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Circular Grid System — A Valuable Aid for Evaluating Sheet Metal Formability

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A KEY WORD in describing the production of successful stampings is formability. The term, which denotes the ability of metal to be deformed into desired shapes, is a communication link between the user and supplier of sheet metal. The fabricator attempts to specify desired levels of formability for each application and then makes quality control checks on incoming material. The producer wants to tailor his production practices to impart the specified level of formability into his products. Both agree that sheet metal should possess maximum formability.

Formability, however, is an elusive quality to measure. While our understanding and techniques are by no means complete, recent advances have greatly reduced the problem. One of the current attempts to measure formability is the grid analysis system in which grids composed of very small diameter circles (0.25-0.05 in.) are used. This system was first proposed in May 1965. (1)[*] At that time very limited press shop experience with the technique had been obtained; the bulk of the results had been derived from laboratory experiments. Now, after more than two years of production trials, a reexamination of the technique is in order. Our goals, therefore, are to:

1. Briefly review the evolution and mechanics of the technique.
2. Critically assess the present state-of-the-art.
3. Suggest areas of application.

A paper by G. M. Goodwin (2) examines specific case histories of applying the circular grid system.

EVOLUTION OF THE PROCESS

Traditional evaluations of formability are based on both fundamental and simulative tests. Within the first category are direct measurements of mechanical properties derived from a standard tensile test, such as yield stress, tensile strength, yield point elongation, and total elongation, and measurements of hardness. (3-8) Property levels required for successful stampings are determined either from an accumulation of many past trial and error attempts on similar stampings, or from long statistical correlations with press performance data.

Unfortunately, the relationship between test results and press performance data is often unclear; specifications so established are only partially valuable for selected stampings. Recent work by members of the International Deep Drawing Research Group (4, 5, 9-15) has contributed to a better understanding of this problem. Three new property measurements have evolved as being directly related to press performance: the coefficient of work hardening n (if hardening is parabolic), the coefficient of anisotropy r, and the circle arc elongation e_{ca}. These three measurements are discussed

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[*] Numbers in parentheses designate References at end of paper.

ABSTRACT

The circular grid system, in which a pattern of 0.05-0.25 in. diameter circles electrochemically marked on sheet specimens is used, permits a visual display of the magnitude and direction of the strain from point-to-point of a stamping. Strain values obtained from the grid are plotted relative to an empirical failure curve to indicate proximity of a stamping to failure. Analysis of the strain distribution allows one to reduce the die tryout period, assist in establishing material specifications, evaluate die modifications, and monitor die variables throughout production runs

in detail by R. H. Heyer and J. R. Newby. (16) Measurements of n, r and e_{ca} are routinely used in research and development laboratories, but are not seen extensively in production shops to date.

In an attempt to duplicate more closely actual forming operations, a series of simulative tests have evolved within the forming industry. (4, 5, 17) Examples of these tests include the Erichsen, Olsen, Fukui, Swift and hydraulic bulge tests. Problems are also encountered with these tests. Size effects, lubrication, test equipment standardization, and other test procedures often influence the results obtained as much as the material quality itself.

Even if testing problems could be eliminated, a basic obstacle is present in the philosophy of correlating press performance data with fundamental and simulative test results. This can best be explained with the assistance of Fig. 1. A stamping operation is composed of various combinations of stretch and draw, to which bending, buckling, and other complications are added. One could imagine a particular stamping to have a specific combination within the broad spectrum, as indicated by the arrow. Each of the fundamental and simulative tests can also be positioned along this spectrum, depending upon its relationship to combinations of stretch and draw. It is easy to understand why, in a particular instance, a formability test will correlate with the press performance data of one stamping and yet have no correlation with other stampings.

An excellent correlation between press performance and material property data can be obtained if the relative amounts of stretch and draw in each are matched. These amounts are not generally known except for some extreme cases, such as deep drawn cups and hydraulically bulged domes. Additionally, the exact position within the spectrum varies with material properties, surface roughness, lubrication, blank size, die and punch radii, temperature, press speed, and a multitude of known and unknown variables. To further complicate the problem, each location in a complex stamping not only experiences different amounts of stretch and draw, but the relative amounts change with depth as the stamping is formed.

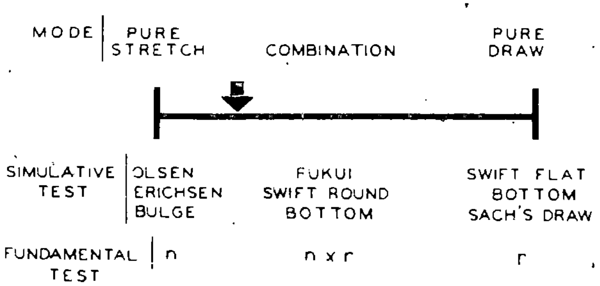

Fig. 1 - Schematic of complex stamping formed by combination of stretch and draw. Formability test must be matched to the particular stamping in order to correlate with press performance data

The correlation techniques just mentioned are sometimes successful if data are collected and analyzed over long press runs. This, unfortunately, is not very useful during die tryout periods or initial runs. The solution to the problem must be a technique which will quickly and accurately measure the ability of a single blank with given material properties to be formed into a specific stamping under the influence of the existing status of press and tool variables.

The first attempt to develop such a technique was the 1 in. scribed square test. (6, 18) This rapid method for determining material specifications from a minimum number of pieces involves scribing a blank with 1 in. squares, forming the blank, and using the maximum deformation in any 1 sq in. to establish steel requirements. For many automotive stampings, however, a grid spacing of 1 in. is too large to measure strain distributions and peak strains accurately. (1, 2, 5) Furthermore, the squares are seldom oriented to indicate directly the principal or maximum strain. The scribe mark can also introduce stress concentrations as evidenced by breakage along scribe lines

The 1 in. scribed square, however, did provide a stepping stone from which the analysis of small diameter circles evolved.

MECHANICS OF THE SYSTEM

The foundation of the circular grid analysis system is imprinting the blank with a grid composed of small diameter circles. (1, 2, 5, 19) The diameters of the circles currently used vary from 0.25-0.05 in., depending upon the strain gradient. For flat areas of large roof, hood, door and quarter panels with relatively constant strain levels, 0.25 in. diameters are satisfactory. For areas bent over sharper radii or punch heads, 0.10 in. diameters are more applicable. Some very sharp character lines and radii require 0.05 in. diameter circles for accurate evaluation of the peak strain. For general applications, however, the 0.10 in. diameter circles are used.

Circles have no preferential orientation. The direction of the principal or maximum strain is clearly displayed in the ellipse that results from deformation of the circle; its magnitude is calculated directly from measurements of the major and minor axes of the ellipse. These axes are measured in numerous ways. For coarse measurements, a flexible rule or specially designed tape is used with or without magnification. Dividers and a rule are also common. For more accurate measurements, a 10-power magnifier with a calibrated reticle is commercially available.

The choice of circle pattern is a matter of individual preference. Four common patterns are illustrated in Fig. 2. Pattern A, composed of separate and distinct circles, aids in the visualization of principal strain direction and magnitude as it varies from point to point. However, there are spaces between circles which are not encompassed by the pattern. Butting circles in pattern B tend to have wide lines at junction points making measurements more difficult; open space also occurs in this pattern. The overlapping circles of pattern C are popular because all of a given area is included in at least one circle; however, some areas are duplicated in measurements which could influence strain distributions - additionally, visualization of individual circles is difficult. The double overlapping in pattern D provides cross marks which act as locators for the centers of the circles and avoids wide lines at junction points.

In the past scribing methods have restricted grids to squares which can easily be ruled from parallel lines. Circle patterns generally cannot be scribed. Can you imagine giving a shop man the following assignment: scribe a pattern of 5000 - 0.10 in. diameter circles, accurate to 1%, on each of six blanks and have them ready for the press line in 15 minutes? Such a requirement demands some type of imprinting system. First attempts consisted of using a rubber stamp and marking ink. (20) Resolution and accuracy of grids prepared in this manner are limited and the ink markings are easily erased.

A photographic process has also been used. (20, 21) A photosensitive emulsion is placed on the metal sheet, exposed to an illuminated negative, and developed. Very fine and accurate grid systems, such as 100 lines to the inch, have been created in this manner. However, the grid is easily removed when rubbing over a die radius, and the time to produce one grid can be greater than 30 minutes. In addition, the technique is generally applied only to small parts evaluated in the laboratory. Similar comments are applicable to silk screen processes for applying grids.

The system currently being used for producing small diameter circular grids, or any other pattern desired, is electrochemical marking. (1, 20, 22) In this process, first used to produce grids by R. H. Heyer, a nonconducting sheet is treated so that the lines forming the desired pattern will conduct electricity. This "electrical stencil" is placed on the blank to be gridded (Fig. 3). Then a felt pad soaked in electrolyte, an electrode, and a weight are then placed on in that sequence. For large 9 by 9 in. grid areas a person standing on a platform placed on the electrode provides the weight. A 14 V a-c current is passed through the system for approximately 5 sec. The amperage required is a function of total conducting area and may reach 200 amp or more. An alternative technique requiring less amperage but more time utilizes a felt pad soaked in electrolyte (placed on the stencil) over which is pressed a rocker type electrode (Fig. 3).

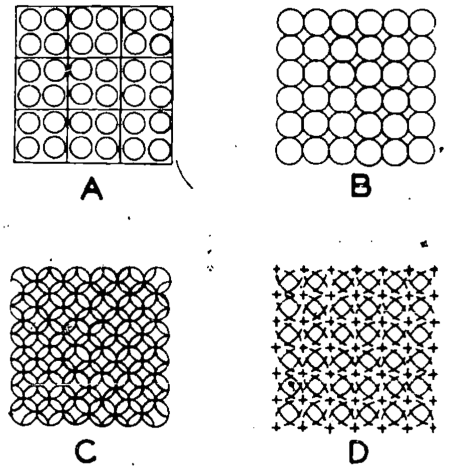

Fig. 2 - Four patterns of commonly used circle grids: A, separated; B, butted; C, overlap, D, double overlap

With either electrode, the grid pattern is etched into the blank and a black deposit replated into the grid lines. The depth of etching is proportional to the time of application. The grid remains visible after abrasion, yet does not introduce stress concentrations (preferential failure sites)

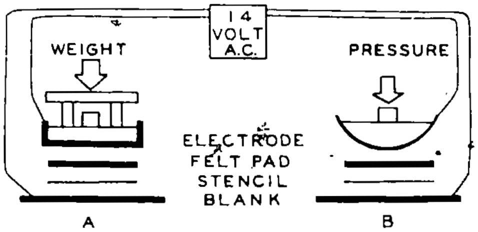

Fig. 3 - Schematic of electrochemical marking system: A, flat electrode requiring high amperage (200 amp or more); B, rocker electrode for low amperage

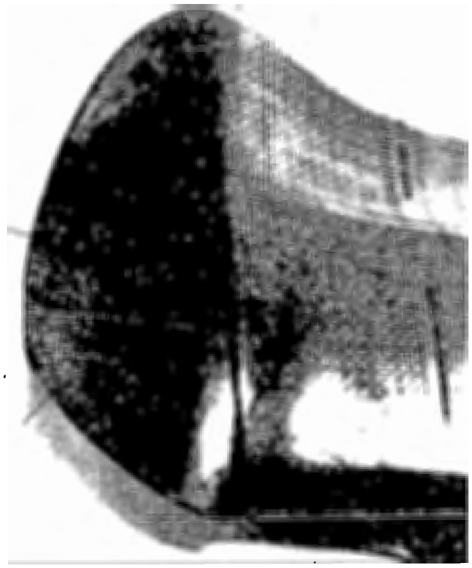

Fig. 4 - Flat blank, imprinted with two 9 x 9 in. patterns of 0.2 in. diameter circles, then formed. Direction and magnitude of principal (maximum) strain is visually displayed from point to point

created by scribed lines. Since the equipment is portable, a grid may be applied rapidly at the press line on any production size blanks. The electrical stencil, power source, and chemicals are commercially available from several companies in the marking business.

An illustration of the grid system on an automotive part is shown in Fig. 4. The grid was applied twice to the flat blank to cover an area larger than 9 by 9 in. Subsequently the blank was lubricated and formed into the final stamping. The grid remains visible even after severe forming operations.

PRESENT STATE-OF-THE-ART

The circular grid system is being used today by an increasing number of companies in the automotive and appliance industry to analyze deformation patterns. There are presently two major areas of utilization: visual display, and estimates of failure proximity.

VISUAL DISPLAY - A grid of small diameter circles visually displays the strain state of the formed stamping. Areas of severe deformation are revealed with the direction and magnitude of the principal (maximum) strains graphically displayed from point to point. The distribution of strain also indicates how localized the high strain area may be. With this system, strains at different stages in the forming process can be measured by deforming blanks to various degrees of completion. These are then plotted as a function of stamping depth to develop a graphic picture of the strain history at each location. Once critical areas are determined, modifications in material, die design, lubrication, etc., can be made to lower the peak strain or redistribute the strain pattern.

This visual display of strain is extremely important and is presently the largest use of these fine circular grids. A minimum of special training is required for interpretation. This visual display is often sufficient to suggest changes to tool and die men. In the example shown in Fig. 5, the high strain is concentrated in area A. Grids also help when two sides of a supposedly symmetrical stamping do not strain identically and one side fails. Observed variations in strain distribution can often be traced to unequal die radii, misgaging of the blank, variation of draw beads, and the like. Correction of these variations will be reflected by changes in the strain distribution patterns. Similar pattern changes can also be observed when changes in material and lubrication occur.

ESTIMATES OF FAILURE PROXIMITY - When a stamping tears in the press, it is obvious that some change in material, lubrication, or tooling is required to produce a successful part. Frequently, however, a stamping will not fail during die tryout because the diemaker often uses slow presses, excellent materials, hand lubrication, and properly set dies. If a stamping has not yet failed but is extremely close to failure, the stamping is said to be critical. In production, however, conditions other than optimum may exist and breakage of these critical stampings may occur. Reworking the dies during this period would cause costly downtime. It would therefore be extremely valuable to identify, during die tryout, those stampings which are critical and make necessary modifications.

Such an identification is possible by combining the information obtained from the small diameter circle grids with a failure curve which has been empirically developed for the more common ductile metals used in the automotive industry.

When a sheet of metal is stretched over a punch, the strain increases. If the stretching limit of the material is reached, the stamping tears. First, however, a trough of very localized deformation or local shear becomes evident on the surface; if punch load measurements are being recorded, an arrest in the load record would be detected. Fracture is more realistically defined in this paper by these events than by the usual concept of physical separation or tearing of the material. Strains have been measured at the onset of this fracture both in laboratory specimens of annealed tough-pitch copper, 1100 aluminum, 70/30 brass and aluminum-killed steel (11) and on production automotive steel stampings. (1, 19) These results are plotted in Fig. 6.

The y axis of the graph is the largest percentage strain found on the surface of the stamping. With a circular grid system, this would be the major axis of the resulting ellipse. The x axis is the surface strain perpendicular to the largest strain, or the minor axis of the same ellipse. The band drawn through these points separates failure and nonfailure conditions and is labeled the critical strain level. By measuring the strains on any given stamping and relating them to Fig. 6, the proximity to failure may be determined for each region of the stamping.

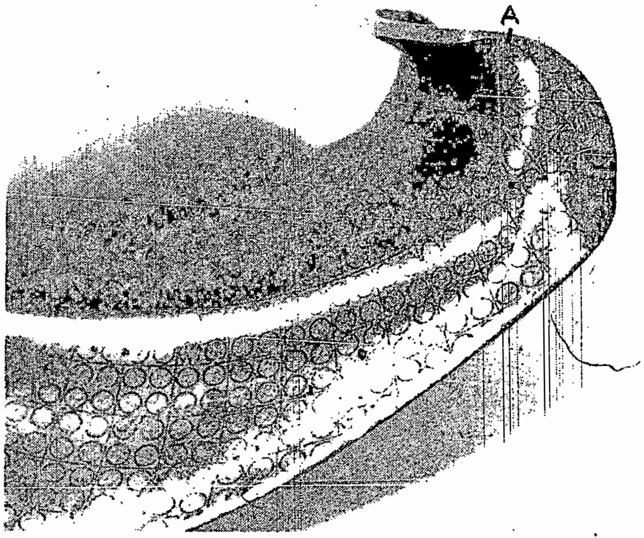

Fig. 5 - Hook portion of a bumper jack (A) showing localized area of high strain parallel to free edge. The 0.1 in. pattern was electrochemically marked on blank prior to two-stage forming operation

A new concept has therefore been established. One can no longer argue that steel A will stretch more than steel B, or that brass will stretch more than steel. The maximum strains, measured in a small length, are identical for equal perpendicular strains. Instead, one must evaluate how well each material distributes the strain in the presence of a stress gradient. Note that the emphasis has changed from which material will stretch more to which material will better distribute the strain. Modification of material properties is now just one of many methods which are available to redistribute the strain more uniformly and therefore permit a deeper stamping before failure or prevent failure at a given depth of formation. Changing material properties, however, may not be the best solution. Slight modifications of lubrication or tool and die geometry are often more effective in distributing the strain more uniformly than large changes in material properties. Goodwin (2) and Heyer (16) also discuss this point.

An interesting feature of the curve is that the critical strain level slopes upward. From this it would seem that one could restrict metal flow[*] perpendicular to the maximum strain direction to increase maximum allowable strain before fracture. It also means that the location of maximum strain may not be the fracture site. As an illustration, the central portion of an automotive bumper had a rounded dome-like nose which had biaxial tensile strains of 54% by 30%. This strain level (shown as A in Fig. 6) was near critical but had not caused failure because of the high perpendicular strain. At a location somewhat removed from the central portion was a sharp character line with a strain of 42% across the sharp ridge and no strain along the ridge (point B in Fig. 6). Critical conditions were satisfied here for a lower peak strain and the bumper failed at that location.

LIMITATIONS - The circular grid system will not presently solve all forming problems, nor is it probable it will do so in the future. The technique, even after two years, is just in its infancy and is in use by only a limited number of companies. More extensive trials are required. Some of the successes and failures achieved by various companies using this technique have not yet been reported.

The critical strain level has been investigated for only a few common ductile metals. One wonders how broad is the base of application, and are there similar curves at lower levels for less ductile metals? Occasional exceptions to the curve have been noted. Even though wide ranges of normal cleanliness do not affect the curve, very large inclusions or other imperfections can lower the failure strain. The critical strain level was obtained for annealed and lightly skin-passed materials; cold work of the metal is known to lower the curve. Presently the critical strain level is well defined for only strains which are tension-tension, although Goodwin (2) describes preliminary work for the tension -- compression combination of strains. The strain must also not be reversed, such as a tension strain imposed on a material previously compressed.

Even with these limitations, the grid analysis system is a valuable aid for evaluating sheet metal formability.

EXAMPLE OF GRID ANALYSIS

Occasionally a problem is found, such as an automotive instrument panel mounting plate, which is ideally suited for grid analysis. Certain lots of electro-galvanized steel encounter severe breakage for this part. A gridded stamping is shown in Fig. 7; the area of interest is shown within the dashed lines. The breakage location is indicated by the solid black line. An initial conclusion might be that the

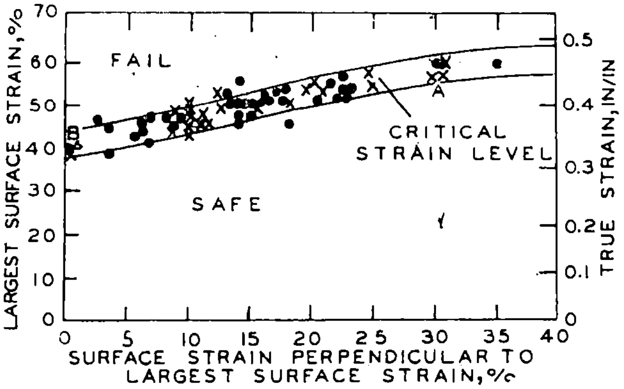

Fig. 6 - Summary of fracture strain measurements. Data values indicated as dots were obtained from laboratory biaxial stretching experiments for various annealed materials, punch geometries, and lubrications, while values indicated by X were derived from measurements of production automotive steel stampings

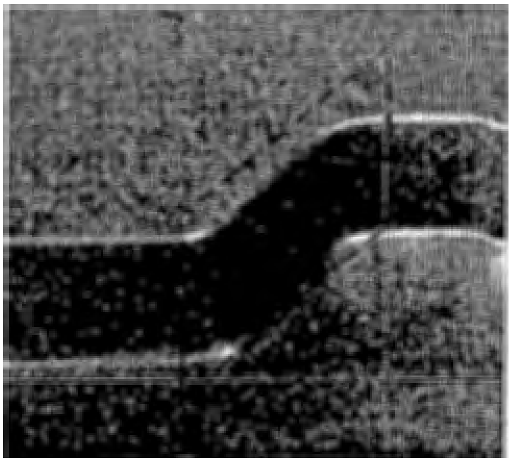

Fig. 7 - Section of instrument panel mounting plate showing failure location indicated by solid black line; dashed line area is shown enlarged in Fig. 8

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[*] Here metal flow means metal flowing in from the flange area. Restricting metal flow will increase the strain over the punch.

metal is restricted in the blank and that the maximum strain direction is perpendicular to the failure.

An examination of the grids within the critical area indicates quite an opposite condition (Fig. 8). The maximum strain direction is diagonal across the flat and at 45 deg to the failure. This is characteristic of the failure found in a tension specimen. Maximum strain values are +80% along the major axis and -25% along the minor axis. The ratios of the two strains are identical to those found in a tension test. This stamping is, in fact, pulling a tensile test along axis A - C. Because the strain values are tension-compression, Fig. 6 is not applicable. However, the strain is critical based on the tension-compression curve of Goodwin. (2)

In order to evaluate whether die or blank changes can reduce breakage, it is necessary to understand the metal flow. Partial stages of formation are not available to generate the strain history. The metal flow, however, can be simulated by forcing a sheet of polyethylene over the stamping. This sheet of polyethylene represents the original flat sheet of steel. A series of ink circles are stamped on the polyethylene sheet to help visualize the deformation. Two pieces of thick carboard are cut to the horizontal profile of the sidewall; these duplicate the die radius and holddown plate. The polyethylene is sandwiched between the two "cardboard dies" and the composite is pulled down the sidewall; the polyethylene is allowed to slip between the cardboard dies. At the bottom position, the polyethylene has stretched (elongated circles) along the diagonal A - C and compressed into wrinkles along B - D. The polyethylene model duplicates to some degree the deformation required of the steel.

The deformation pattern of the polyethylene can be analyzed and simplified. Fig. 9 illustrates the results. A section of the blank A' B P Q' is merely folded down to form the wall A B P Q; strain within this area is approximately 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. However, the initial and final states may be visualized by the flap being folded down. A similar process takes place to form wall C D M L. To maintain geometrical continuity of the blank, the middle section A' B C D' must therefore deform to fill space A B C D of the final part.

Further visualization will show that line A' - C will elongate to become diagonal A - C, the axis of maximum elongation. From geometry, a strain of 62% is calculated for line A - C. This agrees exceptionally well with an average strain of 63% measured between A and C on the stamping. The other diagonal B - D has a calculated strain of -22% and a measured strain of -25%. Because the strains are generated only from material being forced to conform to the geometric shape, changes in die radii, blank size, lubrication, etc., would not radically affect the press performance. Changes in part dimensions, however, would have a very great effect.

Apart from any geometric considerations, there remains the problem of various lots of material generating radically different breakage statistics. From the previous analysis, it can be determined that the stamping is actually tensile testing the steel along axis A - C. Therefore, press performance data on the various lots of steel should be in direct correlation to the stretching ability of the steel, as evidenced by a steep stress-strain curve, a high tensile-to-yield stress ratio (TS/YS), and a high uniform elongation. Such a material would tend to distribute the strain more uniformly in the presence of a stress gradient. The mechani-

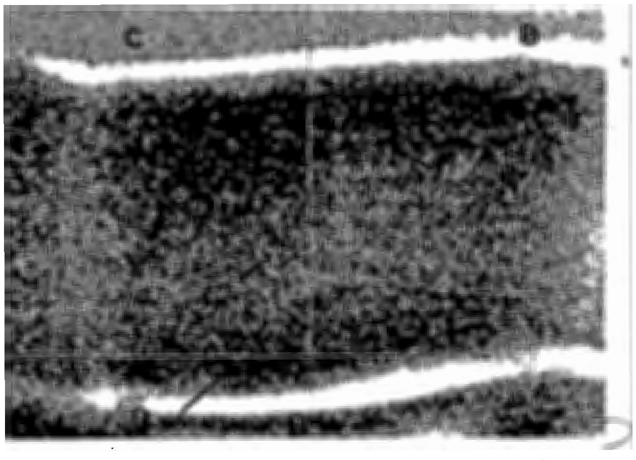

Fig. 8 - Maximum strain direction A - C in critical area is 45 deg to the failure, indicated by solid black line. Original grid pattern was 0.1 in. diameter circles

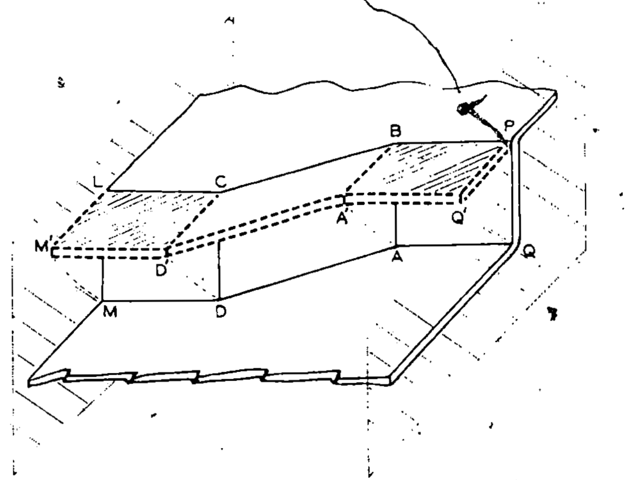

Fig. 9 - Schematic depicting deformation mode in instrument panel mounting plate. Two shaded flaps bend down, forcing material A' B C D' to conform to area A B C D in final part. Average strains along A - C and B - D can be calculated from this model

cal property results in Table 1 confirm the relationship. In this particular case, the mechanical properties required for a successful stamping are now determined.

SUGGESTED APPLICATIONS

REDUCTION OF DIE TRYOUT - The most opportune time to employ the grid analysis technique is during die tryout. A simple, single blank test will identify critical stampings. Efforts can then be directed toward reducing the peak strain by redistributing the strain more uniformly throughout the stamping.

Many modifications can be made to the die and blank geometry. By numerically comparing strain distributions measured from finely gridded blanks formed before and after the modifications, much guesswork and opinion would be removed. Sometimes modifications unintentionally increase the peak strain instead of reducing it. This result and other effects of changes may not be observable without grid measurements.

Progress made during die tryout can be quantitatively recorded. Some master mechanics carry portable electrochemical marking units when visiting various die shops in order to evaluate the current conditions of the dies.

Finally, numbers are available to substantiate requests for engineering changes. If the best material available shows a critical level of strain, then lubrication and/or die changes are the only available avenues remaining.

SPECIFICATION OF INITIAL MATERIALS - Analysis of the circular grid is used today to specify properties (or a commercial grade of steel) for stampings. First, a trial blank with a grid on the surface is formed into a finished stamping; tensile properties are also obtained from a second blank. The maximum or peak strain in the formed stamping is measured. If this peak strain is well below the critical strain level shown in Fig. 6, the mechanical properties of the trial blank are considered to be the property specifications of the material. These properties, in turn, indicate the grade and quality to be used. If the peak strain in the stampings is at the critical level, a material with a higher tensile-to-yield strength ratio and uniform elongation is suggested, or die and press variables must be changed.

Emphasis must be placed on knowing the properties or quality of the blanks used for the circular grid test. Small changes in properties can create widely different press performances; the same property changes also affect the strain distribution. One, therefore, must identify the measured peak strain and strain distribution with a given set of properties. The test blank must be identical to the steel intended for the specific job. A blank with different properties will have a different strain distribution and will respond differently in the press.

Similar tests can evaluate lubricants. Each lubricant is used to form a gridded blank of a standard material. The lubricant which shows maximum reduction of the peak strain below the critical strain level is the best--economic factors being equal.

MONITOR PRODUCTION RUNS - Die conditions often change during an extended production run. Optimum die conditions may then vanish, causing the peak strain to approach the critical level. Periodic checks would forewarn of the impending danger. Alternatively, the peak strain may move away from the critical strain level to increase the safety factor*.

Table 1 - Physical Properties of Samples Used in the Instrument Panel Mounting Plate

Per Cent Breakage		Yield, psi	Tensile, psi	TS/YS Ratio	Per Cent Elongation in 2 in.	Rockwell B	n (a)	$\bar{r}$ (b)
0	L	25,500	44,500	1.75	44	44	0.23	1.80
	T	26,800	44,800	1.67	43	44	0.23	
50	L	26,500	42,000	1.58	42	43	0.22	1.92
	T	28,500	45,000	1.58	41	43	0.22	
100	L	31,500	45,100	1.43	41	47	0.22	1.50
	T	34,600	46,000	1.33	40	48	0.20	

(a) Calculated by the Nelson - Winlock method.

(b) $$\bar{r} = \frac{r_{0\ deg} + 2\, r_{45\ deg} + r_{90\ deg}}{4}$$

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*The safety factor is taken to be the difference between the critical strain level and the actual strain level in the stamping. A safety factor of 0 indicates a critical stamping.

Sometimes sudden breakage occurs and it is not known whether the material or die has changed. By maintaining a library of standard material, a "check blank" with a grid could be rapidly formed and measured. If the strain distribution remained the same, then the tools most likely did not change and the material would be suspected. If, on the other hand, the strain distribution had peaked to a higher strain, then tool or press variables should be investigated. This would be especially helpful information when resetting tools back into a press after removal.

Experimental steels could be rapidly evaluated with only a few blanks by comparing the strain distribution obtained from the experimental steel with that found in the production steel.

SUMMARY

1. Current formability measurements derived from fundamental and simulative test data often do not correlate with press performance results. The formability value obtained is usually influenced more by test procedure than by the quality of the material itself. Amounts of stretch and draw in the stamping do not always match those of the formability test.

2. Strain distributions and maximum strain values are measured from a grid-type pattern composed of small diameter (0.25-0.05 in.) circles, which indicate directly the principal (maximum) strain direction and magnitude. The grids are imprinted on the blanks by a rapid and accurate electrochemical marking system.

3. The grid creates a visual display of the high strain areas, which can provide a clue for eliminating failures.

4. A failure analysis can be conducted which will indicate the proximity of a stamping to failure. The empirical failure criterion is the largest allowable (critical) strain in the surface of the sheet. The level of this critical strain increases with increasing surface strain perpendicular to the largest strain. Failure is anticipated for strain conditions above this critical level.

5. The critical strain level is presently limited to annealed and lightly skin passed steel, copper, brass, and aluminum subjected to tensile-tensile surface strains. Studies are being conducted on the effect of cold work and on tensile-compressive strain states.

6. A report of an instrument panel mounting plate illustrates one example where analysis of the circular grid provided a solution to the breakage problem.

7. Strain distribution analysis may be used to detect critical stampings, reduce production breakage, monitor die modifications, and evaluate material specifications.

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