Understanding Sheet Metal Formability

You can reduce die tryout time and minimize breakage of stampings in production by using simple techniques described in this article. The result: better stampings faster.

Forming of sheet metal is undergoing a transition from art to science. As explained in preceding installments of this article, guesswork has been replaced by engineering analysis.

The key to successful forming is to obtain as uniform a strain distribution as possible under the limit established by the critical strain level of the material. If this limit is exceeded, the stamping will break during forming.

The direction and magnitude of maximum strain are easily determined by electrochemically etching a pattern of small-diameter circles on the surface of the blank. During forming, the circles are deformed into ellipses. The direction of maximum strain corresponds to the major axes of the ellipses and the magnitude of that strain is determined by measuring the increase in length of the ellipses over the diameters of the circles.

Through the analysis of these visible strain patterns, die tryout and die modification can be simplified, the selection of optimum materials and lubricants can be made easier, and breakage of stampings in production can be minimized.

Successful forming requires the right combination of material, lubrication and die design. Small changes in lubrication and die design are often more effective in reducing breakage of stampings than changing to materials with different properties. By analyzing strain patterns, the changes needed to convert an "unformable" stamping into a formable stamping can be determined and the effects of those changes can be quickly evaluated.

Ideally, this is done during die tryout, where dies are given the necessary modifications for satisfactory production runs. The fact that a stamping is successfully formed during die tryout does not necessarily mean that it can be successfully formed in production.

During die tryout, press speeds are usually slower than those used in production. Good materials are used, blanking and trimming punches are sharp and well-adjusted, gaging is carefully set and other press variables correctly adjusted, lubricants are hand-applied. In short, all variables are optimized in order to produce acceptable stampings.

When the dies are installed in production presses, conditions may no longer be optimum. A stamping that was successfully formed during die tryout may break when it is formed under production conditions. This can lead to costly delays and the danger of missing deadlines for the startup of production.

One of the major benefits of using the etched-circle system during die tryout is that it makes it possible to find critical stampings—stampings that are likely to break when formed under production conditions—before production trials are made. For many tool and die men, the visual display of strain patterns provides sufficient information to suggest changes that will make the stamping formable in production, even when forming conditions are far from optimum. When a critical stamping is identified, the magnitude, directly and distribution of strain can be altered to provide a margin of safety in production forming.

Another advantage of the etched-circle system is that it provides a quantitative record of progress made during die tryout. At intervals, a prepared blank can be formed. The peak strain or, more important, the safety factor, can be compared with a previous trial and the progress recorded. A mathematical measurement of the current state of the dies replaces opinion.

Use of blanks with etched patterns of circles is also helpful in the selection of materials, particularly when stampings are critical. When a blank of the material tentatively selected for the stamping is formed, its safety factor is determined by comparing its peak strain with the critical strain level. If a safety factor of, say, 10

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percent is present, the mechanical properties of that blank become the required properties and dictate the material grade.

If the safety factor is less than that desired, materials of increasingly better quality will have to be tried until a satisfactory safety factor is attained. The alternative is to modify the die design or try different lubricants until the peak strain is reduced sufficiently to provide an adequate safety factor.

If the safety factor is larger than required, it may be possible to use a lower-cost grade of material. The safety factor of the new material must be checked, of course.

In some cases, the required material properties are in an area of overlap between two grades. For example, the properties may fall in the upper range of a rimmed DQ steel and in the lower range of an aluminum-killed steel. In such cases, grade selection depends on other factors, including uniformity from shipment to shipment, inventory turnover and aging of the rimmed steel.

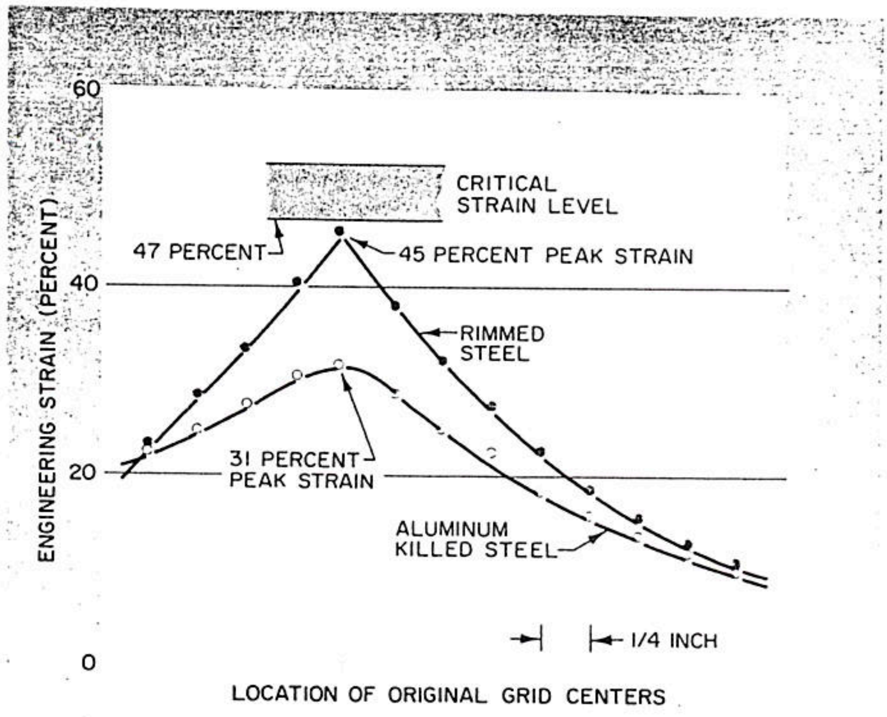
Ideally, the safety factor of the material selected is evaluated for the high, average and low portions of the specified grade range. From this, the sensitivity of the safety factor to variations in material properties can be determined and appropriate safeguards imposed.

In a few special cases, a harder steel (having higher yield stress) may have a higher safety factor than a softer steel. The harder steel appears to resist straining over the punch head and to pull more metal in from the flange, thus reducing the peak strain over the punch head and increasing the safety factor. This illustrates that it may be beneficial to evaluate steels that have forming properties above and below the tentative specification.

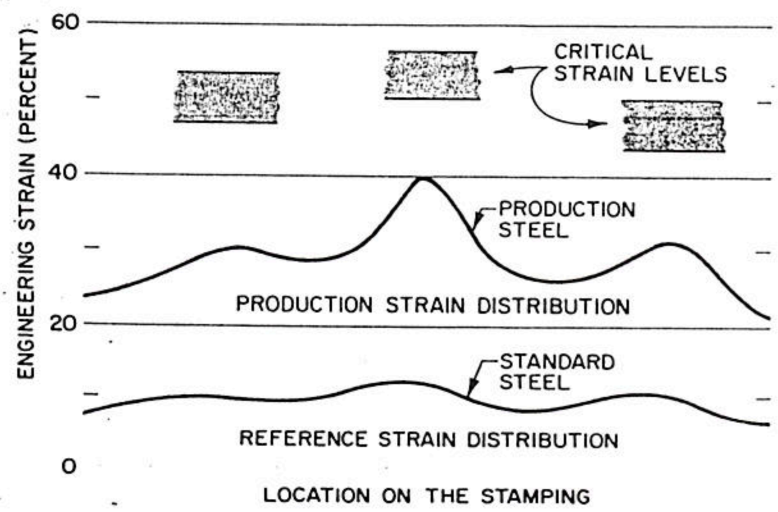
The etched-circle system can open up many possibilities in material selection, some of which can be resolved only by a management decision. An example is shown in *Figure* 1.

This figure illustrates the strain distribution in an automotive fender. Two different steels are being tried out —a rimmed steel and an aluminum-killed steel. Both steels are fresh and have average mechanical properties.

The critical strain level for the fender is 47 percent. The peak strain for the rimmed steel is 45 percent, providing a safety factor of only 2 percent. This safety factor is inadequate, since



1. STRAIN DISTRIBUTION in an automotive fender. The critical strain level begins at 47 percent. Peak strain for stampings made from the rimmed steel is 45 percent, allowing a safety factor of only 2 percent. Slight variations in material properties or press conditions can lead to breakage during forming. The aluminum-killed steel, with its 31 percent peak strain and 16 percent safety factor, will be more satisfactory for this stamping. Long storage times could be tolerated.



2. STRAIN DISTRIBUTIONS of a production steel and a standard (reference) steel are shown in this plot. Both strain distributions were obtained at the start of the production run. The reference strain distribution—even though different than the production strain distribution because of different properties—can be used as a norm to evaluate future die conditions. Any difference between this norm and any future strain distribution obtained with the standard steel can indicate that the press or die conditions, or lubricants, have changed.

any rimmed steel having borderline properties (resulting in a higher peak strain) would probably break during forming. Further, the properties of rimmed steels are changed by aging (higher yield stress and lower TS/YS ratio) so using rimmed steel that had been in storage for some time would probably result in breakage of stampings in production.

The aluminum-killed steel has a more-than-adequate safety factor of 16 percent, since parts formed from this steel exhibit a peak strain of only 31 percent. Wide variations in properties and long storage times could be tolerated.

If the decision were made to use rimmed steel, an attempt would have to be made to reduce the peak strain 10 or 12 percent by modifying the dies or using a different lubricant. Also, it would be necessary to establish an inventory control program to promote early usage of the rimmed steel. A quality control check on incoming material would be desirable to make sure that properties were as specified. And any steel not purchased for immediate consumption should be aluminum-killed.

The etched-circle system provides a reliable means of checking steel quality or evaluating trial steels. The advantage of this system is that—unlike traditional tests—it shows the formability of the material when used on a specific set of dies with a specific lubricant.

It should be pointed out that no single, universal formability index can be determined for a given lot of material. What counts is how successfully the material can be formed on a certain press, using certain dies and a certain lubricant on a certain day. The fact that a given steel cannot be successfully formed to make a given stamping under a given set of conditions simply means that its forming characteristics are not suitable for those circumstances. The same steel may have excellent characteristics for other stampings, or even for the same stamping if die design or lubrication are modified.

When evaluating steel quality or trial steels, the tests should be made under the same conditions as those used when forming the steel with which a comparison is being made. If variables are changed, no true comparison of forming characteristics of several steels is possible.

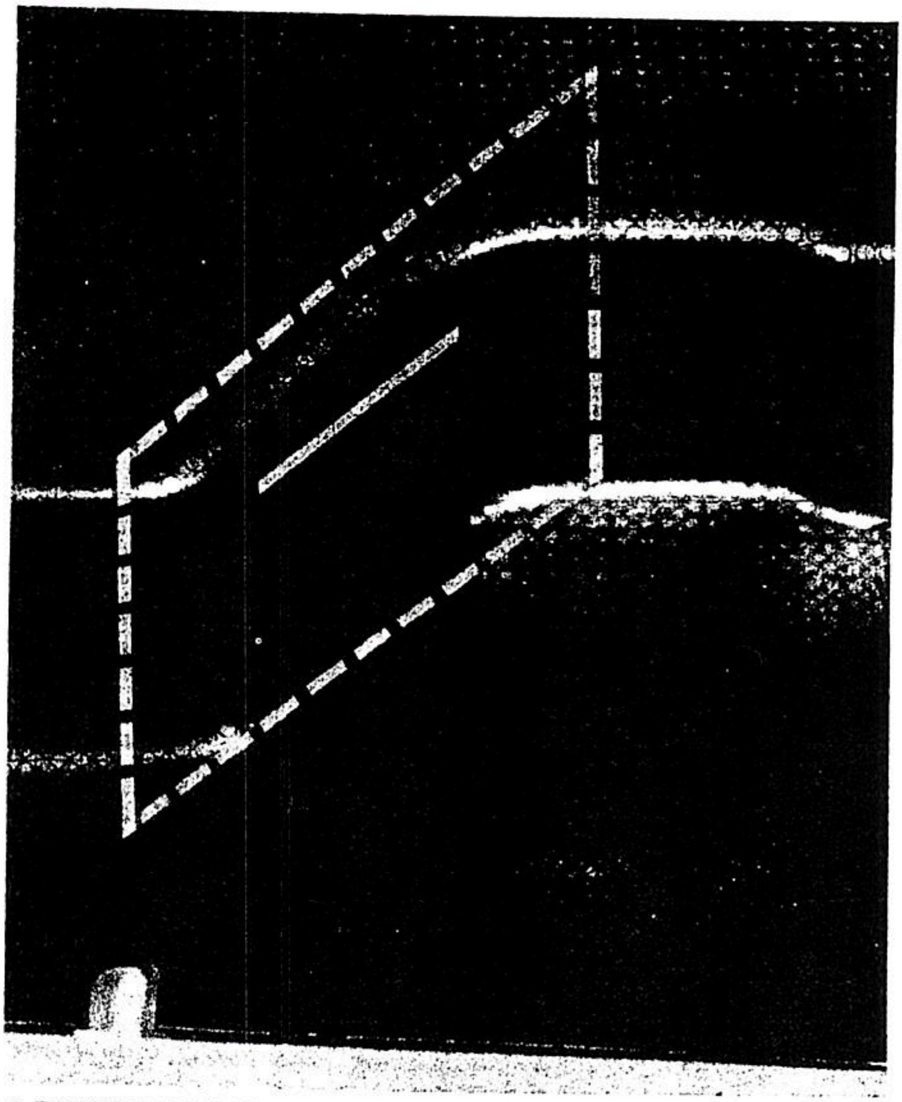
Suppose, for example, that a safety factor of 10 percent is required for a particular stamping. The production steel originally met the requirements; a trial steel, with a safety factor of 2 percent, does not.

Normally, the trial steel would be rejected as not having sufficient formability. It is possible, however, that the safety factor of the production steel is no longer 10 percent. A recent change in pad pressure, or a change in any one of a number of other variables, could reduce the current safety factor of the production steel to as little as 1 percent. The trial steel, with its safety factor of 2 percent, would actually be superior to the production steel. This illustrates the importance of continued monitoring.

Production monitoring is simple when the etched-circle system is used. After die tryout is completed, a blank of a standard or reference steel is gridded and formed. The strain distribution pattern of this steel would be different from that obtained with the production material (*Figure* 2), but could be used as a norm to characterize the die, press and lubricant conditions.

A library of these standards or reference steel blanks is stored. If the blanks are of a stabilized, aluminum-killed steel they need not be protected against aging. If the blanks are of rimmed steel, they should be stored in a deep freezer.

If stampings start to break in production the fault may lie in the material, the lubricant, or the die and press variables. Its mechanical properties may



3 FAILURE LOCATION on this instrument panel mounting plate is indicated by the solid white line. The 0.1-inch-diameter circles were electrochemically etched into the blank before forming. The area enclosed by the dashed line is shown in Figure 4. The circles indicate the strain patterns of this stamping.

PHYSICAL PROPERTIES OF SAMPLES USED IN INSTRUMENT PANEL MOUNTING PLATE

Percent of Breakage	Yield Strength (PSI)	Tensile Strength (PSI)	Ratio of TS/YS	Elongation in 2 Inches (%)	Rockwell B Hardness	Value of n^1	Value of $\bar{r}^2$
0	25,200	44,500	1.75	44	44	0.23	1.80
	26,800	44,800	1.67	43	44	0.23	
50	26,500	42,000	1.58	42	43	0.22	1.92
	28,500	45,000	1.58	41	43	0.22	
100	31,500	45,100	1.43	41	47	0.22	1.50
	34,600	46,000	1.33	40	48	0.20	

1. Coefficient of work hardening. 2. Average value of plastic anisotropy. (See Part 3, April issue.)

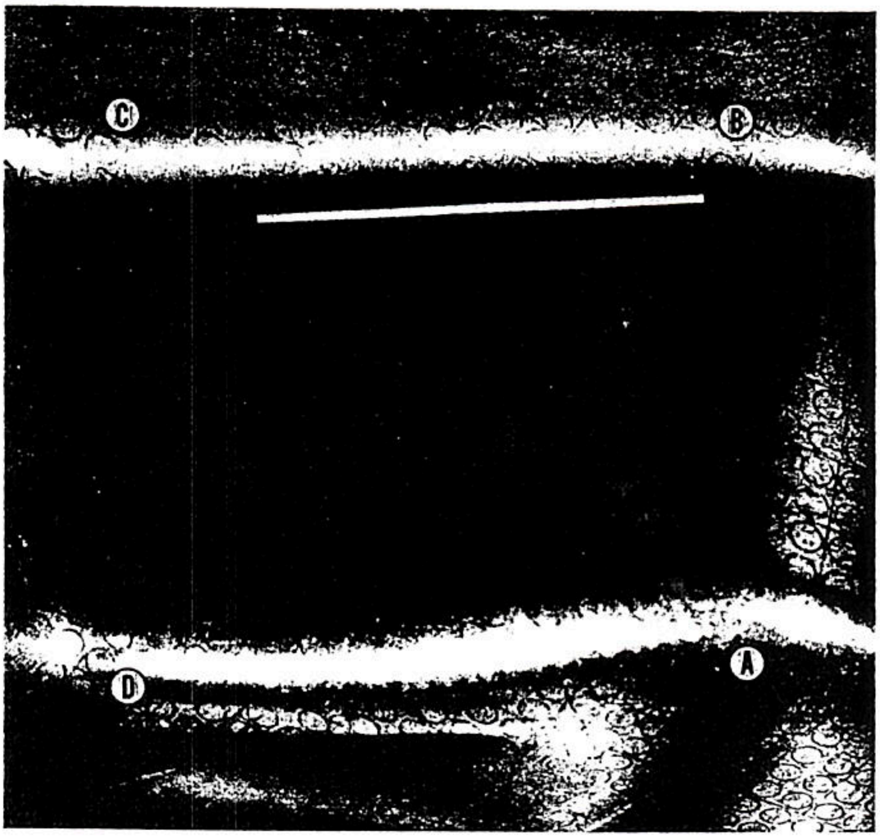
be different. When stampings start to break in production, a blank of the standard or reference steel can be formed. If the strain pattern is identical to the initial pattern or norm for that stamping, the die and lubricant have not changed so the material is at fault. If the standard steel shows a greatly changed strain pattern or increased maximum strain from the norm, the dies, lubricant or some other production variable have probably changed. The etched-circle system can be the key factor in identifying the cause of breakage.

In the same way, standard lots of lubricant can be made up for use in distinguishing between troubles caused by tools and troubles caused by lubricants.

Dies can be monitored, too—say once a month—with the aid of the etched-circle system. Tool wear can cause changes in strain distribution. Comparison of production stampings with stampings made from standard blanks from the library can show whether the safety factor is increasing or decreasing. If the safety factor is gradually becoming smaller, breakage can be anticipated and the dies modified during a normally scheduled maintenance period so that breakage will not interrupt a production run.

Standard blanks are also useful when resetting tools into a press, especially when evaluating alignment and pitman arm adjustments. If the strain patterns of stampings produced on the reset tools are identical with the norm, then the die alignment and pitman arm adjustments are similar to the initial conditions.

The etched-circle system is useful when evaluating lubricants. Lubricants greatly influence peak strains and safety factors. Since each lubricant performs differently in different dies, bench type testing of forming lubricants is only marginally satisfactory. For rapid comparison of lubricants under forming conditions, a series of prepared blanks is formed, each with a different lubricant. A safety factor for each lubricant can be quickly obtained. The lowest-cost lubricant that provides the required safety factor can then be selected.



4. CRITICAL AREA of the stamping shown in Figure 3. The electrochemically etched circles have been deformed into ellipses in this area. The direction of maximum strain is along the major axes of the ellipses. Unexpectedly, this is at an angle of 45 degrees to the failure direction shown by white line.

Causes of production difficulties can be analyzed through the use of the etched-circle system. In one case, automotive bumpers had a frosty appearance after plating. The plating process could have been at fault, or a high strain in the base material might have been causing "orange peel." There was no correlation between strain values and the degree of frosty appearance, so attention was turned to the plating process. Incorrect placement of plating anodes turned out to be the cause of the difficulty.

Slight differences in die construction can be found by analysis of strain distributions. This is particularly useful when symmetrical areas, and right-hand and left-hand parts, are being compared.

In one case, troubles occurred in the forming of a home clothes dryer top. Splits occurred in one corner, a neck in another corner. The third and fourth corners were formed without difficulty. According to the part print, all four corners were supposed to be identical. Strain readings, however, showed 65 percent peak strain in the torn corner, 55 percent peak strain in the necked corner, and peak strains of 45 percent and 35 percent in the other corners. Measurements of the radii of the four corners showed that strain levels were inversely proportional to the radii of the corners. When all radii were made the same as the largest radius, splits and necks disappeared.

The etched-circle system can be used for many different types of forming operations, even for explosive forming. Strain distributions in explosively formed domes proved to be very uniform in one case, enabling rather high domes to be obtained from a material having a very low ratio of tensile strength to yield strength.

Strain distributions in tubing have been obtained by electrochemically marking a pattern of circles on a coil of steel entering a tube mill. The steel was subsequently rolled into a round tube, welded, reformed into a rectangular tube by a turk's head and finally cut to length. The strain distribution around the perimeter of the tube was subsequently evaluated.

The circle patterns are an excellent training aid. The metal flow can be observed in successive forming steps. The effects of die changes are easily seen. Since the circle pattern can be applied electrochemically in 1 minute, tedious layout and hand scribing are avoided, and the educational process is accelerated. Only limited trial-and-error experience is needed to make intelligent decisions when the etched-circle system is used to analyze strain distributions.

How a typical stamping problem is solved, using prepared blanks and other techniques described in this article, can best be illustrated by a case history.

The problem stamping is an automotive instrument panel mounting plate. A section of the first draw is shown in *Figure* 3. When certain lots of electrogalvanized steel were formed, breakage was severe. Location of the break is indicated by the heavy solid white line.

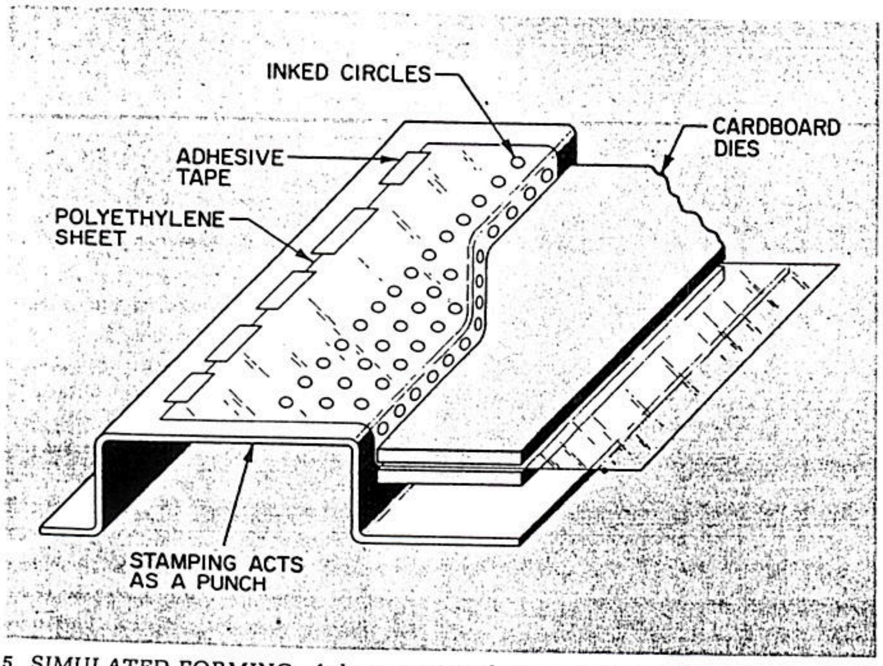
Looking at this photograph, one might conclude that the metal is restricted in the blank and/or in the upper and lower die radii, causing the direction of high strain to be vertical —up the stamping wall. Maximum strain would probably be between 40 and 60 percent (from the empirical critical strain level presented in Part 4 of this article) and failure would be perpendicular to the direction of maximum strain.

Three lots of steel had been used to make this stamping. Their breakage rates were 100 percent, 50 percent and zero. To analyze the reasons for breakage, mechanical property tests were made for samples from each lot and circle patterns were etched on blanks from each lot.

Torn stampings made from prepared blanks exhibited a condition quite different from what was expected. An enlarged view of the failure, showing the strain pattern, appears in *Figure* 4. The maximum strain direction is along a diagonal of the wall of the stamping. Failure is at an angle of 45 degrees to the direction of maximum strain. This is a failure condition often found in a tension test specimen after localized necking.

The failure strain was measured as 80 percent major strain (*AC*) and minus 25 percent minor strain (*BD*). This strain is just on the bottom edge of the critical strain level curve. (See *Figure* 7 of Part 4 of this article.) In terms of true strains, the major true strain is 0.59 and the minor true strain is minus 0.29. The ratio of minor true strain to major true strain is minus 0.49. This is almost identical to the ratio of minus 0.5 found in uniaxial tension tests. From the strain ratio and failure mode, it could be concluded that the failure was similar to that in a tension test—a long axis *AC*. Accordingly, the formability of the steel for this stamping should be directly related to its stretchability, as evidenced by a steep stress-strain curve, a high tensile-to-yield stress ratio and a high uniform elongation.

Such a material would tend to distribute the strain more uniformly in the presence of a stress gradient. No correlation with the anisotropy ratio *r* would be anticipated. The mechanical properties of the steels shown in the accompanying table confirm these relationships. Therefore a steel with a minimum longitudinal tensile-to-yield stress ratio of 1.75 was specified. For successful forming, a good aluminum-



5. SIMULATED FORMING of the stamping shown in Figures 3 and 4. The blank is a sheet of polyethylene. The punch is a completed stamping. The polyethylene sheet is sandwiched between two cardboard dies. As the dies are moved downward, the sheet is stretched over the punch. Inked circles on the sheet indicate the direction and magnitude of maximum forming strain in this stamping.

killed steel is undoubtedly required.

Once a suitable steel was selected, the origin of the strain was determined to see if the maximum strain could be reduced. To do this, it was necessary to understand the metal flow. Since no partially formed stampings were available for study, metal flow was simulated as shown in *Figure* 5, using a sheet of polyethylene as the blank and a completely formed stamping as the punch. One edge of the sheet was taped to the "punch"; the other end was free. Two cardboard dies simulated the die radii and the hold-down plate. The sheet was sandwiched between these dies, which had profiled edges to fit the contour of the punch.

During simulated forming, the polyethylene sheet was slowly pulled over the punch and was allowed to slip between the cardboard dies. Inked circles on the sheet helped to make the deformation (direction and magnitude of strain) visible.

When the sheet was fully formed, it had stretched (elongated circles) along diagonal *AC* and compressed into wrinkles along diagonal *BD*. This duplicated, to some degree, the deformation of the metal stamping.

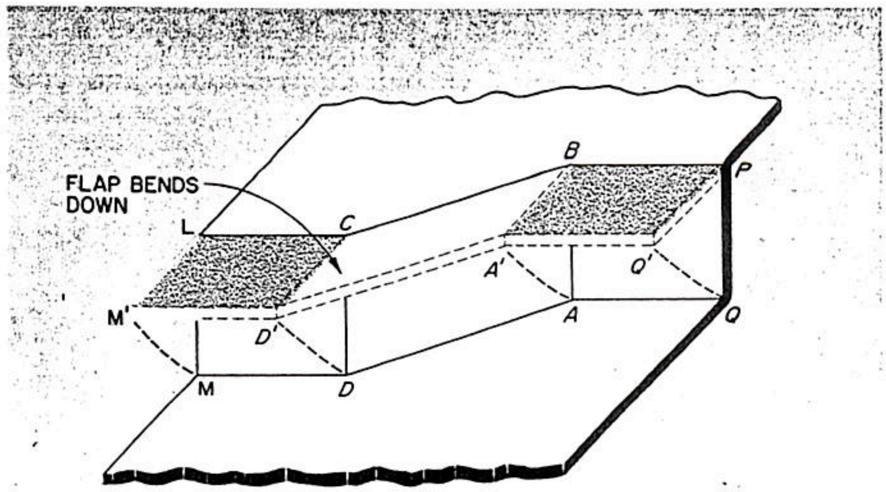
The next step in this analysis was development of the model shown in *Figure* 6. A section of the blank, *A'BPQ'*, is merely folded down to form the wall *ABPQ*. Strain within this area is practically zero. There is, of course, a bending and unbending of the steel in this section as it passes from the blank over the die and then flattens out into the wall. The initial and final states can be visualized by the flap being folded down, however.

A similar process takes place to form wall *CDML*. To maintain geometrical continuity of the blank, the middle section *A'BCD'* therefore must deform to fill space *ABCD* of the final stamping.

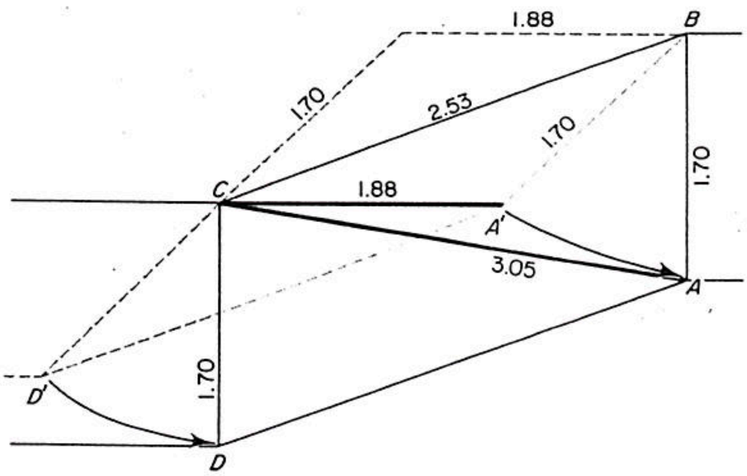
Further visualization shows that line *A'C* elongates to become diagonal *AC*. From the geometry of the stamping, *Figure* 7, a strain of 62 percent was required along the line *AC*. This agrees exceptionally well with an average strain of 63 percent measured between *A* and *C* on the stamping.

The other diagonal, *BD*, had a calculated strain of minus 22 percent and a measured strain of minus 25 percent.

The strains are generated only by the material being forced to conform to the geometrical shape of the punch.



6. DEFORMATION MODE in the instrument panel mounting plate shown in Figures 3, 4 and 5. The shaded flaps are bent down, forcing material A'BCD' to conform to area ABCD in the final part. Average strains are calculated from this.



$$\text{PERCENT STRAIN} = 100 \times \frac{\Delta e}{l_0} = \frac{3.05 - 1.88}{1.88} \times 100$$

STRAIN = 62 PERCENT

7. MAXIMUM STRAIN along diagonal AC of the instrument panel mounting plate stamping can be calculated from the geometry of the blank. This calculated strain corresponds with the actual strain measured on the formed part.

For this reason, changes in die radii, blank size and lubrication would not greatly affect forming. Changes in geometry of the stamping would have a great effect on the formability of the stamping but, since the geometry was fixed, the only way to avoid breakage was to carefully control the properties of the material.

Although the advent of strain measurement with the aid of the etched-circle system represents an important forward step in the engineering evaluation of stampings, further research is needed to broaden our understanding of sheet metal formability. Work is being done to determine the effects of cold working, cleanliness, aging, yield point elongation and many other variables. As research findings reach the stage of practical application, they will be reported in *Machinery*. ▲▲

Further Reading

The author has prepared an extensive list of worthwhile technical articles, papers and books for use by readers who would like to broaden their understanding of sheet metal formability. For a free copy of this bibliography, write to the editors of Machinery, *200 Madison Ave., New York, N. Y. 10016.*