Spinning

Introduction

SPINNING is a method of forming sheet metal into seamless, axisymmetric shapes by a combination of rotation and force. On the basis of techniques used, applications, and results obtainable, the method can be divided into two categories: manual spinning and power spinning. This article will discuss the spinning of sheet; tube spinning is covered in the article "Tube Spinning" in this Volume.

Manual Spinning

Manual spinning involves no appreciable thinning of the work metal. The operation is accomplished with the use of a lathe, and it consists of pressing a tool against a circular metal blank that is rotated by the head-stock. The blank is usually forced over a mandrel of a predetermined shape, but simple shapes can be spun without a mandrel. Various mechanical devices are used to increase the force that can be applied to the workpiece.

Any metal that is ductile enough to be cold formed by other methods can be spun. Most spinning is done without applying heat to the workpiece; the metal is sometimes preheated to increase ductility or to allow thicker sections to be spun.

Applicability

Manual spinning is used to form flanges, rolled rims, cups, cones, and double-curved surfaces of revolution (such as bells). Several typical shapes formed by manual spinning are shown in Fig. 1. Products include light reflectors, tank ends, covers, housings, shields, and components for musical instruments. Manual spinning is also extensively used for the production of aircraft and aerospace components, often with mechanical assistance for increased force.

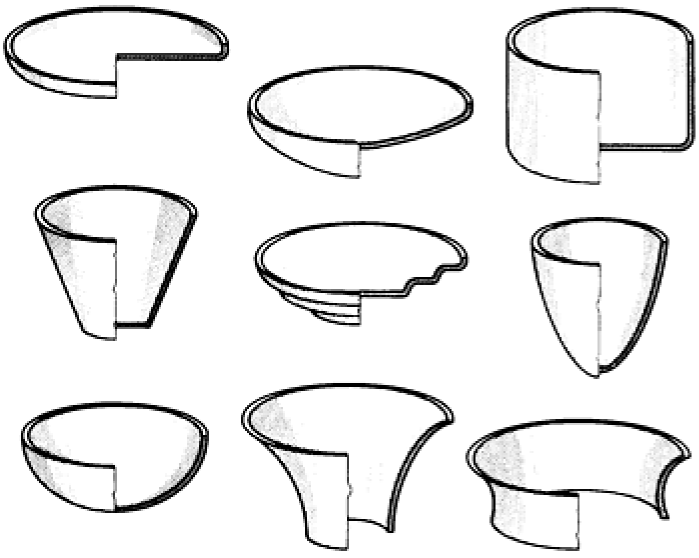

Fig. 1 Typical conical, cylindrical, and dome shapes that can be formed by manual spinning.

The practical maximum thickness of low-carbon steel that can be spun without mechanical assistance is 3.2 mm ($\frac{1}{8}$ in.). In this thickness, the diameter can be as great as 1.8 m (72 in.). Diameters can be greater when the sheet steel is thinner, but the maximum practical diameter is often limited by the availability of equipment. The upper limit of thickness increases as work metal ductility increases or as strength decreases. For example, the manual spinning of aluminum as thick as 6.4 mm ($\frac{1}{4}$ in.) is feasible.

Advantages and Disadvantages

Manual spinning has several advantages over a competitive process such as press forming:

- Tooling costs less, and investment in capital equipment is relatively small
- Setup time is shorter
- Design changes in the workpiece can be made at minimum expense
- Changes in work metal composition or thickness require a minimum of tool changes

The disadvantages of manual spinning include:

- Skilled operators are required, because uniformity of results depends greatly on operator skill
- Manual spinning is usually slower than press forming
- Available force is more likely to be inadequate in manual spinning than in press forming

Equipment

A simple tool and workpiece setup for manual spinning is shown in Fig. 2(a). The mandrel is mounted on the headstock of a lathe. The circular blank (workpiece) is clamped to the mandrel by the follower block. An antifriction center is used between the follower and the tailstock spindle, and pressure is applied at the tailstock by means of a screw or by air or hydraulic pressure, depending on the size and type of lathe. The tool rest and pedestal permit the support pin (fulcrum) to be moved to various positions by swinging the tool rest and moving the support pin from one hole to another as needed. Spinning is done by manually applying the friction-type spinning tool as a pry bar.

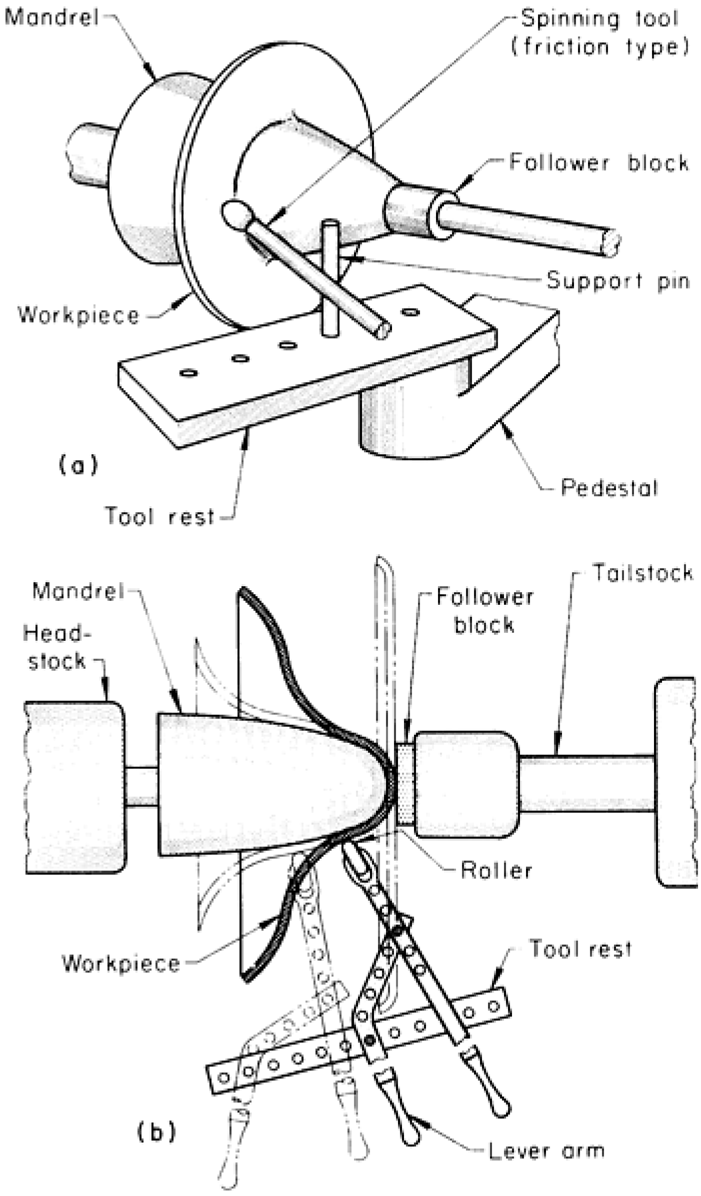

Fig. 2 Manual spinning using a lathe. (a) Simple setup using a hand tool applied as a pry bar. (b) Setup using scissorlike levers and roller spinning tool.

Figure 2(b) shows a more complex setup for manual spinning. In this configuration, the spinning tools (rollers) are mounted in the fork sections of long levers, and the tool support has a series of holes for the rapid changing of tool position. The tool is manipulated by pulling, pushing, or pivoting the two scissorlike handles, with the roller against the workpiece.

Lathes. Several sizes of standard horizontal spinning lathes are available that can spin blanks ranging from 6.4 mm to 1.8 m ($\frac{1}{4}$ to 72 in.) in diameter. Special pit lathes permit the spinning of blanks as large as 4.9 m (192 in.) in diameter. Standard lathes can be fitted with special chucks for making oval parts. Lathes should be equipped with variable-speed drives to permit quick changes of speed as judged necessary by the operator.

Mandrels, also known as form blocks or spin blocks, are usually made of seasoned hard-maple wood. Most hardwood mandrels are constructed by gluing strips of 25 to 50 mm (1 to 2 in.) thick maple into the main block to create a cross-laminated structure, then turning the glued structure to the desired shape. Such mandrels are stronger and more durable than mandrels turned from a solid block. Some wooden mandrels are steel reinforced at the ends and at small radii to ensure maintenance of radii in the spun workpieces. Sharp corners can be produced in workpieces by spinning them over mandrels cornered with steel; but minimum inside radii of 1.6 mm ($\frac{1}{16}$ in.) are more common than sharp corners, and 3.2 mm ($\frac{1}{8}$ in.) minimum radii are preferred where possible.

Some mandrels are constructed of alternating wood and steel plates or rings in order to obtain a more economical yet durable mandrel. Other materials include fiber compositions, steel, cast iron, aluminum, magnesium, and plastic-coated wood. Few mandrels are made entirely of heavy metals such as steel and cast iron, except for close-tolerance work. Cored castings of these metals are then preferred, because of the weight savings. Solid steel or cast iron mandrels must be statically balanced, and for use at high speed, they should also be dynamically balanced.

Spinning Tools. Simple spinning tools are usually made by forging carbon or low-alloy tool steels (such as W1 or O1) to the desired shape, hardening the working ends to about 60 HRC, and polishing them. Several typical shapes are illustrated in Fig. 3. Tools of shaped aluminum bronze are also satisfactory, especially for the spinning of steel. Hardwood tools have performed satisfactorily in spinning thin-gage ductile metals.

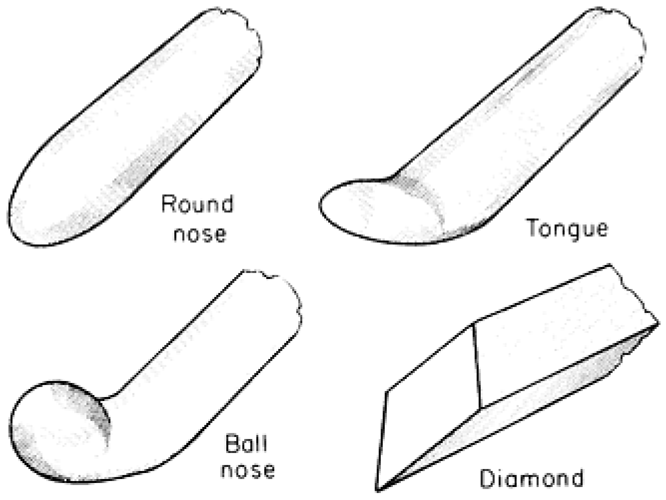

Fig. 3 Typical shapes of working ends of tools used for manual spinning. Round nose, tongue, and ball nose tools are for spinning; the diamond tip is for trimming.

With the lever arrangement (Fig. 2b), the tools usually consist of rollers (sometimes called tool rings) mounted in forks. Most rollers are made of hardened tool steel or of aluminum bronze.

Manual Spinning Practice

Because of the low tooling cost, manual spinning is extensively used for prototypes and for production runs of 1000 pieces or fewer. Larger lots can usually be produced at lower cost by power spinning or press forming.

For example, the part in the middle of the second row in Fig. 1 is a stainless steel cover for a food-processing machine, produced in one plant at the rate of 100 per year. The parts were produced satisfactorily by manual spinning with only two hardwood mandrels, the cost of which was only a fraction of the tooling cost for the press forming of the same shape.

Conical parts (such as the shape on the left in the middle row in Fig. 1) are ideal for spinning because only one tool is required; drawing in dies would require four or five operations. Many such cones, depending on their included angle, can be spun in one operation at a moderate production rate. Therefore, manual spinning is often used for quantities up to medium production (<1000 units). For large-quantity production, power spinning is generally less expensive than manual spinning.

Control of quality, including freedom from wrinkles and scratches and maintenance of dimensional accuracy, is largely a function of operator skill. Dimensional tolerances increase as the diameter of the blank increases, as indicated in Table 1. These tolerances are typical of demands for commercial products and parts for aerospace applications.

Table 1 Typical dimensional tolerances for manual spinning

Diameter of blank		Tolerance			
		Commercial		Aerospace	
m	in.	mm	in.	mm	in.
Up to 0.305	Up to 12	±0.4	$\pm\frac{1}{64}$	±0.20	±0.008
0.33-0.90	13-36	±0.8	$\pm\frac{1}{32}$	±0.38	±0.15
0.94-1.37	37-54	±1.6	$\pm\frac{1}{16}$	±0.51	±0.020
1.4-2.4	55-96	±3.2	$\pm\frac{1}{8}$	±0.76	±0.030

Speeds that are best suited to manual spinning depend mainly on work metal composition and thickness. For example, a given blank of stainless steel is successfully spun at 60 m/min (200 surface feet per minute, or sfm), and speed is determined by "operator feel" to be maximum for the conditions. Under otherwise identical conditions, changing to an aluminum blank will permit speeds of 120 to 180 m/min (400 to 600 sfm). Similarly, if the thickness of the stainless steel blank were decreased to one-half the original thickness (no other changes), speed could be safely doubled or tripled.

Selection of optimal speed depends largely on "operator feel." In many spinning operations, speed is changed (usually increased) during the operation by means of a variable-speed drive on the headstock.

Lubricants should be used in all room-temperature spinning operations, regardless of work metal composition, workpiece shape, or type of spinning tools used. The usual practice is to apply the lubricant to the blank with a swab or brush before loading the blank into the machine. In some cases, additional lubricant is added during operation as judged necessary by the operator. The need for additional lubricant depends on the tenacity of the lubricant used and on blank-rotation speed.

The most important property of a lubricant used for spinning is its ability to adhere to the rotating blank. Ordinary cup grease is often used. It can be heated to reduce its viscosity, thus making it easier to apply to the blank. Upon application to the cold blank, the viscosity of the grease increases. In addition, cup grease can be easily removed.

Other lubricants used for spinning include soaps, waxes and tallows (and proprietary mixtures of two or more of these materials), and pigmented drawing compounds. All of these, however, are more difficult to remove than simple grease. Therefore, the more tenacious lubricants are not used if an easier-to-remove lubricant will provide acceptable results.

Spinning

Power Spinning

Power spinning is also known as shear spinning, because in this method metal is intentionally thinned by shear forces as high as 3.5 MN (400 tonf). Power spinning is used in two broad areas of application: cone spinning and tube spinning. In cone spinning, the deformation of the metal from the flat blank is in accordance with the sine law (see the section "Mechanics of Cone Spinning" in this article).

Virtually all ductile metals can be processed by power spinning. Products range from small hardware items made in large quantities (metal tumblers, for example) to large components for aerospace applications in unit or low-volume production.

Blanks as large as 6 m (240 in.) in diameter have been successfully power spun. Plate stock up to 25 mm (1 in.) thick can be power spun without applying heat. When heated, blanks as thick as 140 mm ($5\frac{1}{2}$ in.) have been successfully spun.

Conical and curvilinear shapes are those most commonly produced from flat (or preformed) blanks by power spinning. The mechanics of the process should be known and the rules followed when planning manufacturing processes that include power spinning.

Mechanics of Cone Spinning

The application of shear spinning to conical shapes is shown schematically in Fig. 4. The metal deformation is such that forming is in accordance with the sine law, which states that the wall thickness of the starting blank, t_1, and that of the finished workpiece, t_2, are related as follows:

$$t_2 = t_1 (\sin \alpha)$$

where α is one-half the apex angle of the cone. When spinning in accordance with the sine law, the axial thickness is the same as the thickness of the starting blank (Fig. 4).

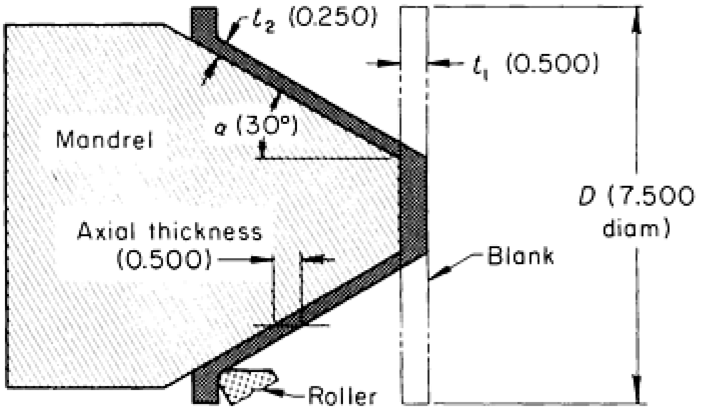

Fig. 4 Setup and dimensional relationships for the one-operation power spinning of a cone. D, mandrel diameter; t_1, original (blank) thickness; t_2, spun thickness; α, included angle. Dimensions given in inches.

When spinning cones to small angles (<35° included angle), the best practice is to use more than one spinning pass with a different cone angle for each pass, as illustrated in Fig. 5. When using this technique, the workpiece is annealed or stress relieved between passes.

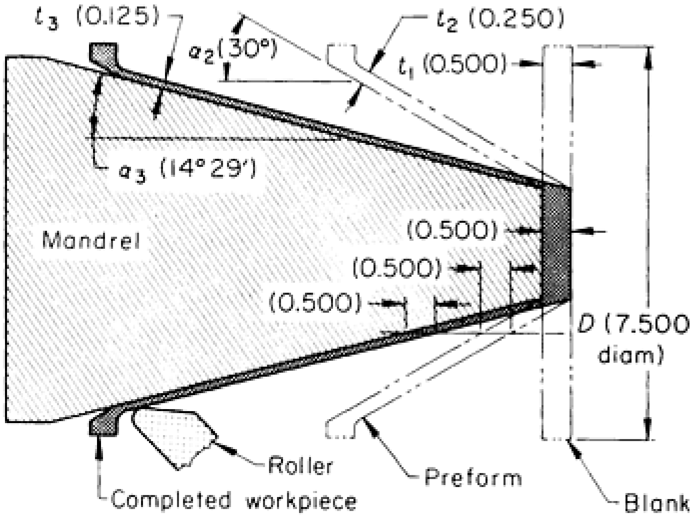

Fig. 5 Setup and dimensional relationships for the two-operation spinning of a cone to a small angle (35° included angle). Dimensions given in inches.

This practice permits a high total reduction while maintaining a practical limit of 50 to 75% between process anneals. The reduction between successive annealing operations is determined by the maximum acceptable limits of deformation for the metal being spun (Table 2); this value is obtained by multiplying t_1 by a factor (0.5 for 50%, 0.25 for 75%, and so on) and then dividing the result by t_1 to obtain the sine of the required half angle.

Table 2 Recommended maximum reductions for the single-pass power spinning of various metals

Metal	Maximum reduction, %	
	Cone	Hemisphere

Aluminum alloys		
2014	50	**40**
2024	50	. . .
3000	60	**50**
5086	65	**50**
5256	50	**35**
6061	75	**50**
7075	65	**50**
Pure beryllium(a)	35	. . .
Copper	75	. . .
Molybdenum(a)	60	**45**
Nickel-base alloys		
Waspaloy	40	**35**
René 41	40	**35**
Steels		
4130	75	**50**
4340	70	**50**
6434	70	**50**
D6ac	70	**50**
H11	50	**35**

Stainless steels		
Type 321	75	**50**
Type 347	75	**50**
Type 410	60	**50**
17-7PH	65	**45**
A286	70	**55**
Titanium[(a)]		
Commercially pure	45	. . .
Ti-6Al-4V	55	. . .
Ti-3Al-13V-11Cr	30	. . .
Ti-6Al-6V-2.5Sn	50	. . .
Tungsten[(a)]	**45**	. . .

(a) Hot spun

Even in multiple-pass spinning, the original blank diameter is retained, and the exact volume of material is used in the final part. At any diameter of either the preform or the completed workpiece, the axial thickness equals the thickness of the original blank. For example, if a flat plate has a diameter of 190 mm ($7\frac{1}{2}$ in.) and a thickness of 12.5 mm ($\frac{1}{2}$ in.), the spun preform has this same 12.5 mm ($\frac{1}{2}$ in.) axial thickness, but the wall thickness is only 6.4 mm ($\frac{1}{4}$ in.) (t_1, Fig. 5), thus satisfying the sine law. Similarly, the final workpiece has an axial thickness of 12.5 mm, ($\frac{1}{2}$ in.), but in accordance with the sine law, it has a wall thickness of only 3.2 mm ($\frac{1}{8}$ in.) (t_3, Fig. 5).

Effects of Deviation From the Sine Law. Deviation from the sine law is usually expressed in terms of overreduction or underreduction. In overreduction, the final thickness of the workpiece is less than that dictated by the sine law; in underreduction, the thickness is greater. In overreduction, the flange will lean forward; in underreduction, the flange will lean backward. If a thin blank is spun with severe underreduction, the flange will wrinkle. This phenomenon corresponds to a deep-drawing operation in which the blankholder pressure is insufficient.

In power spinning, overreduction has an additional effect on the shape of the workpiece. As the workpiece is overreduced, back extrusion can occur (Fig. 6). For a given amount of reduction, the likelihood of back extrusion increases with increasing mandrel angle (Fig. 6).

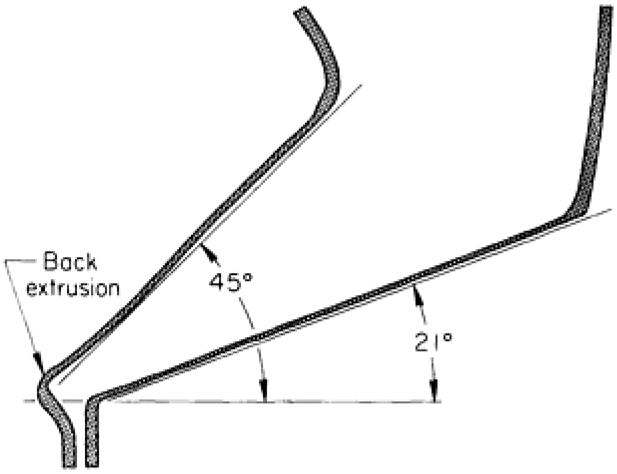

Fig. 6 Back extrusion as a result of overreduction in the power spinning of low-carbon steel.

The phenomenon of back extrusion in spinning is explained in terms of the compressive stress in the spun workpiece that pushes the spun section backward. If the tailstock of the machine is removed, it is possible to obtain curvilinear shapes on a conical mandrel by varying the amount of overreduction during spinning.

Machines for Power Spinning

Most power spinning is done in machines specially built for the purpose. The significant components of such a machine are shown in Fig. 7. Although Fig. 7 illustrates the power spinning of a conical shape, similar machines are used for the spinning of tubes (see the article "Tube Spinning" in this Volume).

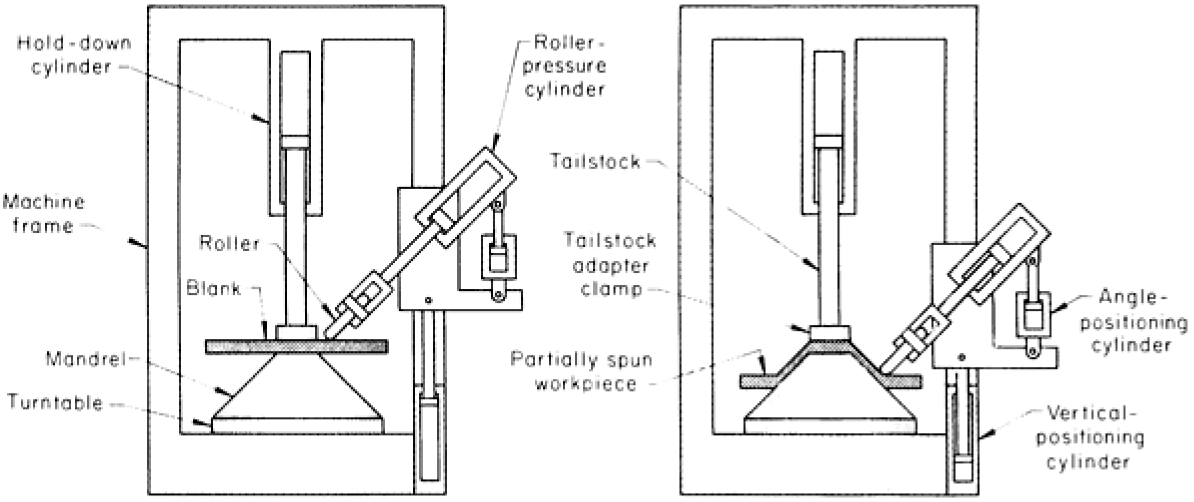

Fig. 7 Schematic of power spinning in a vertical machine.

Machines for power spinning are usually described by specifying the diameter and length (in inches) of the largest workpiece that can be spun and the amount of force that can be applied to the work. It is also common practice to specify that the machine can spin a given thickness of metal at a 50% reduction in thickness in one pass.

The capacity of spinning machines ranges from 455 × 380 mm (18 × 15 in.) at 18 kN (4000 lbf) to machines capable of spinning workpieces as large as 6 m (240 in.) in diameter × 6 m (240 in.) long. Force on the work can be as great as 3.5 MN (800,000 lbf). Machines have been built that spin steel 140 mm ($5\frac{1}{2}$ in.) thick.

Spinning machines can be vertical or horizontal. Machines used for spinning workpieces 1.8 m (70 in.) or more in diameter are usually vertical because they are better suited to handling large work.

Machines for power spinning can be automated to various degrees. Most spinning machines use template guides that control the shape and accuracy of the workpiece. Most machines used for production spinning are semiautomatic; that is, they are loaded and unloaded by the operator, but the entire spinning cycle is controlled automatically. Machines can also be equipped with automatic loading and unloading devices, thus making them fully automatic.

Tools for Power Spinning of Cones

Mandrels, rollers, and other tools are subjected to more rigorous service in power spinning than in manual spinning; therefore, more careful consideration must be given to design and materials of construction.

Mandrels. A typical mandrel profile is illustrated in Fig. 8. Dimensions *A* and *B* and angle α can vary as required. Usual practice is to have, first, an integral flange to permit the mandrel to be bolted to the headstock and, second, a boss of suitable diameter and at least 16 mm ($\frac{5}{8}$ in.) in thickness that fits into the headstock of the machine (Fig. 8). Radius *R* can vary from a minimum of 0.8mm ($\frac{1}{32}$ in.) to a round nose.

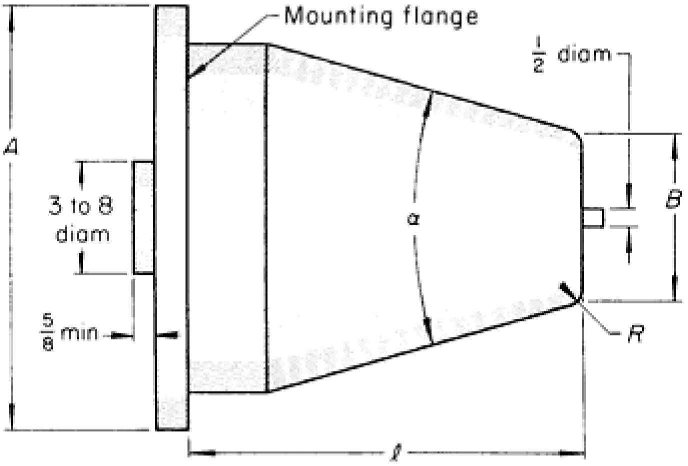

Fig. 8 Typical profile of a mandrel for the power spinning of cones. Dimensions given in inches.

Mandrel wear or failure is frequently a problem in the power spinning of conical shapes. The mandrels used in production spinning must be hard in order to resist wear, and they must resist the fatigue resulting from normal eccentric loading. Failure is often caused by spalling (flaking off). Mandrels can also be damaged by the rollers plunging into the workpiece at the start of metal flow. The need for plunging can sometimes be eliminated by machining a ring on the preform to a depth equal to the depth the rollers would otherwise be plunged. This technique permits the rollers to enter the machined space before they start moving along the mandrel, thus eliminating the severe stress on the mandrel as spinning is begun.

Materials selection for the mandrels used in cone spinning depends primarily on the number of identical workpieces to be spun. Based on quantity, the most commonly used materials are:

- Gray iron (as-cast) for the low-production spinning of soft metals (10 to 100 pieces)
- Alloy cast iron (sometimes flame hardened in areas susceptible to high wear), for spinning 100 to 250 pieces
- 4150 or 52100 steel hardened to about 60 HRC, for spinning 250 to 750 pieces
- Tool steels such as O6, A2, D2, or D4 hardened to 60 HRC or slightly higher, for high production

The finish of the mandrels should be no rougher than 1.5 μm (60 μin.). The various diameters should be within ±0.025 mm (±0.001 in.) concentric with each other within approximately 0.05 mm (0.002 in.) total indicator reading.

Rollers. Three types of rollers are shown in Fig. 9. Rollers are usually 305 to 510 mm (12 to 20 in.) in outside diameter, depending on the type and size of the spinning machine. Roller widths are usually 50 to 75 mm (2 to 3 in.), and inside diameters range from 255 to 380 mm (10 to 15 in.). The shape of the rollers depends largely on the shape of the workpiece to be spun. Full-radius rollers (Fig. 9a) are usually used to produce curvilinear shapes, while those illustrated in Fig. 9(b) and 9(c) are preferred for the spinning of cones.

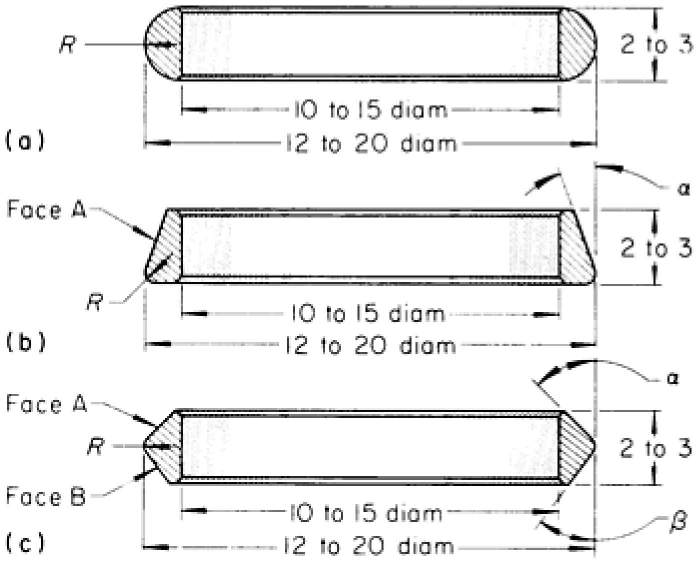

Fig. 9 Typical rollers used in the spinning of cones and hemispheres. (a) Full-radius roller. (b) Corner roller. (c) Thinning roller. Dimensions given in inches.

Angle α shown in Fig. 9(b) and 9(c) is necessarily varied to suit the work being spun (particularly the angle of the cone). This angle is intended for clearance and should be such that the work metal does not touch face A (Fig. 9b) or either face A or face B (Fig. 9c). The radius *R* should not be less than the final wall thickness.

The type of roller illustrated in Fig. 9(b) is widely used in cone spinning. A typical setup, using two of these rollers opposed, is illustrated in Fig. 10. When two rollers are used to spin a part from flat plate, the rollers are set the same. However, when spinning is done from a preformed shape, common practice is to make one the lead roller and to set it ahead of the other by 1.6 to 3.2 mm ($\frac{1}{16}$ to $\frac{1}{8}$ in.). If more than two rollers are used, this increment is continued between successive rollers. The angle between the axis around which the rollers revolve and the workpiece (angle α, Fig. 10) is usually about 10°, while the angle between the same roller axis and the peripheral face of the roller (angle β, Fig. 10) may vary and is shown in Fig. 10 as approximately 30°.

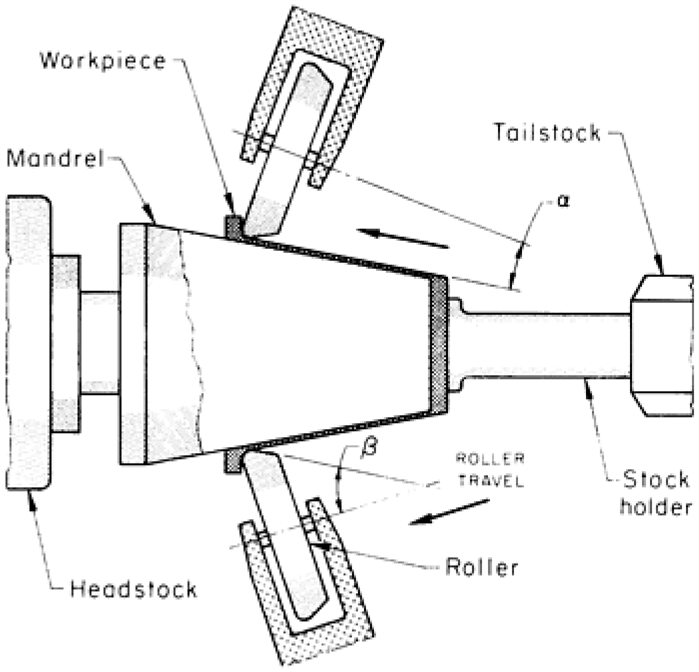

Fig. 10 Relative positions of rollers and workpiece in the spinning of a cone.

Rollers are made from a variety of hard materials. The five materials most widely used for the power spinning of conical shapes, in order of ascending wearability and cost, are W2 tool steel, O6 tool steel, D2 tool steel, D4 tool steel, and carbide. Choosing among these materials is usually done on the basis of quantity of workpieces to be spun. The less costly W2 and O6 tool steels are generally suitable for low-to-medium production quantities. Tool steels D2 and D4 are preferred to high production quantities. Carbide is seldom used except for specialized applications in which the need has been proved and the high cost can be justified.

Rollers made from any of the above tool steels should be hardened to 60 to 65 HRC. All rollers should be polished to a maximum surface roughness of 0.25 μm (10 μin.).

Auxiliary tools for cone spinning include tailstock adapters, tracer templates, tracer followers, and stripping devices. A tailstock adapter clamps the work to the mandrel (Fig. 7) and is made of carbon or alloy steels or of tool steel. The clamping face of the tailstock adapter must be ground square to the spindle axis.

Tracers are used to spin workpieces that vary in wall thickness or shape. Tracer templates are made of low-carbon steel, such as 1020, that is, 3.2 to 4.8 mm ($\frac{1}{8}$ to $\frac{3}{16}$ in.) thick. Large templates have lightening holes for easier handling. Tracer templates are made to the same standards of accuracy as dies and similar tools. Tracer followers can be ball bearings or hardened tool steel fingers, depending on cone shape.

Stripping devices can be full rings or fork-type fingers, attached to the roller carrier. The need for stripping devices depends on the size and shape of the workpiece.

The use of preforms is common in cone spinning when the included angle of the cone is less than 35° or when the percentage of wall reduction is high. Preforms are usually prepared by cold forming in a die, although hot forging or machining or a combination of both can be used. Some preforms are made by spinning.

Speeds and Feeds for Cone Spinning

Most metals spin best at high speeds. The minimum speed considered to be practical is about 120 m/min (400 sfm), but speeds this low are seldom used except for the spinning of small-diameter workpieces. Machine spindles sometimes cannot rotate fast enough with such workpieces to achieve the desired surface speed. Speeds of 305 to 610 m/min (1000 to 2000 sfm) are most widely used, regardless of work metal composition, workpiece shape, or reduction per pass.

Feed. Most cone-spinning operations are done at feeds of 0.25 to 2 mm/rev (0.01 to 0.08 inches per revolution, or ipr). In practice, however, feeds are usually calculated in millimeters per minute (mm/min) or inches per minute (ipm). Most machines used in cone spinning are equipped with electronic or hydraulic devices that steplessly change the rate of feed as the diameter on which the rollers are working changes continuously. The rate of feed usually ranges from 38 to 380 mm/min ($1\frac{1}{2}$ to 15 ipm).

Feed rate is important, because it controls the workpiece finish and the fit of the workpiece to the mandrel. With all other factors constant, an increase in feed rate will make the workpiece fit tighter on the mandrel, and the finish of the workpiece will coarsen. On the other hand, a decrease in feed rate will cause a loose fit, and workpiece finish will improve. The diameter of the mandrel should be the same as the inside diameter required on the workpiece (no allowance for springback), and the workpiece should be spun to fit the mandrel. The fit may be loose, snug, or tight.

To find the optimal combination of speed, feed, and pressure, a few pieces should be spun experimentally when a new job is set up. During continuous operation, the temperature of the mandrels and spinning tools changes; therefore, after the first hour or so, it is often necessary to adjust the pressure, speed, and feed for uniform results.

Power Spinning of Hemispheres

The use of preforms to control percentage of reduction has enabled power spinning to be applied to the forming of hemispheres, ellipses, ogives, and in general, any curvilinear surface of revolution. However, the design of the preform for curvilinear shapes is more complicated than that for conical shapes. In the spinning of conical shapes, it is possible to find an axial thickness of the spun part that corresponds to the thickness of the blank (Fig. 5). No such relationship exists for a curvilinear surface. In the path from the pole to the equator, the axial thickness of the metal on a hemisphere changes from stock thickness at the pole to infinity at the equator (the inverse of sin 0° being infinity). The blank thickness must be back tapered to compensate for the change in thickness that will take place during spinning. This is shown in Fig. 11; the machined taper started at 3.8 mm (0.150 in.) in thickness (in the center of the blank) and ended at 7.6 mm (0.300 in.) in thickness at the circle where the 30° radial line of the sphere was projected to the blank. At the corresponding 45° line, the blank thickness was 5.38 mm (0.212 in.); at the 15° line, 14.73 mm (0.580 in.). Below the 30° line, however, the reduction was greater than permissible for the material, and the operation was planned as if spinning a cylinder. The blank for this portion had a flange with a thickness proportional to the percentage of reduction.

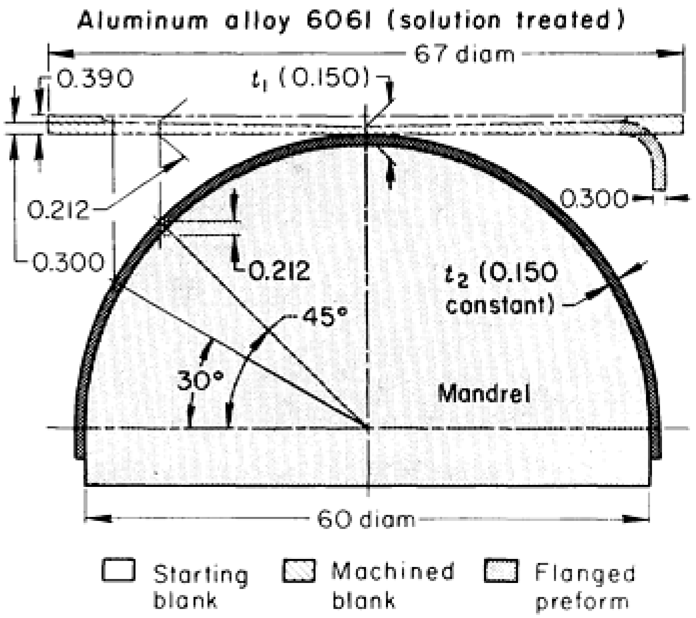

Fig. 11 Hemisphere spun from a machined and preformed blank. Dimensions given in inches.

A usable blank can be designed by first finding in Table 2 the allowable reduction for the work metal to be used. A beginning stock thickness should be selected that, with the maximum reduction, will give the thickness desired on the sphere. The ratio of finished stock thickness to original stock thickness is then taken as the sine of an angle, which will be the angle of the surface at the latitude at which preforming must start. Beyond this point, the reduction required to make the hemisphere will be greater than is permissible for the work metal. There will be no reduction at the pole, because at that point blank thickness and final thickness will be the same. At 45° from the pole, final part thickness will be 0.707 times the original thickness (sin 45° = 0.707). At a corresponding circle on the blank, therefore, the original thickness must be 1.414 times the final part thickness. Other latitudes can be similarly chosen, and necessary stock thickness at a corresponding circle on the blank determined. Preforming must start at the circle corresponding to the limiting latitude (the point where the maximum permissible reduction has taken place). In a cross-section view, the circles resulting from the above method will appear as points, and the thickness of the stock at these points can be determined. When the points are laid out, a dozen or more points are connected to yield the final part shape.

In modern shops, such calculations are usually performed with the aid of a computer. It is common practice in such systems to use 1200 to 1500 points on a shape such as a large hemisphere.

The thickness of the starting blank can be obtained by multiplying the known thickness of the finished part by an appropriate factor. Similarly, by dividing the starting blank thickness by the appropriate factor, the thickness of the finished part is obtained. The factors are related to the percentage of reduction and are the reciprocal of the difference between the percentage reduction (expressed as a decimal) and one, as follows:

- For 50% reduction, use a factor of 2
- For 66 $\frac{2}{3}$% reduction, use a factor of 3
- For 75% reduction, use a factor of 4

- For 80% reduction, use a factor of 5

Use of this system is illustrated in the following example.

Example 1: Forming a 1.5 m (60 in.) Diam Hemisphere by Power Spinning.

Large hemispheres (Fig. 11) were power spun from solution-treated aluminum alloy 6061 using the following calculations. From Table 2, it was determined that a 50% reduction could be made with this alloy. Preliminary calculations for thickness of the starting blank were as follows:

t = final wall thickness · factor for percentage reduction
= 3.81 mm (0.15 in.) · 2
= 7.62 mm (0.300 in.)

In calculating the blank thickness at various points on the sphere, it was found that at the pole, or 90° point, the thickness had to be reduced to 3.81 mm (0.150 in.) and that some reduction was required out to a point directly above the 30° tangency on the hemisphere, where the thickness of the starting blank had to be 7.62 mm (0.300 in.). Beyond this point, a flange would be preformed by spinning, and an additional thickness would be required. It was estimated that an increase in blank thickness of 30% would be enough, and initial blank thickness established at 9.91 mm (0.390 in.).

Machining of the blank to graded thickness was done in a tracer-controlled vertical boring mill, with the blank held on a vacuum chuck. After machining, the flange was preformed to the desired contour by conventional power spinning, accomplishing a reduction in wall thickness that provided a uniform 7.62 mm (0.300 in.) wall.

Final spinning was accomplished in one pass of the rollers after the alloy was given a controlled amount of room-temperature aging (usually 13 to 18 h). During final spinning one roller led the other by a vertical offset of 1.6 to 3.2 mm ($\frac{1}{16}$ to $\frac{1}{8}$ in.), using 19 mm ($\frac{3}{4}$ in.) radius tool rings at a feed of about 2.3 mm/rev (0.09 ipr). Speed varied from 300 rpm maximum down to 40 rpm at the flange.

The procedure described in Example 1 has also been successfully applied to the forming of hemispheres and ellipses 152 mm to 1.8 in (6 to 70 in.) in diameter from 17-7 PH and type 410 stainless steels, from alloy steels such as 4130 and 4140, and from aluminum alloys 5086, 2014, and 2024 (as well as 6061). In one case, the procedure was used for the hot spinning of an ogive 762 mm (30 in.) in diameter and length from molybdenum.

Hot Spinning of Hemispheres. The use of heat for decreasing the strength and increasing the ductility of the work metal is sometimes required because the machine capacity is insufficient for cold forming the thickness to be spun or because the room-temperature ductility of the work metal is too low. Hot spinning is done only when necessary, because heating, subsequent cleaning, and increased tool deterioration all contribute to increased cost.

Lubricants and Coolants for Power Spinning

Power spinning requires the use of a fluid that serves as both a lubricant and a coolant. Because of the large amount of heat generated, a water-base fluid is most commonly used. Usually, a colloidal suspension of zinc in lithium soap or molybdenum disulfide paste is mixed with water to function as the lubricant. These lubricant-coolant combinations are satisfactory for most metals, although zinc-free lubricants and coolants should be used for the spinning of stainless steel to avoid surface contamination.

Various oils and oil mixtures, such as 10% lard oil in kerosene, have also been successfully used for power spinning. Regardless of composition, the fluid must be free flowing and applied by pumps in copious amounts, or both workpieces and tools will be damaged from heat.

When spinning aluminum or stainless steel, the workpieces or mandrels or both are sometimes coated with the lubricant before spinning. During spinning, workpieces and tools are flooded with a coolant, such as an emulsion of soluble oil in water.

Effects of Spinning on Work Metal Properties

Power spinning is a severe cold-working operation and therefore has a marked effect on the mechanical properties of the work metal. A well-defined and directional grain flow pattern is produced by power spinning. The surface finish of a spun workpiece is usually good enough so that no additional machining is required after spinning. Spun finishes are commonly about 1.5 μm (60 μin.), although finishes as smooth as 0.5 μm (20 μin.) have been produced by power spinning.

Strength and Hardness. In spinning, tensile and yield strengths increase, and ductility decreases. The magnitude of effect depends on the amount of wall reduction and on the susceptibility of the metal to work hardening.

In many applications, the increase in strength caused by spinning is highly desirable because it eliminates the need for heat treating. In other applications, the change in mechanical properties is not desired, and the workpieces must be annealed after spinning.

To measure the work hardening in the deformation zone, Rockwell F (HRF) readings were taken on the cross section of a spun copper workpiece that was reduced 43%. The results are shown in Fig. 12. It is evident that the area near the roller contact has higher hardness than the area at the mandrel side.

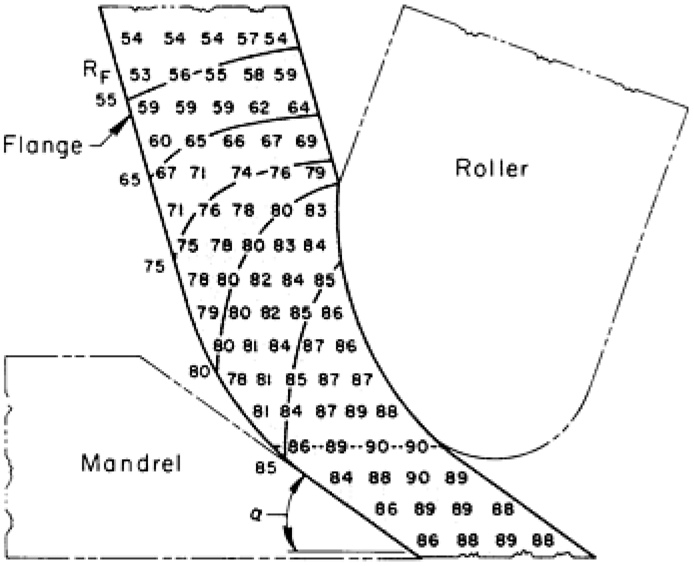

Fig. 12 Hardness distribution (HRF) in a copper workpiece reduced 43% by spinning.

Spinning

Assembly by Spinning

Spinning is frequently used for less conventional applications than those described earlier in this article and in the article "Tube Spinning" in this Volume. It is often the least expensive means of joining two or more parts to form an assembly. For example, a tube can be inserted through a hole in a plate, and the protruding end of the tube can then be spun to secure it to the plate. Small parts are assembled by this technique with a special tool rotated by a drill press.

Rubber-Pad Forming

Introduction

RUBBER-PAD FORMING, also known as flexible-die forming, employs a rubber pad or a flexible diaphragm as one tool half, requiring only one solid tool half to form a part to final shape. The solid tool half is usually similar to the punch