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# New Methods for Severe Plastic Deformation Processing

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**Several new concepts for possible methods of severe plastic deformation (SPD) of bulk quantities of materials are presented. The first of these are variations of equal channel angular extrusion (ECAE) in which the conventional fixed die is replaced by rotating tools, for the inner die corner, the outer die corner, or both corners. Other methods share some characteristics of ECAE in that they use shearing strains to deform the material; these are reversed shear spinning and transverse rolling. Deformation sequences for a cylindrical or annular workpiece that deform the workpiece while eventually restoring the initial workpiece geometry can be performed by numerous processes. These techniques can be used to accumulate high strains by repeated deformation cycles. These methods offer possible alternatives to ECAE and high-pressure torsion, with potential benefits that include different and larger workpiece geometries, simplified tooling design, lower tooling loads, ease of lubrication, automated or reduced part handling, and, in some cases, potentially continuous operation. It is hoped that these suggestions will prompt new examination of alternative methods for SPD.**

**Keywords** annulus, cylinder, equal channel angular extrusion, repetitive deformation cycle, reversed shear spinning, rotating tooling, severe plastic deformation, transverse rolling

## 1. Introduction

Severe plastic deformation (SPD) is the name for the general concept of using large plastic strains to produce ultrafine-grained materials. Such materials can have unique physical and mechanical properties, and are currently of great interest. Numerous methods for SPD have been developed. Conventional deformation processes such as swaging, wire drawing, or torsion can achieve large plastic strains. High-pressure torsion (HPT) (Ref 1, 2) and ring torsion (Ref 3, 4) use shear applied by torsion under high compressive hydrostatic loads to suppress fracture and achieve large plastic strains. Accumulative roll bonding (Ref 5, 6) uses repeated cycles of rolling, cutting, stacking, and re-rolling. Constrained groove pressing (Ref 7) or rolling (Ref 8) uses repeated shearing deformations imposed by grooved tools to accumulate strain. Several versions of reciprocating extrusion have been developed (Ref 9-13) in which the workpiece is alternately extruded and then upset to accumulate strain. Repetitive, multiaxial forging is a similar process in which a deformation cycle that recreates the workpiece's original geometry is used to accumulate strain (Ref 14-17). Friction stir processing (Ref 18) uses the technology for friction stir welding to locally achieve very high strains, using a rotating tool with a shoulder and a stirring nib. Twist extrusion (Ref 19), KOBO forming (Ref 20), and severe torsion straining (Ref 21) are other possible deformation techniques.

By far the most intensively studied method for SPD is equal channel angular extrusion (ECAE) (Ref 22), in which the workpiece is forced through a die with inlet and outlet channels with (nominally) the same cross section. Deformation is forced to occur by shearing, under highly compressive hydrostatic stresses, on the plane at the intersection of the two channels. ECAE is the most common method for processing bulk quantities of material. It is simple, and shows promise for scaling up to permit processing of large billets. There are obvious extensions of the basic ECAE process that can be imagined, such as processing longer billets, and billets of different shape and cross section, such as bars, rods, sheet, strip, or flat plates (Ref 23, 24). Multiple billets could be processed simultaneously. However, conventional ECAE is not without problems, particularly as the workpiece size increases. Processing a large, long workpiece will require a press that can produce both large forces and long strokes. The ram force is roughly proportional to the square of the workpiece diameter (or width), so larger workpieces will require significantly greater force as the workpiece size increases. The tooling must resist these large forces, which will make buckling of a long ram a concern, and the dies will become massive (and increasingly expensive) as the workpiece size increases. Lubrication is critical to the successful processing, and maintaining proper lubrication as the part length increases will become more difficult. HPT, another frequently used SPD method, involves very high hydrostatic pressures. These high pressures can be achieved for small sample sizes, but become increasingly difficult to implement as the sample size increases, again because the applied force will scale approximately as the square of the part diameter. Both of these methods are well suited for laboratory work, but are very labor intensive, and less practical for industrial application. New methods for SPD are of interest as they may offer advantages over conventional ECAE

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and HPT methods, such as different workpiece geometries, different strain paths, reduced tooling loads and stresses, ease of lubrication, etc. Several concepts for new SPD methods that should be suitable for processing bulk quantities of material will be described. The first methods are similar to conventional ECAE. Rotating tooling is used to replace a portion or all of the fixed die that is used in conventional ECAE. The use of rotating tooling provides several potential benefits as compared to conventional fixed tooling. Several new methods of SPD are also discussed. The first are related to ECAE and HPT in that they use shearing strains to deform the workpiece, avoiding tensile loading that can result in failure of the workpiece. Combinations of deformation steps for cylindrical or annular workpieces that restore the workpiece geometry are proposed. Repetitive cycles of deformation allow the accumulation of strains to achieve SPD.

## 2. New Methods for SPD

### 2.1 ECAE with Rotating Tooling

ECAE with Rotating Tooling is similar to conventional ECAE in that the sample is forced to move from an inlet channel to an outlet channel, and deformation occurs in a deformation zone at the intersection of the two channels. However, the fixed tooling that forms the inlet and/or outlet channels in conventional ECAE is replaced, at least in part, by rotating tools. Rotating tools can be positioned at the outer corner of the deformation zone, the inner corner, or both corners.

For the outer corner, the rotating tool may be a single roller, or a series of smaller rollers. The rolling tool is positioned so that the final workpiece thickness is (nominally) the same as the initial thickness. Just as in conventional ECAE, this will allow the sample to be processed repeatedly to attain the desired level of strain.

There are several versions of this method, and it can be used for either intermittent or continuous (or semi-continuous) operation. In the simplest version, the rotating tool is a single large diameter roller, as shown in Fig. 1(a). The workpiece is fed down toward the large roller, which forces the workpiece past the upper die in a continuous shearing mode. This single roller could be replaced by a cluster of smaller work rolls, as shown in Fig. 1(b) and (c).

The choice of continuous or intermittent operation depends on the method of feeding the workpiece into the deformation zone. Continuous operation can be used with all three of these versions. Intermittent operation means that the speed of motion of the workpiece will change periodically; the versions with the small work rollers are most appropriate in this case.

There are numerous ways in which the necessary synchronization of the workpiece and the rollers could be provided for intermittent operation. The simplest concept would be to move either the work roll or the inlet channel so that the work roll only contacts the workpiece while the workpiece is being advanced. For example, the work roll or roll assembly could be retracted by a suitable mechanism when the workpiece was not being fed into the deformation zone, and moved into position to allow contact of the work rolls on the workpiece only when the workpiece was being fed. While simple in concept, such an approach would complicate the actual machinery used for the processing. For the case of a single large work roll, the profile of the work roll could be contoured so that the work roll only contacts the workpiece while it was being fed, and a gap is provided while the workpiece is stationary (see Fig. 2a). An eccentric drive could be used to achieve the same result (Fig. 2b).

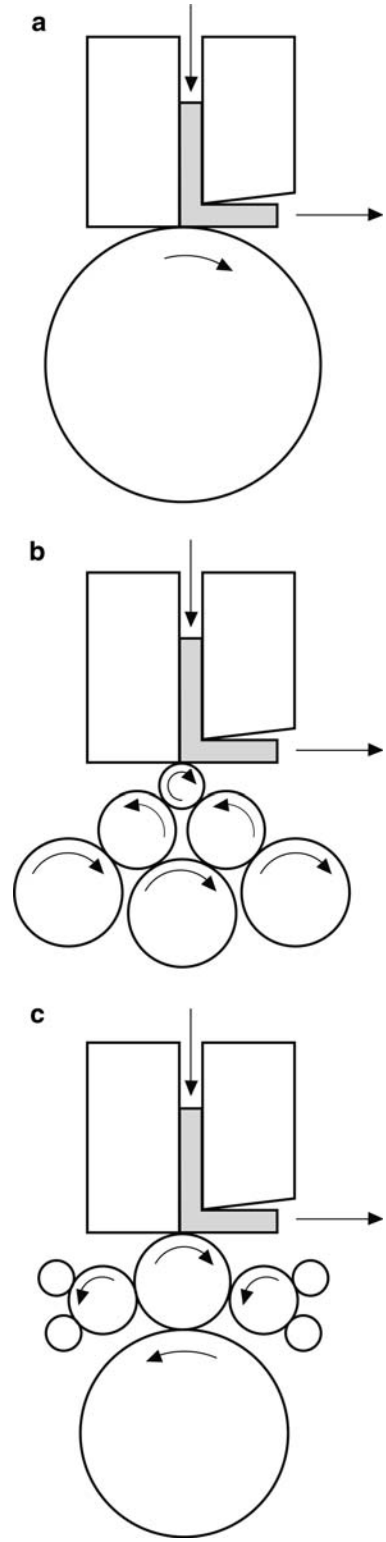


**Fig. 1** Use of a single rotating roller to form the outlet channel for equal channel angular extrusion: (a) single large work roller; (b) small work roller with cluster of support rolls; (c) intermediate-size work roll with side support rolls

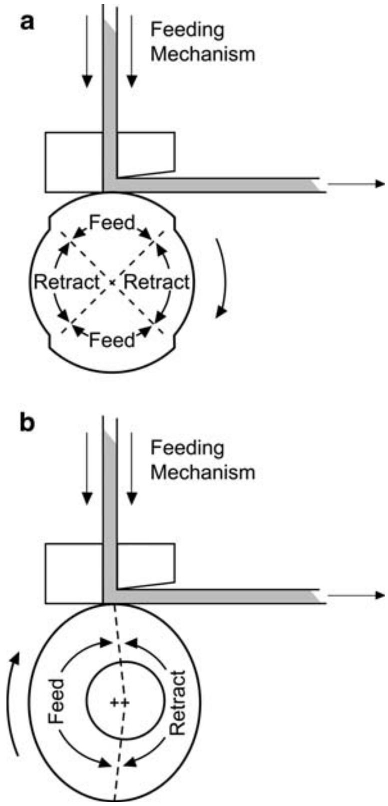


**Fig. 2** Methods for synchronization between feeding of workpiece and contact of workpiece with work roll to permit intermittent feeding of workpiece: (a) large contoured work roll; (b) eccentric work roll

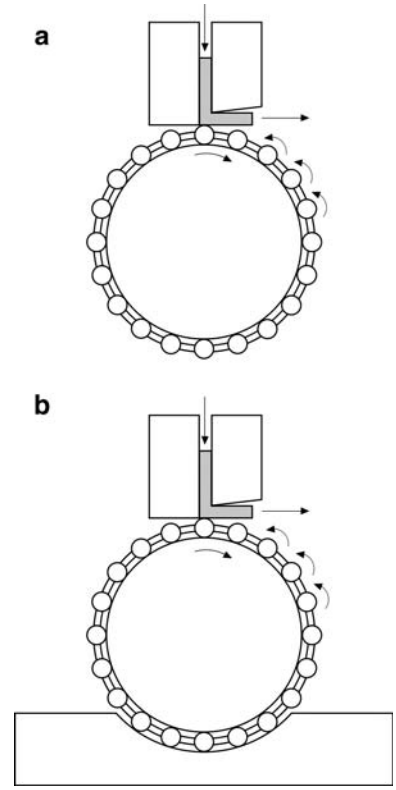


**Fig. 3** Planetary arrangements of multiple small work rolls with large central support roll: (a) single row of work rollers in conventional planetary arrangement; (b) single row of work rollers with lower support surface

Instead of using a single work roll, multiple rollers could be used, in a planetary arrangement similar to that used in planetary rolling mills. A single layer of small rolls could be arranged around a central support roll in a conventional planetary arrangement (Fig. 3a). The central roll is driven in the same direction as the workpiece. The small work rolls can be driven, or they can be allowed to be idle, with their motion being controlled by the motion of the workpiece and the support roll. A lower support can be provided for the roll system (Fig. 3b.) A double ring of work rolls (Fig. 4a) could also be used. In this case, the double ring of work rolls is forced to move in the direction of the workpiece motion, and the central support roll is fixed. The double ring of rolls can also use a lower backing to directly support the roller assembly, if desired (as shown in Fig. 4b). The double roll systems have the additional advantage that a contoured working surface or wear segment can be inserted at the deformation zone area, since the central support roll is fixed. Thus, the geometry of the lower surface of the outlet channel can be controlled as desired with a suitable insert.

For the versions that use multiple work rolls, the deformation will occur by a series of incremental, sequential deformations as the workpiece is fed into the deformation zone. The rollers will require support and fixturing so that their longitudinal axes remain parallel to each other and to the longitudinal axis of the support roll. This can easily be achieved by appropriate gearing.

The deformation zone and outlet channel could also be formed by rotating tooling that is carried by a linearly reciprocating support structure. Single (Fig. 5a) or multiple work rolls (Fig. 5b, c) could be used. The reciprocating versions could readily be designed so that the work rolls are moved in the necessary direction as the workpiece is fed into the deformation zone, and then are returned to their starting position while the workpiece is stationary, in preparation for the next feeding increment of the workpiece. Other alternate versions could incorporate a pendulum motion, with either single (Fig. 6a) or multiple (Fig. 6b) rolls, and either cycloidal (Fig. 7a) or orbital (Fig. 7b) motion of the work rolls.

The feeding mechanism and the work rollers in Fig. 1-7 are shown oriented so that the workpiece is deformed through an angle of 90°. However, the feeding mechanism could be tilted or inclined at some other angle should this be desired.

All of these versions can be adapted to process different geometries of the workpiece by choosing an appropriate design for the work rolls. Workpieces with square or circular cross sections could be processed. Sheet or strip with a rectangular cross section could be processed, again with appropriate design of the work rolls. Side rolls or fixed restraints may be needed to prevent lateral deformation of the workpiece, to control the width of the workpiece.

These methods can be used to process long or short workpieces, and even continuous samples such as long sheets. All that is needed would be suitable methods for feeding the workpiece into the deformation zone. For long or continuous workpieces, buckling of the undeformed portion of the workpiece as it is being forced into the deformation zone will have to be prevented. This can easily be accomplished by providing restraining rollers, wheels, or a fixed guide to support the workpiece as needed.

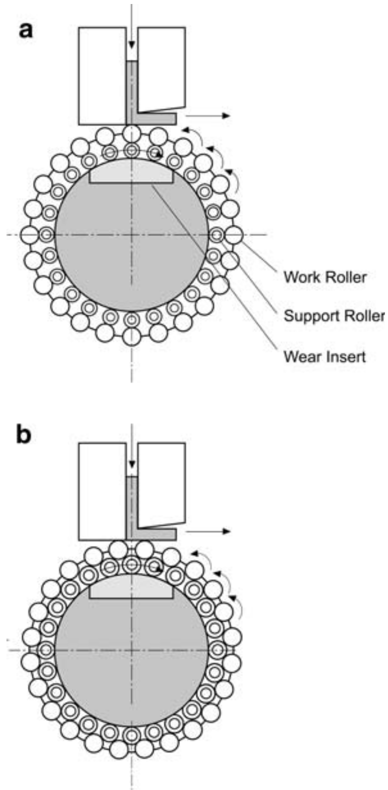


**Fig. 4** Planetary versions with double row of rollers: (a) double row of rollers, with single support roller for each work roller; (b) double row of rollers, with double support rolls for each work roller. Note the potential for the use of a contoured insert, as central support roll is fixed

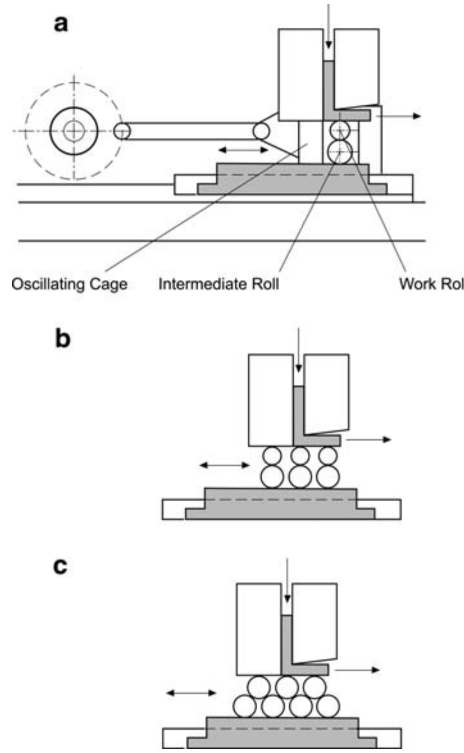


**Fig. 5** Rotating rollers carried by a linearly reciprocating support structure: (a) single work roll; (b) multiple work rollers, each with a single support; (c) multiple work rollers, each with double support

The planetary arrangements of working rolls offer the additional possibility for multiple working operations on the same set of rollers. Multiple sets of feeding mechanisms could be provided so that ECAE could be performed at multiple sites using the same work rolls. This would be most practical for the versions that have a large central roller. Possible examples with ECAE being performed in multiple sets of tooling located around one central roll are shown in Fig. 8. Independent processing at multiple locations is shown in Fig. 8(a) (note that similar or different types of workpieces could be processed at each location), while processing of a continuous strip or sheet is shown in Fig. 8(b). Figure 8(b) shows a strip being processed at three locations, with a similar orientation of the strip at each location; this results in conventional route A processing. The strip could be given a twist of 180° between processing locations, which would produce route C processing. Many similar arrangements can be imagined for bars, rods, or other workpieces.

The concept of using rotating tooling to form the deformation zone can be extended to the inner corner. The tooling that forms the inlet and outlet channels in ECAE is replaced by simple flat beds and a set of rotating rollers at the intersection of the beds (Fig. 9). The inlet bed carries the plate sample into the deformation zone, where the sample is forced to move from the inlet bed to the outlet bed. The deformation zone is controlled by rotating work rollers that revolve around a central supporting device that supports and controls the position of the rollers. The rollers contact the sample sequentially as they are carried over the sample surface. The total deformation occurs in a series of small incremental deformations. The amount of deformation that each roller imposes (and consequently the force on each roller) will depend on the roller speed and the rate of feed of the workpiece; these can be varied independently. The support mechanism maintains the roller positions such that the final plate thickness is (nominally) the same as the initial plate thickness. Just as in ECAE, this will allow the sample to be processed repeatedly to attain the desired level of strain.

There are two versions for inner corner rotating tooling, for either curved or flat workpieces, respectively. For the curved workpiece version (Fig. 9a), the workpiece (in this example a plate) will have a curvature that matches the total outer radius of the rotating work rolls on the carrier; that is, the overall outer radius of the roller-holder assembly. This means that the center of rotation of the tooling support structure can be fixed, which will simplify construction of the machine tool. For the second version for flat workpieces (Fig. 9b), the workpiece (again, a plate is shown as an example) will be flat, so the rotating work rolls must be guided along a straight path parallel to the workpiece. A possible means by which this could be achieved would be to have a chain of rollers, with an inner chain of support rollers and an outer set of work rollers, much like the planetary arrangement shown previously in Fig. 4(b). Each work roller would be supported only by a pair of support rollers, to which it would be attached with a triangular bracket at each roller end. The support rollers would be linked together to form a continuous chain. As the support rollers move against a fixed holder that will provide the needed rigidity and support for the deformation process, they will be forced to turn. The work rollers will then be forced to turn in the opposite direction, which is the desired and correct rotation for their

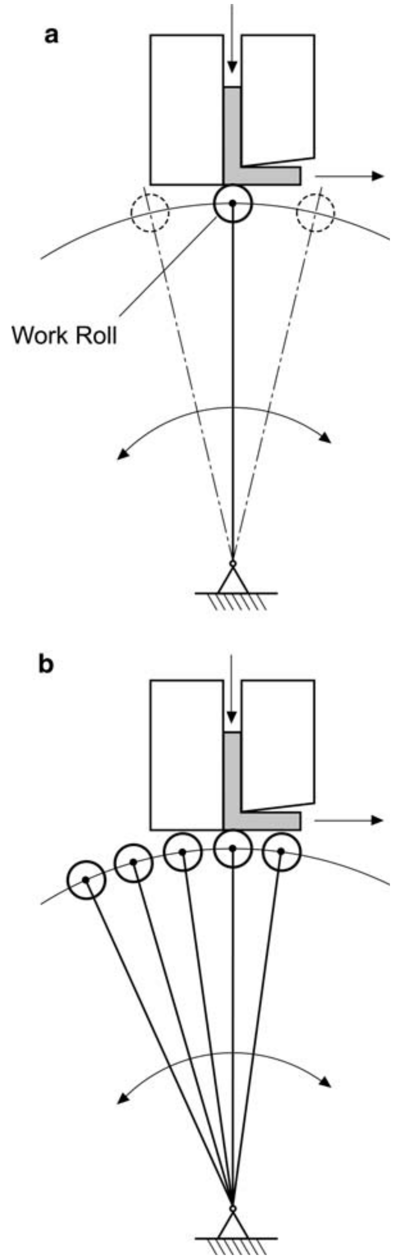


**Fig. 6** Schematic illustration of other possible paths for the work rollers: (a) pendulum motion, with single work roller; (b) multiple work rollers

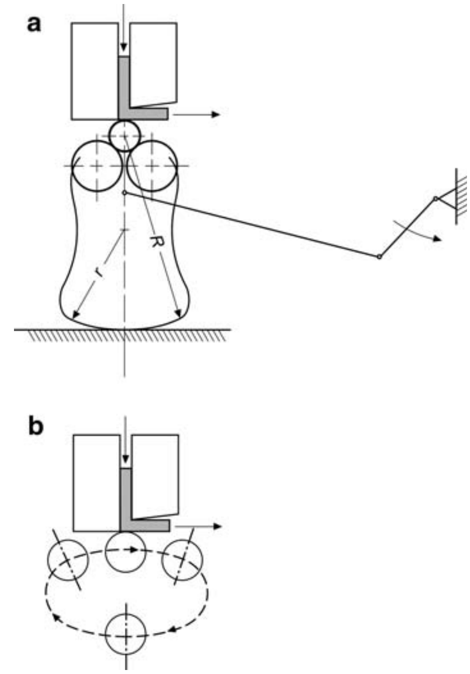


**Fig. 7** Schematic illustration of other possible paths for the work rollers: (a) cycloidal path; (b) orbital path

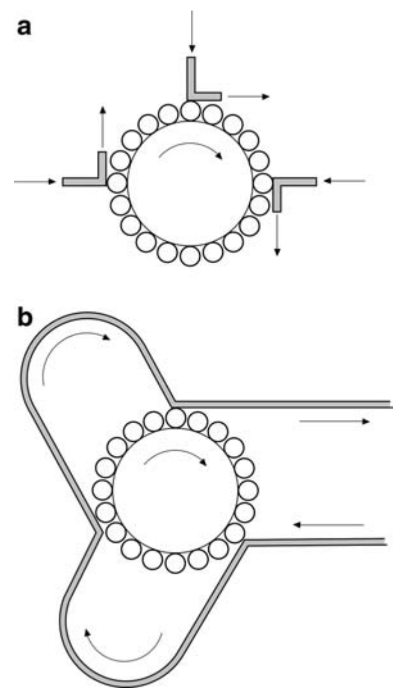


**Fig. 8** Multiple work stations for planetary arrangements of work rollers: (a) independent work stations; (b) continuous processing at multiple work stations. Details of feeding mechanisms and tooling have been omitted for clarity

contact with the workpiece. Since the work rollers contact only the two adjacent support rollers, the chain will be able to flex and follow the shape of the supporting holder, so the chain can be made to loop around and return to the deformation zone after each traverse across the sheet. The path that the work rolls and chain follows in Fig. 9(b) is an oval, but other shapes could be used, if desired.

The deformation process can be intermittent or continuous, depending on the motion of the workpiece as it is controlled by the feeding mechanism. Buckling of the undeformed portion of the workpiece on the inlet bed as the workpiece is being forced into the deformation zone will have to be prevented. This can easily be accomplished in the intermittent versions by providing restraining rollers, wheels, or guides to hold the plate against the moving bed as the plate is processed. For continuous versions, a fixed shoe or other guide before the deformation zone will prevent buckling.

The work rollers and roller support structure in Fig. 9 are shown to be oriented so that they bisect the angle between the

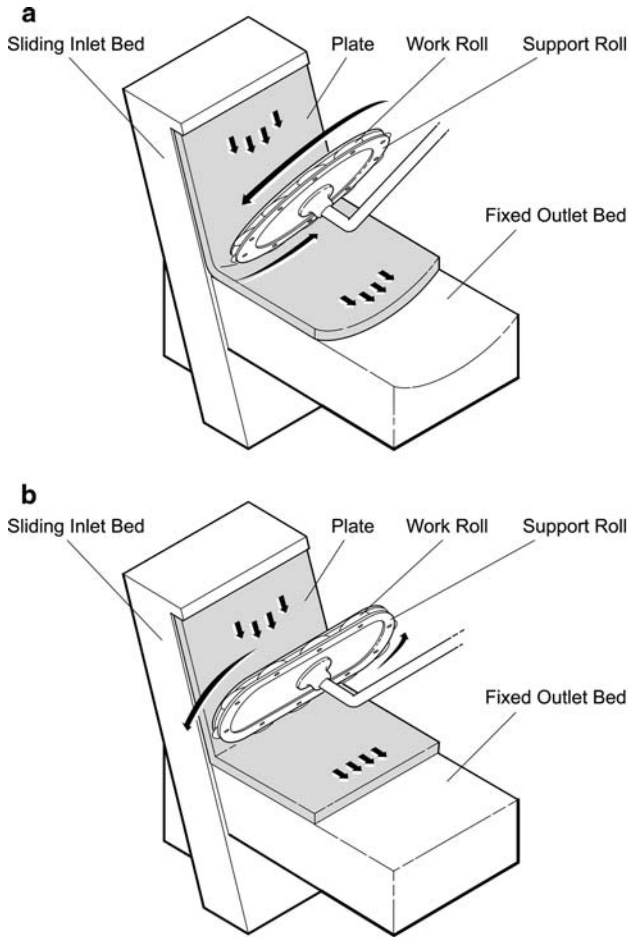


**Fig. 9** Rotating tools at the inner corner: (a) curved workpiece; (b) flat workpiece

inlet and outlet beds. However, the rollers could be tilted or inclined at some other angle should this be desired. Also, the work rollers need not be aligned parallel to the roller support structure, and could be tilted with respect to the roller support, should this be desired. The contact surface between the work rollers and the roller support structure could be flat, or it could be ridged or have shoulders to assist in maintaining the necessary alignment of the work rollers. In Fig. 9 the angle between the inlet and outlet beds is approximately 120°, but angles more or less than 120° may be used.

An advantage of these versions is that they will significantly increase the size of the workpiece that can be processed. Plates or long sheets or strips can be processed, rather than small cylindrical samples as in conventional ECAE. Plates or sheets can be used to fabricate components that cannot be made from small cylindrical volumes, which will greatly expand the range of potential applications for material processed by SPD. The loads imposed on the tooling will be low, since the deformation is carried out incrementally by a series of small, localized deformations, rather than as a single large deformation. Thus, the stressed volume of material at any one instant is much smaller than in conventional processing or in equivalent ECAE processing, so the total loads will be reduced. Friction effects will be greatly reduced, as compared to conventional ECAE processing, since the fixed die has been replaced by the moving inlet bed and rotating tools. Friction on the inlet channel is entirely eliminated, and friction on the outlet bed will be very small, since there is one free surface. There will be significant friction only in the small localized regions where the rolling tools contact the workpiece, and the open nature of the rolling tools and support structure will readily allow lubricants to be applied.

This concept can be adapted to a wide range of strains per pass by changing the angle between the inlet and outlet beds, with work rolls that match this angle. This will be most practical for a flat workpiece. The tooling for the inlet and outlet beds is simple, requiring only linear motions, which will simplify machine design and construction. Another benefit is that a plate-shaped workpiece can be re-oriented in different ways than a cylindrical specimen can. This means that processing options are available for plates that cannot be matched by conventional ECAE processing, which may be desirable. The plate sample can either be flat or curved. If the diameter of the tool holder is made very large, the curved plate will be very nearly flat, and can be easily flattened after processing. The same machine can be used for plate samples with a range of widths. A machine that could be adjusted for different plate thicknesses could easily be designed. Thus, the same tooling and machinery could be used for different plate thicknesses, plate widths, and deformation zone angles, unlike conventional ECAE where each cross section and each deformation angle would require a different set of tooling. Thick or thin plates can be processed, as well as long or short plates.

Rotating tooling will allow much higher speed processing of sheet or strip material than in conventional ECAE processing, with a commensurate increase in productivity, an important consideration for industrial application. The speed of the rotating tooling can be controlled to alter the deformation conditions, if desired. Rotating tooling on the outer corner could be moved at a speed slower than that of the workpiece, so that a back-pressure is created. This may be beneficial for certain materials with lower ductility. It may be possible to control the rotation of the tooling so that it will help to pull the material through the deformation zone. This should decrease the force that the feeding mechanism will need to supply.

### 2.2 Reversed Shear Spinning

There is another common, well-established industrial deformation process that can produce large strain deformations by a shearing process. This is shear spinning, which is also known as spin forming, spin forging, shear forming, flow forming, or power spinning in the technical literature (Ref 25-27). This is a process that is primarily used to produce rotationally symmetric conical parts (Fig. 10), although many other variations are possible. A flat, circular blank is held against a rotating mandrel, either by a fastener or an external tailstock, and one or more rollers held at the necessary specific spacing travel parallel to the side of the mandrel, causing the blank to take the mandrel's shape. The resultant wall thickness of the formed part remains constant, and deformation of the metal is essentially by simple shear (see Fig. 10), with the result that the diameter of the blank remains constant throughout the spinning process. This requires that no metal be displaced radially. The deformation is analogous to the axial displacement of a series of concentric rings, each of which is slightly shifted next to each other to achieve the final cone shape, but which do not change their radial dimension.

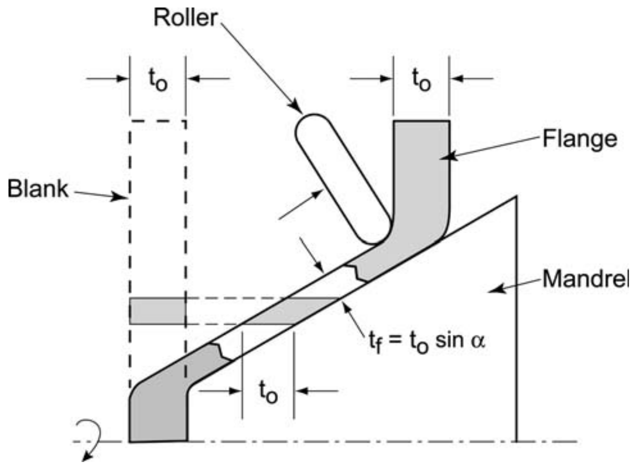


**Fig. 10** Shear spinning. Note that no radial motion of material is permitted, so deformation is almost entirely by shear

The specific roller spacing that results in the desired constant wall thickness depends on the initial blank thickness, and the cone angle, and is given by what is known as the sine law (Ref 25, 26); i.e.

$t_f = t_o \sin \alpha,$

where $t_f$ is the final wall thickness, $t_o$ is the original blank thickness, and $\alpha$ is the cone angle (half of the total included cone angle). Thus, the thickness of the cone in the direction perpendicular to the wall of the cone is given by $t_f$. This thickness is constant along the side of the cone. The thickness of the cone measured in the vertical or axial direction is also constant, and is the same as the original blank thickness, $t_o$. This is the result of the shear deformation, and the lack of any radial movement of the metal. It is this lack of radial movement of the metal that results in the blank diameter remaining constant during the shear-spinning process, and this is also the key to the reversed shear-spinning concept. Since the diameter and axial thickness of the blank remain constant during shear spinning, it should be possible to reverse the process, and do the shear spinning backwards, so that the cone is returned to its original flat shape. This will only be possible if there is no radial movement of metal, either during the initial cone forming, or during the reverse shear-spinning (RSS) process.

The cone forming is usually done with the aid of a mandrel that determines the final cone angle, although it is possible to perform the shear spinning without a mandrel. The mandrel has a nose with which it holds the blank, either by an appropriate fastener through the blank into the mandrel, or by the use of a tailstock that presses against the blank and holds it against the mandrel. The mandrel and tailstock rotate, causing the blank to rotate also. One or more rollers, which will also rotate when they come into contact with the blank, move along the mandrel, and form the blank to the shape of the mandrel. For shear spinning, the edge of the roller moves parallel to the conical mandrel, at a distance given by the sine law. Thus, the deformation is simple shear, and the wall thickness of the cone remains constant.

It is well established that shear spinning can be used to form the cone, and that the deformation can be reasonably approximated as occurring primarily by simple shear. Experiments with gridded blanks (Ref 28) and embedded markers (Ref 29) have shown that the deformation is largely simple shear, although some radial distortion does occur (Ref 28-30). The wall thickness is constant and follows the sine law (Ref 28-30). However, it is not yet known whether it is possible to reverse the operation, with the cone being returned to its original flat shape.

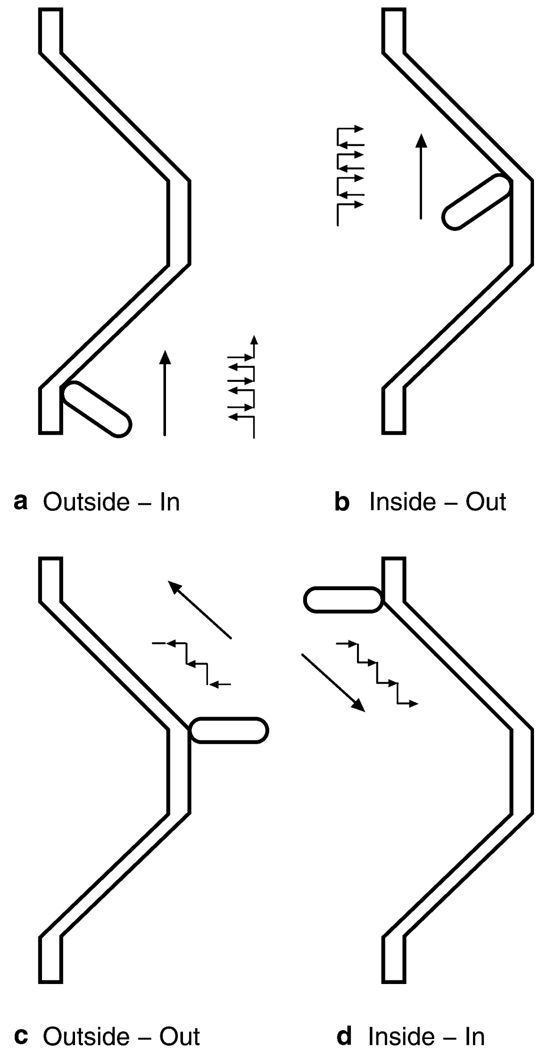


**Fig. 11** Four possible sets of motions for the work rollers for reversed shear spinning. The rotating tool can contact the workpiece on its Inside or Outside, and can move In toward the central axis, or Out toward the workpiece edge. (a) Outside-In; (b) Inside-Out; (c) Outside-Out; (d) Inside-In

There are four possible versions of roller motion that could be used to reverse the initial shear spinning (see Fig. 11). We can define the inner surface of the cone that includes an angle of less than 180° as the Inside surface, and the other surface of the cone as the Outside surface. Similarly, we can define the direction of movement of the roller from the middle of the cone to the outer edge of the cone as Out, and movement from the outer edge toward the center as In. Thus, the reversing deformation can be done by Outside-In (Fig. 11a), Inside-Out (Fig. 11b), Outside-Out (Fig. 11c), or Inside-In (Fig. 11d) processes. These can use either continuous or intermittent roller motion. The rollers can be moved in either the axial or the radial directions, or a combination of both. Multiple rollers could be used, on either or both surfaces. If a tailstock is used, additional force can be applied by the tailstock to assist the deformation.

As an example, one possibility for the RSS process would be to use the Outside-In path for the work rollers. The workpiece, previously formed into a cone by shear spinning, could be held by its flange to a flat plate, with a circular clamp. The plate and cone would rotate, and a tailstock (which may not be necessary) would press on the nose of the cone to assist in the flattening process. One or more rollers would move parallel to the flat plate surface, starting from the outer flange edge, and moving in toward the center. As they moved toward the center of the holder, the cone would be flattened, and the nose of the cone would be pushed toward the flat plate by the tailstock. As the height of the cone was reduced, the work rolls would approach the tailstock. For the final flattening, the tailstock would be removed to allow the rollers to reach near the center of the blank. The work rolls would have to be held at a distance $t_0$ from the support plate, and moved in a straight line parallel to the support plate, in a radial direction. Thus, force would be applied to the workpiece in a radial direction. Alternatively, the rollers could be positioned at some greater distance from the support plate, and advanced with an axial motion toward the support plate to the distance $t_0$, followed by a retraction, an incremental advance toward the workpiece axis, and another axial motion to continue the deformation. Thus, a series of small deformations would be applied in the axial direction to flatten the cone. Similar possibilities can be imagined for the Outside-Out, Inside-In, and Inside-Out roller paths. Instead of a flat support plate, additional rollers might be used to support the workpiece, so that one or more rollers were simultaneously present on both the inside and the outside of the workpiece.

The strain that is imposed on the metal during shear spinning depends on the angle of the cone. Flattening the cone will double the total accumulated strain from the initial shear spinning. The forming-flattening cycle could be repeated to further increase the total strain. Alternatively, the flattened blank could be flipped over after each cycle of forming and flattening, so that the next cycle would occur in the direction opposite to the previous one. This may affect the resultant microstructure.

The result of this process would be a large blank of severely deformed material. The workpiece will contain a small central portion and an outer ring of material that will not have been deformed. This material may be removed, if necessary.

Reversed shear spinning offers many advantages over ECAE or other methods of severe plastic deformation. The equipment for RSS is already commercially available, and widely used industrially. The primary advantage of RSS is that a much larger sample may be processed as compared to samples typically processed by ECAE, limited only by the capacity of the spinning machine. Spinning machines have been built for samples as large as 6 m (almost 20 feet) in diameter, and for thicknesses up to 140 mm (5.5 in.) (Ref 25). This is an enormous increase from conventional ECAE processing, which typically uses samples about 10 mm diameter by 50 mm in length ($0.4 \times 2$ in.). Shear-spinning machines are already widely available, and can easily be adapted to the reversed shear-spinning process. The tooling needed would be simple, and would largely already exist. The mandrels needed for cone forming are simple to fabricate, and are likely to already exist. It is even possible to form cones without a special mandrel. The rollers and tailstock needed would already exist. In addition, the sample may be processed at a variety of temperatures, following conventional industrial practice, and lubrication can be readily applied by existing methods.

As in ECAE, the shape of the blank is unchanged after a cycle of RSS, which would allow the blank to be processed again to increase the level of imposed strain. Unlike ECAE, there are only two options for choosing the deformation path of the blank after each cycle of forming and reverse shear. The blank can be deformed in the same manner, or it can be flipped over so that the next cone forming is in the direction opposite to that of the previous cone formation. Both of these possibilities are similar to route C processing in ECAE. Thus, ECAE provides more possible deformation paths than does RSS. However, research on various deformation paths in ECAE has shown that the route-C-type reversed deformation path that will be present in RSS processing is capable of efficient grain refinement, so the limited choice of deformation paths in RSS is not expected to be a severe drawback.

Because the sample used in RSS can be very large, the amount of material lost to end and edge effects is relatively small, which will improve the yield of RSS as compared to ECAE. The undeformed flange and central portion may need to be discarded for some applications. The width of the flange and the diameter of the central portion can be reduced to limit this effect, to some extent.

RSS offers additional flexibility in that lower amounts of strain can be achieved by increasing the total included angle of the cone. Lower levels of strain are not as readily achieved in ECAE, where increasing the angle between the intersecting channels may result in bending of the sample, rather than the desired shearing deformation. Shearing will still occur in the shear-spinning operation, even for low strain levels. In addition, different increments of strain could be applied at each step, if desired, by choosing a mandrel with a different angle.

Since shear spinning only deforms a small amount of material at the point of contact between the workpiece and the forming roller, the loads required for the deformation will be low. If multiple rollers are used, the deformation zone is further distributed over the additional rollers. Existing spinning machines can supply the necessary forces, and it may even be possible to use a conventional lathe to perform the spinning and flattening for material that is not too thick.

The workpiece and the microstructure produced by RSS should have an axial symmetry, rather than the orthogonal symmetry that a flat plate produced by conventional ECAE would be expected to have. This may be advantageous for components with circular or rotational geometries.

### 2.3 Transverse Rolling of Rod or Bar

Transverse wedge rolling (TWR) (also known as cross wedge rolling) is a process in which a round billet is inserted between appropriately shaped rolls or flat plates that deform the workpiece as it rotates. These tools incorporate a wedge-shaped profile, from which the process takes its name. There are several versions of TWR (Fig. 12). If rolls are used, they rotate in the same direction and drive the workpiece. Either two or three rolls can be used. If flat tools are used, they move in opposite directions while rotating the workpiece between them. A planetary system with a single large work roll and a fixed work segment is also possible, or concave-tooling segments can be used.

Transverse rolling (TR) is a new extension of TWR that can be used for SPD of rods or bars, using tooling that does not

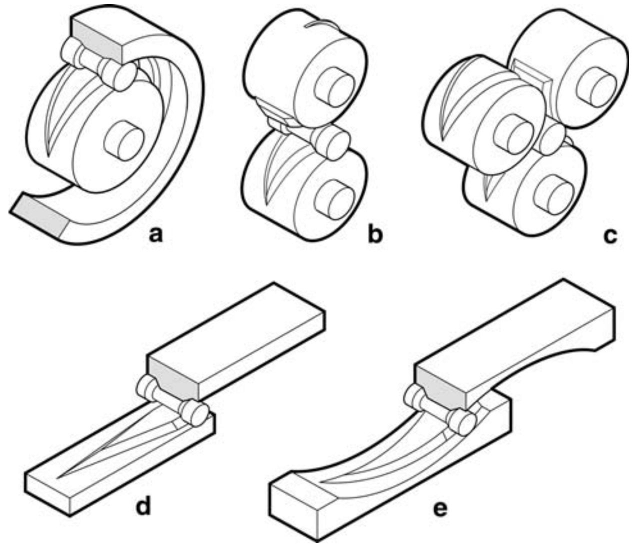


**Fig. 12** Versions of transverse wedge rolling, using tools with a wedge-shaped working surface: (a) concave segment; (b) two rolls; (c) three rolls; (d) flat tools; (e) concave tools

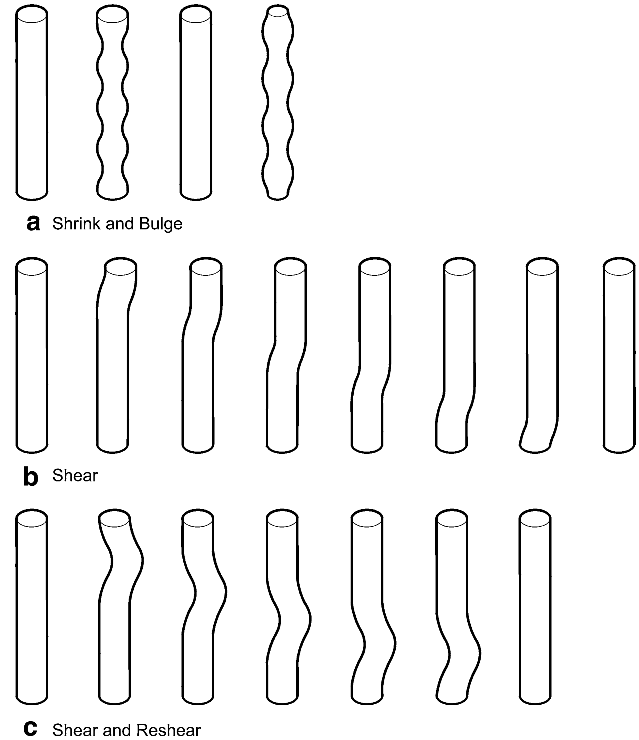


**Fig. 13** Possible deformations for transverse rolling: (a) shrink and bulge; (b) shear; (c) shear-and-reshear

have a wedge-shaped profile, but instead uses a profile that gradually deforms the workpiece as the tools and the workpiece rotate. The work rolls will be designed so that they impart deformation to the workpiece as it rotates. There are three versions of SPD by TR, which have been named shrink-and-bulge, shear, and shear-and-reshear, respectively. In the shrink-and-bulge method (Fig. 13a), a locally reduced diameter is formed in the bar at several equally spaced locations along the bar's length. The material displaced from this reduced cross section moves into the areas between the reduced sections, and causes them to bulge out to a larger diameter. These bulged areas are then forced to reduce their diameter, and material must flow into the previously reduced areas, causing them to bulge while the previously bulged areas shrink. This process can be repeated to reach the desired level of strain. These cycles of shrinking and bulging can be accomplished in two ways, either intermittently by periodically moving the work rolls apart, repositioning the workpiece, and then moving the work rolls together so that different portions of the workpiece are forced to alternately shrink and bulge, or continuously by having the rod fed through the tools, either by the rolls themselves or by an auxiliary drive mechanism. Also, the depth of deformation in the shrink-and-bulge method can be shallow or deep. If the depth of deformation is shallow, the initial part of the process is very similar to thread rolling, with the valleys being analogous to the thread roots and the hills analogous to the thread crests. However, unlike thread rolling the process is continued so that the crests are then flattened and the roots are filled in, to return the bar to its original shape. The depth of deformation will depend on many factors, such as the geometry of the tool, the workpiece diameter, the strength of the workpiece material, its work-hardening properties, the temperature at which deformation occurs, the strain-rate sensitivity of the workpiece material, the depth of penetration of the tool into the workpiece, etc.

Another version of the shrink-and-bulge method forms a reduced diameter region and associated bulged regions of increased diameter at one end of the bar. These regions are then forced to propagate along the length of the bar, so that the entire volume of the bar is eventually processed, and regains its original diameter. Again, the process can be repeated to increase the strain level. The deformed regions can be made to travel back and forth along the bar, or can travel in the same direction each time the bar is processed.

The shear method offsets one end of the bar, and then propagates this offset along the length of the bar, until the entire bar is displaced parallel to its original position (Fig. 13b). This shearing procedure can be repeated to increase the strain level. The shearing can be done back and forth along the length of the bar, or in the same direction each time. The shear-and-reshear mechanism displaces only a small localized region of the bar parallel to the bar axis by a shearing mechanism; the displaced portion will still have a circular cross section, but its axis is parallel to the rest of the bar (Fig. 13c). This portion is then forced back into its original position by a reversing shear, so that the bar returns to its original shape. This shear-and-reshear operation can be repeated to reach the desired level of strain. This shear-and-reshear can also be done in different ways: intermittently by displacing a segment of the bar and then restoring it to its original position, or continuously by propagating the displaced portion along the length of the bar (Fig. 13c). The shear-and-reshear operation can be done back and forth along the length of the bar, or in the same direction each time.

The primary advantage of TR is that it will significantly increase the size of the sample that can be processed. It would allow long bars or rods to be processed, which is not possible with conventional ECAE processing in which the load must be applied to the end of the bar, which will cause buckling of the bar or the ram that is used to apply the load. If desired, short bars could be processed. Bars of greater diameter than are generally processed by ECAE could also be processed. The bars can be deformed incrementally by repositioning the bar between forming cycles, or continuously, by having the bar move across the forming tool, either by using the tools themselves to move the bar, or by an external drive mechanism.

TR is also unique in that it utilizes a rotary motion to impose the shear deformations and offsets. The displacements occur while the bar is rotating. Thus, the deformation is a combination of shearing and torsion, at least for the shear and shear-and-reshear versions of the method. The deformation will be somewhat similar to route C in conventional ECAE. The bulge-and-shrink versions will not have the torsion component in the deformation, since the centerline of the workpiece is not offset in this version of the method. A gradient in strain will be present for the bulge-and-shrink workpiece, with less strain in the center of the workpiece, and greater strains at the surface.

The loads imposed on the tooling will be decreased as compared to conventional ECAE processing, since the deformation is carried out by a series of small, localized deformations, rather than a single large deformation. Thus, the volume of material being deformed at any one instant is much smaller than in conventional ECAE processing, so the total loads will be reduced. Friction effects should be greatly decreased, as the stationary inlet and outlet channels in ECAE have been replaced by rotating tools with only localized regions of contact with the workpiece. Furthermore, the openings between the rolls will readily allow lubricant to be applied to the workpiece throughout the deformation process.

This method uses wedge-rolling machines to deform the workpiece instead of a large press. Wedge-rolling machines are already in use by many fabrication companies, and this method offers a new use for these machines.

A workpiece processed by transverse rolling will have less material that suffers from edge effects than a similar piece processed by conventional ECAE. In ECAE, a portion at the beginning and at the end of each workpiece is inhomogeneously deformed because steady state conditions cannot be established at the ends of the workpiece. The extent of these inhomogeneously deformed regions increases with each pass, at least for some ECAE processing methods. Thus, a significant portion of the workpiece receives less deformation than the remainder. In addition, the outer region of the workpiece (as it turns the corner in the ECAE tooling) will have a lower strain than the inner portions of the billet. Both of these effects are avoided in transverse rolling. This means that the efficiency and yield of transverse rolling will be greater than in conventional ECAE processing, and the material processed by transverse rolling will be more homogeneously deformed than material processed by conventional ECAE.

The same set of work rolls could be used to process a range of bars with different diameters. This would be more economical than ECAE processing, for which a different set of tooling is needed for each bar diameter.

### *2.4 Repetitive Deformation Cycles for a Cylinder or Annulus*

Simple repetitive deformation cycles have been used previously for cubic or cylindrical workpieces, so that cycles of forging or upsetting can be used to accumulate large plastic strains. However, there are many possible new ways in which cylindrical or annular workpieces could be deformed so that a combination of deformations could be used to return the workpiece to its original shape, so that the deformation cycle could be repeated to achieve greater plastic strain.

A cylindrical workpiece can be deformed so that its outer diameter (OD) increases (+) or decreases (−). During these deformations, the height of the workpiece ($h$) must decrease (−) or increase (+), respectively. Thus, if we describe the deformation by considering the change in the OD first, and the change in $h$ second, there are only two deformation paths for a solid cylinder: (+ −) and (− +), which indicate an increase in the OD and an accompanying decrease in $h$, or vice versa. Examples of these deformations are shown in Fig. 14. Deformation of an annular workpiece offers many more possibilities, as it has an outside diameter (OD), inside diameter (ID), and height ($h$). Each of these dimensions can increase (+), decrease (−), or remain constant (0). We can describe the deformation as a triplet of these changes, in the order (OD ID $h$). There will be $3 \times 3 \times 3 = 27$ possible deformations. One of these, (0 0 0), is no change. Several combinations are physically impossible, such as (+ − +) or (− + −). Two versions, (+ + +) and (− − −), are possible for a very limited range of change, which would result in a very small strain, and these are therefore not of

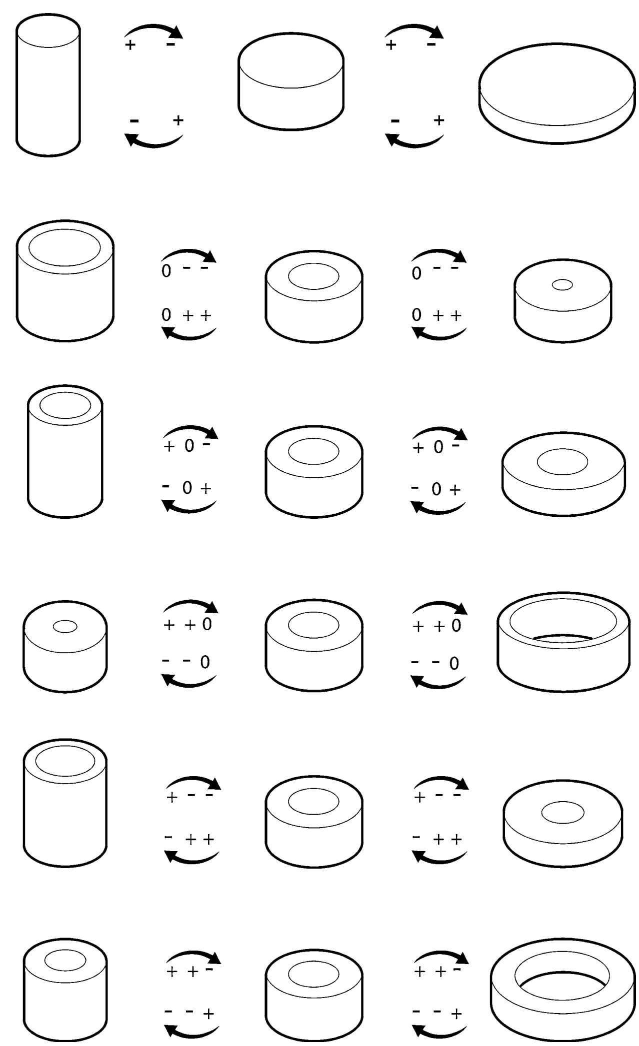


**Fig. 14** Possible deformation steps for cylindrical (top) and annular (bottom) workpieces. An increase in dimension is indicated by "+", a decrease by "−", and no change by "0". The change in the dimensions for the cylindrical workpiece are given in the order (outer diameter, height); for the annular workpiece, they are in the order (outer diameter, inner diameter, height)

practical interest. Eliminating these impractical options leaves ten feasible deformations. Examination of these deformations shows that they can be combined into five pairs of deformations, with one of the pair being the inverse of the other (Fig. 14). These include one pair of deformations that hold the OD constant, one pair that hold the ID constant, one pair that hold $h$ constant, and two pair that allow all three dimensions to change.

There are many conventional deformation processes that can be applied to cylindrical or annular workpieces. Some of the desired deformations may require new deformation methods. These are described briefly, and then combinations of these operations are selected to show how workpieces could be repeatedly processed to reach the desired high strain levels.

Common conventional deformation processes for cylindrical workpieces include upsetting, swaging, or extrusion, but there are other processes that can be considered. Orbital rotary forging uses a slightly inclined rotating tool so that only a portion of the billet is deformed (see Fig. 15). It requires much lower loads and results in less barreling or bulging of the workpiece than conventional upsetting. It can be applied to cylindrical or annular workpieces. Closed-die axial forging is very similar, with the addition of a restraining ring that holds the OD of the workpiece constant (Fig. 16). A similar variant of closed-die axial forging could be used to hold the ID constant.

Ring rolling is a conventional method for processing annular workpieces (Fig. 17) using an inner mandrel roll and an outer work roll. Radial ring rolling (Fig. 17a) results in an increase in both the ID and OD of the workpiece, with thinning of the workpiece thickness. The height of the workpiece is not directly controlled. Radial-axial ring rolling (Fig. 17b) adds additional rollers so that the height of the workpiece is controlled, typically to hold $h$ constant. A new variant is axial ring rolling with an outer restraint (Fig. 17c) that would hold the OD constant while decreasing $h$ and the ID.

Radial forging (Fig. 18) uses hammers that move radially to reduce the workpiece OD. This can be applied to cylinders (Fig. 18a) or if a mandrel is used, to annuli (Fig. 18b). This process is very similar to swaging, which uses multiple hammers instead of only two pairs.

Helical rolling (Fig. 19) uses skewed rolls inclined at an angle to reduce the OD of the workpiece. The tapered rolls can point forward (Fig. 19a) or backward (Fig. 19b). Cylindrical or annular workpieces can be processed. A mandrel can be used for annular workpieces, but is not necessary. This process is also called planetary rolling or rotary rolling. Three rolls are usually used, although two or four rolls could be used.

Flow forming, also called tube spinning, shear forming, or flow turning, is a process that reduces the OD of an annulus while holding the ID constant. This can be done in the forward direction, so that the tool moves in the same direction as the workpiece, or backwards, so that the tool moves in the direction opposite to the workpiece motion.

Transverse wedge rolling, discussed previously, can also be used to reduce the OD of a cylindrical workpiece (Fig. 12). This operation would reduce the OD starting from the middle of the length of the cylinder, working out toward each end. One could imagine versions in which the deformation proceeds from one end of the workpiece toward the other. This method should be applicable to annular workpieces also, although it is usually used for cylindrical workpieces.

Transverse roll forging (Fig. 20) is a new process that is similar in many aspects to transverse wedge rolling and helical rolling. Smooth rolls can be used to decrease the OD of cylindrical or annular workpieces (Fig. 20a). Rolls with a shoulder can be used to decrease the OD of an annular workpiece while holding $h$ constant (Fig. 20b). One or more of the work rolls could be smooth, instead of all rolls having shoulders. One can imagine versions with two, three, or four rolls, or flat or concave tooling, as in transverse wedge rolling. However, in transverse roll forging the deformation zone extends along the entire length of the workpiece, instead of having a localized zone that moves along the workpiece, as in transverse wedge rolling. Unlike helical rolling, the work rolls are straight rather than tapered, and are arranged parallel to each other and to the workpiece, rather than skewed at an angle.

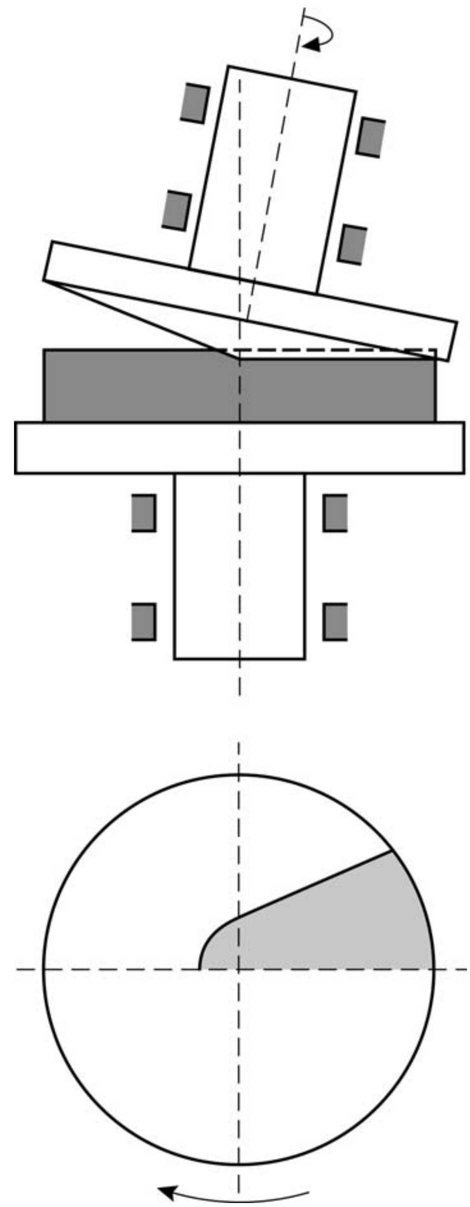

**Fig. 15** Orbital rotary forging

Rotary roll forging with a mandrel (Fig. 21) is a new process for annular workpieces that reduces $h$ while using a mandrel to keep the ID constant. This could also be called rotating roll forging.

Cylindrical workpieces can be upset by conventional upsetting or by rotary forging. These processes will reduce

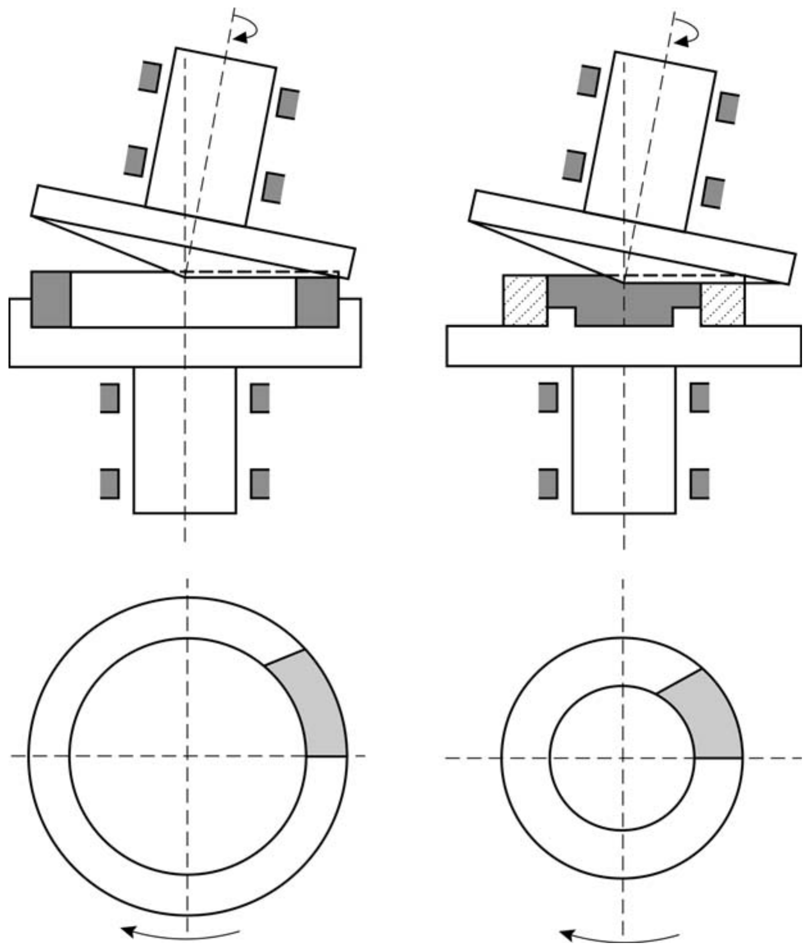

**Fig. 16** Closed-die axial forging with outer restraint (left) or inner restraint (right)

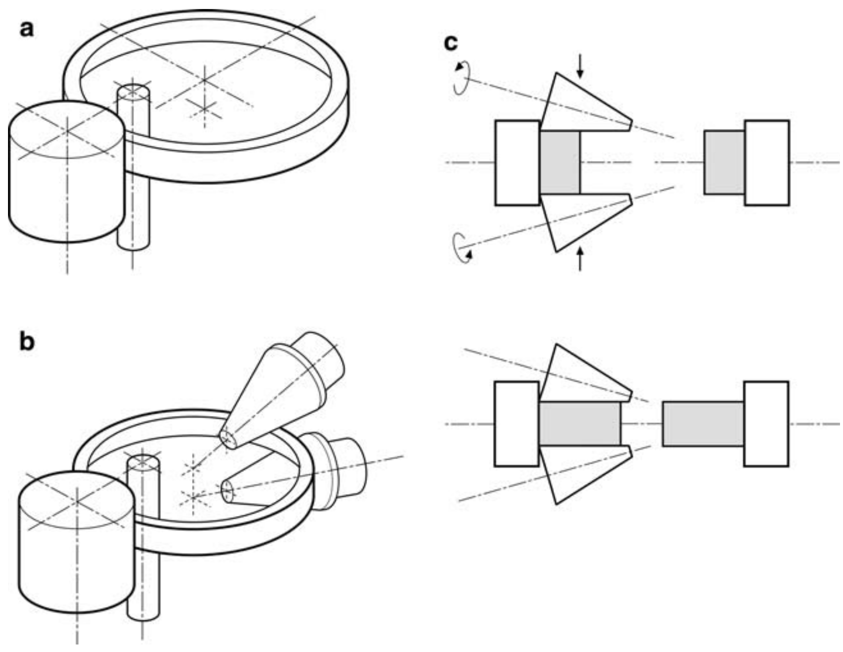


**Fig. 17** Ring rolling variations; (a) radial ring rolling; (b) radial-axial ring rolling; (c) axial ring rolling with outer restraint

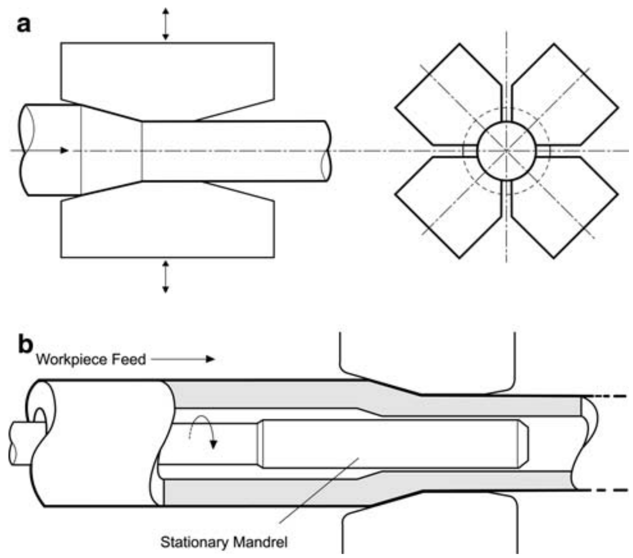


**Fig. 18** Radial forging: (a) solid workpiece; (b) annular workpiece, with fixed (but rotating) mandrel

the billet height while increasing the outer diameter. This deformation can be reversed by helical rolling, transverse wedge rolling, radial forging, swaging, transverse roll forging, or even extrusion, to reduce the OD. This cycle of height reduction followed by diameter reduction can be repeated to achieve the desired strain level. The operations that reduce the workpiece height are simple and straight forward. However, many of the processes suggested for reducing the OD are more commonly applied to long bars or rods. Adapting them to short workpieces may not be a trivial task, as it may be difficult to grip a short workpiece while its OD is being reduced. Transverse wedge rolling and transverse roll forging may be the simplest operations to consider, as handling and holding of the workpiece are easily accomplished by the tools themselves for these operations, rather than having to use separate workpiece holders.

Annular workpieces can be deformed by combinations of rotary forging, ring rolling, radial forging, helical rolling, swaging, flow turning, transverse roll forging, or rotary roll forging. The ID, OD, and $h$ can all change, or one of these dimensions can be held constant. Thus, there are many ways in which an annular billet can be deformed so that it will eventually return to its original dimensions. Repeating the process will increase the level of strain.

The simplest way to process an annular workpiece would use a pair of operations, and alternate between the processes until the desired level of strain was achieved. It would also be possible to select three appropriate deformations that would return the workpiece to its original dimensions, and to repeatedly process the billet with these three operations. The order of the operations could be reversed, if desired. Obviously, four or more operations could be combined to deform the workpiece and eventually return it to its original dimensions, again allowing repeated deformation to achieve high strains. Fewer deformation steps would be more efficient, likely making combinations of three or four operations less favorable in practice.

If we consider the deformations shown in Fig. 14, we can choose suitable methods for each of the deformations to see

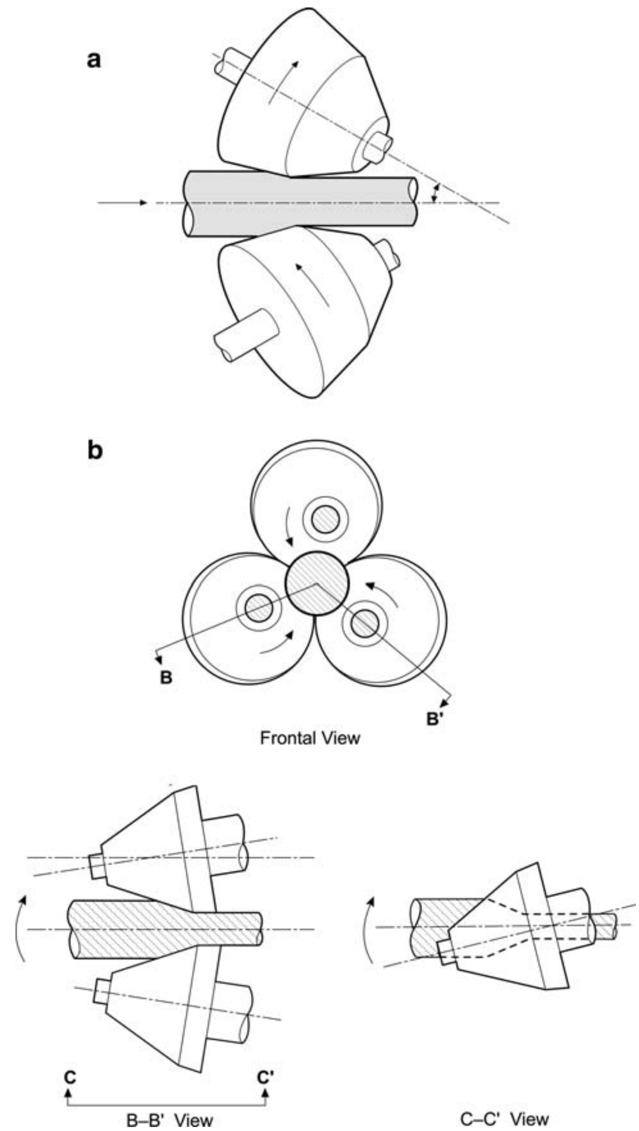


**Fig. 19** Helical rolling, also known as rotary rolling: (a) forward-pointing rolls; (b) backward-pointing rolls

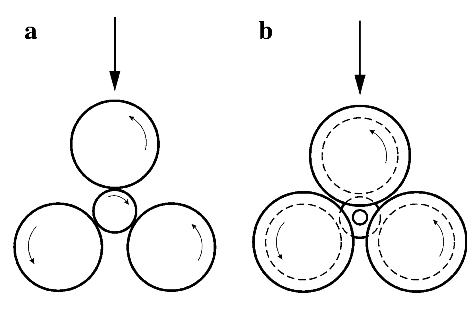


**Fig. 20** Transverse roll forging: (a) smooth rolls; (b) rolls with shoulder to control length of workpiece

which combinations would be most practical. The $(0 - -)$ operation can be performed by closed-die axial forging with outer restraint. The $(0 + +)$ operation can be performed by radial-axial ring rolling with an outer restraint. The $(+ \; 0 \; -)$

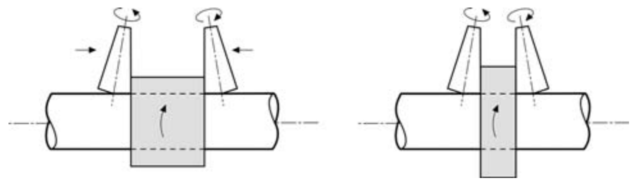

**Fig. 21** Rotary roll forging with a mandrel

operation can be done by rotary roll forging with a mandrel, or by closed-die axial forging with an inner restraint. The (− 0 +) operation can be done by radial forging with a mandrel, flow forming with a mandrel, swaging with a mandrel, or helical rolling with a mandrel. The (+ + 0) operation can be accomplished by radial-axial ring rolling, and the (− − 0) operation by transverse roll forging with shoulder rolls. The (+ − −) deformation can be done by rotary forging under high friction conditions (if friction is too low, the inner diameter will increase). An outer restraint could be used to control the increase in OD. There does not seem to be a method for performing the (− + +) deformation. Thus, this pair of operations [(+ − −) and (− + +)] seem to be the least practical of all the combinations. The (+ + −) deformation could be performed by rotary forging under low friction conditions, or by radial-axial ring rolling. The (− − +) operation could be performed by helical rolling, swaging, radial forging, or extrusion. The choice of which pair of operations to choose will depend on the workpiece size, the available processing equipment, the final part geometry, and other practical concerns.

A significant advantage of these deformation methods is that they can greatly increase the size of the sample that can be processed, as compared to ECAE or HPT. Large cylindrical or annular billets could be processed, which is not possible with conventional ECAE processing. Using these methods can allow near-net shape processing of cylindrical or annular workpieces. As-cast materials can be worked to break down their structure without having to start with extremely large starting billets. Small workpieces could receive sufficient strain to achieve the required refinement of their structure.

These processes can achieve the high strains necessary for SPD without relying solely on shearing deformation, which limits the shape and size of workpieces that can be processed by conventional SPD processes. These methods avoid or reduce the problems of end and edge effects of conventional ECAE processing, which can result in inhomogeneously deformed material near the surface and ends of billets processed by ECAE.

## 3. Advantages of New SPD Methods

The new methods for SPD that have been suggested offer many possible advantages. Much greater volumes of material can be processed with these new methods than with ECAE or HPT. The various new methods offer the possibility of processing different shapes of workpieces, including bars, rods, sheet, strip, plates, and cylindrical or annular workpieces. Continuous or semi-continuous processing can be implemented. Reduced tool loading can be achieved for those methods that use multiple tools and incremental deformation of the workpiece, since the deformation zone is shared at the points of contact, and the total deformation occurs in small, cumulative steps. Existing or similar industrial equipment can be used for many of these processes, which will aid in their implementation. Existing handling and automation technologies can be readily adapted to these methods. Many of the methods feature open tooling components rather than massive, solid tooling; this will facilitate the application of lubricants during the deformation process. Heating or cooling of the workpiece can also be incorporated, if necessary, using existing methods.

## 4. Summary and Conclusions

Several new avenues for achieving the high strain levels needed for SPD have been suggested. The first of these are variations of ECAE in which a portion of the conventional fixed die is replaced by rotating tools, for the inner die corner, the outer die corner, or both corners. Other methods share some characteristics of ECAE in that they use shearing strains to deform the material; these are reversed shear spinning and transverse rolling. Conventional as well as less common deformation processes for cylindrical or annular workpieces have been presented, and new deformation processes suggested where necessary. These techniques can be used to accumulate high strains by repeated deformation cycles that deform the workpiece and then restore its original geometry. These new methods offer many potential benefits for possible industrial application, including alternate and larger workpiece geometries, lower tooling loads, ease of lubrication, automated or reduced part handling, and, in some cases, potentially continuous operation. It is hoped that these suggestions will prompt new examination of alternative methods for SPD. Perhaps these or other new SPD methods will facilitate the spread of SPD processing from academic studies to industrial applications.

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