THE IMPORTANCE OF DIRECTIONALITY IN DRAWING QUALITY SHEET STEEL

By R. L. Whiteley

While directionality which produces earing during drawing is generally objectionable, another component of directionality representing differences in properties perpendicular and parallel to the plane of the sheet can be an asset to good drawability. This component of directionality can be measured in a simple tensile test by the ratio of transverse strains. The relationship between drawability and directionality as measured by this strain ratio is demonstrated in a simple cup drawing operation. The results of the experimental work are explained by a theoretical analysis of cup drawing which allows for the anisotropy or directionality of the metal. (ASM-SLA Classification: Q23q, G4; ST, 4–53)

DIRECTIONALITY in drawing quality steels has long been of major interest to fabricators and the subject of several experimental investigations (1,2,3).[1] Usually it is recognized only in a two dimensional sense as indicated by differences in properties measured in the plane of the sheet. This "planar" directionality is, of course, readily observed in the press shop as "ears" in cup drawing operations, the height of the ears being indicative of the severity of the differences in properties. As such, directionality is usually considered objectionable in drawing quality steels.

Absence of earing during drawing does not preclude other components of directionality in the sheet, however. Directionality is a three dimensional effect and its absence in the plane of the sheet does not assure that properties measured in a direction perpendicular or normal to the sheet are the same as the properties measured in the plane of the sheet. The "normal" directionality of a material is often more pronounced than its planar directionality, and while not visually observed in the press shop, is nevertheless important to the press performance of the material. Moreover, unlike the planar directionality, normal directionality can be beneficial to the press performance of the material.

The importance of normal directionality has probably not been recognized, because it is not visually observed in the press shop and the obvious difficulty of measuring properties perpendicular to the plane of the sheet. However, tensile specimens of sheet material on plastic

[1] The figures appearing in parentheses pertain to the references appended to this paper.

A paper presented before the Forty-first Annual Convention of the Society, held in Chicago, November 2–6, 1959.

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deformation often exhibit different amounts of strain in their width and thickness dimensions. This behavior is a manifestation of normal directionality and can be demonstrated (4) to be a consequence of a difference in the strength of the material perpendicular and parallel to the plane of the sheet. The ratio of the width and thickness strains measured in a tensile specimen at any strain level is almost a constant value. This constant strain ratio, R, has previously been suggested as a measure of directionality (2,3).

If R is measured in several directions in the sheet, an indication of both the planar and normal components of directionality can be obtained. Planar directionality is indicated by a difference in R in the different directions, while the normal directionality is indicated by the average value of R. A completely isotropic material would have a value of R equal to one in all directions. A material with an average value of R greater than one would be generally more resistant to thinning and puckering during forming than a perfectly isotropic material. Such a material should be desirable for most drawing operations.

The strain ratio was first related to drawability by Lankford, Snyder and Bauscher (2) on the basis of the press performance of forty-six lots of aluminum-killed steels applied to unsymmetrical fender draws. They found that materials with high values of R showed better press performance than materials with low R values. However, they felt the correlation established could only be explained by the unsymmetrical nature of the fender draws, and would not persist in a symmetrical drawing operation. Discussions of their paper by Halley, and by Heyer and Solter suggested that directionality indicated by high values of R should be as desirable for symmetrical drawing operations as for unsymmetrical drawing operations. The present study offers an experimental and theoretical demonstration that a relationship between drawability and directionality for a symmetrical drawing operation does exist.

Experimental Method

The experimental work was designed to evaluate the drawability of several materials of widely varying properties and directionality with the purpose of determining the relative effect of directionality and other properties upon drawability.

Twenty-two drawing materials were tested; sixteen low carbon steels (eight rimmed and eight aluminum-killed), two stainless steels, two aluminum alloys, commercially pure copper and 65/35 brass. These materials ranged in yield strength from 5000 psi. to 45,000 psi in total elongation from 25 to 50%. The average strain ratio, R, ranged from 0.6 to 1.6 indicating a considerable degree of normal directionality in certain materials. The stainless steels and nonferrous metals were all commercially processed, but some of the low carbon steels were specially treated to attain a greater range of properties than ordinarily en-

Table I
Description and Mechanical Properties of Materials Tested

Code No.	Material	Condition	Yield Strength psi.	Tensile Strength psi.	% Elongation in 2 inches
10	Rimmed steel	Annealed[1]	23,200	38,500	43.6
11	Rimmed steel	Annealed	31,600	43,600	41.5
18	Rimmed steel	Annealed	31,300	42,900	41.0
22-1	Rimmed steel	As skin rolled	25,700	45,500	39.3
22-2	Rimmed steel	Aged 43 days	31,300	45,200	36.7
23	Rimmed steel	As skin rolled	26,700	44,400	36.4
24	Rimmed steel	As skin rolled	24,700	43,000	40.1
25	Rimmed steel	As skin rolled	26,900	44,600	39.7
1	Killed steel	As skin rolled	23,200	45,100	36.3
2	Killed steel	Annealed[1]	14,400	41,400	42.0
14	Killed steel	As skin rolled	24,600	43,900	40.6
19	Killed steel	As skin rolled	24,600	45,100	40.1
20	Killed steel	As skin rolled[2]	27,300	45,600	37.8
21	Killed steel	Annealed	31,300	44,700	40.6
34	Killed steel	As skin rolled	19,800	42,500	42.2
38	Killed steel	As skin rolled	23,700	44,700	40.5
3	430—Stainless	Annealed	45,400	78,200	25.2
6	301—Stainless	Annealed	43,200	93,900	50.7
4	2SO—Aluminum	Annealed	5,200	13,300	34.6
5	52SO—Aluminum	Annealed	12,800	28,200	25.8
7	Copper[3]	Annealed	12,300	31,300	43.7
9	65/35 Brass	Quarter hard	38,600	55,500	37.0

Notes:
[1] Annealed in wet H_2
[2] Skin rolled—2%
[3] Commercially pure copper

countered commercially. A brief description of the materials and their properties is given in Table I.

The drawability of each material was evaluated by determining the largest blank of the material which could be successfully drawn into a 2-inch flat-bottomed cup like that shown in Fig. 1. This drawing operation was carried out on a small drawing press (5) under conditions proposed by the Swift-Cup-Forming Sub-Committee of BISRA (6). The procedure followed was to draw successive blanks of increasing diameters until the blanks failed to draw. The drawability of the material was then expressed as the ratio of D, the diameter of the largest blank successfully drawn, to d, the diameter of the drawn cup, (in this case two inches). The ratio D/d is called the drawing ratio.

The directionality of each material was determined by measuring the strain ratio, R, at different angles to the rolling direction. This was done by measuring the longitudinal and width strains of a ¾-inch wide parallel sided specimen elongated approximately 20%. The longitudinal strain was measured over a 2-inch gage length while the width strain was the average of five values measured within the 2-inch gage length. On the assumption that the volume of the specimen is constant during plastic deformation, the strain ratio, R, was then calculated from these values of width and length strains (3). Strain ratios determined by this procedure were found to be more accurate and reproducible than values obtained by measuring the thickness strains directly. Other mechanical properties were determined by standard tests.

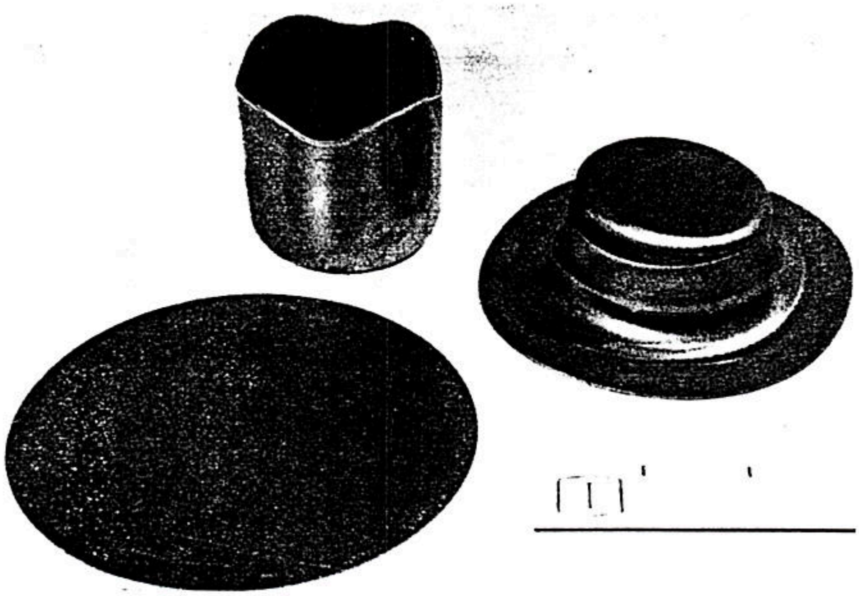

Fig. 1—Initial Test Blank and Final Cups Formed in a Successful and an Unsuccessful Cup Drawing Test. Earing of the successfully formed cup is a result of the planar directionality of the material.

Experimental Results

Considering the extreme range of properties in the materials tested, the range of drawabilities as measured by the drawing ratio was not great. The best material, an aluminum-killed steel, had a drawing ratio

Table II
Drawability and Directionality of Materials Tested

	Drawability		Directionality	
Code No.	Maximum Drawing Ratio D/d	Direction of earing, Angle to R. D.	Average Strain Ratio $R_{avg.}$	Direction of Maximum R, Angle to R. D.
10	2.175	0°, 90°	1.01	0°, 90°
11	2.15	0°, 90°	1.12	0°, 90°
18	2.20	0°, 90°	1.11	0°, 90°
22-1	2.175	0°, 90°	1.13	0°, 90°
22-2	2.175	0°, 90°	1.10	0°, 90°
23	2.175	0°, 90°	1.30	0°, 90°
24	2.20	0°, 90°	1.28	0°, 90°
25	2.175	0°, 90°	1.10	0°, 90°
1	2.25	0°, 90°	1.48	0°, 90°
2	2.30	0°, 90°	1.62	0°, 90°
14	2.225	0°, 90°	1.64	0°, 90°
19	2.25	0°, 90°	1.35	0°, 90°
20	2.25	0°, 90°	1.34	0°, 90°
21	2.225	0°, 90°	1.40	0°, 90°
34	2.225	0°, 90°	1.54	0°, 90°
38	2.20	0°, 90°	1.34	0°, 90°
3	2.15	0°, 90°	1.13	22½°, 90°
6	2.175	No ears	0.93	No max.
4	2.10	0°, 90°	0.65	0°, 90°
5	2.125	0°, 90°	0.58	0°, 90°
7	2.225	No ears	0.95	No max.
9	2.15	No ears	0.74	No max.

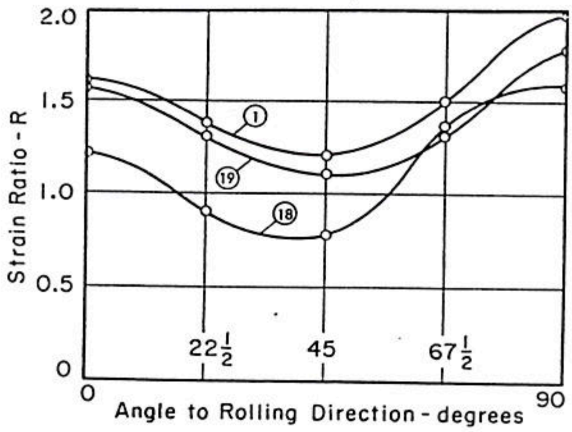

Fig. 2—Typical Directional Variation of the Strain Ratio, R Observed in All the Low Carbon Steels Tested. Steels 1 and 19 are drawing quality aluminum-killed steels while steel 18 is a drawing quality rimmed steel.

of 2.30, while the poorest material, 2S0 aluminum, had a drawing ratio of 2.10. While this is only a 10% difference in drawing ratio, it represents nearly a 30% difference in the depth of cup formed, a perhaps more significant parameter. In general, the aluminum-killed steels showed the best drawabilities, while the stainless steels and nonferrous metals had the poorest (See Table II). The drawing ratios for the aluminum-killed steels and rimmed steels were similar to those reported by Kemmis (6). While most of the materials produced ears when drawn, the occurrence of earing did not appear to affect the relative drawability of the materials.

On the basis of the measured R values none of the materials were perfectly isotropic (See Table II). Copper and the austenitic stainless steel which showed the least directionality had strain ratios slightly less than one in all directions. The 65/35 brass showed little planar directionality but had an average strain ratio of 0.74 indicating a significant degree of normal directionality. All other materials possessed considerable planar directionality as indicated by the different values of strain ratio measured in different directions. Fig. 2 shows the directional variation in R for three low carbon steels, these variations being typical of that found in almost any box-annealed low carbon steel. The correspondence between earing and the directional variations in R was quite good; the height of the ears produced generally varied according to the degree of fluctuation in R and in almost all cases the ears formed in the directions in which R was a maximum. All the low carbon steels tested exhibited ears at 0° and 90° to the rolling direction, and the only materials which did not ear (brass, copper, and austenitic stainless steel) were those which showed only little or no directional variation in R.

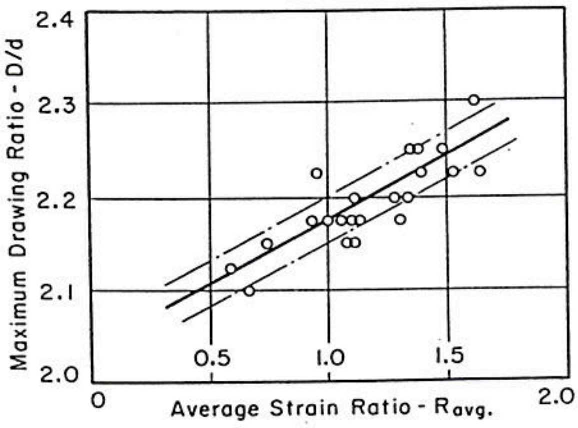

Fig. 3—Effect of the Average Strain Ratio, $R_{avg.}$, On the Maximum Drawing Ratio, D/d. The dashed lines represent the limits of experimental error.

Table III
Correlation of Drawing Ratio with Mechanical Properties

Mechanical Property	Coefficient of Correlation—r[1]	Significance of Correlation
Yield Strength	−0.12	Not significant
Tensile Strength	+0.07	Not significant
Yield-Tensile Ratio	+0.16	Not significant
Elongation in 2"	+0.42	Not significant
Olsen Ductility	+0.44	Not significant
Strain Hard. Exp.-n	+0.04	Not significant
Strain Ratio—$R_{avg.}$	+0.83	Highly significant[2]
Factor—R × n	+0.73	Highly significant[2]

[1] For perfect correlation r = ±1, a negative coefficient indicating an inverse correlation.
[2] Probability that correlation is due to chance is less than 0.1%.

The normal directionality of each material was determined by averaging the strain ratios measured in all directions. Fig. 3 shows the relationship between the drawing ratios and the average strain ratios of the materials. While the data show considerable scatter, a definite relationship exists between drawability and normal directionality. If we assume the experimental accuracy of the drawing ratio is ±.025, a value suggested by Kemmis, a direct straight-line relationship is indicated between the drawing ratio, D/d, and the average strain ratio, R_{avg}.

The relative dependence of drawability on the strain ratio and other mechanical properties was determined by treating the data statistically to determine coefficients of correlation between the drawing ratio and each of the properties measured. The results of this statistical analysis are summarized in Table III. The only single property to show a significant relationship to drawability was the average strain ratio. The best indication of press performance found by Lankford, et al., was the factor R × n, where n was the strain-hardening exponent of the steel. While a similar correlation can also be established for the present data, the correlation is not as good as that between the drawing ratio and the value of R alone. The present data indicates that drawability is determined largely, if not entirely, by the normal directionality of the material.

Discussion

The singular dependence of the drawing ratio upon R found by the above experiments is predicted by an analysis of the forces acting during drawing. The analysis, described in the Appendix, shows that the strength of the wall of the forming cup increases with the value of the strain ratio of the material. Because a material with a high strain ratio can support a greater punch load than an isotropic material of the same tensile strength, a larger diameter blank can be drawn into the die without failure in the wall of the cup. Other properties which act to strengthen the wall of the cup (for instance, tensile strength) also act proportionately to increase the punch force required to draw a blank of a given diameter. As a result these properties do not affect the overall drawability of the material.

The relation between press performance and the factor $R \times n$ found by Lankford, et al., is probably due to the character of the forming operations they studied. The drawing of a flat-bottomed cup involves almost no stretching, but the forming of a fender usually involves a considerable degree of stretching as well as drawing. In a pure stretching operation the forming limit is determined by the useful ductility (uniform elongation) of the material. This can usually be related to the strain-hardening exponent, n, of the material. Thus in a forming operation which involves both stretching and drawing, such as a fender draw, the press performance would more than likely depend on both R and n.

The superior press performance of aluminum-killed steels over rimmed steels recognized by fabricators for some time was also observed in the present experiment. Past efforts to correlate this superior performance with a simple material property have heretofore been unsuccessful. However, in the present experiment the superior drawing performance of the aluminum-killed steels can be attributed entirely to their higher average strain ratios, i.e., their greater directionality.

Conclusions

Directionality is an important property of drawing quality steels not always detrimental to press performance. While planar directionality is usually objectionable, normal directionality indicated by a high average strain ratio is desirable for good drawability even in symmetrical drawing operations. The general superiority of aluminum-killed steels over rimmed steels for deep drawing applications can be attributed to the greater normal directionality of the aluminum-killed steels.

Appendix

In a simple cup drawing operation, the portion of the blank beyond the die opening is drawn inward toward the punch. As each circular element reaches the die opening it is bent down over the die profile and pulled through the die opening to form a portion of the cup wall. The operation is completed when the periphery of the blank is reduced to the circumference of the cup wall.

The punch load required for this operation is determined by the forces required to plastically deform that portion of the blank outside the die opening. This force acts from the perifery of the die opening in the form of radial tensile stresses. These stresses are comparable to the internal stresses required to plastically deform a hollow cylinder whose outer diameter is equal to the initial blank diameter, D, and whose inner diameter is equal to that of the final cup diameter, d. The solution of this problem for a directional or anisotropic (but nonstrain hardening) material has been carried out by Hu (7). The radial stress is:

$$\sigma_r = \sqrt{\alpha_{33}/G}\,\kappa \ln(D/d) \qquad \text{Equation 1}$$

where α_{33} and G are anisotropic parameters
κ = the effective strength
σ_r = the radial stress acting at $r = d/2$.

This stress multiplied by πdt (t = thickness of the blank) is the portion of the punch load required to plastically deform the material itself. Willis, (8) summarizing the work of Swift, states that this load must be increased by a factor of $(1 + \eta)$ to account for frictional forces. The parameter η is constant for given conditions of geometry and friction, and usually has a value between 0.2 and 0.3. The total punch load required to draw a blank of diameter D, is thus:

$$P_r = (1 + \eta)\pi dt\sqrt{\alpha_{33}/G}\,\kappa \ln(D/d) \qquad \text{Equation 2}$$

However, the maximum diameter blank that can be drawn is limited by the axial (punch) load which can be supported by the material forming the wall of the cup. Using Hu's (7) equations for plane stress, we can also determine this load in terms of the same anisotropic parameters. Hu expresses the effective strength of the material in plane stress by the equation:

$$\alpha_{11}\sigma_{11}^2 - 2\alpha_{12}\sigma_{11}\sigma_{22} + \alpha_{22}\sigma_{22}^2 = \kappa^2 \qquad \text{Equation 3}$$

where $\alpha_{11}, \alpha_{12}, \alpha_{22}$ are anisotropic parameters
σ_{11} = the principal stress in the 11 direction
σ_{22} = the principal stress in the 22 direction

Associating 11 and 22 with the axial and circumferential directions of the cup wall we must impose the restricting condition that the circumferential strain, $de_{22} = 0$. Applying this restriction to Hu's stress-strain increment equations and solving Equation 3 for σ_{11}, the axial strength of the cup wall is found to be:

$$\sigma_a = \sqrt{\alpha_{22}/G}\,\kappa \qquad \text{Equation 4}$$

This strength multiplied over the cross-sectional area of the cup wall πdt gives the maximum punch load which can be supported by the cup wall:

$$P_{max} = \pi dt\,\sqrt{\alpha_{22}/G}\,\kappa \qquad \text{Equation 5}$$

The maximum diameter blank which can be drawn is that which requires a punch load just equal to the maximum load which can be supported by the wall of the cup. Thus equating 2 and 5, the maximum drawing ratio D/d is found to be determined only by the anisotropic parameters of the material for given conditions of geometry and lubrication, i.e., for η = constant.

$$\ln (D/d) = 1/(1+\eta)\,\sqrt{\alpha_{22}/\alpha_{33}} \qquad \text{Equation 6}$$

Note that κ, the effective strength of the material, does not effect the maximum drawing ratio.

If we assume a material with only normal directionality (rotational isotropy) the above anisotropic parameters can be expressed in terms of the average strain ratio, R. Such a material requires that:

$$de_{33}/de_{22} = R_{11} = R_{22} = de_{33}/de_{11}$$

Applying this restriction and that of symmetry in the 11 and 22 directions, and arbitrarily setting $\alpha_{11} = 1$, the following relationships are found:

$$\alpha_{11} = \alpha_{22} = 1$$
$$\alpha_{33} = 2/(1+R$$
$$\alpha_{12} = R/(1+R)$$
$$\alpha_{13} = \alpha_{23} = 1/(1+R)$$
$$G = (1+2R)/(1+R)^2$$

Using these relationships, Equations 2, 5, and 6 can be rewritten in terms of the strain ratio, R.

$$P_r = (1+\eta)\,\pi dt\,\sqrt{(2+2R)/(1+2R)}\,\kappa \ln (D/d) \qquad \text{Equation 2-R}$$

$$P_{max} = \pi dt\,\sqrt{(1+R)^2/(1+2R)}\,\kappa \qquad \text{Equation 5-R}$$

$$\ln (D/d) = \sqrt{(2+R)\,/\,(2+2\eta)} \qquad \text{Equation 6-R}$$

Equation 6-R indicates a nearly linear relationship between D/d and R over the range of values usually experienced in practice. The effect of R on the maximum drawing ratio is primarily due to the effect of R on the strength of the cup wall as defined by 5-R, the effect R on Pr only being slight.

A similar analysis of the forces obtained in cup drawing was carried out by the author in which the strain-hardening properties of the material were also considered. The relationship between the drawing ratio and the strain ratio was found to be approximately the same as that expressed by Equation 6-R.

Acknowledgments

The author wishes to acknowledge the suggestions and encouragement given this project by Dr. D. J. Blickwede and Mr. J. W. Frame, and to acknowledge the assistance of Mr. J. W. Covino in performing the various tests.

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DISCUSSION

Written Discussion: By R. H. Heyer and J. R. Newby, Research Laboratories, Armco Steel Corporation, Middletown, O.

The use of cupping tests as a measure of drawability has blown hot and cold for a number of years. The authors have developed a correlation between cup drawing ratio and plastic strain ratio which encompasses materials with widely varying tensile properties. C. L. Altenburger has also demonstrated that cups of comparable severity can be drawn from materials with widely different tensile properties. This raises a question as to the sensitivity of cup tests. Cup tests undoubtedly measure cup drawability, but direct correlation with press performance on other types of draws is needed.

In the Lankford experiment a substantial amount of press performance data were correlated with the plastic strain ratio, modified by work-hardening rate. From this and other less extensive observations of press performance it has become fairly certain that high plastic strain ratio is desirable for drawability, not only of cups, but of larger parts formed by a combination of stretching and drawing. This kind of information would be desirable for correlating the cup test with drawability.

Our experience parallels that reported here in many ways. Using Dr. S. Fukui's conical cup test instead of the British or Swift cylindrical cup test, a correlation very similar to the author's Fig. 3 was obtained for rimmed and aluminum killed steels. This relationship was improved by taking a strength factor into consideration. For example, tensile strength minus 20,000 divided by R can be plotted against drawing ratio, with improved results. This seems logical since the strength level can be raised by changes in chemistry, excessive temper rolling, and strain aging, with very little change in plastic strain ratio but with loss of drawability.

The author's statement that the drawability is determined largely, if not entirely, by the normal directionality of the material is correct for the data presented, but may need to be qualified when larger amounts of data for a given class of materials are considered. It is certainly true that dissimilar metals such as low strength aluminum alloys and high strength brasses will not be accommodated by a relationship which includes strength level. On the other hand, when the above mentioned correlation is applied to the author's data for low carbon rimmed and killed steels the relationship is equally as good as in Fig. 3, if not improved.

The dashed lines in Fig. 3 represent the limits of experimental error. How are the limits determined for the cup drawing test? We find it difficult to stabilize test data for the conical cup test from one run to another, presumably due to variations in cleaning and lubrication, and other intangible factors.

The author's explanation of the influence of plastic strain ratio on cup drawing ratio is of great interest. We have as yet been unable to check through the mathematics in the appendix, and suspect there are some typographical errors in the preprint.

Written Discussion: By L. R. Shoenberger, metallurgical development supervisor, Jones & Laughlin Steel Corporation, Pittsburgh.

The author has ably presented an interesting concept in demonstrating the significance of the "normal" directionality in deep drawing sheet metal, which may explain some of the troublesome discrepancies that are encountered in common drawing problems, where frequently both true drawing and stretching are involved. Jevons (2) stated almost twenty years ago that in many deep drawing operations, where the metal is worked nearly to its limit, the degree of directionality will determine whether it will withstand the amount of deformation in a desired manner. Since then, various metal manufacturers have come to recognize this fact, although there are still many who do not fully appreciate its influence.

In our laboratory, considerable work has been done on the planar directionality of low carbon steel. Using the torque magnetometer (3) to obtain torque values at 22½° and 67½° displacement to the rolling direction, we were able to reduce these to a useful directionality rating by first correcting for steel volume and then adding the 22½° value to the other after arbitrarily changing its sign. For example, a typical torque curve for 90° earing steel has first a positive sinusoidal loop and then a negative one (4). The rating would be highly positive since the sign of the latter is changed.

From a large number of samples, we were able to develop a typical planar directionality pattern for subcritically annealed rimmed, capped, or semikilled low carbon steel as shown by the solid line in Fig. 4. Where negative values are shown, 45° earing tendencies are indicated; where plus values are shown, 90°

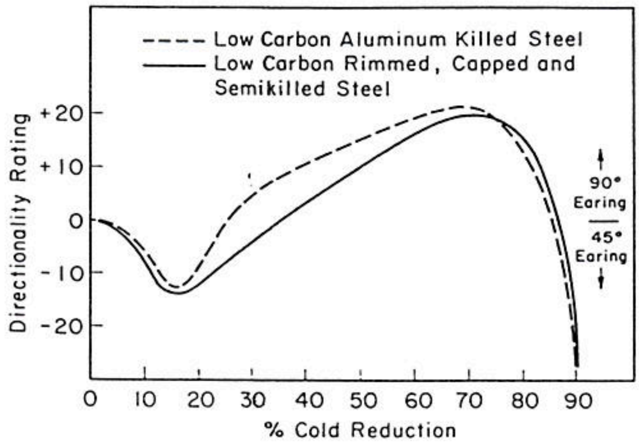

Fig. 4—Typical Directionality Behaviors of Low Carbon Steel Cold-reduced and Subcritically Annealed.

earing tendencies are present; at the zero points and for practical purposes for some small distance on either side, nonearing conditions prevail. The dashed line shows the pattern for aluminum killed steel—different in that a nonearing state and similar amounts of 90 ° earing are achieved with lesser cold reductions. Thus, it is apparent that cold rolled steel sheet may have 45 °, nonearing, or 90 ° earing behavior depending on the amount of cold reduction prior to annealing.

It should be noted that this pattern is based on the cold working of a randomly oriented hot-rolled strip, which is the usual condition when steel is finished above the $A_{r/3}$ temperature. Finishing colder in the roll train produces ferrite that is hot-worked at relatively low reductions, rapidly recrystallized, and therefore has appreciable 45 ° earing characteristics after cooling. Such initial hot rolled orientations distort the typical cold-rolled directionality pattern by enlarging the 45 ° earing ranges and minimizing the 90 °, at times to such a degree that only 45 ° earing or nonearing conditions may be obtained.

Many drawing applications for steel sheet require that metal slides over the draw ring. In a circular cup draw, nonearing steel minimizes thickness variation and scalloping irregularities around the rim; in a rectangular or square type of draw, 90 ° earing characteristics relieve the usual side pull-in. These facts have been applied extensively for some years to the production of drawing quality steel with general success. In the future we will endeavor to determine whether a similar consideration of the normal directionality is also needed to avoid those inconsistencies that occur at irregular intervals. It may be that the normal directionality is more significant than planar directionality or that both must be considered as an interrelated influence.

Having demonstrated here the importance of the amount of cold reduction and the initial hot-rolled state, we would like to ask, in an effort to obtain a better understanding, whether the author's samples had similar initial states of directionality and whether they were cold reduced the same amounts to nearly the same thickness. Might the author expect a similar dependence of the normal directionality on these factors?

In aluminum-killed steels such as those considered by the author, the shape of the annealed ferrite grains, if elongated, could be expected to slip more extensively in the plane of the sheet than in a direction normal to it. Equiaxed grains would tend to slip more uniformly in both planar and normal directions. What were the grain size and shape conditions of the samples involved?

Then too, what explanation might the author propose for the fact that strain aging had apparently no effect on the drawability of rimmed steel?

Written Discussion: By S. P. Keeler and W. A. Backofen, Metals Processing Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.

It is a remarkable accomplishment to have isolated so clearly a material characteristic of such importance in cylindrical-cup drawability. Sheet texture and plastic anisotropy in deep drawing must now become subjects of more general interest than ever before.

The significance of properties or indices describing the rate of strain hardening is obviously ruled out by the statistical treatment of these interesting data. Included in the discard are tensile-yield ratio, uniform tensile elongation, strain-hardening exponent, etc.; of all, the exponent, n, from the power-law approximation of the tension true stress-strain curve, $\sigma = K\epsilon^n$, is a particularly convenient measure of over-all hardening rate. There is, however, another way in which one might become suspicious of the importance of these properties in cylindrical flat-bottom cup drawing, and that is by making a fairly straightforward analysis of the drawing limit for an isotropic strain-hardening material.

Assuming, as in the Appendix, pure radial drawing, the applied stress at any stage of the operation is

$$\sigma_r = K\,(1/2)^n \int_{r_o}^{r_p} [\ln\,(R_o^2 - r_o^2/r^2 + 1)]^n\, dr/r$$

where R_o is the initial blank radius, r_o is the radius to the outer edge of the undrawn flange, r_p is the punch (or cup) radius, and r indicates a radius between r_o and r_p. From opposing tendencies due to strain hardening (acting to increase σ_r) and diminishing reduction (giving a drop in σ_r) as the draw progresses, σ_r passes through a maximum for any ratio of blank-to-cup diameter and $\sigma_{r(max)}$ is obtained by a series of integrations, each for a different r_o between R_o and r_p. Then, for the specified conditions, a limit is established when the peak drawing load becomes as large as the load for pure tensile instability at the unworked bottom of the cup wall; this is the really important restriction and seems quite appropriate for the case at hand. Neglecting the constant friction factor, drawability is found to be related to n as shown in Fig. 5. Clearly, the dependence of drawability on n is slight, and if higher drawing limits are to be obtained through property control, when failure involves cup-wall tearing, there must be strengthening of the wall relative to the deforming flange; as the author has pointed out, texture is an important variable for that purpose. Interestingly, drawability might even be expected to decrease as n increases from zero. This trend in fact seems to have been observed by Swift (5), who has reported, as part of a "drawing anomaly," that the maximum drawing ratio for half-hard aluminum sheet (very low n) is actually a bit greater than that for soft aluminum of higher n value, when the drawn part is a flat-bottom cylindrical cup.

A similar but much less tedious analysis can be made for the steady-state drawing of rod or wire. Due to the steady-state character of such processing, maximum drawing ratio (or cross-sectional area entering, A_o, and leaving the die, A_1) now

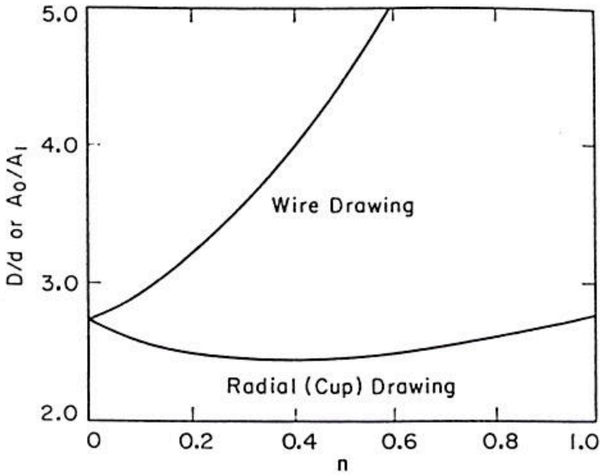

Fig. 5—Dependence of Drawability on Strain-hardening Exponent in Pure Radial Sheet (cup) Drawing and Wire Drawing. In both cases, the drawing operation is taken to be frictionless and without redundant strain.

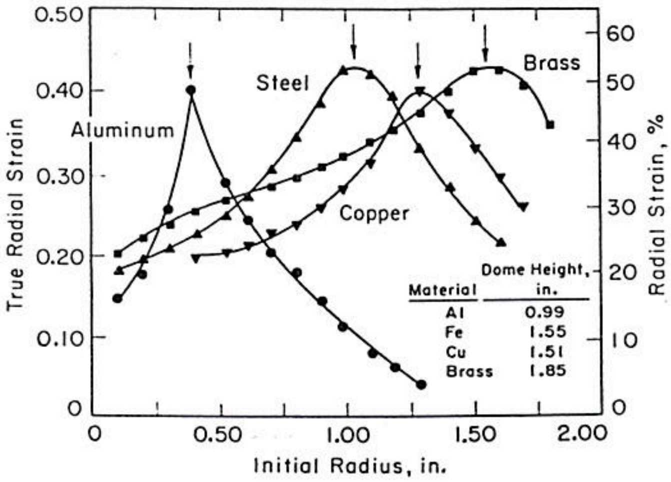

Fig. 6—Distribution of Strain. Measured Along Radial Lines on the Original Blank, After Stretching to Failure Over a 4-inch Diameter Hemispherical Punch with Teflon Lubrication at the Punch-blank Interface. All materials 0.032-inch thickness. Place of tearing is marked by short vertical arrow. Maximum uniform tensile elongation: half-hard aluminum, 0.03; killed steel, 0.20; soft copper, 0.31; and soft brass 0.47.

increases substantially with n (Fig. 5). In wire drawing, a limit is to be expected when the drawing stress becomes equal to the stress for tensile yielding in material at the die exit. If this same criterion could be made to apply in sheet drawing, much greater drawability would surely be enjoyed.

As the author points out, by introducing more punch-head stretching in forming other shapes the strain hardening characteristics should begin to influence limits.

Current work in our laboratory is concerned with the development of instability under conditions about as different as can be from those in the flat-bottom cup, e.g., stretching tightly clamped blanks over a punch with hemispherical end. A sample of data in Fig. 6 demonstrates how sensitive the dome height at failure now is to variations in strain-hardening exponent. Somewhat curiously, the maximum radial strains at the places of tearing are nearly the same, regardless of n. Yet the distribution is much broader and total height is greater as n increases. The rest of the Swift drawing anomaly is that soft aluminum gives the same drawing limit for cups of hemispherical as for flat bottom, but that the limit for half-hard stock is much lower for the hemispherical case; the explanation would seem to be that greater stretching over the hemispherical punch head now brings the n differences into play.

A general impression, bolstered strongly by this paper, is that the important properties for different kinds of forming are being identified. The emphasis on texture seems especially timely and helps very much in developing awareness that processing history contributes substantially to final properties and behavior.

References

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4. G. H. Enzian's discussion of J. K. Stanley's paper, p. 368, Fig. 10.
5. H. W. Swift and S. Y. Chang, "Cup-Drawing From a Flat Blank," *Proceedings of the Institution of Mechanical Engineers*, Vol. 165, 1951, p. 199.

Author's Reply

Mr. Shoenberger has pointed out that certain processing variables can have an appreciable effect on the planar directionality of low carbon steel. Our own studies have shown that these same variables have a similar effect upon the degree of normal directionality obtained in the low carbon steels. This is not surprising since both planar and normal directionality are probably the result of the preferred crystallographic orientations in the steel and would be similarly effected by those factors which produce this preferred orientation.

For this particular experiment, however, the cause of different R values in the steels was not known. The materials were selected at random from production stocks and their previous history was not recorded, although all materials were of the same thickness, i.e., approximately twenty gage (0.0359 inch).

As suggested by Mr. Shoenberger, there was a distinct difference in the shapes of annealed ferrite grains in the aluminum-killed steels, and in the rimmed steels. The grain sizes of all steels tested ranged from ASTM 7 to 8, and all aluminum-killed steels had definitely elongated shaped grains while those of the rimmed steels were all equiaxed. While there is a tendency to conclude that the elongated grain structure of the aluminum-killed steels is itself responsible for high R values, careful analysis of a large number of samples does not wholly support this conclusion. While it is generally true that materials with high R values have an elongated grain structure, there are a significant number of exceptions to this general rule.

We feel that high R values are the result of a preferred crystallographic orientation usually found in aluminum-killed steels which exhibit an elongated structure (3). This preferred orientation is a result of the particular method of processing which is used to obtain the elongated grain structure. The high R values are thus the result of a particular processing technique, one which incidentally also produces an elongated grain structure in aluminum-killed steels. This hypothesis, however, has not been proven as yet.

As to Mr. Shoenberger's question of the effects of strain aging, we must recognize that deep drawing is a combination of both pure stretching and pure drawing and deep drawing performance depends on both the drawability and the stretchability of the metal. The drawability is best measured by the test described and consequently is independent of aging, because, as we have shown, it depends only on the R value, a property unaffected by aging. This is indicated by the results in Table II for specimens 22–1 and 22–2. On the other hand, the stretchability of a metal, as measured by the Olsen cupping test, is decidedly decreased by strain aging. Thus where a deep drawing operation involves considerable stretching strain aging is an important factor detrimental to the overall performance of the metal. This is not the case, however, in drawing a flat-bottomed cylindrical cup or similar shape.

Messrs. Heyer and Newby's comments on the need for further correlation with actual performance are well taken. Their suggestion for improving the correlation of drawability with R values by including a factor of tensile strength is quite interesting. There seems to be no theoretical reason for the inclusion of this other parameter, however. We have also carried out additional tests with some forty low carbon steels and still find a singular correlation between drawability and the R value. The inclusion of a tensile strength factor does not seem to improve these results.

The limits of experimental error used are those reported by Kemmis based on studies of the reproducibility of the Swift cup-drawing test which were carried out at the University of Sheffield. We also included in all our tests a standard material, checking the drawing ratio of this material on each test run. We found this drawing ratio to be quite reproducible when the proper test procedures were followed.

The comments by Messrs. Backofen and Keeler speak for themselves. Much work has been done to establish the relationship between, "n," the strain-hardening exponent of a metal and its limit of useful ductility under various ideal stretching conditions. Their attempt to extend this relationship to stretching conditions more representative of typical forming operations should be of interest to those concerned with the subject of deep drawing.