Part 3 - Properties Related to Forming

Understanding Sheet Metal Formability

Two properties of materials—the work hardening coefficient and the anisotropy coefficient—strongly influence the formability of sheet metals. These properties can be evaluated on standard tension testing machines.

Formability of sheet metal is dependent on the mechanical properties of the material. Some materials form better than others. A material that has the best formability for one stamping may behave very poorly in a stamping of another configuration, however. For these reasons, extensive test programs are often conducted in an attempt to correlate the performance of a material in stamping operations with the level of some mechanical property. Different stampings seem to be influenced by different properties.

Complex stampings require varying amounts of stretching and drawing, to which bending, unbending, buckling and other complications are added. Most forming operations can be qualitatively, though not quantitatively, categorized as primarily stretching, primarily drawing, or varying ratios of each. It would be useful, therefore, to know which material properties influence either stretching or drawing. From this, an intelligent modification of material specifications could be made in an attempt to improve the formability of a given stamping.

The trouble with this approach is that the mechanical properties most commonly measured today have either an unknown or an indirect relationship to stretching and drawing. Mechanical properties included in this category are yield stress, tensile strength, yield point elongation, tool elongation and hardness.

An example of the problems encountered when using mechanical properties of a material to predict formability is furnished by total elongation measurements. Total elongation includes both uniform elongation and elongation after necking. Its value is

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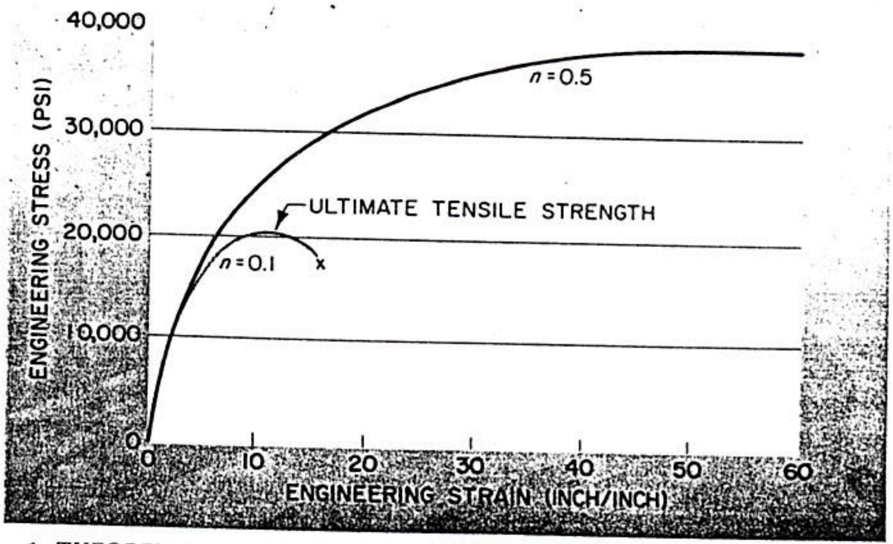


1. THEORETICAL STRESS-STRAIN CURVES for two values of the work hardening exponent n. Engineering stress is load divided by original area. Engineering strain is percent change in length. Necking is at maximum load.

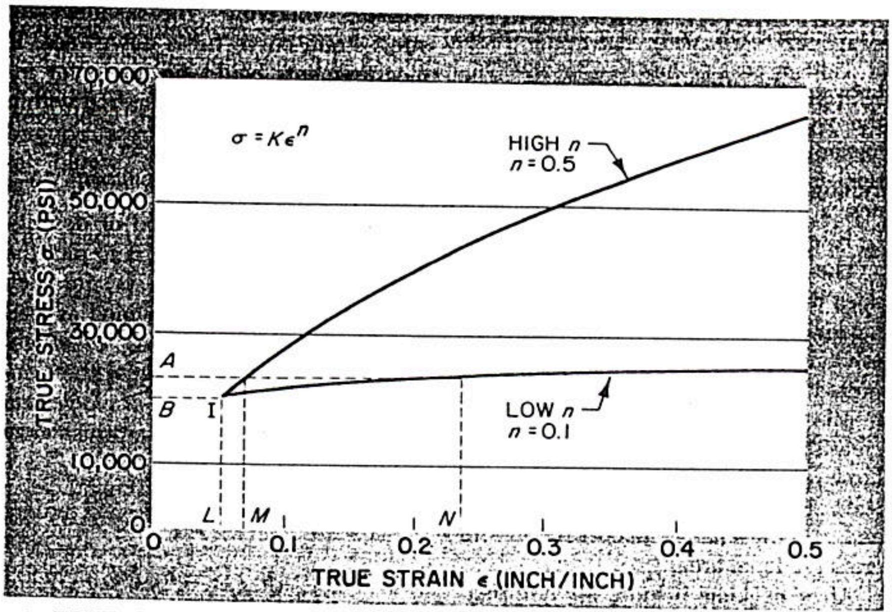
1968 V.74 n.8 Apr.

also dependent on the gage length over which the measurement is made. Necking in a stamping is often cause for rejection, however, and elongation after necking cannot be utilized. Therefore, total elongation data on a material correlate poorly with the performance of that material in stamping.

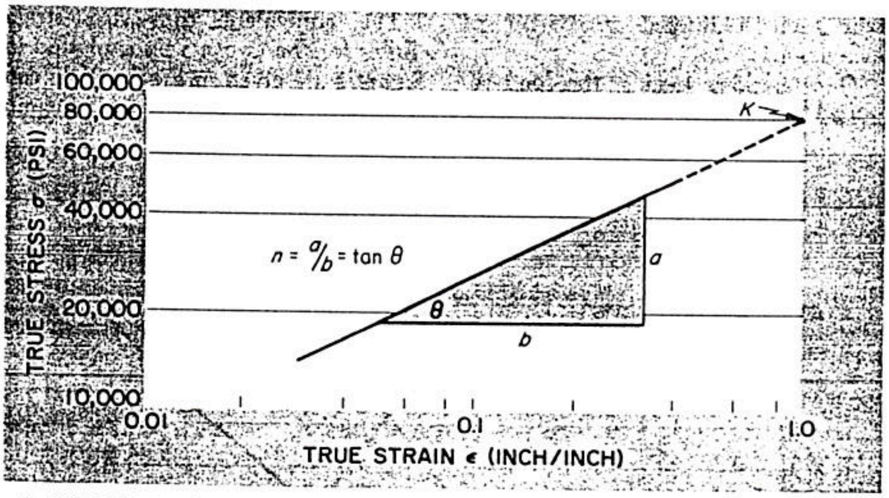
Another popular mechanical property used to evaluate formability is the yield stress. As a general rule of thumb, formability decreases as yield stress increases. While this may be true for varying lots of similar steel processed in a similar manner, it is a poor generalization. The yield stress merely indicates the stress at which plastic deformation begins and does not indicate the amount of plastic deformation permissible before necking. A comparison of low carbon steel and stainless steel is an excellent example. The yield stress of stainless steel may be twice that of low carbon steel but its formability is usually better.

Forming limits relate primarily to the exhaustion of ductility. To have better formability, a material must be capable of withstanding more strain before failure or it must have the ability to resist straining. A means of determining the material properties that characterize this ability is needed.

Recent research work in laboratories and press shops has shown that two properties strongly influence the ability of a material to be formed. These two properties can be evaluated using a standard tension testing machine and normal tensile specimens. The first is the work-hardening exponent, better known as the *n* value. The *n* value determines the ability of the material to be stretched. The second property is the anisotropy coefficient, or the *r* value. This property strongly controls the ability of a material to be deep-drawn into a flat-bottom cup. These two parameters are being used today in some shops to study critical stampings. Their day-to-day use as a quality control check is increasing.



2. TRUE STRESS-TRUE STRAIN CURVE represents the work hardening characteristics of a material better than the theoretical engineering stress-strain curves shown in Figure 1. True stress is load divided by instantaneous area; true strain is the integrated change of length divided by instantaneous length. The two theoretical curves have been normalized to have equal stress values at a strain of 0.05. The rate of work hardening is given by exponent n.



3. CALCULATION of the n value. The true stress-true strain curve is plotted on log-log paper. The n value is the slope of the line. K is the stress value at a strain of 1.0. If the line is curved, an instantaneous n value must be obtained for each strain value. If the line is straight, n is known to be a constant.

The increase in strength of steel and other metals after being bent, twisted, rolled, stretched or otherwise deformed is well known. The yield strength—the stress required to initiate and continue deformation—increases as the amount of the strain increases. The deformation may be tensile or compressive. It may even be a cyclic reversal of strain, where tensile strain is followed by an equal amount of compressive strain. In the latter case, the dimensions and shape of the deformed specimen are identical to those of the initial specimen; however, the stress required to initiate yielding is larger. The parameter that controls the increase in yield stress or strength of a material during deformation is the *n* value.

One method of observing the amount of work hardening is to plot the traditional engineering stress-strain curve obtained from a uniaxial tension test, *Figure* 1. Engineering stress (S) is load required to deform the specimen divided by the initial cross-sectional area. The other axis, engineering strain (E) is change in length, divided by initial length of the gage section. For mathematical simplicity, it is assumed that the initial yield stress of the material is zero, or that plastic deformation begins as soon as a load is applied. A specific yield stress can be obtained by merely shifting the axis.

Theoretical (calculated) stress-strain curves for materials with high and low *n* values are shown. The material with the higher *n* value is characterized by a steeper stress-strain curve. This means a greater separation between the ultimate tensile stress and the yield stress. The strain value at maximum load—the uniform elongation—is also larger for increased n values, a very important effect that will be discussed later.

The engineering stress-strain curve does not truly portray the actual behavior of each element in the specimen. Looking at the curve, the stress required to continue deformation of the tensile specimen appears to be decreasing after necking. This occurs, however, because the engineering stress reflects only the change of load and not the change occurring in the cross-sectional area.

After necking begins, all deformation is restricted to a very small portion of the gage length—the necked area. For necking to start, geometrical softening (reduction in load due to reduced cross section) must be greater than the work hardening of the material (increased load required to sustain each additional increment of elongation).

Once necking begins, the load required to sustain deformation decreases; therefore the engineering stress-strain curve turns downward. If measurements could be made for independent elements of material within the necked region, the stress required to continue deformation would increase.

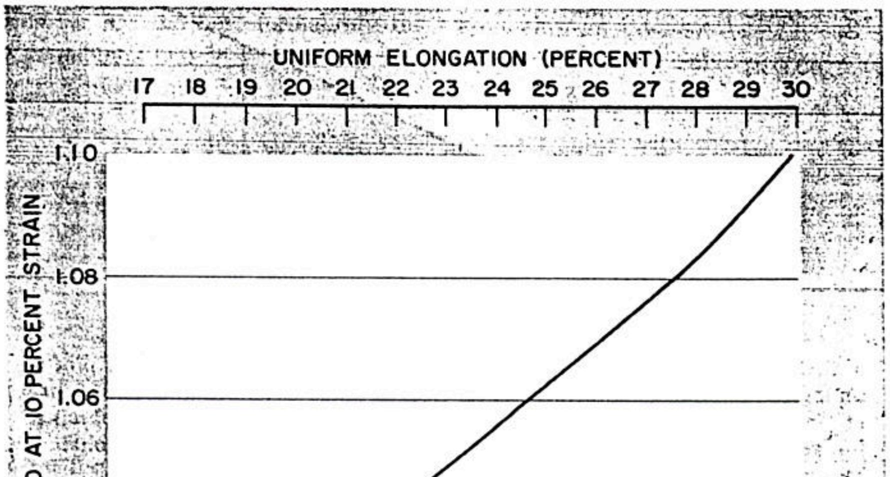
A more realistic method of describing the material behavior is to plot the true stress (σ) and strain (ϵ) for each element. True stress is defined as load divided by instantaneous cross-sectional area, and true strain is the summation of each increment of elongation divided by the instantaneous gage length. For calculation purposes,

$$\sigma = P/A \text{ and}$$

$$\epsilon = \int_{l_0}^{l} dl/l = \ln l/l_0 \;\ldots\ldots 1$$

where P is load required to deform the specimen, A is the original cross-sectional area, l_0 is length before elongation, l is length after elongation and ln is the natural logarithm.

The equivalent true stress-strain curves for the two n values plotted in *Figure* 1 are given in *Figure* 2. As can be seen, the stress continues to climb without a maximum for increasing strain.



4. UNIFORM ELONGATION and n value can be obtained directly from this graph, which is taken from "Correlation of Deep Drawing Press Performance with Tensile Properties" by R. L. Whitely. (ASTM Publication STP 390.)

The stress-strain curves for many metals, especially steel, can be approximated by the power law equation:

$$\sigma = K\epsilon^n \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where K is a constant for the material. From this power law equation, n is defined as the exponent of the stress-strain relationship. Also called the coefficient of work hardening, it determines the increase in stress for each increment of strain. The higher the n value, the more the material will work harden.

Physically, the n value can be related to the tensile strength/yield stress ratio. The higher the n value, the higher the TS/YS ratio. (For this reason, the author dislikes the common practice of reporting YS/TS. This ratio is less than 1 and decreases for increasing formability.) Similar mathematical calculations show that the n value is equal to the true strain at the onset of necking, which is the uniform elongation of the material. The higher the n value, the greater the resistance to necking.

Several methods are available for evaluating the n value. The basis for most of them is to rewrite the power law equation as:

$$\log \sigma = \log K + n \log \epsilon \;\ldots\ldots 3$$

which is in the form of a straight line having the equation $y = a + nx$ when plotted on log-log paper, *Figure* 3. If the plot is a straight line, n is a constant and is obtained by measuring the slope of the line. The value of K is the stress intercept of the line at a strain value of 1.0. It is not to be confused with the initial yield stress of the material.

If the line is curved, an instantaneous n must be calculated for each strain value of interest. The line may have two straight segments. This occurs for some stainless steels. Here each segment must be described by its own n value. For most low carbon steels and many of the nonferrous metals commonly used in the forming industry, a constant n will approximate the stress-strain curve.

To obtain n by this method, the stress is obtained for various strain values and plotted on log-log paper. The procedure is tedious but yields the best accuracy and is ideally suited to computerization. Some testing machines are equipped to digitize the values and place the information on punched cards. These are then fed to a computer for calculation. For high volume testing, twenty or more tensile test machines can be connected directly to a computer that interrogates each machine at the proper time. Other mechanical properties, as well as *n*, are then automatically calculated and printed at a central station. The only human function is to reload specimens in the machines. Such installations are in existence today.

A second procedure that is very common today is the Nelson-Winlock procedure, which assumes that the log stress-log strain equation plots as a straight line. Therefore, any two points are sufficient to define the curve and permit calculation of the *n* value. Two convenient strain values are chosen and the load at each point is read from the machine dial or autographic record. One point, the easiest to measure, is the maximum load (P_u). The other load value can be obtained at any strain value that avoids the initial portion of the curve containing yield point elongation and other variations. For convenience the load is read at 10 percent elongation (P_{10}). The 10 percent elongation is obtained by preset dividers and 2-inch gage marks, or from the autographic record. Any crosshead speed can be used, although 0.2 ipm is convenient. It is important that the strain rate be kept constant between P_{10} and P_u. For good reproductibility, load measurements must be made accurately on calibrated machines.

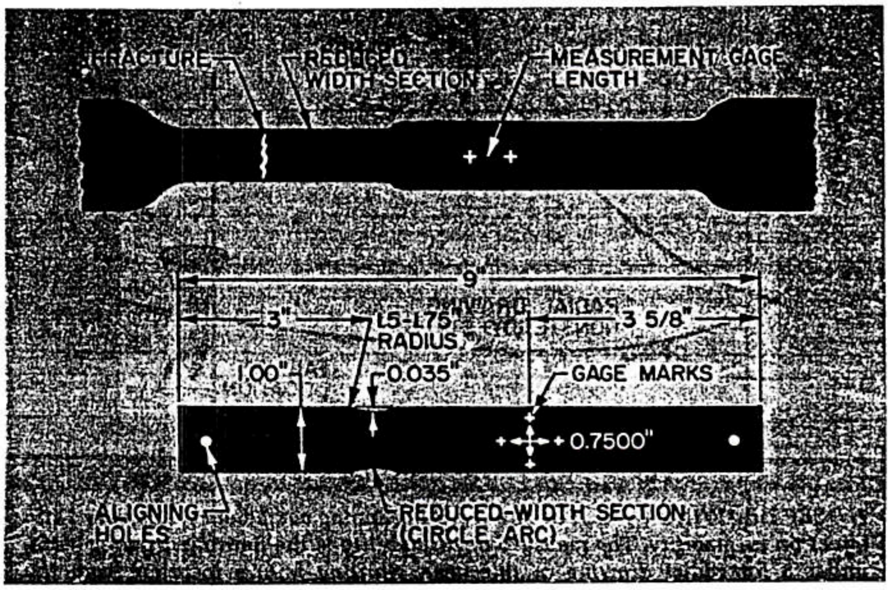
The ratio P_u/P_{10} is calculated and the *n* value obtained from either a table or a graph, *Figure* 4. The corresponding uniform elongation is also given. Conversion from one to the other is made using the formula:

$$n = \ln(1 + \epsilon_u) \quad \ldots\ldots\ldots\ldots 4$$

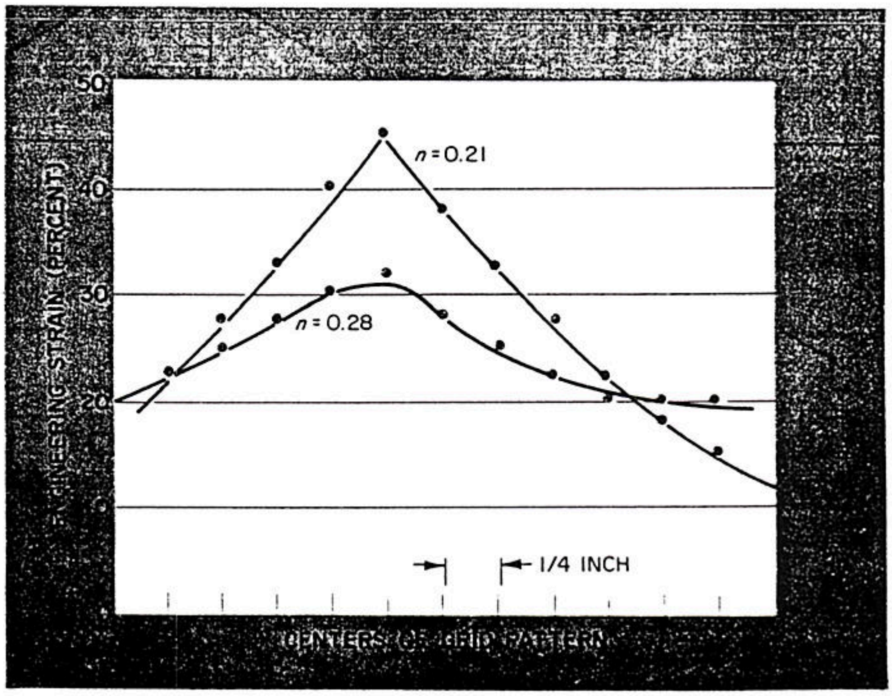
where ln indicates natural logarithm and ϵ_u is uniform elongation. The precision of the Nelson-Winlock method is currently limited to about $n \pm 0.02$, as indicated by recent work of the American Deep Drawing Research Group.

Some recently developed test methods produce a value for *n* that is related to, but not equal to, the uniform elongation. The major advantage of these techniques is that no load or elongation measurements are required during testing; the specimen need only be broken. The desired value is read directly from the broken specimen without calculations.

One such method, which is gaining popularity, is the circle arc elongation technique developed by R. Heyer of Armco Steel. A special two-step tension specimen is used, *Figure* 5. In a normal single-section specimen, the entire specimen length deforms uniformly up to the onset of necking. Further deformation is then localized in the necked area. Strain measurements from gage marks located away from the necked region would indicate the strain value just at the onset of necking. This, by definition, is the uniform elongation of the material. There is a danger of fracture or necking taking

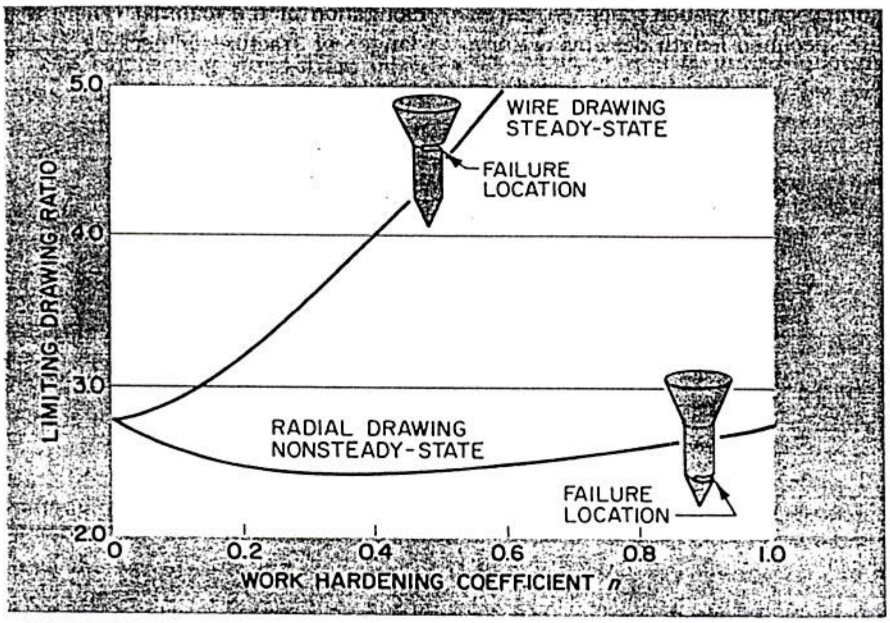


5. *TWO-STEP TENSILE SPECIMENS are used to obtain formability parameters that indicate the uniform elongation and anisotropy coefficient of the material. Fracture takes place in the reduced-width section. Measurements are made in full-width section. This method was developed at Armco Steel.*

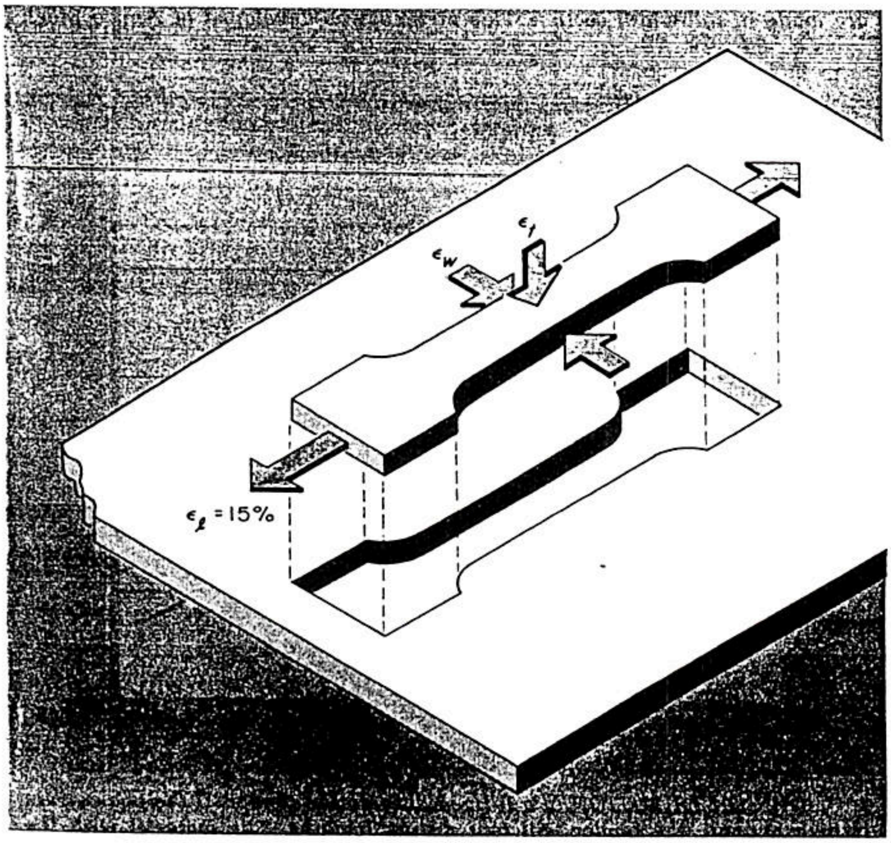


6. *STRAIN DISTRIBUTION in a formed automotive fender. If the peak strain is high enough, the fender will tear during forming. The material with the higher n value gives a more uniform strain distribution, hence there is less chance it will tear during forming. This is a stretching type operation.*

place between the gage marks, thereby ruining the measurements. By making one portion of the gage section slightly smaller in width than the remainder of the section, the strain values will be slightly higher and failure will almost always occur in the reduced-width section. Gage marks are now placed in the wider section. Rather than mill a complete two-step specimen, Heyer mills only a slightly reduced section in the form of a circle arc. Hence the name, circle arc elongation. The value measured is proportional to, but slightly lower than, the uniform elongation and the *n* value. The procedure is ideally suited for production testing.



7. DEEP DRAWING OF CUPS. The work hardening coefficient n *has very little effect on formability. The measure of formability is the limiting drawing ratio, under 3 for radial drawing in this case. Shifting failure location from the bottom of the cup wall (lower curve) to the top of the cup wall (upper curve) permits utilization of* n *to increase formability, as in wire drawing.*



8. ANISOTROPY VALUES are evaluated from this tensile specimen, machined from sheet or plate. A strain of 15 percent is imposed on the specimen.

Some typical *n* values are given here to indicate what values might be expected.

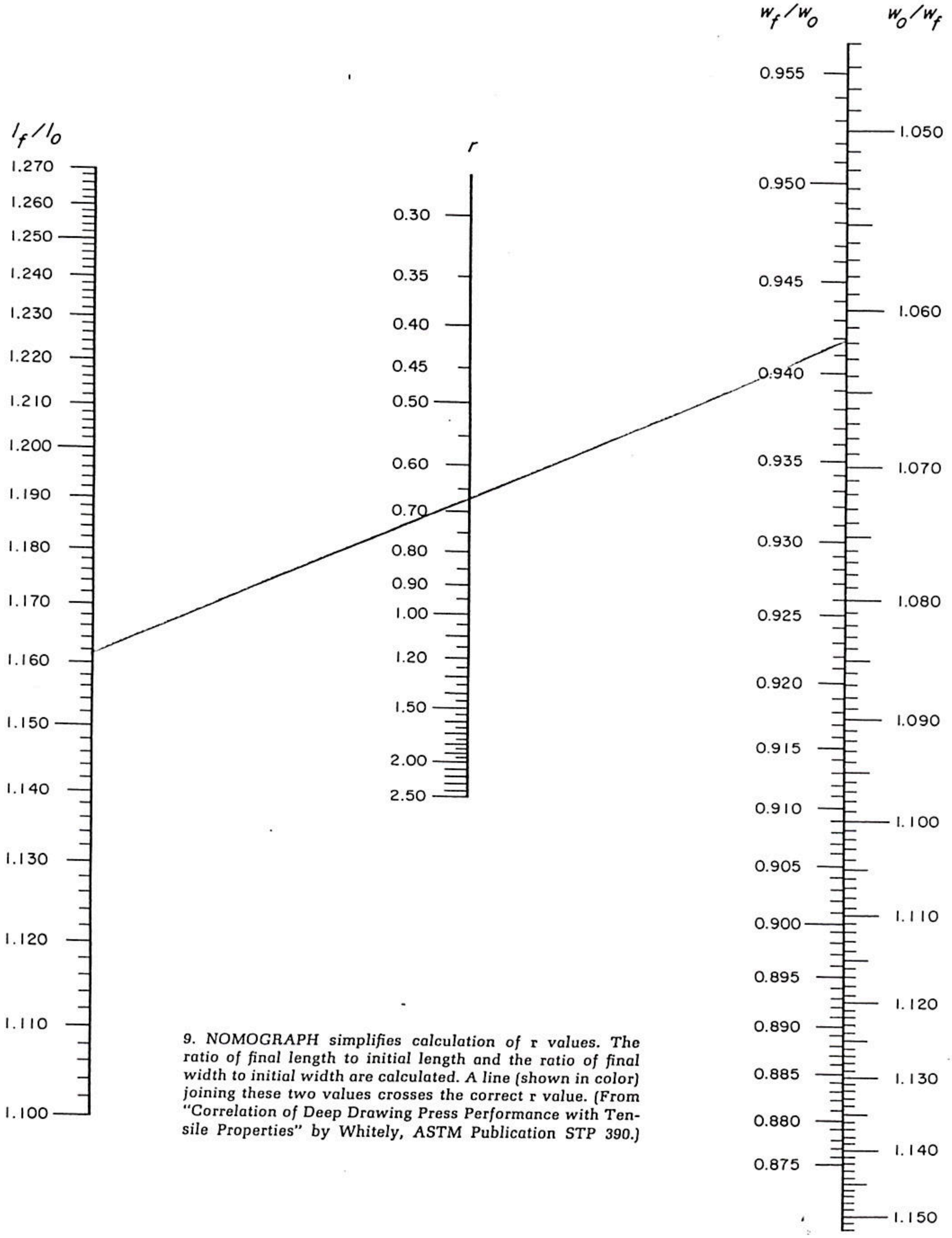
Aluminum	0.20
Low carbon steel	0.25
Copper	0.30
Brass	0.40
Stainless steel	0.50

As with most properties, the values are influenced by testing techniques, testing speed, temperature and direction from which the specimen is removed from the sheet. The *n* value will also decrease with aging of rimmed steel and with cold working.

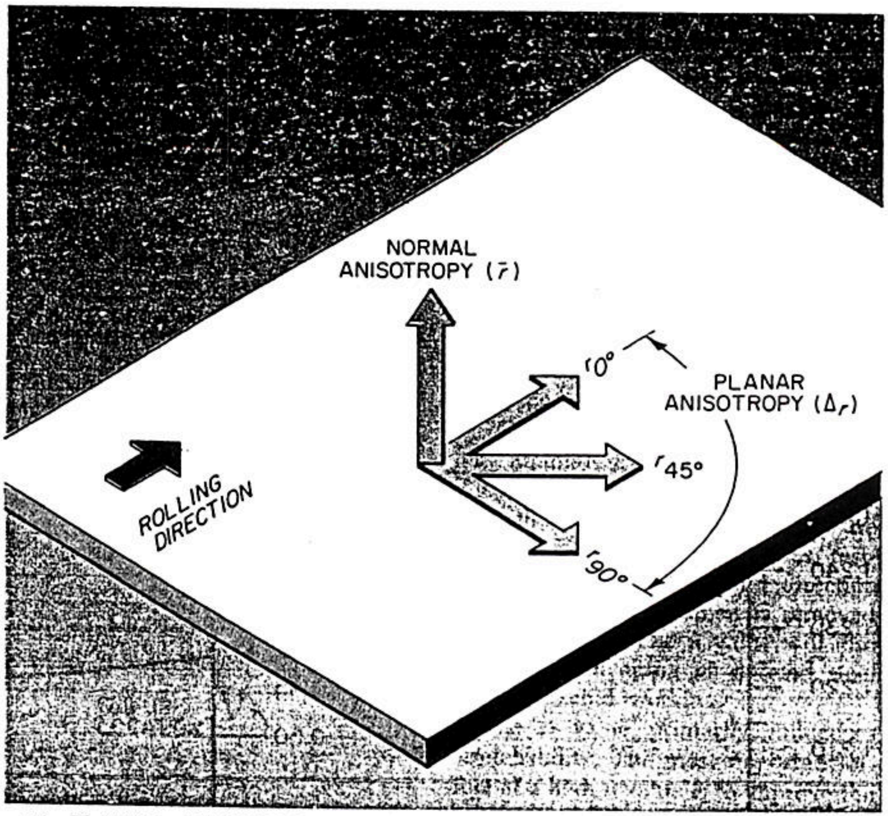
The *n* value primarily influences stretchability. The most important effect of a high *n* value is to improve the uniformity of the strain distribution in the presence of a stress gradient. This effect can be shown graphically in *Figure* 2. Assume for simplicity that two materials have the same stress level ($B = 20{,}000$ psi) for an initial strain value of $L = 0.05$ inch/inch. Let the stress value at some adjacent location in the stamping be $A = 23{,}000$ psi. The strain value at this location for the high *n* material would be only 0.07 or an increase of 0.02. The low *n* material, however, would strain to a value of 0.24. This increase of 0.19 is ten times that of the high *n* material. This would create a highly nonuniform strain distribution—a very undesirable condition.

In addition to the higher peak strain, a low *n* material begins necking at a lower strain value. Necking creates an even greater nonuniformity of the strain distributions.

The effects of *n* value on strain distribution can be shown by plotting measured strain values as a function of location on the blank, *Figure* 6. The example is based on the forming of an automotive fender. If the peak strain is high enough, the stamping will tear. Even without tearing, a roughening of the material is observed at high strain values, resulting in extra material finishing. The goal, therefore, is to have as uniform a strain distribution as possible in the presence of a stress gradient developed during stretch forming.



9. NOMOGRAPH simplifies calculation of r values. The ratio of final length to initial length and the ratio of final width to initial width are calculated. A line (shown in color) joining these two values crosses the correct r value. (From "Correlation of Deep Drawing Press Performance with Tensile Properties" by Whitely, ASTM Publication STP 390.)



10. PLANAR ANISOTROPY is determined with the aid of specimens cut parallel and at various angles to the rolling direction. Normal anisotropy is equal to the average of anisotropy values around the surface of the sheet.

Very little effect of n is observed in deep drawing of cups, *Figure* 7. Here the measure of formability, or drawability, is the limiting drawing ratio (LDR), which is defined as the ratio of maximum blank diameter to punch diameter. This theoretical curve was calculated with no allowance for friction, or for bending and unbending over the die and punch radii. Thus, for more or less isotropic sheets of ductile material at uniform temperature, the LDR is approximately 2.

The independence of deep drawing on n is not unreasonable and has important production implications. In pure radial drawing, load originates in the deformation of the flange region and must be transmitted through the lower cup wall. This area is normally unstrained and therefore is the structurally weak link of the system. Increasing the load carrying capacity of the cup wall by increasing n also increases the load required to deform the flange. The two effects cancel each other out. Therefore, various tempers of materials should all have approximately the same LDR.

The slight initial downward trend, with n increasing from zero, might well account for an observed drawing anomaly, according to which more heavily prestrained materials (characterized by relatively lower n value) are found to yield slightly deeper cups (other conditions fixed) than softer materials capable of a larger overall amount of strain hardening, and therefore characterized by larger n.

A basis for improving drawability is the relocation of the failure site nearer to the die exit or further up the cup wall. Here strain hardening can be exploited for increasing the load-carrying capacity at failure, as shown in the upper curve of *Figure* 7. LDR now increases with n much as would be expected for steady-state operations of wire and rod drawing. A shift in the fracture site may be accomplished in practice through manipulation of such nonmetallurgical variables as tooling and lubrication. In some special forming devices, the drawing load is distributed more uniformly over the punch-cup wall interface by pressing more firmly against the punch with the aid of rubber backing. Withholding punch lubrication will also help.

Ductility is the ability of a sheet to undergo plastic deformation; failure occurs when the level of ductility is less than that required in the forming operation. Measurement of this ductility may include the largest diameter blank that can be successfully drawn into a cup of fixed height, the height of a hydraulically bulged dome or the tensile stress to yield stress ratio.

Whatever the measure of ductility, the assumption is commonly made that it is isotropic, or independent of direction of measurement within the sheet. Reduction of metal from an ingot into a sheet, and its subsequent fabrication, create various types of directionality or anisotropy of properties in almost all metals, however. The inevitable anisotropy of mechanical behavior has often been regarded as a curiosity, or even as undesirable in the case of earing in deep-drawn cups.

Wrought metal may contain more than a half billion grains or crystals per cubic inch, each with its own identifiable orientation. In a completely random material, all orientations are present on an equal basis. The material is isotropic with respect to the associated mechanical properties. In most wrought materials, however, a tendency exists for the grains to have certain crystallographic planes or directions clearly aligned with directions of prior working. As a result, slip systems are oriented, which allows easier deformation in some directions than in others. This condition creates plastic anisotropy, in which properties in the rolling direction are different from those in the transverse directions.

The overall shape of the stress-strain curve, and the attendant properties such as yield stress, tensile strength and rate of work hardening, are affected by this crystallographic orientation.

A useful mechanical index of this plastic anisotropy is r, which is defined as the ratio of the true width strain to true thickness strain in testing of a standard 2-inch gage length tensile coupon, *Figure* 8. One method of obtaining the r value is to plot width strain (ϵ_w) against thickness strain (ϵ_t) for various specimen elongations up to necking. For most common forming materials the curve will be a straight line. The r value is constant and is simply the slope of the curve.

Since the plot of ϵ_w versus ϵ_t is a straight line, a two-point method can be used. The first point is at zero strain. The other is some convenient elongation, such as 15 or 20 percent. After forming, the r value is calculated from the formula:

$$r = \frac{\ln (w_f/w_o)}{\ln (t_f/t_o)} \quad \ldots\ldots\ldots\ldots 5$$

where w_o and t_o are the initial width and thickness measurements, respectively, and w_f and t_f are the final width and thickness measurements.

Unfortunately, large errors are possible in measuring the thickness of thin sheets. Using the fact that the volume of the metal remains constant during plastic deformation, the formula can be rewritten in terms of the width and length strain of the specimen:

$$r = \frac{\ln (w_o/w_f)}{\ln (l_f w_f / l_o w_o)} \quad \ldots\ldots\ldots\ldots 6$$

where l_o and l_f are the initial and final length measurements, respectively.

The general test procedure is:

1. A standard ASTM 2-inch gage length or other parallel-sided specimen is milled, with a gage length at least four times the specimen width. Duplicate specimens are recommended.

2. A gage length, usually 2 inches, is marked on the specimen, accurately measured to ±0.0005 inch, and recorded as l_o. The total width of the specimen is measured at four points within the gage length to within 0.0001 inch and recorded as w_o.

3. The samples are elongated approximately 15 percent (below the strain at which necking begins) at any convenient strain rate.

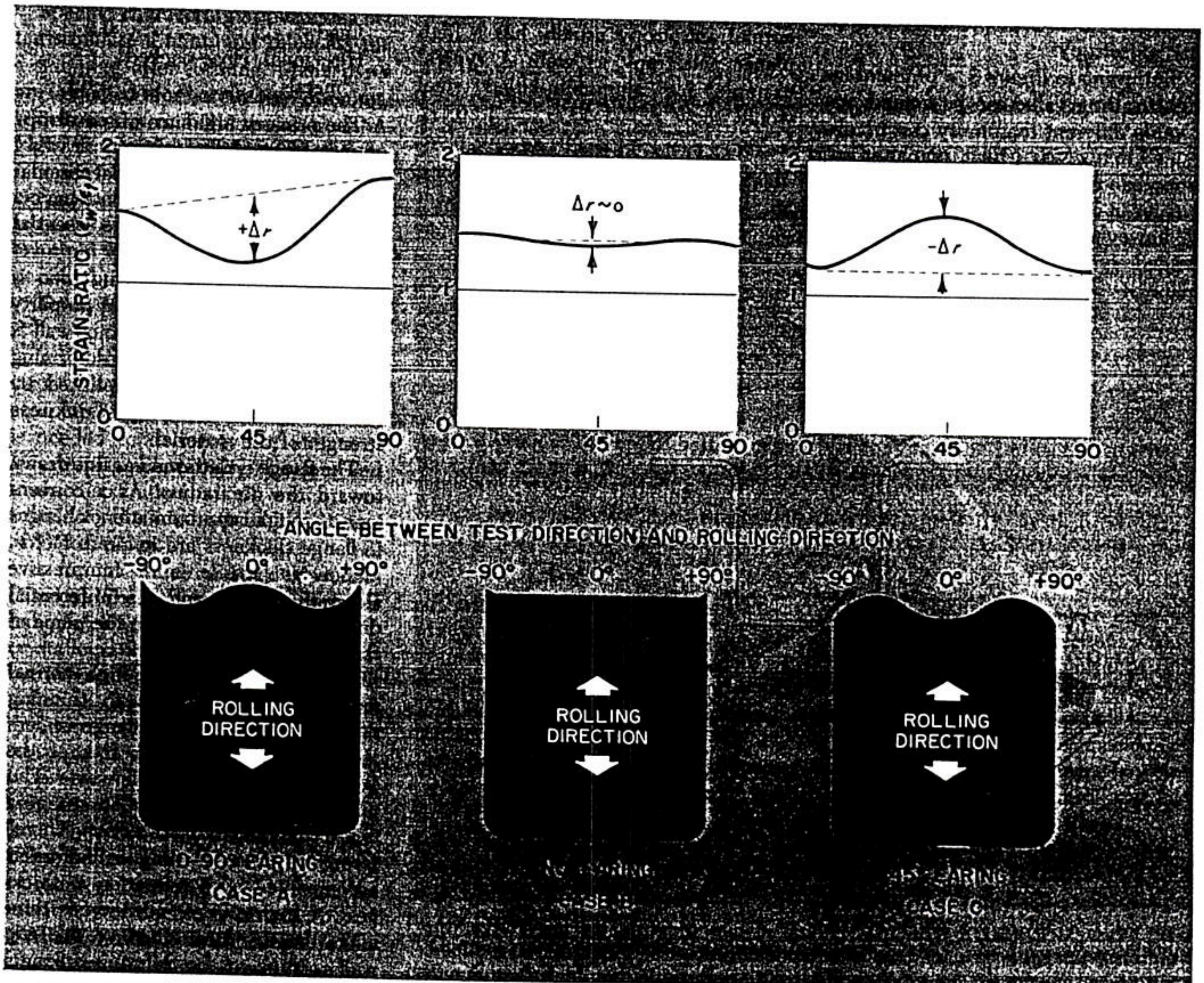
4. The final gage length l_f and gage width w_f are measured as described in Step 2.

5. The r value is calculated, using Equation 6. In order to save considerable calculation time, a nomograph can be used to obtain a value for r, as shown in *Figure* 9.

The anisotropy parameter r can be obtained for different directions in the sheet. Normally, specimens are removed from the sheet at 0, 45 and 90 degrees to the rolling direction. In testing a perfectly isotropic or nondirectional sheet, all the r values would be equal to unity. For most steels and other materials, however, there is a variation of the r value with direction. This variation of r within the plane of the sheet, *Figure* 10, is called the planar anisotropy (Δr) and is responsible for earing in deep-drawn cups. The formula for planar anisotropy is:

$$\Delta r = \frac{r_o + r_{90} - 2\, r_{45}}{2} \quad \ldots\ldots\ldots 7$$

The r values can be plotted as a function of angle, *Figure* 11. Here Δr is the difference between the r_{45} value and the average values in the r_o and r_{90} directions. Ears or crests occur at the high r value directions. For steel (Case A), high r values, and therefore the ears, are usually found at 0 and 90 degrees to the rolling direction. If $\Delta r = 0$ (Case B), no ears are formed. If the r_{45} value is the largest (Case C), ears form at 45 degrees. Earing is considered a liability in



11. EARING OF CUPS can be related to r values. When cup is drawn in rolling direction, there is no earing, because r is low.

wrought materials; a trimming operation is usually required, which limits the useful length of drawn cup walls.

Directionality occurs in three directions, however (*Figure* 10), and its absence in the plane of the sheet does not mean that properties measured in a direction perpendicular or normal to the sheet are equal to those in the plane of the sheet. The practical importance of this "normal" anisotropy was not fully recognized until recently for two reasons—the properties in the thickness direction are usually not known nor can they be readily measured, and the effects of normal anisotrophy are not visually evident, as in the case of earing. Lately, recognition has been given to the fact that sheet metals often exhibit a flow strength in their thickness direction quite different from that in their plane. It is, in fact, possible to have a very high level of normal (thickness) anisotropy in a sheet with little or no planar (rotational) anisotropy.

Returning to *Figure* 8, a physical insight of the r value can be gained. An r value different than unity can be obtained in two ways. First, planar anisotropy can cause the width strain to be greater in one direction than the other. If, however, the r values are now averaged for specimens taken in the plane of the sheet at 0, 45 and 90 degree angles to the rolling direction, this effect will be cancelled. The average value is defined as:

$$\bar{r} = \frac{r_0 + 2\,r_{45} + r_{90}}{4} \quad \ldots\ldots\ldots\ldots 8$$

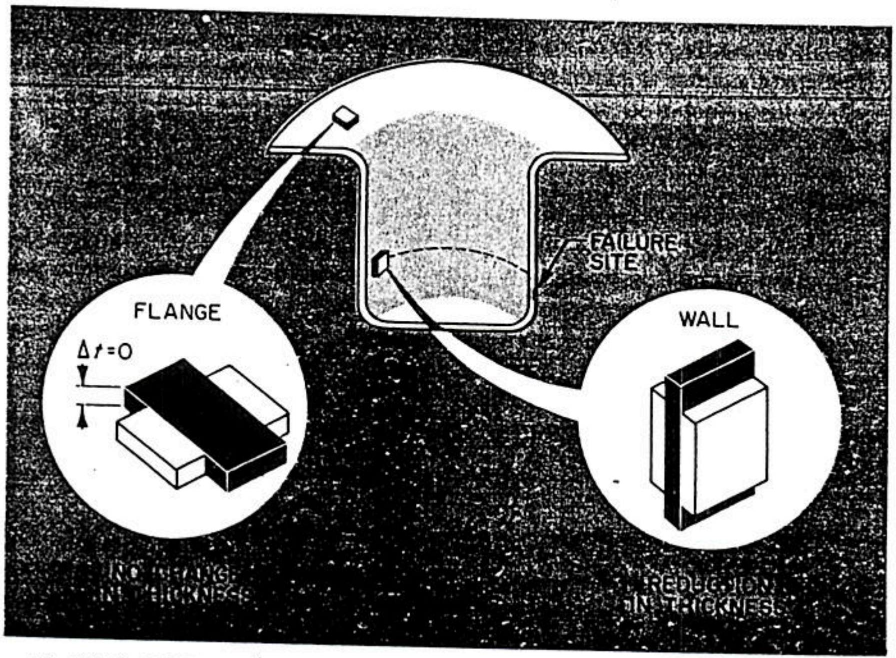
Thus the $\bar{r}$ value is independent of rotational anisotropy.

The other way of obtaining an r value greater than unity is for a material having resistance to thinning. In this case ϵ_t will be small relative to ϵ_w. Since all specimens taken in the plane of the sheet will be influenced in the same manner, this increase will not be averaged out in the calculation of $\bar{r}$ from Equation 8.

The $\bar{r}$ value then is a measure of normal anisotropy. If $\bar{r}$ is greater than unity, the material is characterized as having resistance to thinning and has an increased through-thickness strength. In the same manner, an $\bar{r}$ value less than unity implies ease of thinning.

Unfortunately, a material with high normal anisotropy usually has a high planar anisotropy as well. A typical example for aluminum-killed steel would show $r_0 = 1.43$, $r_{45} = 1.20$, $r_{90} = 2.50$, $\bar{r} = 1.58$ and $\Delta r = +0.76$. Many materials producers are working on the problem of obtaining a sheet metal with a high $\bar{r}$ value and a Δr value of zero.

The degree of anisotropy is closely related to the crystal structure of the metal or alloy. In general, anisotropy develops more strongly in the hexagonal, close-packed metals (beryllium, titanium, zirconium) than the body-centered or face-centered cubic metals (steel, copper, brass, aluminum). The types and amounts of alloying elements also influence the nature of the anisotropy. An excellent example is the effect of aluminum in increasing the anisotropy of aluminum-killed steel over that of the rimmed steel. For a given metal and composition, the plastic anisotropy is a consequence of its entire processing history. Especially important for steel are finishing temperature, coiling temperature, amount of cold reduction and the annealing cycle.



12. *TWO MODES OF DEFORMATION in cup drawing. In the flange, the material thickness is unchanged. In the wall, material thickness is reduced. Failure is thus apt to take place in the wall. A material with a high* r *value will resist thinning, hence it is the best choice for successful cup drawing.*

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Typical $\bar{r}$ values for several common metals used in forming are:

Normalized steel	1.0
Rimmed steel	1.0-1.35
Aluminum-killed steel .	1.35-2.0
Copper, brass	0.8-1.0
Lead	0.2
Hexagonal, close-packed metals	3-6+

The primary influence of anisotropy on metal formability is in cup drawing or deep drawing, where a flat circular blank is drawn into a flat-bottom, cylindrical cup, *Figure* 12. The essential metallurgical requirement for improvement of the limiting drawing ratio is for some kind of differential property control, whereby the lower cup wall is strengthened relative to the deforming flange. This can be accomplished by increasing the through-thickness strength of the material.

The flange is deformed as it is drawn toward the die radius. As a convenient, if rough, approximation, changes in flange thickness are ignored. Deformation is tensile and compressive along the radial and circumferential directions, respectively, in the plane of the blank.

In this strain state, a high normal anisotropy or resistance to thinning does not strengthen the flange region.

The structurally weak link of the system is in the cup wall, however. The punch effectively precludes straining in the circumferential direction. Therefore, elongation leading to failure is accompanied by a reduction in thickness. A high r value now resists thinning. thereby strengthening the cup wall relative to the deforming flange. The cup wall can now support a larger drawing load without failure. The wall of the cup is said to be strengthened by texture hardening. A larger blank can be made into a cup of fixed diameter, thereby increasing the limiting drawing ratio.

The influence of anisotropy is very graphically shown by Atkinson, who summarized the drawing limit for many materials, *Figure* 13. In changing the strain ratio from 0.2 for zinc to 6.0 for titanium, the limiting drawing ratio increases from 2 to 3. Translated into height of a fixed-diameter cup, the height is increased by a factor of three.

The drawability of several materials can be compared on the basis of their r values, *Figure* 14. The variation of r with angle determines the amount of earing. Unlike the case shown in *Figure* 11, the Δr for all three cases is equal, indicating equal amounts of earing. However, the average $\bar{r}$ level now varies greatly. The lower the $\bar{r}$, the poorer the drawability.

Specific engineering applications often stipulate a minimum thickness for a stamping after forming. Many parts are rejected for excessive thinning, which occurs in high strain areas. A high resistance to thinning, or an increase in the through-thickness strength of the sheet, will reduce the amount of this thinning and will help to retain a thickness dimension more nearly that of the original thickness.

Turning now to stretch forming, the influence of anisotropy on stretchability is illustrated by contradictory findings, although any influence is small compared to cup drawing. More work is needed to delineate the effects of anisotropy on instability, fracture and strain distribution, all of which contribute to the total attainable amount of deformation.

A second source of anisotropy—mechanical fibering—will be mentioned only briefly. This anisotropy is noncrystallographic in origin and is present in varying degrees in all wrought materials. Its greatest influence is on the termination of the stress-strain curve, or on ductile fracture—a gradual process during which substantial amounts of plastic flow culminate in a final separation. Any alignment of particles, pores or weak interfaces during mechanical working will create an anisotropy of ductile fracture.

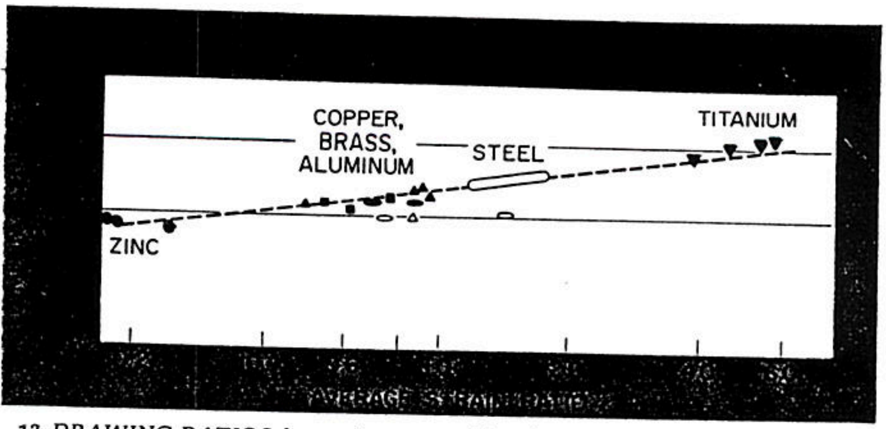
Attempts have been made to increase ductility by removal of the more obvious patterns of mechanical fibering. Among new developments underway in the steel industry are vacuum degassing units that remove some of the gases from the melt prior to solidification, thereby reducing the inclusion content and porosity. Similar advantages are to be gained from vacuum melting, controlling the additives and alloying elements, and proper slagging procedures. The primary goal is to obtain as clean and sound an ingot as possible prior to subsequent reduction techniques.

Control over production practices can also result in reduction of anisotropy. For special applications, plate is cross-rolled in an attempt to equalize the deformation in all directions within the plane of the sheet. Control of rolling temperatures, amount of reduction and reheat practice is essential.

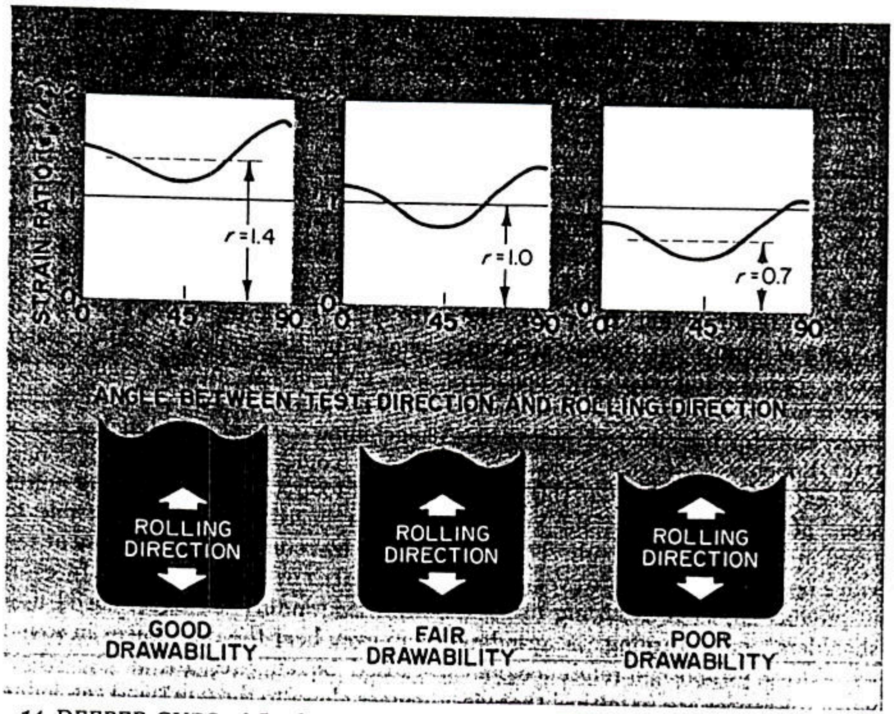
Attempts to eliminate mechanical fibering by thermal treatment have reduced the degree of anisotropy but never removed it completely.

Special fabrication techniques using hydrostatic compression can often suppress the effects of mechanical fibering.

Next month, a predictable forming limit for many metal stampings will be presented. Subsequent installments will discuss applications. ▲▲



13. *DRAWING RATIOS for various materials, plotted against* r. *A high* r *value indicates good drawability. (From "Assessing Normal Anisotropic Plasticity of Sheet Metals" by M. Atkinson,* Sheet Metal Industries, Vol. 44, page 167.)



14. *DEEPER CUPS of flat-bottom cylindrical configuration can be drawn when* r *values are high. The amount of earing is traceable to the variation of* r *with direction. (From "Relationship Among Texture, Hot Mill Practice and the Deep Drawability of Sheet Steel, Flat Rolled Products III" by R. L. Whitley and D. E. Wise.* Metallurgical Society Conferences, Interscience Publishers.)