Part 1—The State of the Art

Understanding Sheet Metal Formability

Sheet metal forming is undergoing a transition from an art to a science. Trial and error are giving way to knowledge. Numbers and graphs are replacing opinions and guesses. This six-part article, written by one of America's top authorities, tells you how to put the new science of metal forming to work.

①(An understanding of the formability of sheet metal is essential for the production of quality stampings,) *Figure* 1. Process planners and tool designers must determine the formability level required for each stamping. And they must measure the formability of each lot of sheet metal to be used in production so that they can be sure it meets formability standards. Producers and suppliers of sheet metal, too, must measure and control formability so they can be sure that their customers receive sheet metal that is formable under production conditions.

①(Formability is an elusive quality to measure. There is no single index that will enable the formability of a specific material to be reliably predicted for all production conditions or all stampings. A material that is readily formable for one stamping design may break when it is used for a stamping having a different configuration.)

①(In die tryout it is often necessary to change to a more formable material, to modify the die design and even to modify the design of the stamping in order to successfully form a new stamping. All of this takes time and money, and illustrates the need for a better understanding of sheet metal formability.) —> p 1-a

Problems do not end when a few hundred quality stampings have been

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1. COMPLEX STAMPINGS are required for today's automobiles and hundreds of other products. Industry can no longer afford trial-and-error design of stampings and the tooling used to produce them. Stampings like these are now developed with the aid of data that enable the formability of sheet metals to be reliably predicted. Results: shorter lead times, lower costs. ►

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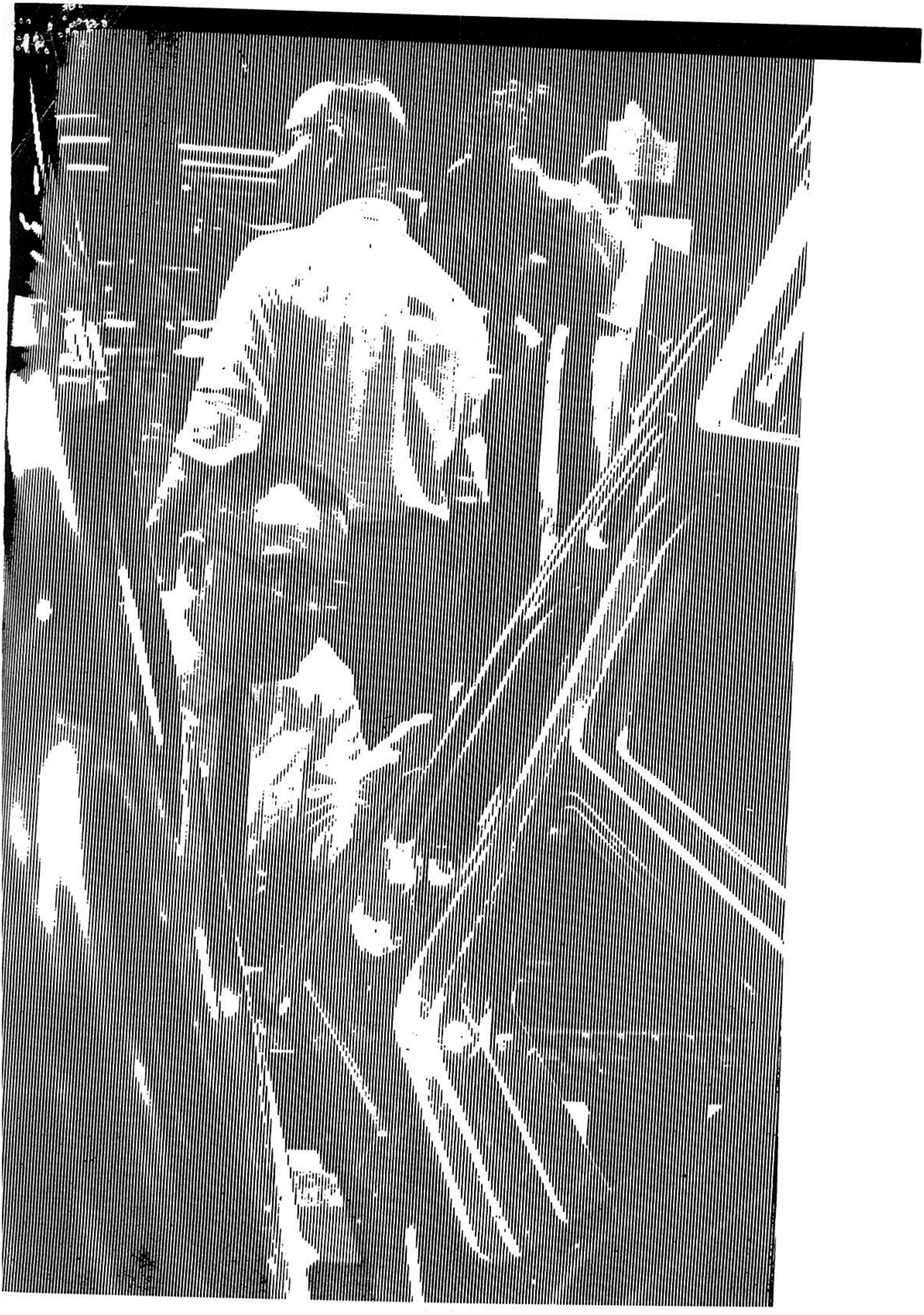


produced during die tryout. In the tryout shop, the presses may be slow, die adjustment perfect, lubrication correct, gaging proper and tools prepared for one specific set of material properties. In production, press speeds are usually high, dies are aligned differently, lubrication is automated and material properties vary. If the stampings are unsatisfactory, further trial-and-error testing, further modification of the die, and perhaps even a change to a more formable material, will be necessary. Again, time is lost and costs increase.

Even when thousands of stampings have been successfully made, troubles still occur. Often, these are caused by variations in the properties of the sheet metal or by changes in the dies as they wear.

Material Property Tests A17

From the examples given, (it is evident that there is a real need for a way to predict or evaluate the formability of sheet metal in a single, quick and meaningful test. Such a test should show whether or not a given lot of sheet metal is suitable for a particular stamping. It should also be capable of evaluating the current condition of a set of dies.

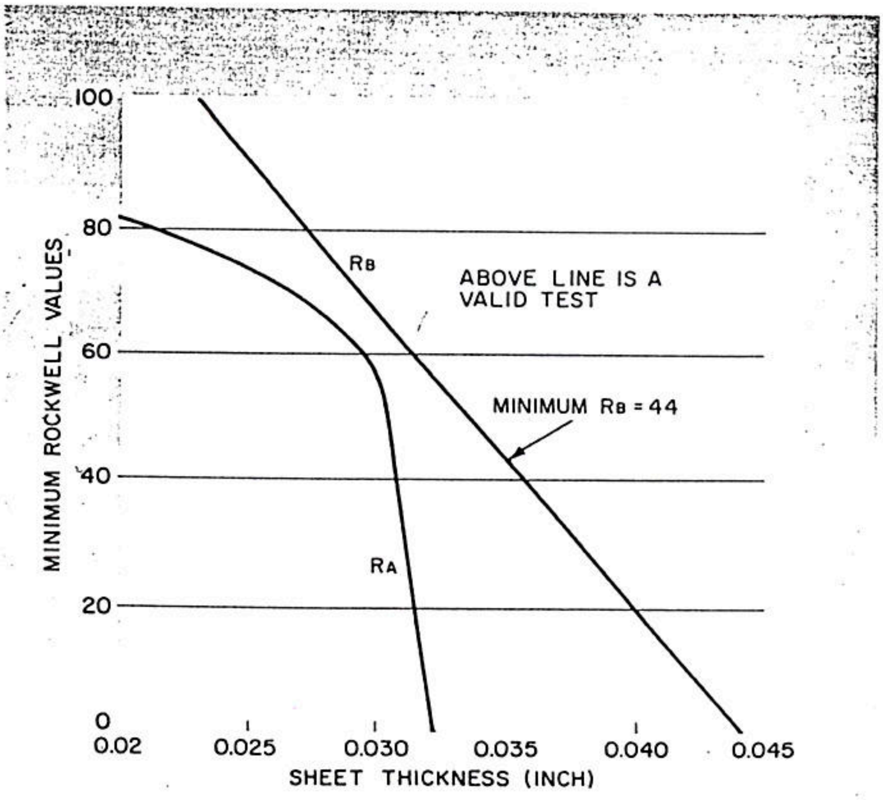
In the past, there have been two main methods of determining the forming characteristics of sheet metal—testing the fundamental mechanical properties of the sheet metal and testing the forming properties by simulating forming operations.

The most popular test in the fundamental mechanical properties group is the Rockwell hardness test.) The hardness number obtained is a measure of the sheet metal's resistance to penetration by an indenter.

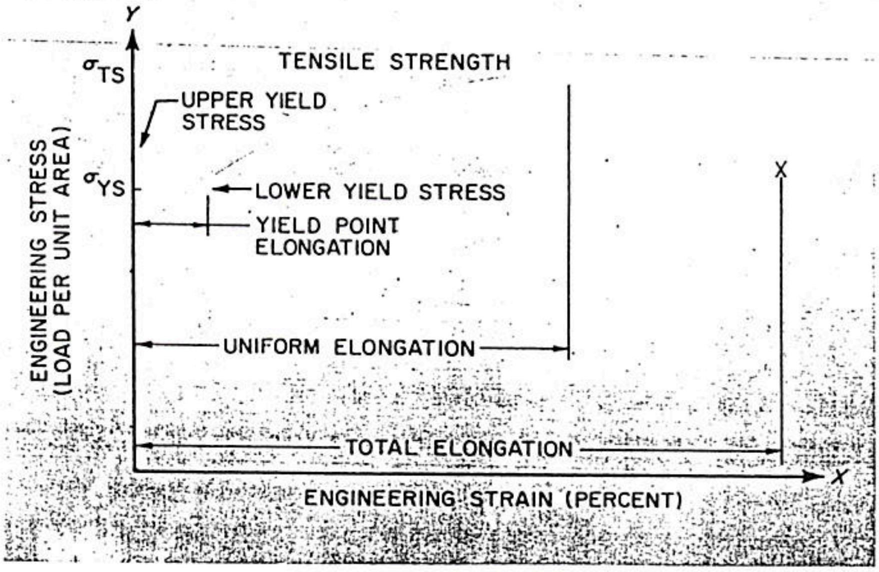
(The reason for the popularity of the Rockwell test is its simplicity. Usually, any piece of sheet metal can be tested without any special preparation of the specimen. The test can be conducted in a few minutes on rather simple equipment, and no calculations are required.

Despite the simplicity of the Rockwell hardness test many problems are encountered in making accurate measurements and using them as formability indexes. Readings are sensitive to surface conditions, flatness of the specimen and test procedures.)

A frequent error is to use the wrong hardness scale. (Two different hardness



2. *ROCKWELL HARDNESS TESTS measure the resistance of a material to penetration. The Rockwell B scale is used for soft materials and the Rockwell C for high-strength materials. The minimum hardnesses that can be measured for a given sheet thickness and Rockwell scale are shown here. Hardness values obtained below the minimum hardness line for each scale are invalid. Any material softer than this will permit the indenter to penetrate so far that the anvil influences the reading. This is a common reason for inaccuracy.*



3. *STRESS-STRAIN CURVE of dead soft mild steel. The material deforms elastically until the upper yield stress is reached. Up to that point, it will return to its original length when the load is released. Beyond that point, it takes a permanent set. Elongation is uniform until a maximum load point or ultimate tensile strength is reached. This is the principal type of elongation experienced during the forming of a stamping. Deformation becomes localized after maximum load point is reached. Eventually, the specimen breaks.*

scales are commonly used for tests made in stamping plants—the Rockwell B scale for soft materials and the Rockwell C scale for hard materials.

As shown in *Figure* 2, there is a minimum hardness that can be accurately measured for a given sheet thickness and Rockwell scale. For example, an 0.035-inch-thick sheet of a steel frequently used in the automotive industry must be harder than R_B 44 to yield a valid R_B hardness reading. The indenter will penetrate too deeply into any steel softer than this. The hardness of the anvil that supports the sheet will influence the reading, which will be too high.

Rockwell hardness values vary along the surface of the sheet. They are strongly affected by the amount of cold working near the surface of the material in temper rolling or skin passing operations, so a soft material may appear to be harder than it really is.

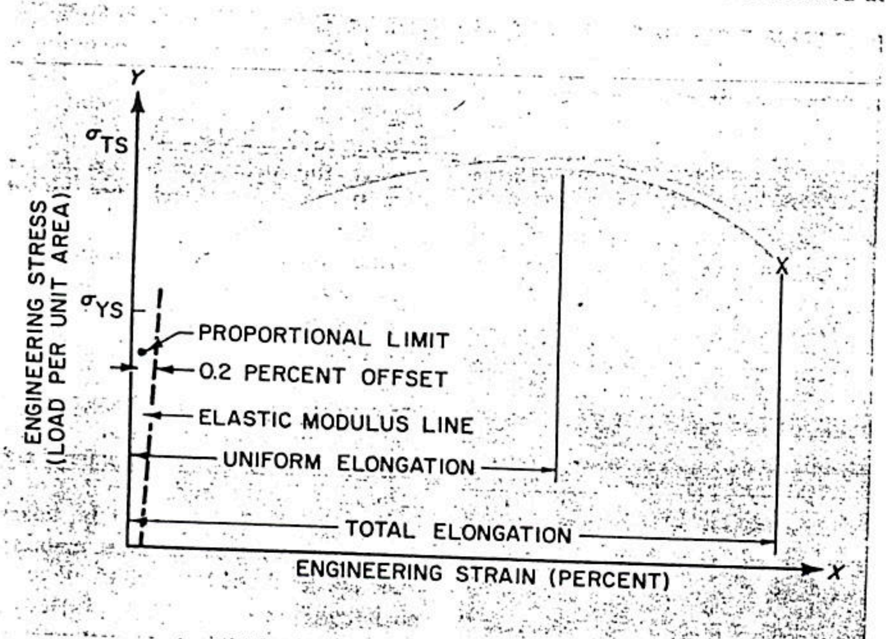
Occasionally, after long statistical correlations, relationships are found between Rockwell hardness and formability of a specific material for a specific stamping. In general, steels with high Rockwell hardness values are more difficult to form, although this is not always the case.

Other mechanical properties influence the formability of sheet metal more than Rockwell hardness, so hardness values alone should not be the basis for rejecting sheet metal. Rockwell hardness values are useful, however, when making comparisons between several shipments of identical grades of steel. They serve as an indicator of whether or not the steel in each shipment was processed in the same way.

Uniaxial tension tests provide more accurate information on the fundamental mechanical properties of sheet metal than Rockwell hardness tests. In these tests, a tensile specimen is blanked or milled from the sheet. The specimen is stretched in a tensile test machine, and the load and elongation are measured simultaneously. Information obtained for a dead soft, mild steel is plotted in *Figure* 3. The curve derived from the load-elongation measurement is called the engineering stress-strain curve.

The Y (vertical) axis is load divided by the original cross sectional area of the specimen, or engineering stress. The *X* (horizontal) axis is elongated length divided by the original length of the gauge section over which the elongation is measured. This is percentage extension, or engineering strain.

When the test starts, the load rises very rapidly. This is the elastic portion of the curve. If the load is released at any point on this portion of the curve, the specimen will return to its original length.



4. STRESS-STRAIN CURVE *of temper-passed mild steel. The curve is similar to that for dead soft steel (see Figure 3) but the sharp load drop at the upper yield point, and the yield point elongation have been eliminated. The 0.2 percent offset line parallel to the elastic modulus line is an arbitrary value to give yield stress. The yield stress is often used in attempts to evaluate the formability of a material—usually with indifferent success. This is because the yield stress may change with increasing speed of deformation.*

Once the upper yield stress is reached, the material deforms plastically and will have a permanent set when the load is released.

As the material starts to deform plastically, the load often drops, then remains constant for a varying amount of elongation. This constant load is called the lower yield stress, or simply the yield stress, of the metal. The amount of elongation during this constant load is called yield point elongation. During this time, stretcher strains traverse the length of the specimen. After the whole specimen has yielded, or the stretcher strains have traversed the entire length of the specimen, the load rises again. The specimen is then undergoing uniform elongation—the principal type of elongation in the forming of stampings.

During uniform elongation, the rate of the load increase is reduced as the specimen is elongated. Eventually, a maximum load point, the ultimate tensile strength, is reached. Uniform elongation is measured from the onset of plastic deformation to the ultimate tensile strength. At the ultimate tensile strength, necking (very localized deformation) begins. The final elongation, measured after the specimen breaks, is known as total elongation.

If the material has been temper-passed sufficiently to eliminate all yield point elongation, an engineering stress-strain curve like that shown in *Figure* 4 is obtained. The sharp load drop at the upper yield point, and the yield point elongation, have been eliminated. All other properties, with the exception of the yield stress, are measured in a manner similar to that used for the dead soft material whose properties are shown in *Figure* 3.

For yield stress, some arbitrary value must be obtained. A common practice is to draw a line parallel to the elastic line, offset at a strain of 0.2 percent. The stress value at which this line intersects the curve is called the yield stress.

Several properties from the stress-strain curve have been used in attempts to evaluate the formability of the metal—yield stress, ultimate tensile strength and total elongation. Yield stress has the disadvantage of being rather sensitive to speed of deformation. It increases with increasing speed. Since tensile tests are run at slower speeds than those used in production stamping operations, the value of the measured yield stress will be lower than that encountered during stamping. The method of specimen preparation also affects the yield stress. Mechanical properties such as ultimate tensile strength and total elongation are also very sensitive to test conditions, surface scratches, specimen preparation methods and specimen geometry.

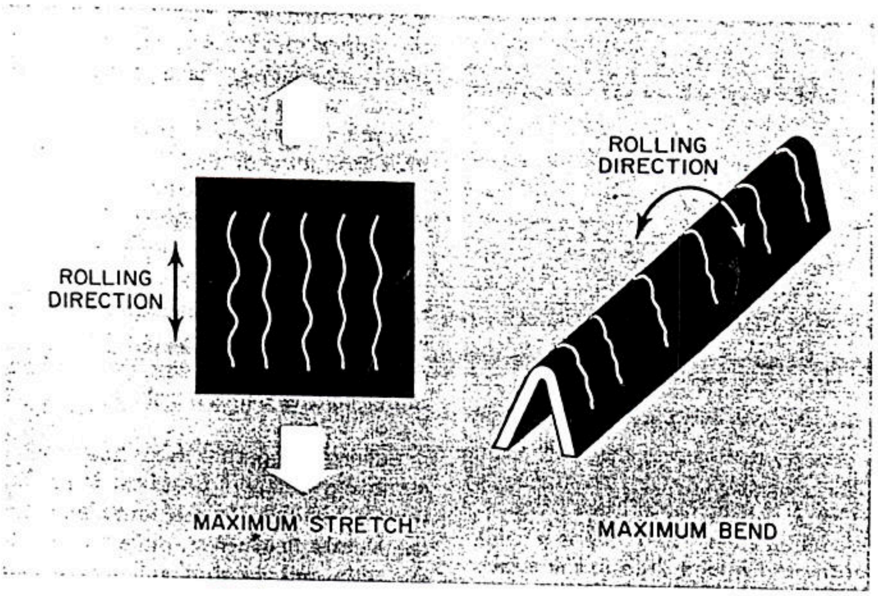
In another part of this article, a new property—the *n* value of the material—will be used to evaluate the relationship between the formability of the material and the stress-strain curve. The *n* value is proportional to the uniform elongation of the material or to the tensile-to-yield-strength ratio. This value is not presently used in most plants, except for unusual conditions of die tryout or when attempting to solve serious production problems.

There have been many attempts to use chemical composition to evaluate the formability of materials. Most steel stampings, however, are made from low carbon steels. These steels contain from 0.02 to 0.08 percent carbon, plus varying amounts of aluminum, silicon, manganese, nickel, chromium and other elements.

Forming tests have proved that minor variations in chemistry cannot be correlated to the formability of sheet steels. Other factors in the processing of the steel—finishing temperatures, coiling temperatures, the amount of cold reduction, characteristics of the anneal, skin passing and the like—can completely overshadow small variations in chemistry.

A diversity of fundamental material properties can be tested. Lengthy statistical correlations of test results with extensive data on the performance of the material in production stamping operations are needed to determine which properties influence performance, and to what extent, and at what levels. The relationships obtained from such studies are often purely statistical. And the relationship between the property that is statistically significant and the stamping process is not always obvious.

An example is an automotive oil pan stamping normally considered to be difficult to form. In several cases, an evaluation of all mechanical properties showed that only yield point elongation had any significant correlation with the performance of the sheet metal used for this job. One investigator found that the best material for an oil pan stamping was the one that had the highest yield point elongation. A second investigator, studying the forming of an oil pan of different configuration, found that a steel with no yield point elongation performed best. A third investigator found no relationship at all between the performance of the sheet metal in stamping and yield point elongation or any other property.



5. *ROLLED MATERIAL has segregations and inclusions elongated in the rolling direction. In a stretching type of operation (left) maximum stretch should be oriented parallel to the rolling direction. In bending, maximum bend is obtained when the bend axis is perpendicular to the rolling direction (right).*

This is an example of how little is known about the influence of mechanical properties on formability.

Through statistical analysis, unsuspected correlations are sometimes found. In one case, the performance of a material in stamping production was directly correlated to the longitudinal tensile strength along the edge of the sheet divided by the sulfur content in the center of the sheet. The physical significance of such a correlation would be difficult to determine.

Functional Requirements

Many stampings made today are acceptable if there are no obvious tears, cracks, buckles or necks in the finished stamping. They serve a decorative, rather than structural, purpose. Other stampings serve a structural purpose (and sometimes a decorative purpose as well). Examples are the frame members of automobiles, power steering pump housings, propane tanks, fire extinguisher cylinders and side panels of monocoque automobile bodies. These parts require strength and ductility in the finished condition.

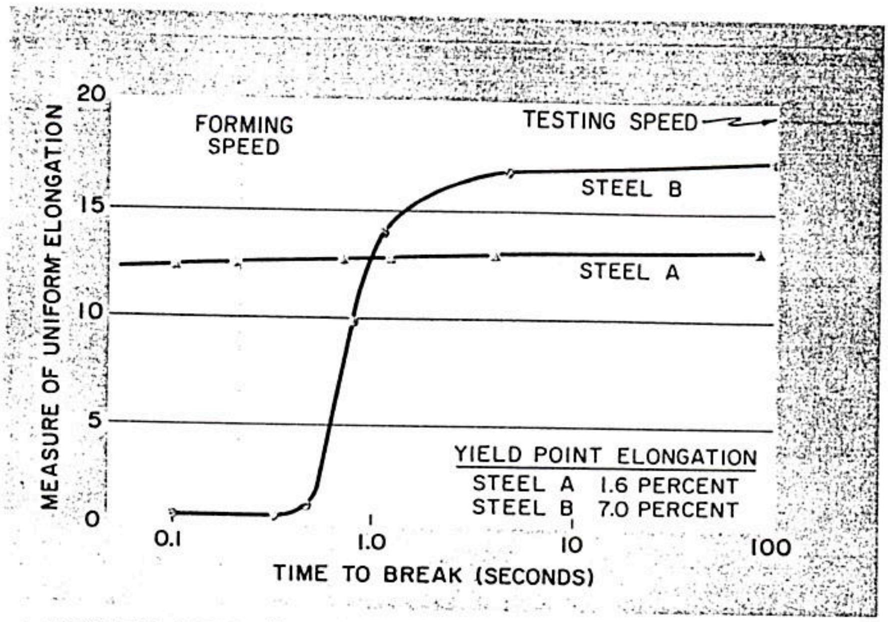
The behavior of the steel after forming of these parts is extremely important. There may be minimum strength specifications for the part. Specifications may state that when loaded either in bending or by internal pressure, the parts must withstand the stresses without failure and also not change dimensionally beyond tolerance limits. As an additional requirement, enough ductility must be left in the metal after forming so that if the yield stress is exceeded, the metal will deform to reduce the overload, thereby preventing catastrophic failure.

Other requirements—minimum thickness, for example—may be imposed for engineering reasons to control the stress and load bearing capabilities of specific parts. The fatigue properties of the material are important in parts that undergo alternating stresses.

All of these design requirements are influenced by the initial forming of a stamping. All of them must be taken into consideration when sheet metal is selected. In short, formability alone is no longer the sole criterion. Performance after forming is of paramount importance for structural stamping.

Factors Influencing Tests

Formability can be radically influenced by several factors that have not been mentioned so far. These factors may represent the difference between successful production of a stamping and 100 percent breakage during pressworking operations.



6. FORMING SPEED affects the ability of metals to elongate uniformly. Here Steel B showed a higher measure of uniform elongation (formability) than Steel A at normal testing speeds. In high-speed production, Steel B broke, because its formability at high speeds was almost zero, while Steel A performed well, despite poorer low-speed formability. (From a paper by R. Heyer and J. Newby, presented at the 1966 AIME Mechanical Working Conference.)

The first of these factors is directionality. Values of almost all material properties of sheet metals vary with rolling direction. Values of properties transverse to the rolling direction are different from those measured parallel to the rolling direction. This phenomenon, called anisotropy, is related to the basic crystallographic structure of the metal, which strongly influences the shape of the stress-strain curve, and therefore the yield and tensile properties of the sheet.

A second type of anisotropy—mechanical fibering—is created when a material is rolled from an ingot to a sheet. Inclusions, segregation, banding, porosity or other imperfections are all oriented and elongated parallel to the rolling direction.

In the presence of this anisotropy, maximum strength and greatest deformation without failure are possible when the maximum strain (or stress) is imposed along the rolling direction—along the axis of the imperfections in the sheet metal.

Two ways in which the effects of anisotropy can be minimized, are shown in *Figure* 5. In a stretching type of operation (left-hand drawing), maximum stretch should be oriented perpendicular to the rolling direction. To obtain maximum bending deformation (right-hand drawing), the sheet is bent so that the axis of the bend is perpendicular to the rolling direction, or so the maximum strain is along the rolling direction.

In some cases, it is possible to reorient the direction of rolling 90 degrees by physically rotating symmetrical blanks at the press or by employing a different blanking direction. Although this simple procedure can greatly reduce failure, it is often overlooked.

A condition where the yield stress in tension is not equal to that in compression can cause trouble. This condition, called the Bauschinger effect, can occur when a piece of metal is worked in one direction (say, in compression) and is then subjected to a working or testing stress in the opposite direction (tension).

This effect can be important in the fabrication of pressure tubes. When sheet metal is rolled and welded to form a pressure tube, it may not be completely round. It is sized and rounded by compressing it several percent. If a section of this tube is subsequently tested in compression, its yield stress might be as high as 35,000 psi. When subjected to internal hydrostatic pressure, however, the tube is under a tensile stress and may have a yield stress as low as 10,000 psi. It is important, therefore, that the metal be worked last in the direction in which it is to be service loaded. This design problem is often overlooked.

The proportional limit—the stress at which the stress-strain curve deviates from a straight-line slope—should also be considered by designers of sheet metal parts that are used structurally. Usually, the proportional limit is not equal to the yield point. For a yield stress of 35,000 psi, the proportional limit may be at 15,000 or 20,000 psi. A designer who assumes that the 30 million psi slope will continue to the yield stress of 35,000 psi, and then calculates the deflection at 30,000 psi, can be quite far off if the material has a proportional limit of only 10,000 psi.

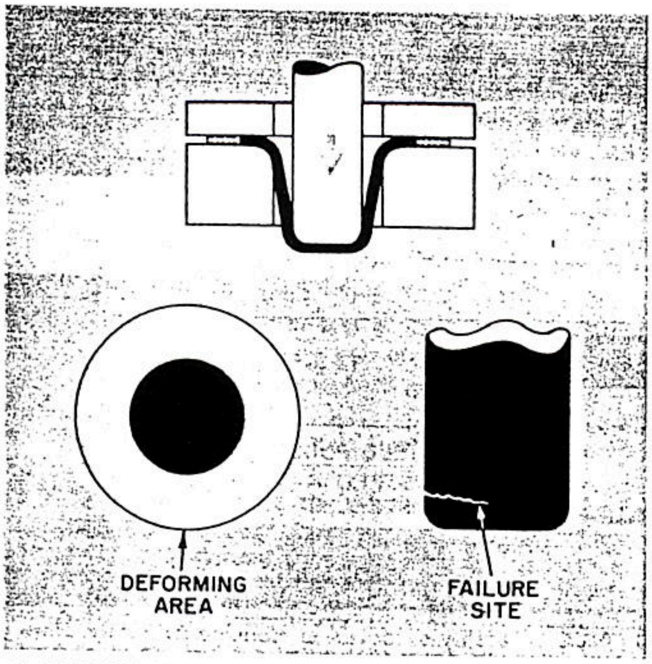
Deformation speed has a profound effect on the formability of sheet metals. Sometimes a certain steel may make satisfactory stampings on a slow-speed press yet be completely unsatisfactory on a high-speed press. The opposite also happens occasionally.

As already mentioned, the yield stress increases with deformation speed. Tensile strength also increases, to a lesser degree. Formability of the sheet, if measured by the tensile-to-yield-strength ratio, therefore decreases when speed increases. Similarly, the yield point elongation of the material increases. If there is a 1 percent yield point elongation at a testing speed of 0.2 ipm, a tenfold increase in testing speed may double or triple the yield point elongation. Characteristics of lubricants, too, change with speed—another factor that may influence formability of sheet metals.

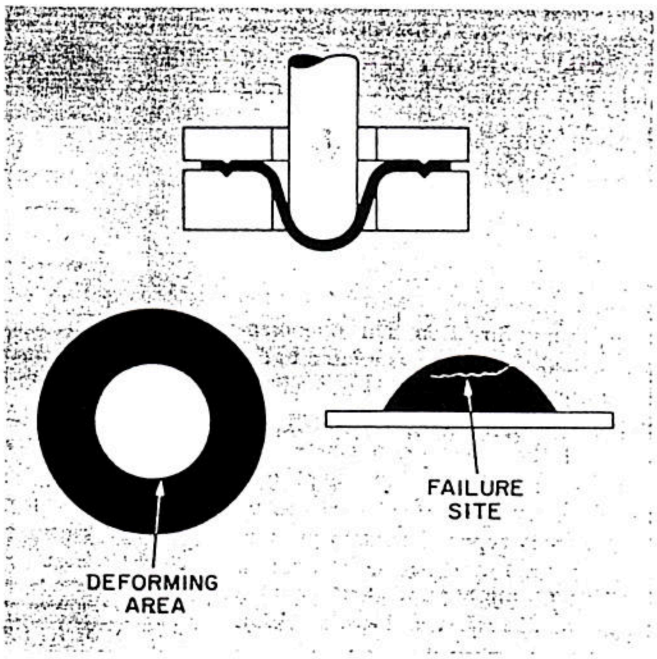
To fully understand the formability of a material, then, it must be tested over a broad range of deformation speeds. In this connection, the results of some tests conducted at Armco are of particular interest. (The results were reported at the AIME Mechanical Working Conference in Philadelphia, December 1966, in a paper titled "Measurement of Ductility of Low Carbon Steel Sheets" by R. Heyer and J. Newby.)

In these tests, two steels were tested at the usual slow speeds. A measure of the uniform elongation was used as the forming index. One steel had a higher forming index than the other at test speeds. In a press tryout, however, the steel that had the higher forming index in low-speed tests broke, while the other steel performed satisfactorily.

When both steels were tested in tension, at various speeds from low to



7. DEEP DRAWING OPERATION. In this type of operation, the edge of the blank is not held. The flange, drawn into the die, forms a flat-bottom cup. The metal in the bottom of the cup is not deformed. When failure occurs, it is usually in the wall area, close to the cup bottom.



8. STRETCH FORMING OPERATION. Here the edges of the circular blank are securely clamped. Only the metal in the die area is formed. Failure can occur anywhere, depending on the material and forming conditions. Most stamping operations are combination stretch, draw.

high, as seen in *Figure* 6, it was discovered the steel with the lower formability index had a relatively constant formability index at all speeds, while the formability index of the other steel decreased at higher speeds. That is why it broke in press tryouts.

In addition to the factors already discussed, variations in material properties from shipment to shipment, from coil to coil, from one edge of a coil to the other, and from one end of a coil to another, must be considered. The problem is how many tests must be made, and at what points in the coil, to find the typical properties of the material.

There is, of course, a need for evaluation of the material properties discussed. But the tests described do not give a true picture of formability. Their use should be restricted to making sure that properties do not vary from shipment to shipment or coil to coil. One can generally assume that if the fundamental mechanical properties in one lot of steel are identical to those in another lot of steel that has been successfully formed, the steel mill has processed the steel in both lots in the same manner. The formability of the steels should be similar.

A second type of test method, in which formability is evaluated by simulating production stamping, will be discussed shortly. First, some terms will be defined.

Stretching and Drawing

Many individual operations may be required to produce a complex stamping. The word forming is used to cover all of the operations required to form a flat sheet into a part. These operations may include deep drawing, stretching, bending, buckling and others.

In deep drawing, which is also called cup drawing or radial drawing, a parallel-walled cup is created from a flat blank. The blank may be circular or rectangular, or of a more complex outline. This blank is drawn into the die cavity by the action of a punch, as shown in *Figure* 7. Deformation is restricted to the flange areas of the blank. No deformation occurs under the bottom of the punch—the area of the blank originally within the die opening. As the punch forms the cup, the amount of material in the flange decreases.

In drawing, the limit of deformation is reached when the load required to deform the flange becomes greater than the load-carrying capacity of the cup wall. Site of the failure will be in the unworked area near the bottom of the cup wall. Hold-down pressures, friction, and bending and unbending over the die radius, also limit deformation. The deformation limit (Limiting Drawing Ratio or LDR) is defined as the ratio of the maximum blank diameter that can be drawn into a cup without failure to the diameter of the punch.

Examples of deep-drawn parts are automotive oil pans, hydraulic pump housings, propane cylinders, vegetable pans for refrigerators and bathtubs.

Another type of forming operation, stretching, is illustrated in *Figure* 8. In stretching, the flange of the flat blank is securely clamped. Deformation is restricted to the area initially within the die. Normally, a rigid punch is used to form the part. Elastomer punches are also used, and punches are dispensed with when stretching is done with the aid of explosive charges, hydraulic fluids under high pressure and the like.

The stretching limit is the onset of metal failure. Location of the failure depends on the material and the forming conditions.

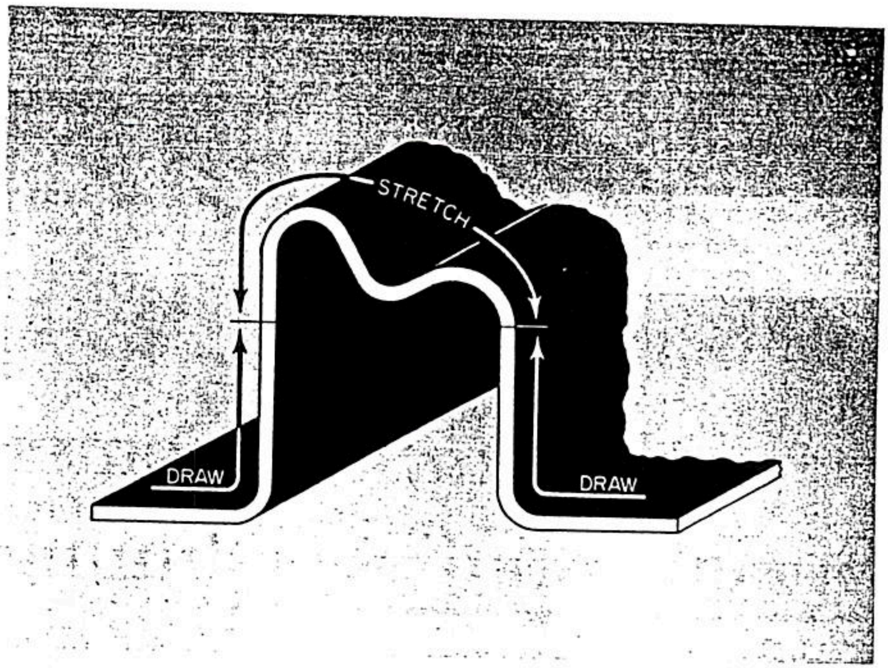
In most complex forming operations, bending and unbending are added to the deformation as the metal changes direction in flowing over the punch, the die, draw beads and contoured areas.

Unwanted types of deformation—buckling or wrinkling of the flange—are often encountered. In deep drawing, buckling and wrinkling are due to excessive metal in the flange. They can be minimized by decreasing the yield stress of the metal, by raising the hold-down pressure, by reducing the clearance between punch and die, by increasing the thickness of the blank, or by reducing the size of the blank.

Forming operations that consist only of deep drawing or pure stretching are rare. Most often, the deformation is a combination of deep drawing and stretching. The amounts of stretching and drawing vary from stamping to stamping, or even at different locations within a stamping.

An example is the automotive bumper shown in *Figure* 9. The walls of the part are formed by drawing metal in from the flange. A complex shape is formed over the head of the punch by stretching. The relative amounts of stretching and drawing vary with material properties, lubrication and die design. If, for some reason, the drawing action of the flange is restricted, the material must stretch more over the punch and vice versa. Even though the cause of failure of this stamping may be restricted flow of metal from the flange, the failure will usually be in the stretch forming region over the head of the punch. This fact is important when the maximum formability of the metal is predicted.

The relative amounts of stretching and drawing may also vary with time or with the depth of the stamping. As the edge of a blank passes over a series of draw beads, the restraint decreases and drawing is made easier.



9. COMPLEX STAMPING is the result of both stretching and drawing operations. The walls of this part are formed by drawing metal in from the flange. A complex shape is formed over the head of the punch by stretching. If failure occurs, it will normally be in the stretched area, rather than in the drawn area.

Types of Forming Tests

Tests that subject sheet metal to the same types of deformation found in stamping are now being used to evaluate formability. These simulative tests also enable the effects of surface textures of materials, lubrication, anisotropy and large surface areas to be evaluated.

Two tests—the Swift flat-bottom cup test and the Sach's wedge-draw test—are used to simulate deep drawing. Two of the most common stretch forming tests are the Erichsen and Olsen tests, in which small punches are pushed into a large sheet of clamped metal. (In some cases, larger punches —4, 8 and even 15 inches in diameter —are used.)

Combined stretching and drawing are simulated in the Fukui conical cup test and the Swift round-bottom cup test, sometimes used in research.

Simulative tests, like mechanical property tests, are of limited value for the evaluation of sheet metal formability. There is a broad spectrum of possible forming combinations, ranging from pure deep drawing to pure stretching. And several types of forming operations may be combined in one stamping. One simulative test will evaluate only one of the many combinations of forming operations. Therefore none of the simulative tests will give a reliable formability index for such a part.

Variations in grade and type of lubricant influence the results of simulated forming tests strongly. Lubricant specifications—and even the manufacturer—must be stated to make sure that test conditions can be duplicated. The speed at which the test is run is of critical importance. A slight burr, a blanked (rather than ground) edge on the blank and dimensional variations —all of these can affect test results. In some of the tests, reliance must be placed on the operator's judgment. In the Olsen test, for example, the height of the punch at maximum load must be measured. Using the same system of measurement, different results are obtained by different operators.

Lastly, there is the problem of a scale factor. Whether or not a 1-inch-diameter punch can truly represent a punch used to form a stamping 2 or 8 feet in diameter is questionable.

The need to adhere to exacting specifications makes simulated forming tests time consuming and costly. Many hours can be spent in attempts to correlate test results.

Need for Better Tests

It appears that no matter how much any test is perfected, no single mechanical property test or simulated forming test is sufficient to accurately evaluate formability. The futility of this approach can be appreciated when the press performance of a single lot of material in the same die and press with the same lubricant can vary from shift to shift, day to day, operator to operator or even from weather condition to weather condition.

An ideal test would measure directly the behavior of a given sheet of material under all press conditions. It would also answer the question of how well that sheet of material can be formed in the press under current conditions. Because extensive testing is expensive, the ideal test should require only a single blank. It should be very sensitive to slight changes in material properties or in press conditions. And it should yield information that can be used to order material with similar forming capabilities.

Such a test has been developed. It will be described in Part 3 of this article, which will appear in the April 1968 issue of *Machinery*. ▲▲