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# The Conventional Spinning and Flow Forming

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***Abstract:*** *The thin wall cup products are largely used in industries, it is usually made by a conventional spinning process to produce the cup shape, followed by wall thickness reduction process (Flow Forming) to reduce the cup wall thickness. There is no one process can perform a thin wall cup in one stroke. The deep drawing process with ironing at the same stroke is now being investigated in some literatures, but it still cannot reduce the wall thickness up to 50 or 70%. This article is aiming to investigate the conventional spinning process and the flow forming process; how these two processes conducted and the development in the two processes. A review of the two processes is included in this article. After that; suggestions for future work in the two processes and to conduct the two processes together are prescribed.*

**Keywords—**Conventional spinning, Flow forming, Thin wall cup

## 1. INTRODUCTION

Production process is mainly a compound activity, concerned with people who have a broad number of disciplines and skills and a widespread kind of equipment, tools, and utensils with several levels of computerization, such as CPUs, robots, and other equipment. Manufacturing searches must be accessible to several requirements and progress [1]. The metal forming is an important branch of the manufacturing processes, this is due to its ability of manufacturing a part without any metal loss. Many types of metal forming are available now, but the spinning process is the concerned subdivision of the forming processes.

Sheet metal spinning is one of the metals forming processes, where a flat metal blank is formed into an axisymmetric part by a roller which progressively forces the blank onto a mandrel, orienting the final shape of the spun part. As shown in Figure 1, through the spinning process, the blank is fixed between the mandrel and backplate; these three elements rotate synchronously at an identified spindle rotation speed. Materials used in the spinning process include non-alloyed carbon steels, heat-resistant and stainless steels, non-ferrous heavy metals and light alloys [2].

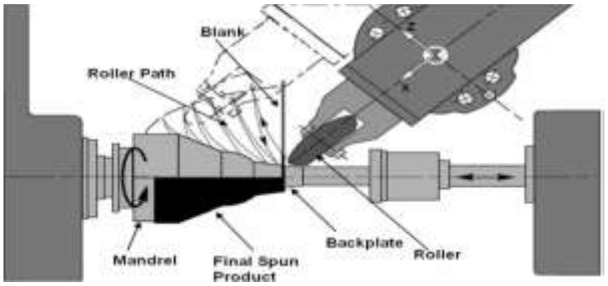


**Fig. 1.** *Setup of metal spinning process [2]*

The process is capable of forming a workpiece with a thickness of 0.5 mm to 30 mm and diameter of 10 mm - 5 m.

Due to its incremental forming aspect, metal spinning has some exclusive advantages over other sheet metal forming processes. These include process flexibility, non-dedicated tooling, low forming load, good surface finish and improved mechanical properties of the spun part [3]. Hence, the sheet metal spinning process has been frequently used to produce components for the automotive, aerospace, medical, construction and defense industries, as shown in Figure 2.

Fig. 2. *Applications of spun parts from*

There are two types of sheet metal spinning: in conventional spinning, as shown in **Error! Reference source not found.** on the left, a blank is formed into the desired shape by multiple roller passes to maintain the original wall thickness ($t_0$); however, the diameter of the spun part ($D_1$) has been reduced from the original diameter ($D_0$). Conversely, during shear forming, the roller deforms the blank by one single pass as shown in **Error! Reference source not found.** on the right. The diameter of the spun part ($D_1$) remains unchanged but the wall thickness of the spun part is reduced deliberately. The final thickness of the spun part, $t_1$, can be determined by the sine law:

$$t_1 = t_0 \sin\alpha$$

where $t_0$ is the original thickness of the blank, α is the inclined angle of the mandrel.

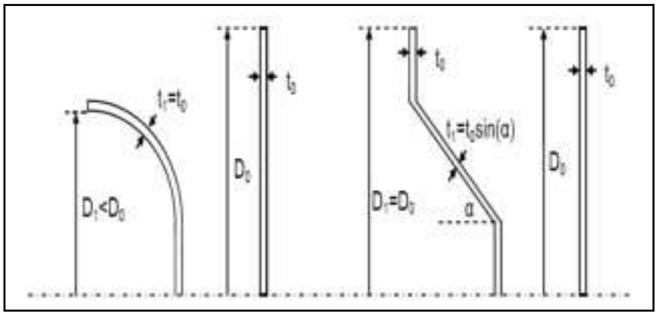


Fig. 3. *Conventional spinning and shear forming*

Up to now, research on the sheet metal spinning process has been carried out by using three techniques, i.e. theoretical study, experimental investigation and FE simulation. Each technique has its own advantages and disadvantages. For instance, theoretical study is the least expensive method used when analyzing the metal spinning process and it has the potential to assist process design and predict material failures. However, due to the complex nature of metal spinning, theoretical study has to be developed on certain simplified assumptions. It is therefore almost impossible to obtain detailed and reliable results, such as stress and strain, by applying the theoretical analysis alone. On the other hand, accurate tool forces, strains and material failures can be obtained via experimental investigation. Nevertheless, carrying out experiments with various parameters at different levels costs a significant amount of time and material; thoroughly analyzing their effects on material deformation is extremely difficult. FE simulation has the potential to provide in-depth understanding of the material deformation and failure mechanics and can therefore develop guidance in determining process parameters and improve product quality. However, FE simulation of the spinning process involves three areas of non-linearity: material non-linearity, geometry non-linearity and boundary non-linearity. It generally takes extremely long computational time due to the nature of incremental forming and complex contact conditions.

The shear forming process has been investigated intensely by many researchers who have been using both experimental and numerical approaches since 1960. On the other hand, limited publications on conventional spinning mainly focus on one-pass deep drawing conventional spinning and simple multi-pass conventional spinning (less than three passes, linear path profile). The process design of conventional spinning thus still remains a challenging task and material failures significantly affect production efficiency and product quality. In the present industrial practice, the trial-and-error approach is commonly used in the process design [4].With the aid of Playback Numerical Control (PNC) of the spinning machine, all the processing commands developed by experienced spinners are recorded and used in the subsequent spinning productions (Pollitt, 1982 adapted from [5]). Nevertheless, the process design inevitably results in significant variations and discrepancies in product quality and geometrical dimensions [6].Furthermore, the procedure of the PNC process development and validation unduly wastes a considerable amount of time and materials. It is therefore essential to study the material deformation and failure mechanics in the multi-pass conventional spinning process and to analyze the effects of process parameters on the quality of spun products.

The mechanism of plastic deformation will vary with each forming process, making it necessary to have different forming limit tests. Extensive research has been performed on forming limit diagrams, which are useful when considering deep drawing. [7] proposed a method of determining the forming limit of different metals under the specific condition of shear forming. [8] later studied the spinnability test method further. By Kegg’s definition, spinnability is the maximum reduction in thickness that a particular material can achieve.

$$\%R = \frac{t_b - t_{fr}}{t_b}$$

Where %R is the limit percentage reduction in thickness

$t_b$ is the blank initial thickness

$t_{fr}$ is the fracture thickness

The spinnability test, shown in Figure 4, involves shear forming a circular metal disk over a hemi-ellipsoid mandrel. According to the sine law the material thickness will vary from the original blank thickness at the tip, to zero by the end of the mandrel. This reduction in thickness is caused by the change in angle from 90° to 0° relative to the revolving axis. More ‘spinnable’, ductile, materials will form further along the mandrel before fracture occurs, while the more brittle materials will fracture early. The type of fracture will vary depending on the ductility of the tested metal. For brittle materials failure will occur by shear under the tool tip. Ductile materials fail slightly behind the tool radius in the previously formed material [8]. This test method allows for a quick, low cost way of determining how a particular material will perform in a shear spinning process.

In addition to the spinnability test procedure [7] has shown a link between tensile data and spinnability. Comparing the thickness at fracture from spinnability and tensile tests allows the spinnability of a given material to be determined without testing, since tensile data is readily available. Other material characteristics such as strength and strain hardening exponent show no significant correlation to spinnability [7], [8] has also shown that the maximum reduction depends on ductility for materials where tensile testing gives a true fracture strain below 0.5. Larger values do not result in a significant increase in reduction with greater ductility. For shear forming of a cone the maximum angle is roughly 30° from the revolving axis to the wall.

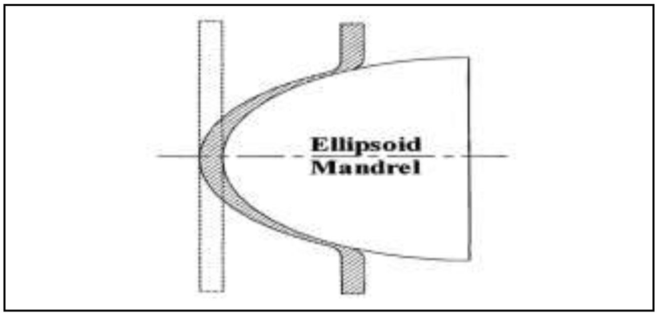


**Fig. 4.** *Shear spinnability test designed by [10].*

## 2. DEVELOPMENT IN SPINNING PROCESS

In recent years, novel spinning processes are being developed which challenges the limitation of traditional spinning technology being used for manufacturing axisymmetric, circular cross-section, and uniform wall-thickness parts [4,9]. [10] developed a 3D non-axisymmetric spinning process, in which the workpiece was free from the rotational motion during processing and the roller set was installed on the main spindle and rotated together with the main spindle of the machine. Using the developed process, a thin-walled hollow part with a partial axis paralleling or being a certain inclined angle to the original axis of the workpiece can be produced without the need of using subsequent welding processes. [11,12] developed a non-circular spinning process, thin-walled hollow parts with tripod shaped cross-section were manufactured, by a standard spinning lathe with a pair of diametrically opposite, spring-controlled rollers. [13] proposed a new flow-splitting spinning method, where the tool configuration design consisted of one splitting roll and two supporting rolls, and the distance between the splitting roll and each supporting roller was adjusted to a specified value, therefore overcame the limitation of attainable radial splitting depths successfully. [14] developed a stagger inner gear spinning method, where three rollers were 120º equally positioned along the circumference of the workpiece and there was a certain distance between rollers along both the axial and radial directions of the workpiece. The method has been successfully used to form various cup-shaped thin-walled inner gears [14]. The development of these novel spinning processes has broadened the scope of the traditional spinning technology being used to manufacture axisymmetric, circular cross-section, and uniform wall-thickness parts for various industrial applications. However, these newly developed spinning processes do not belong to any existing spinning processes if using the traditional classification method, thus the classification of the recently developed novel spinning processes is necessary. In this paper, the advancement of novel spinning processes is reviewed, and a classification of the non-axisymmetric spinning, non-circular cross-section spinning, and tooth-shaped spinning is proposed. Examples of industrial applications of the novel spinning processes are analyzed to provide an insight into the material deformation characteristics during forming.

## 3. PROCESS VARIABLES

There are numerous process variables that contribute to the successful production of a spun product. Some of the more significant process variables and their effects on conventional spinning, investigated by other researchers, are discussed below.

### 2.1 Feed ratio

Feed ratio is defined as the ratio of the roller feed rate to the spindle speed. As long as the feed ratio remains constant, the roller feed and the spindle speed can be changed without any significant effect on the quality of the product. Maintaining an acceptable feed ratio is vital as high feed ratios generate higher forces that may lead to cracking. In contrast, too low a feed ratio will cause excessive material flow in an outward direction, which unnecessarily reduces workability and unduly thins the wall [4]. Wang et al. [6] explained that an increase of spindle speed would lead to two effects. One is an increased magnitude of spinning force due to the high deformation rate; the other is that the deformation energy required per revolution is likely to decrease because the feed rate is inversely proportional to the spindle speed (mm/rev).

### 2.2 Roller path

The roller path is particularly important in affecting the quality of a spun part. Different roller paths such as linear, concave, convex, involute and quadratic relative to the workpiece have an influence on the deformation of the blank. The tendency to buckle and cause wrinkles as well as cracking can be avoided by introducing the correct roller path. A concave roller path is the most widely used one in conventional spinning. The thinning rate in designing a roller path for the first pass should be taken into account as it plays a decisive role in the final wall thickness [25]. Liu et al. [26] established an elastoplastic FEM model to analyze the stress and strain distribution of the first pass of conventional spinning with different roller paths, namely linear, involute and quadratic, to convert the shape of the blank to that of the mandrel. They reported that both the radial and the tangential stress and strain are the smallest for the involute curve. They concluded that a comparison of the distribution of stresses and strains under the three different paths could provide a theoretical basis for selecting a suitable roller path in conventional spinning.

### 2.3 Spinning ratio

Spinning ratio is defined as the ratio of blank diameter to mandrel diameter. The higher the spinning ratio, the more difficult is the spinning process. If the spinning ratio is too large, the remaining material cross section is no longer able to transmit the very high radial tensile stresses generated in the wall. This will lead to circumferential splitting along the transition from the flange to the wall. On the other hand, the spinning ratio is at its upper limit when the wrinkling in the flange becomes so large that subsequent passes of the tool cannot remove them.

### 2.4 Roller design

The design of the roller needs to be considered carefully as it can affect the component shape, wall thickness and dimensional accuracy. Although roller diameter has little effect on the final product quality, too small a roller nose radius will lead to higher stress and ultimately lead to poor thickness uniformity. Figure 5 shows examples of different shapes of roller [15].

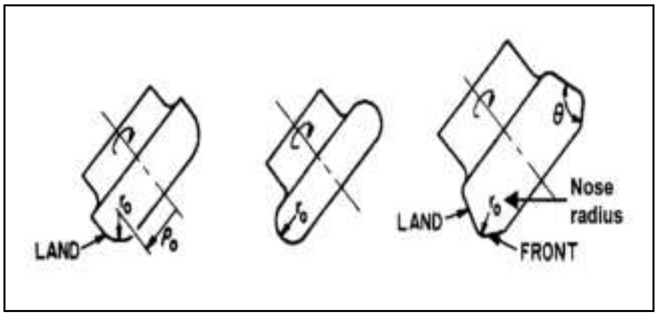


**Fig. 5.** *Different shapes of roller for spinning.*

## 4. PROCESS ADVANCES AND APPLICATIONS OF NOVEL SPINNING PROCESSES

Various novel spinning processes have been developed to produce a range of geometries in recent years. This section presents some examples of the development of novel spinning processes for industrial applications and analysis of tool design and their associated controls as well as spun part defects and material processing failures.

### 4.1 Non-axisymmetric spinning

Xia et al. [16] has successfully produced the offset parts (where various rotating axes are parallel to each other) and the oblique parts (there is a certain angle between the rotating axes) by using the non-axisymmetric spinning processes, without the need of post-processing such as welding. Figure 6 shows a typical automobile exhaust tube with offset axis on the left-end side and oblique axis on the right-end side, as reported by Xia et al. [17]. The traditional manufacturing method of the part is to separate the final geometry into three sections, the middle section of the circular tube (II) is welded with the two end tubes (I and III). Each of the end tubes are divided into two stamping parts from its center line (O1-O1 and O2-O2) respectively, then welded together. By using this traditional manufacturing method, not only the welding quality cannot be guaranteed but also the production cost is much higher because a number of the manufacturing procedures are required. By replacing the traditional method with the spinning process, not only thermal distortions and potential fatigue cracks caused by welding can be avoided effectively; but also, the mechanical properties and dimensional accuracy of tubes can be improved.

Xia et al. [16] developed the non-axisymmetric tube spinning process and associated equipment and tools, to manufacture non-axisymmetric thin-walled hollow parts with two or more rotational axes in one piece by using 6061 aluminum alloy tubes of 100 mm in diameter and 1.8 mm in thickness, as shown in Figure 7, the deviation of wall thickness, straightness and ovality of spun part are 0.2 mm, 1.4 mm and 1.0 mm respectively. Comparing with the traditional manufacturing method, i.e., welding following stamping, the utilization of material increases from 70% to 90%, the production procedures are reduced from 10-passes to 2-passes. Therefore, the production cost is reduced significantly by spinning. Xia et al. [16] also developed a multi-function CNC spinning machine for the non-axisymmetric process, as shown in Figure 8.

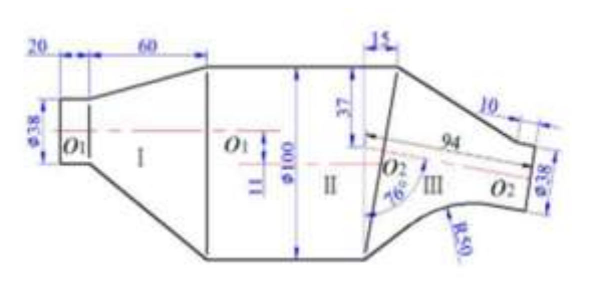


**Fig. 6.** *Example of vehicle exhausts tube*

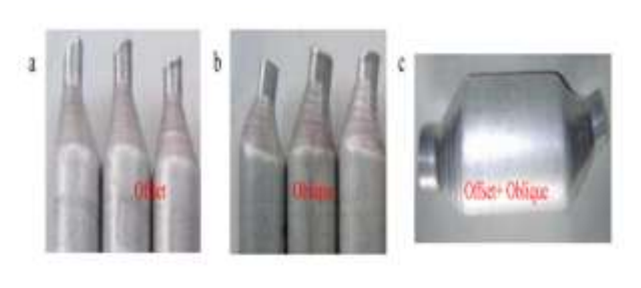
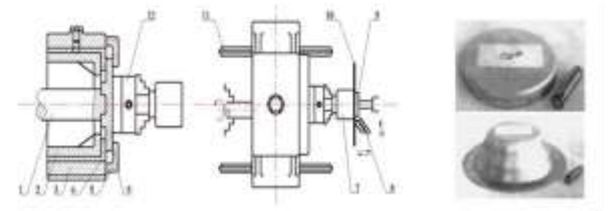


**Fig. 7.** *Non-axisymmetric spun parts [35].*

**Fig. 8.** *HGPX-WSM multi-function CNC spinning machine [24]*

### 4.2 Non-circular cross-section spinning

Amano and Tamura reported a non-circular spinning method by using a radially offset roller on a modified spinning lathe to produce the hollow parts with elliptical cross-section [18]. Gao et al. developed another mechanical setup in which the spindle axis coincident with the revolution was offset [19]. In the experiment, the aluminum sheet of 1 mm in thicknesses is used as the blank. Figure 9 shows the spinning device and the spun workpieces of elliptical cross-section with φ110 mm in long axis and φ 90 mm in short axis. As can be seen in **Error! Reference source not found.**(a), the transmission shaft is installed on the holding chuck of a lathe at one end, while the holster is fixed onto the slideway of the lathe. Two slide blocks are fixed onto the revolving drum. The three-jaw chuck is installed on the rotor disc, on which two orthogonal sliding chutes are attached. The slide blocks and the block mounted at the end of the shaft extend into the two sliding chutes and can slide along them. Therefore, the rotor disc and the revolving drum can be rotated by the lathe through the transmission shaft. The sheet blank is fixed onto the end surface of the mandrel by a supporting tail. The roller is installed in a small tool carrier of the lathe, so that the path of the roller can be controlled by the motion of the tool carrier. By changing the path of the roller, the spinning of parts with different elliptical shapes can be realized, and the maximum wall-thickness thinning ratio of spun workpiece is 16% [19].

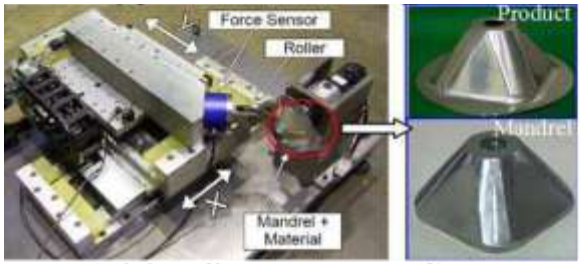


a) diagram of spinning machine. (b) elliptical spun parts.
1-transmission shaft 2-revolving drum 3-holster 4-slide block 5-clamping
6-rotor disc 7-elliptical mandrel 8-roller 9-supporting tail 10-blank
11-slideway 12-three-jaw chuck

**Fig. 9.** *Elliptical spinning device based on two slide blocks and elliptical spun parts [31]*

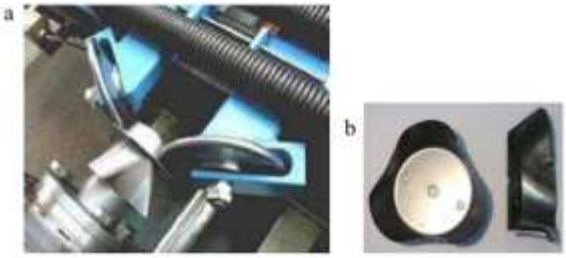
Arai [32] developed a novel metal spinning method based on hybrid position/force control for manufacturing non-circular cross-section parts and developed the corresponding equipment. The parts with quadrilateral roundness-type cross-section were successfully produced by using the pure aluminum (1050-O, annealed) sheet of 120 mm in diameter and 0.78 mm in thickness, as shown in Figure 10[32]. Using this method, the roller is controlled by following the contour of the mandrel to force the material to deform onto the mandrel. This enables a non-axisymmetric spun part to be produced which bearing the same geometry as the mandrel, and the spring back is small and the product tightly conforming onto the mandrel.

Awiszus et al. developed a spinning method with a pair of diametrically opposite, spring-controlled rollers on a standard spinning lathe, and the parts with tripod shaped cross-section were successfully produced by using pure aluminum sheet of 120 mm in diameter and 1.5 mm in thickness, as shown in Figure 11 [13]. The important factors which affect the distribution of wall-thickness of formed parts were investigated, and the non-circular cross-section parts with 24% wall-thickness thinning ratio were obtained by adopting the motion control of the rollers and combining with the optimized forming processing parameters.



a) spinning machine. (b) spun parts.

**Fig. 10.** *Linear motor driven metal spinning machine and spun parts [32]*



a) spinning device. (b) spun parts.

**Fig. 11.** *Tripod shaped spinning device and spun parts [13]*

Sekiguchi et al. developed a spinning method which can be used to produce curved shapes and non-axisymmetric sectional shapes without using a dedicated die. A numerically controlled spinning lathe was used to force the spherical head tool onto the prehemmed blank disc fixed on the spindle axis via a general-purpose mandrel, with the tool moving along a trajectory which was calculated based on the desired shape. The fundamental strategy of the method was to move the tool along the axial and radial directions synchronously with the rotation of the spindle axis, to form the product according to the virtual curved axis instead of the real spindle-axis, as shown in Figure 12. Since the flange plane of the workpiece is inclined from the normal plane of the spindle axis, the position of the roller and the angle of the spindle should be controlled synchronously. Various curved and non-axisymmetric sectional shapes of spun workpiece were obtained by using the pure aluminum sheets of 150 mm in diameter and 1.5 mm in thicknesses, and the maximum wall-thickness thinning ratio is 60%, as shown in Figure 13 [20].

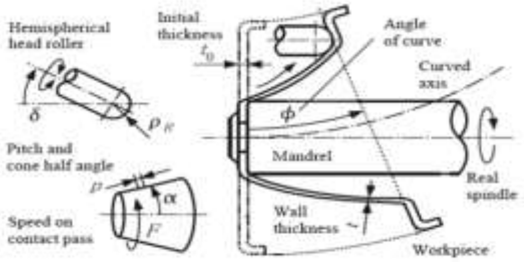
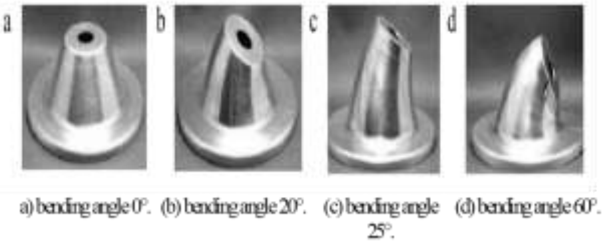


**Fig. 12.** *Schematic of synchronous spinning of curved parts* [20]



a) bending angle 0°. (b) bending angle 20°. (c) bending angle 25°. (d) bending angle 60°.

**Fig. 13.** *Curved conical spun parts* [20].

## 4.3 Tooth shaped spinning

For the manufacture of V-shaped pulleys, dynamic dampers and automobile wheels, blanks having cup shape on both sides are required [21]. An alternative forming method for such geometrical shapes is a special process of spinning, the so-called splitting process, as shown in Figure 14 [22]. This is performed by feeding a tapered roller radially into a rotating disk blank. Initial research findings such as the conventional splitting process are documented in [23]. When manufacturing components by the conventional splitting process, several problems have been observed. Firstly, the process produces tensile stresses at the bottom of the split which can cause the formation of a crack. The severing material deformation frequently results in a crack preceding the splitting roller below the workpiece surface which then can cause production-related failure of the component in subsequent operation. Secondly, positioning the splitting roller and the disk blank relative to each other is problematic thus splitting of the workpiece will not take place necessarily parallel to the disk plane. The consequence of this is that different material thickness prevails in the angular areas. These process-bound disadvantages of the conventional splitting are to be eliminated by means of an innovative flow-splitting method developed by Schmoeckel and Hauk, as shown in Figure 15 [22]. By using this method, the tool configuration consists of three rollers, one splitting roller and two supporting rollers. While the splitting roller causes the material of the blank to flow into the two flange areas, the supporting rollers interact with the deformation zone of the blank underneath the deformation zone. The flange with a given wall-thickness can be formed by adjusting the distance between the splitting roller and each supporting roller. During the beginning of the forming process, the supporting rollers keep the blank from buckling. Once the edge of the blank undergoes deformation, the supporting rolls induce compressive stresses and thus increase the formability of the material.

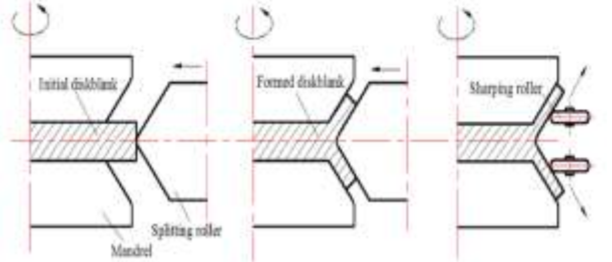


**Fig. 14.** *Schematic* illustration of splitting spinning process [22].

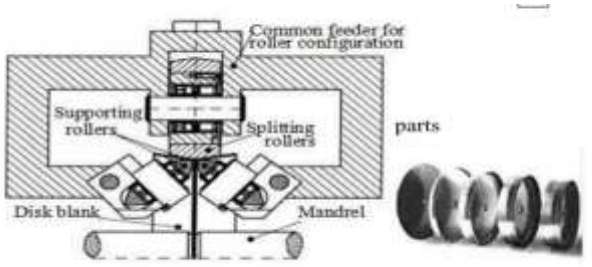
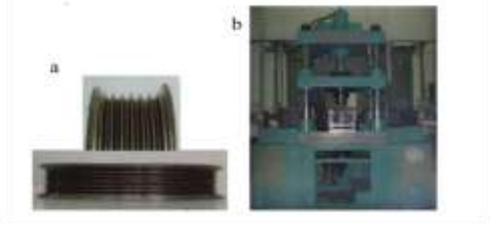


**Fig. 15.** *Split spinning forming device and parts* [13].

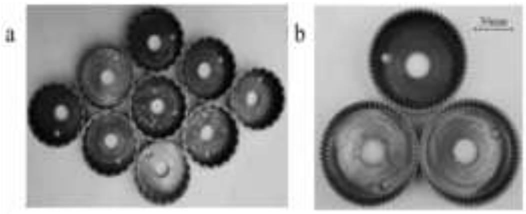
Cheng et al. developed a near-net shape forming process for manufacturing six-wedge belt pulleys by using 08AL steel sheets of 2.5 mm in thickness, as shown in Figure 16(a) [24]. The required tooth shape and size can be formed directly by spinning without machining. Only minor machining procedure is required at the outlines as marked by A and B, The deviation of the bottom diameter and the V-groove angle is 0.36 mm and 0.25°, respectively [24]. Comparing with the belt pulleys manufactured by machining after casting and forging processes, the material utilization by using spinning process increases from 40% to 70%. Furthermore, the spun pulley has inherent advantages, such as low manufacturing cost, improved material strength, thus prolonged service life. A vertical pulley spinning machine, HGQX-LS45-CNC is developed by Cheng et al., as shown in Figure 16(b) [24]. The machine has an embedded system based on ARM (Advanced RISC Machines) which is used as the main CNC controller. The four mounting seats with different shapes of the rollers are driven by servomotors.



a) spun pulley (b) HGQX-LS45-CNC spinning machine

**Fig. 16.** *Spun pulley and spinning machine* [24]

In recent years, considerable works have been carried out in longitudinal-tooth spinning. Xia et al. reported that the defects, such as the non-uniform distribution of tooth height along the axial and tangential directions and the wave-shaped opening-end of workpiece, are greatly affected by the processing parameters [25]. Sun et al. reported that the compressive deformation along tangential direction on the internal surface of part leads to a reduction in root circle of spun part, and the local loading and frictional effects result in the non-uniform radial deformation on the external surface of spun part [26]. Furthermore, in the work reported by Xia et al. [27], the process optimization is carried out by using the Response Surface Method (RSM) to obtain good dimensional accuracy of spun inner gears. A set of optimum processing parameters is obtained by taking the tooth fullness as the optimization target and taking the thickness of circular blank and the reduction of wall-thickness of cup-shaped blank as the optimization parameters. Various spun inner gears are produced based on the selected optimum parameters by using the ASTM A36 steel tube of 76 mm in diameter and 2.5 mm in thickness, as shown in Figure 17**Error! Reference source not found.** [28]. For the involute inner gear, the deviation of the tooth profile and spiral line, and the radial runout is 0.022 mm, 0.025 mm and 0.057 mm, respectively [27]. Spinning has shown a promising progress to become a new technique in gear manufacturing. It overcomes drawbacks of traditional machining processing, such as low production efficiency, low precision and strict requirement for machining tools. By maintaining continuous material flow during deformation, the inner spun gear has improved fatigue strength, good wear ability and prolonged service life. A stagger spinning device with three-rollers distributed uniformly along circumferential direction of the blank is developed by Xia et al., as shown in Figure 18[28]. By using this device, the position of each roller can be adjusted individually both along the axial and radial directions.



a) Rectangular inner gear. (b) Involute inner gear

**Fig. 17.** *Trapezoid and involutes inner gear spun parts* [28]

1- Spindle 2- Mandrel 3-Blank 4-Roller 5-Tailstock

**Fig. 18.** *Stagger spinning device with three-rollers* [28].

The spinning processes of tubular parts with longitudinal inner ribs are also extensively researched in recent years. The difference between these two types of spun parts is that there is no bottom on the end of the tubular parts comparing to the longitudinal inner ribs. Although the geometry of these two types of spun parts is similar, the application is very different. The use of inner gears is to transfer the motion and power, the forming quality of the inner gear is essential, especially the forming accuracy. However, the application of inner ribs is to enhance the stiffness and strength of tubular parts, only the accuracy of forming height of inner rib is required to be maintained.

Abd-Eltwab et al, investigated the process of producing inner longitudinal rips experimentally and theoretically with a new design performing the process using four balls [29]. This research has tested the effect of process parameters such as feed ratio, mandrel rotational speed, sleeve initial thickness, and the depth of feed. The theoretical results were compared with the experimental work and the deviation ratio did not exceed 10%.

## 5. FLOW FORMING

Conventionally, hollow tubes are produced by different methods like extrusion or drawing. However hot extrusion does not give high dimensional accuracy and is not practical for thin wall reductions. Drawing is easier and cheaper compared to extrusion, however, it can result in microcracks or other defect since it is a tensile operation. Furthermore, with these methods, generally, annealing is necessary between the passes which increases the cost of the operation considerably [30,31]. Flow forming is a chip less, near net shape technique to produce especially seamless hollow parts requiring accurate dimensions and high symmetry [32]. The origins of the flow forming process started in Sweden in the mid-1950s. However, the process has improved during the last three decades. Flow forming is an advanced form of the metal spinning process and is sometimes called tube spinning as well. Gur and Tirosh defined the flow forming process as an operation involving the simultaneous extrusion (or drawing) and rolling of the workpiece [33]. According to Rajan et al. [31], flow forming is a process combining rolling, shearing and bending into a single operation. Therefore, flow forming is a very complex process comprising many effects of different operations. Flow formed components can be used in different industries including aerospace, defense, automotive and rail vehicles. Nagele et al. [34], worked on automotive products processed by flow forming. Components, traditionally produced by machining, have started to be processed by flow forming mainly because it is cost effective and good at improving mechanical properties. Drive shaft flange, output shaft, flanged cylinder and link shaft components are among the numerous components produced by flow forming [34].

Flow forming can be applied to many materials including steel, titanium, aluminum, chromium, zirconium and nickel-based superalloys and different shapes of components can be produced as seen in Figure 19 [35].

Flow forming can be considered as an advanced form of metal spinning. The main difference between the two processes is that the starting material in the metal spinning process is thinner than for flow forming and the resulting component is produced from a larger diameter preform [36,37]. In the flow forming process, the resulting components dimensions are calculated beforehand, and the process control is carried out more precisely compared to the metal spinning process. Therefore, if the required dimensions are not very strict, metal spinning can be chosen due to its cost effectiveness [36,37][37]. Another difference between the processes is that the flow forming process is capable of producing different wall thicknesses on the same component [36,37].

**Fig. 19.** *Different shape of components produced by flow forming process*

DIN (German Institute of organization) standard 8582 defines the general spinning process. According to this standard, depending on the process and the shape of the component, tension and/or compression stresses are applied during the process. However, the flow forming process is defined by DIN standard 8584 where only compression forces are applied [32]. Shear forming is also investigated in the same standard since it involves the same type of deformation as flow forming. The classification of these processes according to the DIN standards are given in Figure 20. Generally, the shape of the starting blank (preform) and the applied force are the main factors for the classification.

There are basically three different methods of flow forming. Two of them are classified according to the direction of the flow. These methods are; forward flow forming, backward flow forming, and shear forming.

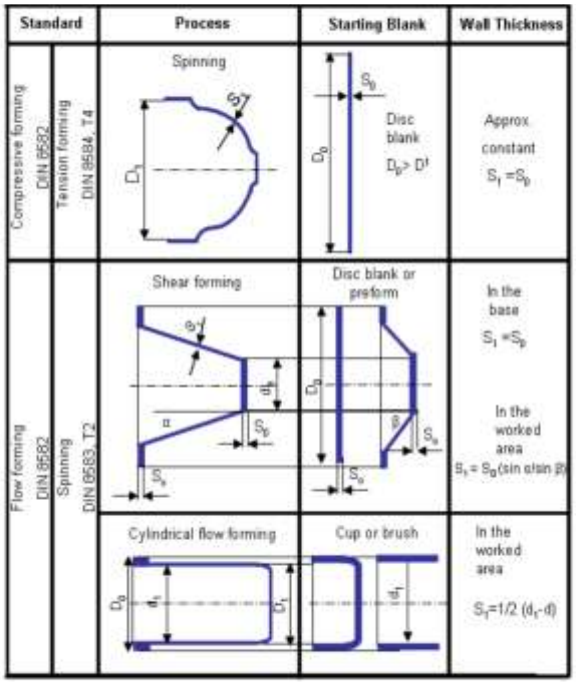


**Fig. 20.** *Classification of the spinning processes according to DIN standard* [32]

One of the most important advantages of flow forming is that this process is capable of producing sections with different wall thicknesses in any combination just by adjusting the gap between the rollers and the mandrel [31,36].

Rollers and mandrels used in the flow forming operation are made from hardened steel, that are heat treated and drawn [36]. In Figure 21 the picture of the flow formed pipe with the flow forming machine is given. The preform (blank) is attached onto a mandrel mounted on the main spindle. After locked with a tailstock, it is rotated via the CNC controlled motor. The rollers come into contact with the preform applying circumferential compressive force [38]. The rollers apply both radial and axial forces to the preform to plasticize the metal under the contact point. The material flows in the axial direction increasing the length of the component by decreasing the wall thickness [39]. Most of the flow forming machines work with two or three rollers. Generally, three rollers are (apart from each other 120 circumferentially) used to keep the balance and achieve a uniform load distribution. The process can be conducted in one or more passes. The metal deforms in two directions: axial and circumferential [32,33]. If the axial plastic flow is dominant, reduction in thickness resembles that of the plane strain extrusion and a good quality product is produced. However, if the reverse is true, circumferential flow will be dominant and cause high constraint of flow in the axial direction. Too much stress in either direction may cause undesirable defects such as wrinkles or cracks [32].

**Fig. 21.** *An example of the flow forming machine*

Another advantage of the flow forming process is related with the cost. Less starting preform material is required compared to other manufacturing methods of tubular components and the material is just displaced during the process minimizing metal removal. Furthermore, less tooling is required. Flow forming can be considered as a near net shape process eliminating secondary machining operations including machining heavy wall forgings or extrusions and the final machining and gun drilling. Since it produces seamless parts, it eliminates the welding costs as well [37]. The finished product has a superior surface finish which can be compared to the inner surface of the components, where deformation is not applied [30,38].

Flow forming is also an effective process in obtaining a refined grain structure [38]. Fonte [36,38] worked on titanium commercially pure grade 2 (Ti CP2) material and compared the flow forming and extrusion processes and concluded that grain size is significantly smaller in flow formed material (2.5 micron) than in extruded material (9.5 micron). Due to the high level of deformation, grain size decreases and microstructure is distributed uniformly through the axial direction. In **Error! Reference source not found.**, the grain structure of the material after the flow forming process can be observed. Typically, the preform material is plastically deformed with wall reductions in excess of 90% of the starting wall thickness, causing a refinement of the grain structure. As seen from the Figure 22, the greater the wall reduction, the finer the microstructure of the finished component.

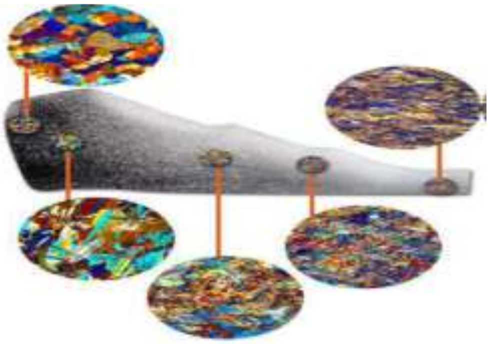


**Fig. 22.** *Schematic grain size distribution of a flow formed sample* [38]

The preform heat treatments should be chosen carefully so that the preform should have low flow stress, high tensile elongation and high tensile strength to yield strength ratio [39]. The preform should be ductile enough to achieve the required deformation during the flow forming process. Preform strength directly affects the strength of the flow formed component. Therefore, to obtain high strength components, high strength preforms are required. However, when the preform strength is too high, this may cause cracking during the process [39].

Hua et al. [40], developed a 3D elastic-plastic computational method for the three rollers backward spinning of a cylindrical workpiece. They examined the total strain distribution of the component to analyze the tube spinning process [40]. They concluded that the stress and strain distributions are very complex during tube spinning. They also claimed that the maximum hoop tensile stress occurs on the outer surface. These hoop stresses and axial stresses can cause cracking on the surface of the tubes. Their model showed that deformation is not uniform throughout the thickness [40]. Wong et al. [41] also worked on a finite element model and studied the effect of roller path and geometry on the flow forming process. They concluded that the flow forming process can be used to produce flange type components as well as cylindrical components. They also claimed that the roller with an approach angle, caused material to flow in the axial direction resulting in pile up in front of the roller. However, rollers with flat approach surface caused the material to flow in the radial direction resulting in a flange of increasing diameter which may cause edge splitting at the end.

Prakash and Singhal [42], conducted some experimental analysis on shear spinning of long tubes. They concluded that the mechanical properties of the shear spun tubes were improved compared to conventional methods. They managed to achieve 80% deformation without applying intermediate annealing in the AISI 304 steel sample [42]. Jahazi and Ebrahimi [43], studied the effects of the microstructure of D6ac steel (0.43 C-0.74 Mn-0.26 Si-1.0 Cr-0.59 Ni-0.96 Mo-0.1 V) on the flow forming process. According to them, a fine grain size of cementite was required to eliminate microcracks. It was seen that the tensile strength of the material increased with forming. Lee et al. [44,45] studied the forward flow forming of C-250 maraging steel and the effect of heat treatment on the microstructure. After the flow forming operation, the grains were elongated in the direction of the plastic deformation and it was observed that the microhardness of the material had increased. Different heat treatments were applied afterwards, and it was observed that direct aging treatment at 480 oC for 6 hours was the most effective way in increasing the hardness of the material. Gur and Arda [46] studied tube spinning of the AISI/SAE type 4140 steel. According to them, 66% deformation resulted in elongated grains and improved mechanical properties. They claimed that these grains arose from rotation of the workpiece in conjunction with the forward motion of the roller, which induces a degree of tangential flow in the material. It was seen that as the amount of deformation increases, the elongation becomes more significant. Chen and Jones. [47], worked on a flow formed oxide dispersion strengthened (ODS) alloy. When they compared the microstructures of the flow formed and extruded components, they found that the flow forming process generates a heterogeneous microstructure. In the axial and hoop directions the grains were elongated. On the flow formed tube they observed some roller marks as seen in **Error! Reference source not found.**. Factors like deformation level and initial grain size are effective in the appearance of these marks. Macroscopic shear bands are common for heavily deformed materials (see Figure 23a) [47].

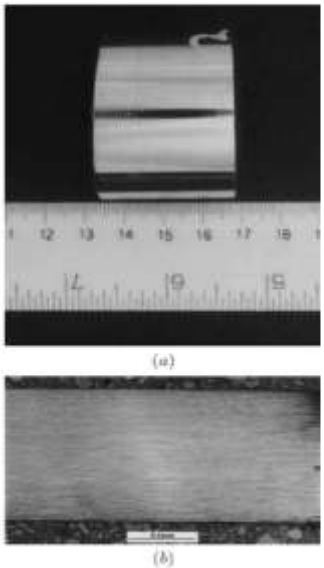


**Fig. 23.** *(a) A flow formed tube showing the roller marks, (b) Under optical microscopy, different local etching bands are observed* [47]

### 5.1 Flow Forming Parameters

Many researchers studied the effect of the flow forming process parameters on the product quality and the required force, some of these researches are discussed here.

To achieve successfully flow formed components, the roller feed and the spindle feed can be changed if the feed ratio is kept constant. If the feed ratio is increased too much, it may cause some defects such as non-uniformity in thickness, contraction in diameter and a rough surface. Furthermore, above a certain critical feed rate value, tearing and cracking may occur [43]. In the same manner, as the feed rate is too low, may cause excessive material flow in an outward direction. According to Wong et al. [41], the increase in the spindle speed affects the process in two ways. First there is an increased magnitude of spinning force due to high deformation rate. Secondly the deformation energy required per revolution is likely to decrease.

Rajan et al. [31], studied the typical defects that can occur during the flow forming process. They worked on AISI 4130 steel tube and investigated the defects like diametral growth, premature burst, buildup, fish scaling and bell mouthing. They managed to produce high strength thin wall tubes with good dimensional accuracy by controlling the machining properties like feed rate, spindle speed and roller geometry. They concluded that a homogeneous microstructure and good formability are the essential factors to obtain heavily deformed flow formed samples without any defects [31]. Davidson et al. [48], studied the effect of feed rate during flow forming aluminum alloy AA6061 tubes. It was seen that, especially at the early stages of the deformation, a feed rate less than 50 mm/min can cause the internal diameter to increase. This is due to the fact that a low feed rate causes the plastic deformation to delay. Therefore, material flows in the radial direction rather than in axial direction. When the feed rate is higher than 100 mm/min, it can result in a wavy like appearance at the surface. The reason is fast moving rollers due to the high feed rate can cause a surface quality problem. It was found that a feed rate of around 30mm/min is ideal for a fine surface finish [48]. Nagarajan et al. [49], claimed that 1.4 to 1.7 mm/rev of feed rate is optimum for a good product. If the rate is below this range, fracture may occur and if it is above this value, marks can appear at the surface of the finished product. The roller path has also an effect on the quality of the product. A wrong roller path choice may cause buckling and wrinkles as well as cracking. Also, the roller design must be done correctly considering the shape and thickness of the component. Roller design is effective in the components shape, thickness and dimensional accuracy. As long as the roller diameter is big enough to prevent higher stresses and non-uniform thickness distribution, the diameter is not the most significant parameter on the quality of the component. Correct roller path should be carried out to prevent defects like buckling, wrinkles and cracking [32]. For spinning process generally, a concave roller path is chosen. Spinning ratio is the ratio of the preform diameter to mandrel diameter. As the spinning ratio increases, the process becomes harder since it is difficult for the remaining material cross section to transmit the stress [32].

According to Davidson et al. [48], an optimum depth of cut is a necessary parameter for a good surface finish. Fish scaling marks may occur on the surface due to the small depth of cut whereas very high depth can result in delay in plastic deformation and produce highly strained roller profiles on the surface [48]. The speed of the mandrel should be high enough to achieve a defect free surface yet vibrations in the machines should be avoided. Furthermore, excessive speeds can result in increased adiabatic temperature causing plastic instabilities [48].

## 6. SUGGESTIONS

The review of the two processes of spinning and flow forming may leads us to think why there is no one process has the ability to conduct the two processes in one pass; why we cannot manufacture a thin wall cup without two subsequent processes.

The conventional spinning process can be performed with balls or not? Why no one tried to perform the conventional spinning process with a metallic ball. What if the ball has the ability to rotate about its center in the three directions; will this affect the spinning process.

Can we perform the two processes in the same stroke with a ball or a set of Consecutive balls!!!

The manufacturing of a thin wall cup in one pass is believed to reduce the part cost by reducing the manufacturing time and may also reduce the required power for the process.

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