeper the stamping will be when failure occurs.

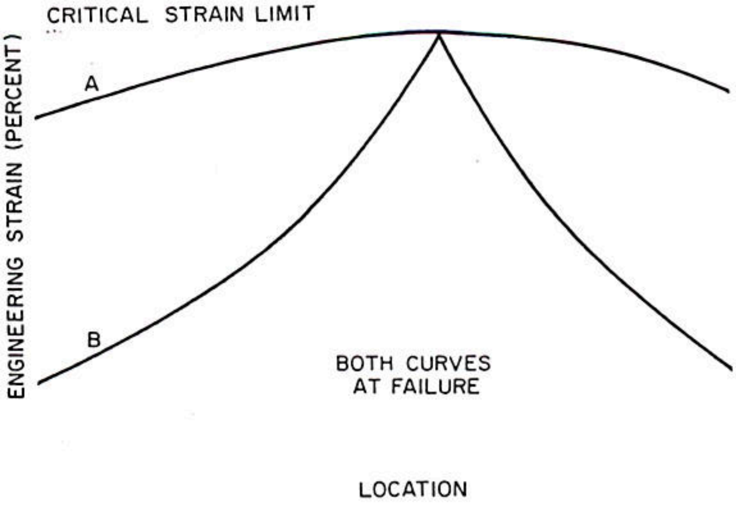
Conversely, if two stampings are at the same depth (equal areas under the curve), the stamping with the most nearly uniform strain distribution will have the lowest peak (maximum) strain, *Figure* 10. This stamping, in turn, will have the greatest safety factor (strain difference between the maximum strain and the critical strain level of *Figure* 7) and the smallest chance of breakage.

Note that the emphasis has changed. In a biaxial stretching condition, there is a critical strain level—a ceiling. Attempts to improve the steel probably will not change this critical strain level. The important criterion now becomes how uniformly a particular steel will distribute the strain in the presence of a stress gradient. This is essentially what the Olsen, Erichsen and other stretch tests measure in a limited manner. The steel that most uniformly distributes the strain will have the highest average strain (and therefore dome height) at failure.

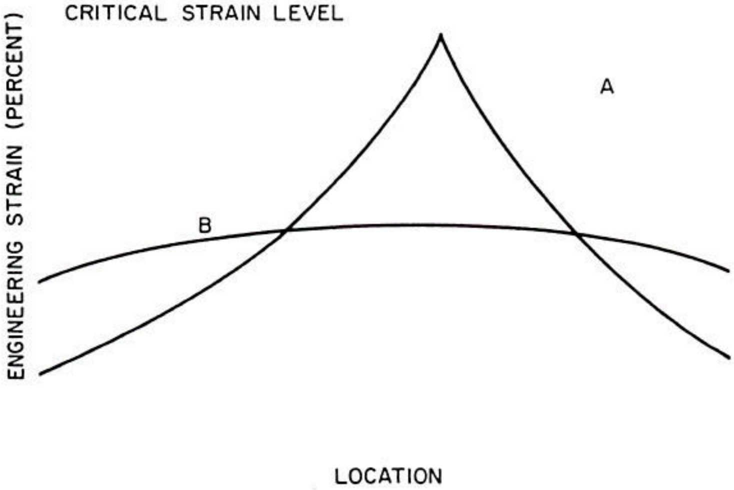
In general, the forming of a successful stamping requires the proper matching of material, lubrication and die design. Excellent material can compensate for poor lubrication or die design, and vice versa. It must be emphasized, however, that material properties—and corresponding grade of steel—are now only one of several variables that can be used in controlling the strain distribution. Small changes in the other two—lubrication and die design (to be discussed in Part 5, June issue)—can completely overshadow large variations in material properties. In addition, economic factors now enter into the consideration of the most practical solution to the breakage problem. Ordering a higher-quality material may not be the most economical solution over the span of a production run.

Experiments have shown that the controlling property in stretch forming is the *n* value of the material, as described in Part 3 of this article. The *n* value, in turn, is generally proportional to the TS/YS (tensile strength to yield stress) ratio, or to the uniform elongation of the material.

Yield stress alone is not a sufficient criterion to evaluate the general formability of the material. The TS/YS for AK steel may be around 1.8. The yield stress of a high-*n* stainless steel may be twice that of low carbon steel. However, the tensile strength is also elevated for the stainless steel, creating a TS/YS of around 2. In practice, the stainless steel usually forms as well as,



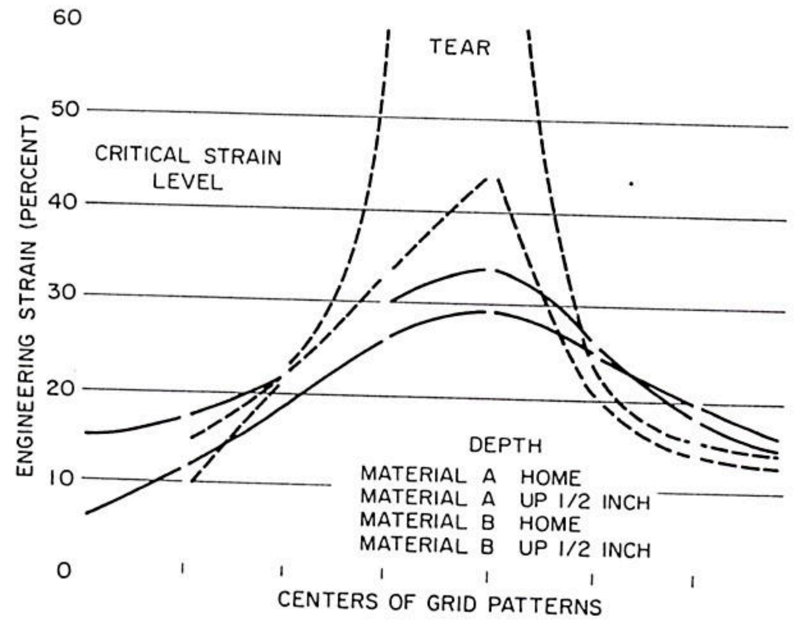
9. STRAIN DISTRIBUTION of two materials strained to the critical strain limit, shown schematically. The depth of stamping is proportional to the average strain value of the stamping, which in turn is related to the area under the curve. Material A has greater depth at failure because the more nearly uniform strain distribution permits a greater average strain.



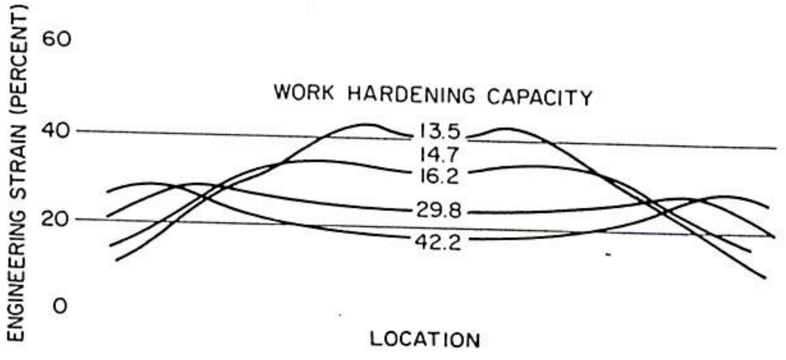
10. SCHEMATIC STRAIN DISTRIBUTIONS for two materials stretched to the same depth. This is indicated by equal areas under the two curves. The more nearly uniform strain distribution of Material B results in a lower maximum of peak strain. The difference between the critical strain level and the peak strain is a safety factor. Both curves are for the same dome height.

or better than, low carbon steel, even though its yield stress is twice as large. The reverse is true for aluminum. Even with a yield stress one-half that of low carbon steel, many grades of aluminum do not stretch form as well as steel.

The effect of the TS/YS ratio on stretchability is shown in *Figure* 11. Here two rimmed steels with different TS/YS ratios and *n* values are compared in forming an automotive fender. At a forming depth of 1/2 inch from home (completed position), Material A has reached the critical strain, which in this case was 45 percent. Material B, on the other hand, produced a more uniform strain distribution with a peak strain of 30 percent. On completion of the forming operation, Material A had split wide open while Material B again had a low strain of 34 percent. Comparison of the material properties showed a TS/YS ratio of 1.35 for A and 1.52 for B. The *n* values were 0.19 for A and 0.22 for B. On this basis, steel for this stamping could be ordered using the mechanical properties of Material B as the desired goal.



11. PRINCIPAL STRAIN across an area of biaxial stretch in a production automotive fender. Two different rimmed DQ steels were used. Strains were measured from an electrochemically marked grid of 0.2-inch-diameter circles. The critical strain level was predicted from an empirical curve. All measurements are plotted at the centers of the undeformed circles.



12. DISTRIBUTIONS OF RADIAL STRAINS obtained by stretching clamped disks of steel over a rigid hemispherical punch, using drawing compound and polyethylene as lubricants. The deformation was stopped when a dome height of 3.1 inches was obtained. The work hardening capacity of the material is related to the uniform elongation. The bottom two curves are for stainless steel specimens. The curve is taken from "Effects of Mechanical Properties on Biaxial Stretchability of Low Carbon Steels," by Heyer and Newby.

Some recent work by Heyer and Newby of Armco clearly shows the influence of mechanical properties on the degree of uniformity of the strain distribution, *Figure* 12. Plotted are the strain distributions for materials having different values of circle arc elongation, which is directly related to the *n* value, uniform elongation or TS/YS ratio of the material, as discussed in Part 3 of this article. The higher the circle arc elongation, the greater the capacity for stretching. The strain distributions shown were measured on various sheets stretched over a rigid hemispherical punch to a fixed depth. The depth was chosen to be just below the level at which the poorest material began to fail. The most nearly uniform strain distribution was obtained for the material having the highest circle arc or uniform elongation. This material happened to be a stainless steel with a yield stress of 34,000 psi.

Cold working can greatly reduce the formability of the material. The cold working may arise from heavy temper passing, excessive flex rolling or a prior forming operation. The cold working influences the material behavior in two ways, as indicated by the schematic drawing in *Figure* 13.

First, the total amount of usable strain a material can undergo before failure is reduced. This results in a lowering of the critical strain limit. Current research work is attempting to determine the exact relationship between prior cold work and the critical strain level.

Second, cold working influences the strain distribution. Each increment of cold work reduces the TS/YS ratio or uniform elongation of the material. This in turn reduces the ability of the material to strain uniformly in the presence of a stress gradient, causing the strain distribution to become more nonuniform, as shown in *Figure* 12. The critical strain curve and the peak strain value approach each other at a rapid rate, strongly reducing the formability of the material.

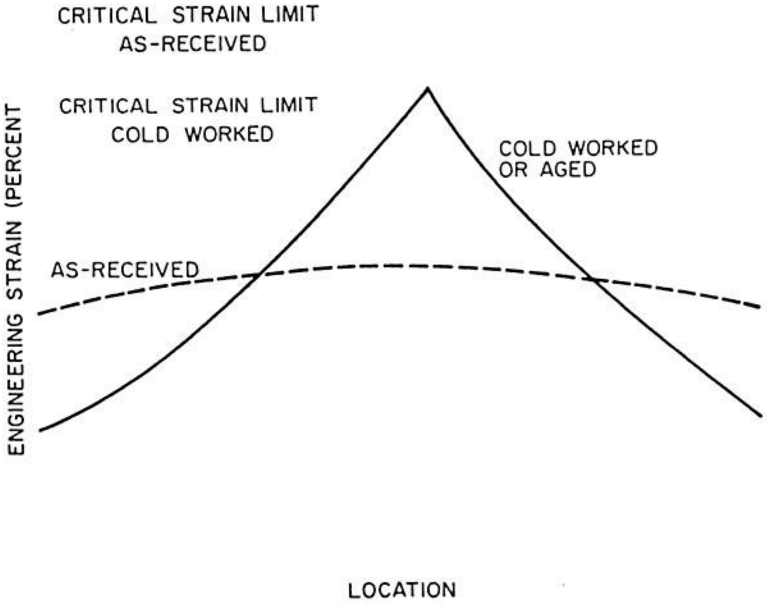
The aging of rimmed steel can change its formability characteristics. In this case, very little change in the critical strain curve is observed. Aging causes the yield strength to increase, however, resulting in a reduction in both the TS/YS ratio and the n value. The strain distribution is therefore less uniform.

The influence of reduced TS/YS ratio and n value of rimmed steel was vividly observed in an automotive quarter panel, *Figure* 14. The curves were obtained from a sequence of stampings removed from the press at various progressive stages of forming ("incremental hits"). The strain of the critical element or any other element of interest is measured on each partial stamping and plotted as a function of stamping depth. The history of the tail light area is quite different from that of the bumper area, even though the final strains are equal. In addition, the peak strain value observed in the stamping made of rimmed steel is considerably higher than that of the stamping made of AK steel. If the critical strain level were 40 percent, the rimmed steel would suffer from severe breakage, while the AK steel would have a safety factor of approximately 6 percent.

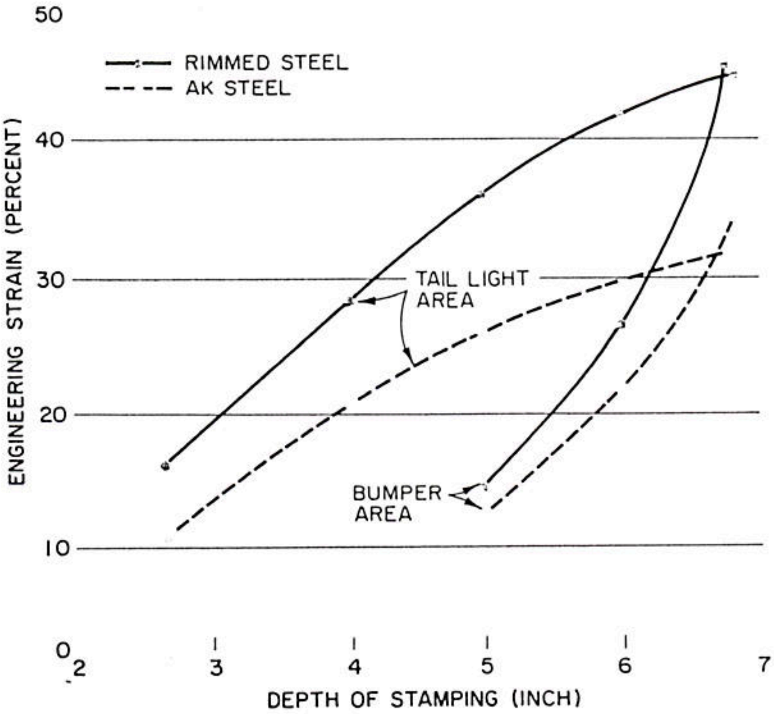
Within a given grade, such as cold rolled DQ rimmed steel, there is a range of properties. Slight changes in the TS/YS ratio and n value of the material can cause large changes in the strain distribution.

Occasionally failure occurs at a very low strain level. In one recent case, inner hood stampings were breaking. Measurements from a grid of 1/10-inch-diameter circles showed strain readings of 5 percent in the critical areas. The material was dead soft. Visual examination of the stamping showed very deep Lüder's bands created by the yield point elongation of the dead soft material. In this case, all strain was localizing. Fracture was created within a Lüder's band. Most of the metal was not allowed to contribute to the total straining of the stamping. The problem was eliminated by a simple flex-rolling operation that decreased the yield point elongation.

In other cases, a surface scratch or subsurface lamination can act as a stress raiser and lead to premature failure. This is especially true when the imperfection is on the tension side of a bending specimen.



13. *EFFECTS OF COLD WORK on the forming capacity of a material before failure. The cold work lowers the critical strain level and makes strain distribution nonuniform. As a consequence, formability is substantially reduced.*



14. *INCREASE OF PRINCIPAL STRAIN with stamping depth for two areas of a biaxial stretch in a production automotive quarter panel. Strain values were obtained by stopping the press at varying amounts of punch travel and removing the partially formed stampings. Last value is for completed part.*

It must be emphasized that the critical strain concept is still relatively new and presently confined to a few of the more common materials used in the forming industry. Several research groups are attempting to understand the mechanism behind the critical strain curve and to extend the technique to other materials, especially to the less ductile materials used in the aerospace industry in this country.

Relationships between lubrication and die design and sheet metal formability will be discussed in Part 5 of this article, which will appear in the June issue of *Machinery*. ▲▲