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(54) **METHOD OF CONTROLLING A MANDREL-FREE SPINNING APPARATUS AND CONTROL SYSTEM**

VERFAHREN ZUR STEUERUNG EINER DORNLOSEN SPINNVORRICHTUNG UND
STEUERUNGSSYSTEM

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(73) Proprietors:

- **Nissan Motor Manufacturing (UK) Ltd
Bedford
Bedfordshire MK43 0DB (GB)**

• **Renault s.a.s**

92100 Boulogne Billancourt (FR)

(72) Inventors:

- **CINDERY, Richard
Sheffield, S9 1XU (GB)**
- **EVANS, Rhodri
Sheffield, S9 1XU (GB)**

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EP 3 854 498 B1

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Description

TECHNICAL FIELD

[0001] The present disclosure relates to a method of controlling a mandrel-free spinning apparatus.

BACKGROUND

[0002] Metal spinning is a metal forming process that has traditionally been used to produce hollow, axially symmetric (axisymmetric) items or articles by forming a metal blank against the surfaces of a mandrel. The mandrel is shaped according to the design of the desired item or article and rotates with the workpiece to provide forming surfaces against which the workpiece can be shaped.

[0003] Figure 1 illustrates a traditional spin forming apparatus 1 used for such purposes. A workpiece 2, typically in the form of a metal blank, is secured to a mandrel 3 on a lathe 4, with an inner surface 5 of the workpiece 2 facing the mandrel 3. The workpiece 2 is gradually deformed into the desired shape by applying pressure, from a forming tool 6, against an outer surface 8 of the rotating workpiece 2 and moving the forming tool 6 so as to trace the surfaces of the rotating mandrel 3.

[0004] The forming tool 6 may be controlled by manual inputs from an operator or by computer numeric control (CNC). When CNC is used, the operator determines a sequence of positions through which the forming tool 6 should be moved to deform the workpiece 2 into the desired shape. For example, the sequence of positions may be determined based on a mathematical equation relating the movement of the forming tool 6 along an axis parallel to the axis of rotation of the workpiece 2 to the movement of the forming tool 6 along an axis perpendicular to the axis of rotation of the workpiece 2. The sequence of positions provides a toolpath that the forming tool 6 follows to form the workpiece 2 against the mandrel 3. Thereafter, the toolpath can be reused with further workpieces 2 to reproduce copies of the desired article and provide some degree of automation.

[0005] This process may, for example, be used to produce any of the axisymmetric articles shown in Figure 2 and may be completed in a single pass of the forming tool 6 over the workpiece 2 (shear spinning) or by multiple passes over the workpiece 2 (conventional spinning).

[0006] Metal spinning is advantageous in that there is minimal springback of the finished article and the initial tooling costs are relatively low. However, a new mandrel 3 is required whenever the shape of the desired article changes. Accordingly, the costs associated with design variations are high.

[0007] More recently, metal spinning methods have been developed that are mandrel-free. WO 2012/042221 A1 describes an example mandrel-free spinning apparatus 10 for spin forming both axisymmetric and non-axisymmetric articles. The mandrel-free spin-

ning apparatus 10, illustrated in Figures 3 to 6, includes a plurality of mobile forming tools 16 that are movable to engage and support or deform a rotating workpiece 14. In this manner, the mobile forming tools can be moved as the workpiece 14 rotates to replicate the profile of a desired article and effectively replace the fully formed mandrel 3.

[0008] Figure 3 illustrates the principle features of a mandrel-free spinning apparatus 10 for gradually deforming a workpiece 14 into a desired shape. As shown, the mandrel-free spinning apparatus 10 includes: a rotatable mounting point, such as a lathe 4, to which the workpiece 14 is secured; a first forming tool 12a arranged to act on an outer surface 16 of the rotating workpiece 14; and a second forming tool 12b, shown proximal to the lathe 4, which is arranged to act on an opposing inner surface 18 of the rotating workpiece 14. Examples of the mandrel-free spinning apparatus 10 may further include one or more further forming tools, such as the third and fourth forming tools 12c, 12d, shown in Figure 3, that may be arranged to act on the inner or outer surfaces 18, 16 of the workpiece 14. For example, the third and fourth forming tools 12c, 12d may act on the workpiece 14 in areas of the workpiece 14 that are distal from the lathe 4.

[0009] Figure 4 illustrates an end view of the mandrel-free spinning apparatus 10 shown in Figure 3. In this example, the first and second forming tools 12a, 12b, are arranged to move in a first plane 20 aligned with a longitudinal axis 22 of the lathe 4, whilst the third and fourth forming tools 12c, 12d are arranged to move within and outside of the first plane 20. The third and fourth forming tools 12c, 12d may, for example, move symmetrically to one another about the first plane 20.

[0010] Figure 5 shows a practical example of the mandrel-free spinning apparatus 10, as depicted in WO 2012/042221 A1 and as illustrated conceptually in previous Figures 3 and 4. In this practical example, the positions of the first, second, third and fourth forming tools 12a-d are adjustable relative to the workpiece 14 by a respective set of actuators 24 controlled by CNC, for example.

[0011] Figure 6 shows a plan view of the mandrel-free spinning apparatus 10 shown in Figure 5. The plan view identifies the longitudinal axis 22, or axis of rotation, of the lathe 4 and a radial axis 26 which extends perpendicularly from the longitudinal axis 22 (in the same horizontal plane). The set of actuators 24 are able to adjust the positions of the first, second, third and fourth forming tools 12a-d relative to the lathe 4, and hence the workpiece 14, along the longitudinal axis 22 and the radial axis 26. In this manner, the longitudinal axis 22 acts as a first axis of movement and the radial axis 26 acts as a second axis of movement for each of the forming tools 12a-d.

[0012] In Figure 6, the first forming tool 12a is shown supported at one end of a first arm member 28 and the second forming tool 12b is shown attached to one end of a second arm member 30. The first forming tool 12a may take the form of a so-called working roller and the second

forming tool 12b may take the form of a so-called blending roller. Each of the working and blending rollers may be metallic and may feature a ceramic coating that provides enhanced durability and/or minimises friction.

[0013] The angle of the first arm member 28 may be adjustable relative to the longitudinal axis 22 and the workpiece 14. The angle may generally remain constant during a single spin forming process.

[0014] In use, the first and second forming tools 12a, 12b can be moved along the radial and longitudinal axes 26, 22 to respectively engage the inner and outer surfaces 18, 16 of the workpiece 14 and to deform the rotating workpiece 14 therebetween into the shape of the desired article. For this purpose, the second arm member 30 may be shaped to allow insertion/removal of the second forming tool 12b into/from an interior volume of the article as the workpiece 14 is deformed into a concave or tubular shape.

[0015] Hence, the mandrel-free spinning apparatus 10 possess sufficient mobility to deform a metal workpiece 14 into a variety of both axisymmetric and non-axisymmetric shapes, such as those shown in Figure 7 to 9. The absence of a fully formed mandrel also enables the production of re-entrant shapes, as illustrated by the profile in Figure 7. In addition, the spinning process can be completed in a single pass of the first forming tool 12a over the workpiece 14 (shear spinning) or in multiple passes over the workpiece 14 (conventional spinning) as practised on traditional spin forming machines. Furthermore, CNC may be used to move each of the first, second, third and fourth forming tools 12a-d according to respective toolpaths.

[0016] However, despite its potential advantages the technology is immature and the existing methods of controlling the mandrel-free spinning apparatus 10 have encountered various problems relating to spring-back, stretching and/or wrinkling of the workpiece 14 as the workpiece 14 is deformed into the shape of the article, i.e. the article shape.

[0017] US 2016/325332 A1 discloses a method and apparatus for forming an elliptical hollow cylinder, in which part of the elliptical hollow cylinder is formed into a circular hollow cylindrical shape using a two-stage spin forming process. The two-stage forming process includes: (i) a first stage, during which part of an elliptical hollow cylinder is formed into a circular hollow cylindrical shape using an inside roller; and (ii) a second stage, during which a diameter of the circular hollow cylindrical shape is then reduced using an outside roller.

[0018] The present invention has been developed to attend to at least some of the above-mentioned problems.

SUMMARY OF THE INVENTION

[0019] Aspects and embodiments of the invention provide a method of controlling a mandrel-free spinning apparatus and a controller for the mandrel-free spinning

apparatus as claimed in the appended claims.

[0020] According to an aspect of the invention there is provided a method of controlling a mandrel-free spinning apparatus to produce an article, having a target geometry, from a workpiece, the mandrel-free spinning apparatus comprising: a rotatable mounting point for the workpiece; a first forming tool; and a second forming tool; the method including: whilst the workpiece rotates, moving the first forming tool so as to: engage a first surface of the workpiece; and urge the workpiece, from an initial workpiece geometry, towards and beyond the target geometry into an intermediate geometry; and whilst the workpiece rotates, moving the second forming tool so as to: engage a second surface of the workpiece, opposed to the first surface of the workpiece; and urge the workpiece from the intermediate geometry towards the target geometry. The first forming tool is moved to urge the workpiece inward, along and towards an axis of rotation of the mounting point, from the initial workpiece geometry into the intermediate geometry, and the second forming tool is moved to urge the workpiece outward, from the intermediate geometry towards the target geometry.

[0021] It shall be appreciated that the target geometry corresponds to the shape of the article.

[0022] Advantageously, the method includes two stages of spin forming. In the first stage, the first forming tool may engage an outer surface of the workpiece and urge the workpiece inwards into the intermediate geometry, which may, for example, be curved to a lesser degree than the target geometry. In the second stage, the second forming tool may engage an inner surface of the workpiece and urge the workpiece outwards and back towards the target geometry. Advantageously, the workpiece is work hardened during the first stage and deformed beyond the target geometry, i.e. deformed such that a portion of the workpiece is further along and/or closer to an axis extending through the centre of the workpiece. Consequently, the subsequent deformation of the workpiece in the second stage may be to a lesser extent, i.e. the strain on the workpiece may be less in deforming the workpiece from the intermediate geometry to the target geometry than in deforming the workpiece from the initial geometry to the intermediate geometry. In this manner, the second stage shapes the workpiece more precisely to form the surfaces of the target geometry, which may be more curved or complex.

[0023] Advantageously, the workpiece may be deformed into a tubular, or concave, shape by the first forming tool and the second forming tool may then be moved so as to indent the workpiece surfaces, increasing the curvature and concavity of the workpiece as the target geometry may require.

[0024] Optionally, the first surface of the workpiece forms an outer surface of the article and the second surface of the workpiece forms an inner surface of the article.

[0025] Optionally, in the intermediate geometry, the workpiece includes: a central hub; and a body portion

extending from the central hub to a rim. Optionally, the surfaces of the workpiece in the intermediate geometry are curved to a lesser degree along the axis of rotation than is necessary to form the target geometry. Advantageously, the workpiece may be more geometrically stable in such an intermediate geometry such that the workpiece is less susceptible to stretching, wrinkling and/or other failure modes as the workpiece is deformed from the intermediate geometry to the target geometry.

[0026] Optionally, urging the workpiece from the initial workpiece geometry into the intermediate geometry comprises moving the first forming tool linearly so that, in the intermediate geometry, the body portion of the workpiece is frusto-conical. Advantageously, the frusto-conical body portion is particularly stable and provides sufficient geometric stability for the subsequent deformation into the target geometry.

[0027] Optionally, urging the workpiece from the initial workpiece geometry into the intermediate geometry comprises moving the first forming tool along a straighter trajectory than is required to form the target geometry. The straighter trajectory produces a more stable intermediate geometry and mitigates the risk of the workpiece failing.

[0028] Optionally, the first forming tool is moved between a start point and an end point along the axis of rotation of the mounting point by a distance corresponding to a length or depth of the target geometry. Advantageously, the full depth of the target geometry is produced in this motion, which minimises the number of passes in the spin forming process.

[0029] Optionally, moving the second forming tool so as to urge the workpiece outward from the intermediate geometry towards the target geometry comprises moving the second forming tool along a curve to deform the body portion of the workpiece outward. Advantageously, in this manner, the second forming tool can deform the workpiece into a curved shape with a varying profile along its length, whilst the first forming tool produces a more linear shape.

[0030] Optionally, moving the second forming tool along the curve deforms the body portion of the workpiece into a domed shape. Optionally, the target geometry is discoidal. In this manner, the method may provide a fast process for spin forming a discoidal article with enhanced surface finish compared to conventional multi-pass spinning methods.

[0031] In an example, the method may comprise supporting the workpiece distally from an axis of rotation of the mounting point relative to the second forming tool whilst moving the second forming tool so as to urge the workpiece from the intermediate geometry towards the target geometry. Supporting the workpiece in this manner may inhibit tilting of the workpiece about the mounting point. In particular, whilst the workpiece is urged towards the target geometry, the second forming tool may apply pressure to radially distal surfaces of the workpiece creating a turning moment acting to tilt the workpiece

and supporting the workpiece in areas that are radially beyond the second forming tool may substantially inhibit such tilting effects. This may improve the quality of the finished article and allow for faster forming speeds.

[0032] In an example, the method may comprise supporting the workpiece at the rim of the workpiece whilst moving the second forming tool so as to urge the workpiece from the intermediate geometry towards the target geometry. Advantageously, the rim of the workpiece provides a radially outer portion of the workpiece that can be supported with minimal force.

[0033] Optionally, in the intermediate geometry, the workpiece includes a flange portion that extends around a circumference of the body portion of the intermediate geometry. The flange portion of the intermediate geometry may be formed from an unworked region of the workpiece. The flange portion may effectively extend from the rim of the intermediate geometry. The flange portion may also help to increase the circumferential stiffness of the workpiece, mitigating the likelihood of wrinkling, as the workpiece is urged towards the target geometry.

[0034] The workpiece may, for example, be oversized for the article. For example, the initial geometry of the workpiece may be circular having a radius corresponding to the net shape of the article plus an additional length corresponding to the flange portion. In this manner, the flange portion is integral with the other portions of the workpiece.

[0035] Optionally, the method comprises supporting the flange portion of the workpiece whilst moving the second forming tool so as to urge the workpiece from the intermediate geometry towards the target geometry. Supporting the workpiece in this manner may mitigate tilting effects that may otherwise occur as the workpiece is urged towards the target geometry.

[0036] The first forming tool may, for example, engage the flange portion of the workpiece to support the flange portion of the workpiece. Advantageously, the first forming tool is reused as a support for the workpiece after deforming the workpiece into the intermediate geometry.

[0037] Optionally, the flange portion of the intermediate geometry includes a flange wall that is sufficiently wide for the first forming tool to engage and thereby support the workpiece. The flange wall may be annular and the width of the flange wall may extend from an inner radius to an outer radius.

[0038] Optionally, the second forming tool is moved so as to urge the workpiece from the intermediate geometry towards the target geometry and into a formed geometry.

[0039] In the formed geometry, the workpiece may, for example, include a central hub; a body portion extending from the central hub to a rim; and a flange portion that extends around the circumference of the rim. In the formed geometry, the central hub and the body portion of the workpiece may correspond to the target geometry.

[0040] Optionally, the method comprises removing the flange portion from the workpiece after urging the workpiece into the formed geometry. This may, for example,

be considered as a finishing process used to remove the excess material of the workpiece and produce the desired article.

[0041] Optionally, the movement of the first forming tool to engage the first surface of the workpiece and urge the workpiece, from the initial workpiece geometry, towards and beyond the target geometry into the intermediate geometry is controlled according to a first toolpath; and/or the movement of the second forming tool to engage the second surface of the workpiece and urge the workpiece from the intermediate geometry towards the target geometry is controlled according to a second toolpath. Advantageously, the first and second toolpaths may allow the process to be at least partially automated.

[0042] The first toolpath may, for example, be arranged to move the first forming tool along a first axis of the mandrel-free spinning apparatus and a second axis of the mandrel-free spinning apparatus. The first axis may be parallel to the axis of rotation of the mounting point and the second axis may be perpendicular to the first axis. The second toolpath may, for example, be configured to move the second forming tool along the first and second axes.

[0043] Optionally, the first toolpath is configured to move the first forming tool along a first line or trajectory arranged along the first and second axes, between a start point and an end point of the first toolpath. Optionally, the second toolpath is configured to move the second forming tool along a second line or trajectory arranged along the first and second axes, between a start point and an end point of the second toolpath.

[0044] The second line may, for example, be curved between the start and end points of the second toolpath and a maximum radius of curvature of the first line may be less than a maximum radius of curvature of the second line. This may, for example, ensure that the workpiece is more stable in the intermediate geometry than the target geometry, meaning that the workpiece is less likely to stretch, wrinkle or otherwise fail as the workpiece is deformed from the intermediate geometry towards the intermediate geometry. The first line may, for example, be straight between the start point and the end point of the first toolpath.

[0045] Optionally, the first toolpath includes: a plurality of passes, each pass of the first toolpath achieving an iterative deformation of the workpiece towards the intermediate geometry. The plurality of passes may, for example, reduce the tendency of the workpiece to fail or stretch during the forming process.

[0046] The second toolpath may, for example, include a plurality of passes, each pass of the second toolpath achieving an iterative deformation of the workpiece from the intermediate geometry towards the target geometry. The plurality of passes may allow for gradual deformation towards the target geometry with lower forces on the forming tool.

[0047] Optionally, the method further includes attaching a forming plate to the second surface of the workpiece

before moving the first forming tool so as to urge the workpiece, from the initial workpiece geometry, towards and beyond the target geometry into the intermediate geometry. The forming plate may, for example, assist the transition between the initial workpiece geometry and the intermediate geometry. The forming plate may provide resistance to deformation of the workpiece in a central region of the workpiece. For example, the forming plate may support the workpiece in a region corresponding to the central hub of the target geometry and may help to guide the deformation of the workpiece around the central hub of the target geometry as the workpiece is urged away from the initial geometry. Accordingly, the forming plate may have a shape corresponding to the central hub of the target geometry.

[0048] The method may, for example, include removing the forming plate from the second surface of the workpiece before moving the second forming tool so as to engage the second surface of the workpiece and urge the workpiece from the intermediate geometry towards the target geometry.

[0049] Optionally, the target geometry is axisymmetric. Optionally, the target geometry is shallow having a diameter that is larger than a depth of the target geometry.

[0050] According to another aspect of the invention there is provided a control system for a mandrel-free spinning apparatus comprising: a rotatable mounting point for a workpiece; a first forming tool; and a second forming tool; to produce an article, having a target geometry, the control system being configured to output one or more signals to: control the rotation of the workpiece; move the first forming tool, whilst the workpiece rotates, so as to: engage a first surface of the workpiece; and urge the workpiece, from an initial workpiece geometry, towards and beyond the target geometry into an intermediate geometry; and move the second forming tool, whilst the workpiece rotates, so as to: engage a second surface of the workpiece, opposed to the first surface of the workpiece; and urge the workpiece from the intermediate geometry towards the target geometry. The first forming tool is moved to urge the workpiece inward, along and towards an axis of rotation of the mounting point, from the initial workpiece geometry into the intermediate geometry, and the second forming tool is moved to urge the workpiece outward, from the intermediate geometry towards the target geometry.

BRIEF DESCRIPTION OF THE DRAWINGS

[0051] One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figures 1 illustrates the operation of a traditional spin forming apparatus to form an article;

Figures 2 illustrates a range of articles, shown from a side view, that may be formed by the traditional spin

forming apparatus, shown in Figure 1;

Figure 3 illustrates the operation of a mandrel-free spinning apparatus to form an article;

Figure 4 illustrates an end view of the mandrel free spinning apparatus, shown in Figure 3;

Figure 5 illustrates a practical arrangement of the mandrel free spinning apparatus, shown in Figure 3;

Figure 6 shows a plan view of the mandrel-free spinning apparatus, shown in Figure 5;

Figures 7 to 9 illustrate a range of non-axisymmetric articles that may be formed by the mandrel free spinning apparatus, shown in Figure 5;

Figures 10 and 11 illustrate an example of an article that may be formed in accordance with the method of the invention;

Figure 12 illustrates a method of forming an article in accordance with an embodiment of the invention;

Figures 13 to 16 illustrate steps of the method shown in Figure 12;

Figure 17 illustrates another method of forming an article in accordance with an embodiment of the invention;

Figures 18 to 21 illustrate steps of the method shown in Figure 17;

Figure 22 illustrates a further method of forming an article in accordance with an embodiment of the invention;

Figures 23 to 26 illustrate steps of the method shown in Figure 22;

Figure 27 illustrates a system of devices that may be used to operate a spin forming machine in accordance with a method of the invention;

Figure 28 illustrates another method of forming an article in accordance with an embodiment of the invention; and

Figures 29 to 32 illustrate steps of another method of forming an article in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

[0052] Embodiments of the present invention relate to a method of controlling a mandrel-free spinning appara-

tus to produce an article from a workpiece 14.

[0053] The mandrel free-spinning apparatus may, for example, take the form of the example mandrel-free spinning apparatus 10 shown in Figures 5 and 6. However, the example mandrel-free spinning apparatus 10 is not intended to be limiting and, in other examples, the mandrel-free spinning apparatus may take any other form that includes at least: a first forming tool, such as the first forming tool 12a, arranged to engage a first surface of the workpiece 14; and a second forming tool, such as the second forming tool 12b, arranged to engage an opposing second surface of the workpiece 14. Such a mandrel-free spinning apparatus may, for example, include three independently controllable and movable forming tools for supporting the workpiece and a single forming tool for deforming the workpiece 14.

[0054] The workpiece 14 may, for example, take the form of a blank sheet of ductile metal, such as aluminium, stainless steel or alloys thereof. Alternatively, the workpiece 14 may comprise any other similarly ductile material that is suitable for a spin forming process.

[0055] Articles formed in accordance with embodiments of the invention, from the workpiece 14, may have a dish-like shape. In particular, such articles may feature a substantially flat central hub and a domed, or otherwise curved, portion that extends around the central hub to define a dished or cupped shape, terminating in an axially distal rim.

[0056] By way of example, Figures 10 and 11 show an axisymmetric discoidal article 40 that may be formed, in accordance with an embodiment of the invention, from the workpiece 14.

[0057] Being discoidal, the article 40 is substantially axisymmetric, having a substantially planar central region, that forms a central hub 42, and a domed body portion 46 that extends from the central hub 42, along a longitudinal axis 48 of the article 40, to define a dome segment, which terminates in a circular rim 56.

[0058] The discoidal article 40 is therefore hollow - having inner surfaces 58 of the article 40 effectively separated from outer surfaces 60 of the article 40 by the rim 56; and shallow - having a maximum diameter that is larger than the depth of the article 40 between the central hub 42 and the rim 56.

[0059] The central hub 42 is formed from a plate-like hub wall 62 that has a circular shape, in this example, extending radially from the longitudinal axis 48 of the article 40 to outline a circular crease line 64 on the inner and outer surfaces 58, 60 of the article 40. The hub wall 62 may include one or more mounting features (not shown) used to attach the workpiece 14 to the lathe 4 during the spin forming process. Such mounting features may, for example, include one or more apertures suitable for bolting the workpiece 14 to the lathe 4 so as to inhibit relative movement.

[0060] The body portion 46 of the article 40 is formed from a side wall 66 that extends radially from the hub wall 62, around the circumference of the circular crease line

64, and curves along the longitudinal axis 48 to define the domed segment of the body portion 46. It shall be appreciated that a radial cross-section of the example article 40 therefore has a concave and curved profile.

[0061] The wall thickness of the article 40, i.e. the thickness of the workpiece 14 between the inner and outer surfaces 58, 60 of the article 40, is substantially constant across the central hub 42 and the body portion 46.

[0062] For the sake of clarity, the article 40 is one such example of an article 40 that may be formed by the method of this invention and is not intended to be limiting.

[0063] Any article produced by this method will inevitably feature a planar central hub 42, where the workpiece 14 is mounted to the lathe 4, and a body portion 46 that extends both radially and axially from the central hub 42. However, in other examples, the central hub may not be circular and may instead be rectangular, ovalled or otherwise non-axisymmetric. Furthermore, in other examples, the body portion may not be domed, as such, but may be otherwise curved to define a generally concave dish-shaped.

[0064] In forming articles, such as the article 40, from the workpiece 14, methods in accordance with the invention may make use of, or otherwise be defined in dependence on, a target geometry that corresponds to the shape of the desired article.

[0065] Hence, in the following examples, the term target geometry 40 is used synonymously with the shape of the article 40.

[0066] In embodiments of the present invention, the methods of controlling the mandrel-free spinning apparatus are configured to produce the dish-shaped article in at least two stages.

[0067] In the first stage, the first forming tool of the mandrel-free spinning apparatus is moved, whilst the workpiece 14 rotates about a longitudinal axis of rotation, so as to engage a first surface of the workpiece 14 and to urge the workpiece 14 inwards, along and towards the axis of rotation, from an initial workpiece geometry into an intermediate geometry, such as a frustum shape. The intermediate geometry is characterised by the fact that the surfaces of the workpiece 14 in the intermediate geometry are curved to a lesser degree (along the axis of rotation) than is necessary to form the dish-shaped article.

[0068] In the second stage, a second forming tool 12b is moved so as to engage a second surface of the workpiece 14, opposed to the first surface of the workpiece 14, and to urge the workpiece 14 outwards, from the intermediate geometry, to thereby increase the curvature and concavity of the workpiece 14 in order to form the dish-shaped article.

[0069] Advantageously, the method is arranged to work harden the workpiece 14 in forming the intermediate geometry and the intermediate geometry provides stability, reducing the susceptibility of the workpiece 14 to wrinkling and other failure modes during the subsequent

formation of the curved surfaces of the dish-shaped article. The two stage process can also offer a relatively short process time when compared to conventional multi-pass metal spinning methods.

[0070] Figure 12 illustrates such a method 100 of controlling the mandrel-free spinning apparatus 10, in accordance with an embodiment of the invention, to produce the example article 40 from a workpiece 14. Figures 13 to 16 are further provided to illustrate the various steps of the method 100.

[0071] In step 102, the workpiece 14 is mounted on the lathe 4 and rotated about the first axis 22, as shown in Figure 13.

[0072] In step 104, whilst the workpiece 14 rotates, the first forming tool 12a is moved so as to engage the outer surface 16 of the workpiece 14 and to urge the workpiece 14 towards and beyond the discoidal target geometry 40 into an intermediate geometry 120. The target geometry 40 is illustrated by dashed lines 122 In Figure 14 and the intermediate geometry 120 is indicated by solid lines 124.

[0073] The intermediate geometry 120 may be shaped like a frustum with relatively straight surfaces, i.e. surfaces that are curved to a lesser degree than the target geometry 40.

[0074] For this purpose, the first forming tool 12a is moved along a first trajectory 130, in step 104, which is relatively straight compared to the curved trajectory required to form the discoidal article 40.

[0075] For example, as shown in Figure 14, the first trajectory 130 may move the first forming tool 12a along a straight, or substantially straight, line between a start point and an end point to deform the workpiece 14 into a tapered shallow dish.

[0076] The start point may be radially proximal to the first axis 22, for example in a position on the first axis 22 corresponding to the outer surface 16 of the workpiece 14; and a position on the second axis 26 corresponding to the radius of the central hub 42 at the outer surface 60 of the target geometry 40. The end point may be radially distal and arranged further along the first axis 22, for example in a position on the first axis 22 that is spaced from the start point by a distance corresponding to the depth of the article 40 between the central hub 42 and the rim 56; and a position on the second axis 22 corresponding to the radius of the rim 56 at the outer surface 60 of the target geometry 40.

[0077] As the first forming tool 12a moves between the start and end points, the workpiece 14 is urged inward, i.e. bent along and towards the first axis 22, from an initial planar geometry to define a central hub 132 and a body portion 134 that extends, along the first axis 22, from the central hub 132 to a rim 136.

[0078] The intermediate geometry 120 and, in particular, the body portion 134 of the intermediate geometry 120 may take various forms in accordance with the invention, but in general the first forming tool 12a is moved as described above, so that, in the intermediate geometry 120, the workpiece 14 features the following common

features.

[0079] Firstly, the central hub 132 of the intermediate geometry 120 corresponds to the central hub 42 of the target geometry 40. Secondly, the rim 136 of the intermediate geometry 120 corresponds to the rim 56 of the target geometry 40. Thirdly, the distance (along the first axis 22) between the central hub 132 and the rim 136 of the intermediate geometry 120 corresponds to the depth of the article 40 between the central hub 42 and the rim 56. Lastly, and most importantly, the body portion 134 of the intermediate geometry 120 is characterised in that the surfaces of the body portion 134 of the intermediate geometry 120 are straighter, i.e. curved to a lesser degree along the first axis 22, than in the body portion 46 of the target geometry 40.

[0080] In the example shown in Figure 14, the features described above are evident in the geometry of the tapered shallow dish 120, which features a frusto-conical body portion 134, extending between the central hub 132 and the rim 136, with substantially linear surfaces that have a constant, or near constant, gradient relative to the first axis 22. It shall be appreciated that the surfaces of the frusto-conical body portion 134 of the intermediate geometry 120 contrast with the curved surfaces of the domed body portion 46 of the target geometry 40.

[0081] Other intermediate geometries may be formed in accordance with the method of the invention provided that they are curved to a lesser degree than the target geometry. In particular, in each intermediate geometry 120, the surfaces of the workpiece 14, between the central hub 132 and the rim 136, shall be curved to a lesser degree along the first axis 22 than the surfaces of the workpiece 14 in the discoidal target geometry 40.

[0082] The body portion 134 of the intermediate geometry 120 may also be narrower than the body portion 46 of the target geometry 40 as a result of the deformation beyond the target geometry 40. In particular, a given point 138 on the workpiece 14, between the central hub 132 and the rim 136, may be urged further along the first axis 22 and closer towards the first axis 22 in the intermediate geometry 120 than in the target geometry 40, as shown in Figure 14.

[0083] In step 106, the second forming tool 12b is moved so as to engage the inner surface 18 of the workpiece 18, as shown in Figure 15, and to urge the workpiece 14 from the intermediate geometry 120 towards the target geometry 40, as shown in Figure 16.

[0084] In particular, the second forming tool 12b is moved along a second trajectory 142 and pressed against the inner surface 18 of the workpiece 14 to urge the workpiece 18 outward. For example, the second trajectory 142 may be arranged to move the second forming tool 12b along a curved line between a start point and an end point to bend or otherwise press the surfaces of the workpiece 14 (illustrated by dashed lines 144 in Figure 16) into the discoidal shape of the article 40.

[0085] The start point may be radially proximal to the first axis 22, for example in a position on the first axis 22

corresponding to the inner surface 18 of the workpiece 14; and a position on the second axis 26 corresponding to the radius of the central hub 42 at the inner surface 58 of the target geometry 40. The end point may be radially distal and arranged further along the first axis 22, for example in a position on the first axis 22 that is spaced from the start point by a distance corresponding to the depth of the article 40 between the central hub 42 and the rim 56; and a position on the second axis 22 corresponding to the radius of the rim 56 at the inner surface 58 of the target geometry 40.

[0086] As the second forming tool 12b moves between the start and end points, the surfaces of the workpiece 14, between the central hub 132 and the rim 136, are urged outward and into a curved and concave shape. In particular, a given point 139 on the workpiece 14, between the central hub 132 and the rim 136 is urged backwards along the first axis 22 and further away from the first axis 22 than in the intermediate geometry 120, which has the effect of increasing the concavity and the curvature of the workpiece 14 between the central hub 132 and the rim 136.

[0087] Deforming the workpiece 14 into such a curved shape would ordinarily lead to wrinkling and/or failure of the workpiece 14, particularly in radially distal regions. However, the method is advantageously arranged so that the workpiece 14 is work hardened and geometrically stabilised as the relatively shallow slopes of the intermediate geometry 120 are formed, during step 104. This mitigates the tendency of the workpiece 14 to wrinkle and/or fail prior to forming the curved surfaces, in step 106.

[0088] At the end of step 106, the workpiece 14 may substantially match the target geometry 40 and the article 40 may be removed from the lathe 4.

[0089] It is noted that the steps of the method 100 are merely provided as an example of the invention and the steps are not intended to limit the method of controlling the mandrel-free spinning apparatus 10. Accordingly, steps may be altered, added and removed as will be appreciated by the person skilled in the art.

[0090] In particular, in another example method 200 of controlling the mandrel-free spinning apparatus 10, the article 40 may be formed from an oversized workpiece 14 and an unworked edge region of the workpiece 14 may form a flange portion that extends around the circumference of the workpiece 14 after the workpiece 14 has been urged into the intermediate geometry 120.

[0091] In this example, the method 200 is arranged to restrain or support the flange portion, for example by engagement with the first forming tool 12a, whilst the second forming tool 12b is moved so as to urge the workpiece 14 towards the target geometry 40. As shall become clear in the description that follows, supporting the workpiece 14 in this manner mitigates titling effects that may otherwise occur as the workpiece 14 is urged towards the target geometry 40. The flange portion also helps to increase the circumferential stiffness of the workpiece 14, mitigating the likelihood of wrinkling, as the

workpiece 14 is urged towards the target geometry 40.

[0092] Before describing this method 200 in detail, it should be appreciated that workpieces for spin forming articles are traditionally net shape, or near net shape, for a desired article so that there is no, or negligible, material wastage when the article is formed. Hence, by an oversized workpiece it is intended to mean a workpiece that is larger than conventional, including additional material for forming the flange portion around the rim 56 of the article 40. The flange portion should be large enough to be engaged, and supported, by the first forming tool 12a so as to substantially inhibit relative movement between the first forming tool 12a and the flange portion whilst the workpiece 14 is urged towards the target geometry 40.

[0093] Figures 17 to 21 illustrate such an example method 200 of controlling the mandrel-free spinning apparatus 10 in accordance with an embodiment of the invention.

[0094] In step 202, the workpiece 14 is mounted on the lathe 4 and rotated about the first axis 22 substantially as described in step 102 of method 100, as shown in Figure 18.

[0095] In step 204, the first forming tool 12a is moved along the first trajectory 130 so as to engage the outer surface 16 of the workpiece 14 and to urge the workpiece 14 into the intermediate geometry 120 substantially as described in step 104 of method 100.

[0096] It shall be appreciated that, as the first forming tool 12a moves between the start and end points, a region of the workpiece 14 that is radially beyond the first forming tool 12a remains unworked and extends radially around the circumference of the workpiece 14.

[0097] Hence, in this example, when the first forming tool 12a reaches the end point of the first trajectory 130, the oversized workpiece 14 includes an edge portion that remains unworked, as shown in Figure 19. The unworked portion of the workpiece 14 forms a flange portion 150 that extends radially around the circumference of the workpiece 14 at the end of the body portion 134. It shall be appreciated that the flange portion 150 effectively extends around the rim of the intermediate geometry 120 formed at the end of step 104 in method 100.

[0098] The flange portion 150 may take the form of a flange wall 152 that has a width extending from an inner radius, at the end of the body portion 134, to an outer radius and the width may be large enough for the first forming tool 12a to engage the flange wall 152 and support the workpiece 14.

[0099] Hence, in step 206, the first forming tool 12a is held in abutting engagement with the flange portion 150 whilst the second forming tool 12b is moved so as to urge the workpiece 14 from the intermediate geometry 120 towards the target geometry 40, as described in step 106 of method 100.

[0100] As the workpiece 14 is deformed towards the target geometry 40, the flange portion 150 serves to maintain the circumferential stiffness of the workpiece 14 and provides a retaining surface that bears against the

first forming tool 12a, as shown in Figure 21.

[0101] This has two advantageous effects, as shall become clear in the description that follows. Firstly, by increasing the circumferential stiffness of the workpiece 14, the flange portion 150 mitigates problems such as wrinkling as the curved surfaces of the target geometry 40 are formed. Secondly, using the flange portion 150 as a retaining surface substantially inhibits tilting of the workpiece 14, relative to the lathe 4, under the influence of the second forming tool 12b, which can otherwise cause the workpiece 14 to become warped and/or to fail.

[0102] Considered in more detail, as the second forming tool 12b moves from the start point to the end point of the second trajectory 142, the second forming tool 12b applies pressure to the inner surface 18 of the workpiece 14 to bend, or otherwise deform, the workpiece 14 between a pair of restraining points. The first restraining point is provided at or around the first axis 22 by the attachment of the workpiece 14 to the lathe 4 and the second restraining point is provided at a radially distal point by the engagement between the first forming tool 12a and the flange portion 150.

[0103] The second forming tool 12b applies an outward force between these radially spaced restraining points to effectively press or bend the tapered surfaces of the frusto-conical body portion 134 into the domed, or otherwise curved surfaces that define the domed body portion 46 of the target geometry 40.

[0104] The force applied by the second forming tool 12b on the workpiece 14 is offset from the lathe 4 and produces a turning moment that acts to tilt the workpiece 14 relative to the lathe 4 in the absence of the first forming tool 12a. However, in this example, the first forming tool 12a applies an opposing force of resistance at the radially distal flange portion 150 whilst the second forming tool 12b applies pressure on the inner surface 18 of the workpiece 14. Advantageously, the resistance of the first forming tool 12a thereby negates the turning moment that the second forming tool 12b applies about the lathe 4, preventing the workpiece 14 from tilting relative to the lathe 4 in the plane of the first and second axes 22, 26.

[0105] With this arrangement, the workpiece 14 is therefore less susceptible to wrinkling or other failure modes as the curve is formed. Furthermore, the method 200 minimises the thinning of the workpiece 14, particularly in the areas of greatest curvature, where the workpiece 14 may otherwise fail if deformed according to conventional forming methods.

[0106] When the second forming tool 12b reaches the end point of the second trajectory 142, the workpiece 14 takes a formed geometry 160, which substantially matches the target geometry 40 except that the flange portion 150 remains, as shown in Figure 21. Hence, in the formed geometry 160, the workpiece 14 may be dish-shaped and correspond to the shape of the article 40, further including the flange portion 150 around the rim 56 of the article 40.

[0107] Thereafter, in step 208, one or more finishing

processes may be performed on the workpiece 14 to produce the article 40. The finishing processes may include removing the flange portion 150 from the formed geometry 160, for example. For example, the flange portion 150 may be trimmed from the end of the domed body portion 6 and the end of the domed body portion 46 may be smoothed to produce the rim 56 of the article 40.

[0108] The formed article 40 can be removed from the mandrel-free spinning apparatus 10 upon completion of the spin forming process and the article 40 substantially retains its moulded shape, with minimal springback.

[0109] In order to form articles according to the above described method 200, It shall be appreciated that it may also be necessary to design a blank 'oversized' workpiece for the article 40 that accounts for the additional flange portion 150.

[0110] In this regard, a blank workpiece 14 may be formed in dependence on the net, or near net, shape of the article 40 and the width of the flange portion 150. For example, the net, or near net, shape of the article 40 may correspond to a circular blank workpiece having a first radius, R1, so that the workpiece 14 may have a second radius, R2. The second radius R2 may be equal to the first radius R1 plus the width of the flange portion 150. The width of the flange portion 150 may, for example, correspond to the size of the first forming tool 12a. For example, the width may be greater than a nose radius of the first forming tool 12a.

[0111] Methods of generating a design of a blank workpiece based on an article shape are described in method 140 of UK patent application no. GB1714189, for example. The skilled person shall appreciate that similar methods may be applied, *mutatis mutandis*, to generate the blank workpiece design for the article 40 with the flange portion 150. However, such methods are not described in detail here so as to avoid obscuring the invention.

[0112] In another example method of controlling the mandrel-free spinning apparatus in accordance with the invention, the method may proceed substantially as described in each of the methods 100, 200 described above, with the following exception.

[0113] Before moving the first forming tool 12a so as to urge the workpiece 14 towards the intermediate geometry 120, for example in step 104 of method 100, the second forming tool 12b may be moved into engagement with the inner surface 18 of the workpiece 14 whilst the first forming tool 12a is moved to urge the workpiece 14 into the intermediate geometry 120. For example, in step 104 of method 100, the second forming tool 12b may be moved into engagement with the inner surface 18 of the workpiece 14 at a radial position corresponding to the central hub of the article 40.

[0114] Thereafter, the first forming tool 12a may be moved, as described previously, to urge the workpiece 14 into the intermediate geometry 120 and the second forming tool 12b may provide a surface against which the workpiece 14 is bent around.

[0115] In particular, as the workpiece 14 rotates, the

second forming tool 12b may resist deformation at the inner surface 18 of the workpiece 14 so as to define the circular crease line 64 of the central hub 132, whilst the first forming tool 12a deforms the workpiece 14 into the intermediate geometry 120.

[0116] In another example method 300 of controlling the mandrel-free spinning apparatus in accordance with the invention, shown in Figure 22, the method 300 may proceed substantially as described in each of the methods 100, 200 described above, with the following exceptions.

[0117] The method 300 further includes mounting a forming plate, or clamp plate, to the lathe 4, in step 303, after mounting the workpiece 14 to the lathe 4, for example in step 202 of method 200.

[0118] An example of the forming plate 170 is shown in Figures 23 to 26, which illustrate the method 300 shown in Figure 22.

[0119] The forming plate 170 is configured to assist the transition between the initial planar geometry of the workpiece 14 and the curved shape of the article 40, providing resistance to deformation of the workpiece 14 in a central region, proximal to the first axis 22. For example, the forming plate 170 may support the workpiece 14 in a region corresponding to the central hub 42 of the article 40.

[0120] Accordingly, the forming plate 170 may take the form of a relatively thin plate having a shape corresponding to the central hub 42 of the article 40. The forming plate 170 may have curved edges, as shown, that reduce the stress concentrations on the workpiece 14 as the first forming tool 12a urges the workpiece 14 towards the intermediate geometry 120. The curved edges of the forming plate 170 help to define a crease line around the central hub 132 of the intermediate geometry 120 as the workpiece 14 is urged away from the initial planar geometry to form the intermediate geometry 120.

[0121] The method 300 may further include removing the forming plate 170 from the lathe 4, in step 305, once the first forming tool 12a reaches the end point of the first trajectory 130, for example in step 204 of method 200.

[0122] In each of the example control methods 100, 200, 300 described above, the first forming tool 12a may be moved along the first trajectory 130 in accordance with a first toolpath and the second forming tool 12b may be moved along the second trajectory 142 in accordance with a second toolpath.

[0123] In which case, a system of devices 171, shown in Figure 27, may be used to implement each method 100, 200, 300. The system of devices 171 includes the mandrel-free spinning apparatus 10, a control system 174 comprising one or more controllers for operating the mandrel-free spinning apparatus 10, and a sensor system 176 comprising one or more sensors configured to monitor the operation of the mandrel-free spinning apparatus 10.

[0124] In such examples, the mandrel-free spinning apparatus 10 is configured to receive control signals from

the control system 174 to execute the steps of each method 100, 200, 300, as will now be described in over-view.

[0125] Firstly, the mandrel-free spinning apparatus 10 may receive control signals to rotate the workpiece 14 on the lathe 4 about the first axis 22, for example in step 202 of method 200.

[0126] Such control signals may control a rate of rotation of the workpiece 14 and may, for example, ensure that the workpiece 14 is rotated through a prescribed angle of rotation within a given interval of time.

[0127] In an example, the rotation of the workpiece 14 may be discretised into a plurality of time points and each time point may correspond to a particular orientation of the workpiece 14, relative to a reference position. The control system 174 may use this arrangement to control the first and/or second forming tools 12a, 12b in accordance with the respective toolpaths.

[0128] Secondly, the mandrel-free spinning apparatus 10 may receive control signals to move the first forming tool 12a along the first trajectory 130, in step 204 of method 200 for example, in accordance with the first toolpath. The first toolpath may take the form of computer readable instructions in the control system 174 that are configured, when executed, to command the set of actuators 24 to move the first forming tool 12a along the first trajectory 130 described above to urge the workpiece 14 from the initial geometry into the intermediate geometry 120.

[0129] For example, the first toolpath may move the first forming tool 12a into engagement with the outer surface 16 of the workpiece 14 and along the first trajectory 130 between the start and end points, where each of the start and end points may be defined by respective co-ordinates on the first and second axes 22, 26.

[0130] Such movement of the first forming tool 12a may, for example, be suitable for forming the tapered surfaces of the intermediate geometry 120 as the workpiece 14 rotates.

[0131] The first toolpath may, for example, include a first set of command positions through which the first forming tool 12a is moved between the start and end points and each command position may be defined by respective co-ordinates on the first and second axes 22, 26. In this manner, each command position may also correspond to a respective time point so that the first forming tool 12a is moved to each command position of the first toolpath at a respective time point corresponding to an associated orientation of the workpiece 14.

[0132] Thirdly, the mandrel-free spinning apparatus 10 may receive control signals to move the second forming tool 12b along the second trajectory 142, in step 206 of method 200 for example, in accordance with the second toolpath.

[0133] The format of the second toolpath may substantially match the format of the first toolpath. For example, the second toolpath may similarly comprise computer readable instructions in the control system 174 that are

configured, when executed, to command the set of actuators 24 to move the second forming tool 12b along the second trajectory 142 to urge the workpiece 14 from the intermediate geometry 120 towards the target geometry 40.

[0134] For example, the second toolpath may move the second forming tool 12b into engagement with the inner surface 18 of the workpiece 14 and along the second trajectory 142 between the start and end points - where each of the start and end points are defined by respective co-ordinates on the first and second axes 22, 26.

[0135] Such movement of the second forming tool 12b may, for example, be suitable for pressing the tapered workpiece 14 into the discoidal shape of the article 40.

[0136] The second toolpath may, for example, include a second set of command positions through which the second forming tool 12b is moved between the start and end points and each command position may be defined by respective co-ordinates on the first and second axes 22, 26.

[0137] As with the first toolpath, each command position of the second toolpath may also correspond to a respective time point so that the second forming tool 12b moves to each command position of the second toolpath at a respective time point, which corresponds to an associated orientation of the workpiece 14.

[0138] Optionally, the mandrel-free spinning apparatus 10 may also receive control signals configured to move one or more of the third and fourth forming tools 12c, 12d in accordance with further respective toolpaths that may substantially match the first or second toolpath.

[0139] The control system 174 may include one or more processing devices configured to determine the computer readable instructions, described above, for generating the control signals of the first and second toolpaths. It shall be appreciated that the computer readable instructions may, for example, take the form of computer generated code that the control system 174 can process to determine the corresponding control signals.

[0140] The control system 174 may be further configured to receive inputs from a memory storage device (not shown) and/or from a user, for example through a human-machine interface device (not shown), in order to determine suitable instructions.

[0141] The sensor systems 72 may include one or more: accelerometers; actuation sensors; and/or force sensors; arranged to monitor the operation of the mandrel-free spinning apparatus 10. The sensor system 176 may, for example, be configured to determine the loading on one or more of the first, second, third and fourth forming tools 12a-d and to relay such measurements back to the control system 174. The control system 174 may adapt the operation of the mandrel-free spinning apparatus 10 based on feedback from the sensor system 176. For example, where the loading on one of the forming tools 12a-d exceeds a predetermined threshold,

the control system 174 may stop the movement of said forming tool 12a-d and return the forming tool 12a-d to the start point of the respective toolpath. The control system 174 may, for example, subsequently repeat the respective toolpath.

[0142] To control the first and second forming tools 12a, 12b according to the first and second toolpaths, each method 100, 200, 300 described above may further include or be modified to include steps of: i) receiving or determining the first toolpath; ii) receiving or determining the second toolpath; iii) controlling the first forming tool 12a in accordance with the first toolpath; and iv) controlling the second forming tool 12b in accordance with the second toolpath; as illustrated in the example method 400 shown in Figure 28.

[0143] In step 401a, the first toolpath may be received, or otherwise determined, at the control system 174. For example, the control system 174 may receive the first toolpath or otherwise receive information relating to the article 40 for use in determining the first toolpath.

[0144] Suitable information for determining the first toolpath and, in particular the start point, the end point and the first set of command positions, may be received from the memory storage device and/or from user inputs through the human machine interface.

[0145] Such information may include one or more of: i) the co-ordinates of the start point, the end points, and/or each command position; ii) the dimensions of the article 40, including the maximum radius of the central hub 42 of the article 40, the maximum radius at the rim 56 of the article 40, and/or the length of the article 40 between the central hub 42 and the rim 56; and/or ii) a computerised representation of the article 40.

[0146] In a relatively common example, the control system 174 may receive the co-ordinates of the start and end points from user inputs, through the human machine interface, and the control system 174 may be configured to determine the first set of command positions that define the first trajectory 130 by interpolating points along a straight line extending between the start and end points. The command positions may therefore be arranged in a linear sequence with successive command positions corresponding to successive time points or orientations of the workpiece 14.

[0147] Collectively, the first set of command positions may effectively define a linear path of movement of the first forming tool 12a between the start and end points, as the workpiece 14 rotates.

[0148] In step 401b, the second toolpath may be received, or otherwise determined, at the control system 174. For example, the control system 174 may receive the second toolpath or otherwise receive information relating to the article 40 for use in determining the second toolpath.

[0149] Suitable information for determining the second toolpath and, in particular the start point, the end point and the second set of command positions, may be received from the memory storage device and/or from user

inputs through the human machine interface and may include one or more of: i) the co-ordinates of the start point, the end points, and/or one or more command positions; ii) the dimensions of the article 40, including the maximum radius of the central hub 42 of the article 40, the maximum radius at the rim 56 of the article 40, the length of the article 40 between the central hub 42 and the rim 56, and/or a mathematical equation defining a curve corresponding to the body portion 46 of the article 40; and/or iii) a computerised representation of the article 40.

[0150] In an example, the control system 174 may receive the co-ordinates of the start and end points of the second toolpath, as well as a mathematical equation defining a curve between the start and end points, from user inputs received through the human machine interface. In dependence on such information, the control system 174 may be configured to determine the second set of command positions that define the second trajectory 142 by discretizing the curve into a sequence of positions arranged along the curve between the start and end points. The command positions may therefore be arranged on a curved trajectory with successive command positions corresponding to successive time points or orientations of the workpiece 14.

[0151] Thereafter, the method may proceed through the remaining steps of each method 100, 200, 300 described above, with the following modifications.

[0152] In step 402, the workpiece 14 is mounted on the lathe 4 of the mandrel-free spinning apparatus 10, as shown in Figure 16, and the control system 174 outputs control signals to cause the workpiece 14 to rotate about the first axis 22 on the lathe 4, substantially as described in step 202 of method 200 for example.

[0153] As mentioned previously, the control system 174 may rotate the workpiece 14 at a rotational speed corresponding to the first and/or second toolpath. This may ensure that the orientation of the workpiece 14 corresponds to a particular time point, and hence corresponds to a respective command position of the first or second toolpaths.

[0154] In step 404, the control system 174 outputs control signals to move the first forming tool 12a in accordance with the first toolpath so as to urge the workpiece 14 into the intermediate geometry 120, substantially as described in step 202 of method 200 for example.

[0155] In particular, the first toolpath is configured so that the first forming tool 12a is initially moved into engagement with the outer surface 16 of the workpiece 14 at the start point of the first toolpath. Thereafter, as the workpiece 14 rotates, the control signals may move the first forming tool 12a through the first set of command positions, from the start point to the end point of the first toolpath, to urge the workpiece 14 into the intermediate geometry 120.

[0156] In step 406, the control system 174 may hold the first forming tool 12a in abutment with the flange portion 150 and outputs control signals to move the second forming tool 12b in accordance with the second toolpath,

substantially as described in step 206 of method 200 for example.

[0157] In particular, the second toolpath is configured so that the second forming tool 12b is initially moved into engagement with the inner surface 12b of the workpiece 14 at the start point of the second toolpath. Thereafter, as the workpiece 14 rotates, the control signals may move the second forming tool 12b through the second set of command positions, from the start point to the end point of the second toolpath, to urge the workpiece 14 towards the target geometry 40.

[0158] In step 408, one or more finishing processes may be performed, as described in step 208 of method 200, to produce the article 40.

[0159] Furthermore, in another example method of controlling the mandrel-free spinning apparatus 10 in accordance with an embodiment of the invention, each of the first and second toolpaths may include a plurality of passes in which the respective first and second forming tools 12a, 12b are moved relative to the workpiece 14.

[0160] As illustrated in Figures 29 to 32, the first toolpath may include a first, a second, a third and a fourth pass 180-d and the second toolpath may include a first, a second, a third and a fourth pass 182a-d. Each pass 180a-d of the first toolpath may move the first forming tool 12a between a respective start point and a respective end point and achieve an iterative deformation of the workpiece 14 toward the intermediate geometry 120.

[0161] Each pass 182a-d of the second toolpath may move the second forming tool 12b between a respective start point and a respective end point and achieve an iterative deformation of the workpiece 14 from the intermediate geometry 120 towards the target geometry 40.

[0162] For example, as shown in Figure 30, the longitudinal positions of the end points may increase between successive passes 180a-d of the first toolpath so that the gradient of the first trajectory 130 increases relative to the second axis 26 and the workpiece 14 is gradually deformed into the intermediate geometry 120.

[0163] Similarly, as shown in Figure 32, the radial positions of the end points, and/or the curvature of the second trajectory 142, may increase between successive passes 182a-d of the second toolpath so that each pass 182a-d deforms the workpiece 14 closer towards the target geometry 40.

[0164] It will be appreciated that various changes and modifications can be made to the above embodiments without departing from the scope of the invention which is defined by the appended claims.

Claims

1. A method (100; 200; 300; 400) of controlling a mandrel-free spinning apparatus (10) to produce an article, having a target geometry (40), from a workpiece (14), the mandrel-free spinning apparatus (10) comprising: a rotatable mounting point (4) for the work-

piece (14); a first forming tool (12a); and a second forming tool (12b); the method including:

whilst the workpiece (14) rotates, moving the first forming tool (12a) so as to: engage a first surface (16) of the workpiece (14); and urge the workpiece (14), from an initial workpiece geometry, towards and beyond the target geometry (4) into an intermediate geometry (120); and whilst the workpiece (14) rotates, moving the second forming tool (12b) so as to: engage a second surface (18) of the workpiece (14), opposed to the first surface (16) of the workpiece (14); and urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40); wherein the first forming tool (12a) is moved to urge the workpiece (14) inward, along and towards an axis of rotation of the mounting point (4), from the initial workpiece geometry into the intermediate geometry (120), and the second forming tool (12b) is moved to urge the workpiece (14) outward, from the intermediate geometry (120) towards the target geometry (40).

2. A method (100; 200; 300; 400) according to claim 1, wherein in the intermediate geometry (120), the workpiece (14) includes: a central hub (132); and a body portion (134) extending from the central hub (132) to a rim (136).
3. A method (100; 200; 300; 400) according to claim 2, wherein urging the workpiece (14) from the initial workpiece geometry into the intermediate geometry (120) comprises moving the first forming tool (12a) linearly so that, in the intermediate geometry (120), the body portion (134) of the workpiece (14) is frustoconical.
4. A method (100; 200; 300; 400) according to claim 2 or claim 3 wherein moving the second forming tool (12b) so as to urge the workpiece (14) outward from the intermediate geometry (120) towards the target geometry (40) comprises moving the second forming tool (12b) along a curve to deform the body portion (134) of the workpiece (14) outward.
5. A method (200; 300; 400) according to any of claims 2 to 4, comprising supporting the workpiece (14) distally from an axis of rotation of the mounting point (4) relative to the second forming tool (12b) whilst moving the second forming tool (12b) so as to urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40).
6. A method (200; 300; 400) according to claim 5, comprising supporting the workpiece (14) at the rim (136) of the workpiece (14) whilst moving the

second forming tool (12b) so as to urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40).

7. A method (100; 200; 300; 400) according to any of claims 2 to 5, wherein in the intermediate geometry (120), the workpiece (14) includes a flange portion (150) that extends around a circumference of the body portion (134) of the intermediate geometry (120). 5
8. A method (200; 300; 400) according to claim 7, comprising supporting the flange portion (150) of the workpiece (14) whilst moving the second forming tool (12b) so as to urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40). 10
9. A method (200; 300; 400) according to claim 8, wherein the first forming tool (12a) engages the flange portion (150) of the workpiece (14) to support the flange portion (150) of the workpiece (14). 15
10. A method (100; 200; 300; 400) according to any preceding claim, wherein: 20
the movement of the first forming tool to engage the first surface (16) of the workpiece (14) and urge the workpiece (14), from the initial workpiece geometry, towards and beyond the target geometry (4) into the intermediate geometry (120) is controlled according to a first toolpath; and 25
the movement of the second forming tool to engage the second surface (18) of the workpiece (14) and urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40) is controlled according to a second toolpath. 30
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11. A method (100; 200; 300; 400) according to claim 10, wherein the first toolpath includes: a plurality of passes (180a-d), each pass (180a-d) of the first toolpath achieving an iterative deformation of the workpiece (14) towards the intermediate geometry (120), and/or wherein the second toolpath includes: a plurality of passes (182a-d), each pass (182a-d) of the second toolpath achieving an iterative deformation of the workpiece (14) from the intermediate geometry (120) towards the target geometry (40). 45
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12. A method (300) according to any preceding claim, further including attaching a forming plate (170) to the second surface (18) of the workpiece (14) before moving the first forming tool (12a) so as to urge the workpiece (14), from the initial workpiece geometry, towards and beyond the target geometry (40) into the intermediate geometry (120). 55

13. A method (300) according to claim 12, further including removing the forming plate (170) from the second surface (18) of the workpiece (14) before moving the second forming tool (12b) so as to engage the second surface (18) of the workpiece (14) and urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40).

14. A control system (172) for a mandrel-free spinning apparatus (10) comprising: a rotatable mounting point (4) for a workpiece (14); a first forming tool (12a); and a second forming tool (12b); to produce an article, having a target geometry (40), the control system (172) being configured to output one or more signals to:

control the rotation of the workpiece (14);
move the first forming tool (12a), whilst the workpiece (14) rotates, so as to: engage a first surface (16) of the workpiece (14); and urge the workpiece (14), from an initial workpiece geometry, towards and beyond the target geometry (40) into an intermediate geometry (120); and move the second forming tool (12b), whilst the workpiece (14) rotates, so as to: engage a second surface (18) of the workpiece (14), opposed to the first surface (16) of the workpiece (14); and urge the workpiece (14) from the intermediate geometry (120) towards the target geometry (40);
wherein the first forming tool (12a) is moved to urge the workpiece (14) inward, along and towards an axis of rotation of the mounting point (4), from the initial workpiece geometry into the intermediate geometry (120), and the second forming tool (12b) is moved to urge the workpiece (14) outward, from the intermediate geometry (120) towards the target geometry (40).

Patentansprüche

1. Verfahren (100; 200; 300; 400) zum Steuern einer dornlosen Drückvorrichtung (10), um einen Artikel, der eine Zielgeometrie (40) aufweist, aus einem Werkstück (14) zu erstellen, wobei die dornlose Drückvorrichtung (10) umfasst: einen drehbaren Montagepunkt (4) für das Werkstück (14); ein erstes Umformwerkzeug (12a); und ein zweites Umformwerkzeug (12b); wobei das Verfahren einschließt:

während das Werkstück (14) sich dreht, Bewegen des ersten Umformwerkzeugs (12a), um: in eine erste Oberfläche (16) des Werkstücks (14) einzugreifen; und das Werkstück (14) von einer anfänglichen Werkstückgeometrie in Richtung der Zielgeometrie (4) und über diese hinaus in eine Zwischengeometrie (120) zu drängen; und

- während das Werkstück (14) sich dreht, Bewegen des zweiten Umformwerkzeugs (12b), um: in eine zweite Oberfläche (18) des Werkstücks (14) einzugreifen, die der ersten Oberfläche (16) des Werkstücks (14) gegenüberliegt; und das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen; wobei das erste Umformwerkzeug (12a) bewegt wird, um das Werkstück (14) nach innen, entlang und in Richtung einer Drehachse des Montagepunkts (4) von der anfänglichen Werkstückgeometrie in die Zwischengeometrie (120) zu drängen und das zweite Umformwerkzeug (12b) bewegt wird, um das Werkstück (14) nach außen von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen.
2. Verfahren (100; 200; 300; 400) nach Anspruch 1, wobei das Werkstück (14) in der Zwischengeometrie (120) einschließt: eine zentrale Nabe (132); und einen Körperabschnitt (134), der sich von der zentralen Nabe (132) zu einem Rand (136) erstreckt.
 3. Verfahren (100; 200; 300; 400) nach Anspruch 2, wobei das Drängen des Werkstücks (14) von der anfänglichen Werkstückgeometrie in die Zwischengeometrie (120) das lineare Bewegen des ersten Umformwerkzeugs (12a) umfasst, so dass der Körperabschnitt (134) des Werkstücks (14) in der Zwischengeometrie (120) kegelstumpfförmig ist.
 4. Verfahren (100; 200; 300; 400) nach Anspruch 2 oder 3, wobei das Bewegen des zweiten Umformwerkzeugs (12b), um das Werkstück (14) von der Zwischengeometrie (120) nach außen in Richtung der Zielgeometrie (40) zu drängen, das Bewegen des zweiten Umformwerkzeugs (12b) entlang einer Kurve umfasst, um den Körperabschnitt (134) des Werkstücks (14) nach außen zu verformen.
 5. Verfahren (200; 300; 400) nach einem der Ansprüche 2 bis 4, umfassend ein distales Stützen des Werkstücks (14) von einer Drehachse des Montagepunkts (4) relativ zu dem zweiten Umformwerkzeug (12b), während das zweite Umformwerkzeug (12b) bewegt wird, um das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen.
 6. Verfahren (200; 300; 400) nach Anspruch 5, umfassend das Stützen des Werkstücks (14) an dem Rand (136) des Werkstücks (14), während das zweite Umformwerkzeug (12b) bewegt wird, um das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen.
 7. Verfahren (100; 200; 300; 400) nach einem der Ansprüche 2 bis 5, wobei das Werkstück (14) in der Zwischengeometrie (120) einen Flanschabschnitt (150) einschließt, der sich um einen Umfang des Körperabschnitts (134) der Zwischengeometrie (120) erstreckt.
 8. Verfahren (200; 300; 400) nach Anspruch 7, umfassend das Stützen des Flanschabschnitts (150) des Werkstücks (14), während das zweite Umformwerkzeug (12b) bewegt wird, um das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen.
 9. Verfahren (200; 300; 400) nach Anspruch 8, wobei das erste Umformwerkzeug (12a) in den Flanschabschnitt (150) des Werkstücks (14) eingreift, um den Flanschabschnitt (150) des Werkstücks (14) zu stützen.
 10. Verfahren (100; 200; 300; 400) nach einem der vorstehenden Ansprüche, wobei:
 - die Bewegung des ersten Umformwerkzeugs, um in die erste Oberfläche (16) des Werkstücks (14) einzugreifen und das Werkstück (14) von der anfänglichen Werkstückgeometrie in Richtung der Zielgeometrie (4) und über diese hinaus in die Zwischengeometrie (120) zu drängen, gemäß einem ersten Werkzeugweg gesteuert wird; und
 - die Bewegung des zweiten Umformwerkzeugs, um in die zweite Oberfläche (18) des Werkstücks (14) einzugreifen und das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen, gemäß einem zweiten Werkzeugweg gesteuert wird.
 11. Verfahren (100; 200; 300; 400) nach Anspruch 10, wobei der erste Werkzeugweg einschließt: eine Vielzahl von Durchgängen (180a-d), wobei jeder Durchgang (180a-d) des ersten Werkzeugwegs eine iterative Verformung des Werkstücks (14) in Richtung der Zwischengeometrie (120) erreicht, und/oder wobei der zweite Werkzeugweg einschließt: eine Vielzahl von Durchgängen (182a-d), wobei jeder Durchgang (182a-d) des zweiten Werkzeugwegs eine iterative Verformung des Werkstücks (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) erreicht.
 12. Verfahren (300) nach einem der vorstehenden Ansprüche, das ferner ein Anbringen einer Formplatte (170) an der zweiten Oberfläche (18) des Werkstücks (14) vor dem Bewegen des ersten Umformwerkzeugs (12a) einschließt, um das Werkstück (14) von der anfänglichen Werkstückgeometrie in Richtung der Zielgeometrie (40) und über diese hinaus in die Zwischengeometrie (120) zu drängen.

13. Verfahren (300) nach Anspruch 12, das ferner ein Entfernen der Formplatte (170) von der zweiten Oberfläche (18) des Werkstücks (14) einschließt, bevor das zweite Umformwerkzeug (12b) bewegt wird, um in die zweite Oberfläche (18) des Werkstücks (14) einzugreifen und das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen. 5
14. Steuersystem (172) für eine dornfreie Drückvorrichtung (10), umfassend: einen drehbaren Montagepunkt (4) für ein Werkstück (14); ein erstes Umformwerkzeug (12a); und ein zweites Umformwerkzeug (12b); um einen Artikel, der eine Zielgeometrie (40) aufweist, zu erstellen, wobei das Steuersystem (172) konfiguriert ist, um ein oder mehrere Signale auszugeben, zum: 10

Steuern der Drehung des Werkstücks (14);
Bewegen des ersten Umformwerkzeugs (12a), während das Werkstück (14) sich dreht, um: in eine erste Oberfläche (16) des Werkstücks (14) einzugreifen; und das Werkstück (14) von einer anfänglichen Werkstückgeometrie in Richtung der Zielgeometrie (40) und über diese hinaus in eine Zwischengeometrie (120) zu drängen; und 20
Bewegen des zweiten Umformwerkzeugs (12b), während das Werkstück (14) sich dreht, um: in eine zweite Oberfläche (18) des Werkstücks (14) einzugreifen, die der ersten Oberfläche (16) des Werkstücks (14) gegenüberliegt; und das Werkstück (14) von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen; 25
wobei das erste Umformwerkzeug (12a) bewegt wird, um das Werkstück (14) nach innen, entlang und in Richtung einer Drehachse des Montagepunkts (4) von der anfänglichen Werkstückgeometrie in die Zwischengeometrie (120) zu drängen und das zweite Umformwerkzeug (12b) bewegt wird, um das Werkstück (14) nach außen von der Zwischengeometrie (120) in Richtung der Zielgeometrie (40) zu drängen. 30

Revendications

1. Procédé (100 ; 200 ; 300 ; 400) de commande d'un appareil de repoussage sans mandrin (10) pour produire un article, ayant une géométrie cible (40), à partir d'une pièce à travailler (14), l'appareil de repoussage sans mandrin (10) comprenant : un point de montage rotatif (4) pour la pièce à travailler (14); un premier outil de formage (12a); et un second outil de formage (12b) ; le procédé comportant : 50

pendant que la pièce à travailler (14) est en rotation, le mouvement du premier outil de for-

mage (12a) de manière à : entrer en prise avec une première surface (16) de la pièce à travailler (14) ; et pousser la pièce à travailler (14), d'une géométrie initiale de la pièce à travailler, vers la géométrie cible (4) et au-delà de celle-ci dans une géométrie intermédiaire (120) ; et pendant que la pièce à travailler (14) est en rotation, le mouvement du second outil de formage (12b) de manière à : entrer en prise avec une seconde surface (18) de la pièce à travailler (14), opposée à la première surface (16) de la pièce à travailler (14) ; et pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40) ; 10
dans lequel le premier outil de formage (12a) est déplacé pour pousser la pièce à travailler (14) vers l'intérieur, le long d'un axe de rotation du point de montage (4) et vers celui-ci, de la géométrie initiale de la pièce à travailler vers la géométrie intermédiaire (120), et le second outil de formage (12b) est déplacé pour pousser la pièce à travailler (14) vers l'extérieur, de la géométrie intermédiaire (120) vers la géométrie cible (40). 15

2. Procédé (100 ; 200 ; 300 ; 400) selon la revendication 1, dans lequel, dans la géométrie intermédiaire (120), la pièce à travailler (14) comporte : un moyeu central (132) ; et une partie corps (134) s'étendant du moyeu central (132) à un bord (136). 20
3. Procédé (100 ; 200 ; 300 ; 400) selon la revendication 2, dans lequel le fait de pousser la pièce à travailler (14) de la géométrie initiale de la pièce à travailler vers la géométrie intermédiaire (120) comprend le mouvement linéaire du premier outil de formage (12a) de sorte que, dans la géométrie intermédiaire (120), la partie corps (134) de la pièce à travailler (14) est tronconique. 25
4. Procédé (100 - 200 ; 300 ; 400) selon la revendication 2 ou la revendication 3, dans lequel le mouvement du second outil de formage (12b) de manière à pousser la pièce à travailler (14) vers l'extérieur de la géométrie intermédiaire (120) vers la géométrie cible (40) comprend le mouvement du second outil de formage (12b) le long d'une courbe pour déformer la partie corps (134) de la pièce à travailler (14) vers l'extérieur. 30
5. Procédé (200 ; 300 ; 400) selon l'une quelconque des revendications 2 à 4, comprenant le support de la pièce à travailler (14) de manière distale d'un axe de rotation du point de montage (4) par rapport au second outil de formage (12b) tout en déplaçant le second outil de formage (12b) de manière à pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40). 35

6. Procédé (200 ; 300 ; 400) selon la revendication 5, comprenant le support de la pièce à travailler (14) au niveau du bord (136) de la pièce à travailler (14) tout en déplaçant le second outil de formage (12b) de manière à pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40). 5
7. Procédé (100 ; 200 ; 300 ; 400) selon l'une quelconque des revendications 2 à 5, dans lequel, dans la géométrie intermédiaire (120), la pièce à travailler (14) comporte une partie bride (150) qui s'étend autour d'une circonférence de la partie corps (134) de la géométrie intermédiaire (120). 10
8. Procédé (200 ; 300 ; 400) selon la revendication 7, comprenant le support de la partie bride (150) de la pièce à travailler (14) tout en déplaçant le second outil de formage (12b) de manière à pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40). 15
9. Procédé (200 ; 300 ; 400) selon la revendication 8, dans lequel le premier outil de formage (12a) entre en prise avec la partie bride (150) de la pièce à travailler (14) pour supporter la partie bride (150) de la pièce à travailler (14). 20
10. Procédé (100 ; 200 ; 300 ; 400) selon l'une quelconque revendication précédente, dans lequel : 25
- le mouvement du premier outil de formage pour entrer en prise avec la première surface (16) de la pièce à travailler (14) et pousser la pièce à travailler (14), de la géométrie initiale de la pièce à travailler, vers la géométrie cible (4) et au-delà de celle-ci dans la géométrie intermédiaire (120) est commandé selon une première trajectoire d'outil ; et 30
- le mouvement du second outil de formage pour entrer en prise avec la seconde surface (18) de la pièce à travailler (14) et pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40) est commandé selon une seconde trajectoire d'outil. 35
11. Procédé (100 ; 200 ; 300 ; 400) selon la revendication 10, dans lequel la première trajectoire d'outil comporte : une pluralité de passes (180a-d), chaque passe (180a-d) de la première trajectoire d'outil réalisant une déformation itérative de la pièce à travailler (14) vers la géométrie intermédiaire (120), et/ou dans lequel la seconde trajectoire d'outil comporte : une pluralité de passes (182a-d), chaque passe (182a-d) de la seconde trajectoire d'outil réalisant une déformation itérative de la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40). 40
12. Procédé (300) selon l'une quelconque revendication précédente, comportant en outre la fixation d'une plaque de formage (170) à la seconde surface (18) de la pièce à travailler (14) avant le mouvement du premier outil de formage (12a) de manière à pousser la pièce à travailler (14), de la géométrie initiale de la pièce à travailler, vers la géométrie cible (40) et au-delà de celle-ci dans la géométrie intermédiaire (120). 45
13. Procédé (300) selon la revendication 12, comportant en outre le retrait de la plaque de formage (170) de la seconde surface (18) de la pièce à travailler (14) avant le mouvement du second outil de formage (12b) de manière à entrer en prise avec la seconde surface (18) de la pièce à travailler (14) et à pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40). 50
14. Système de commande (172) pour un appareil de repoussage sans mandrin (10) comprenant : un point de montage rotatif (4) pour une pièce à travailler (14) ; un premier outil de formage (12a) ; et un second outil de formage (12b) ; pour produire un article ayant une géométrie cible (40), le système de commande (172) étant configuré pour émettre un ou plusieurs signaux pour :
- commander la rotation de la pièce à travailler (14) ;
- déplacer le premier outil de formage (12a), tandis que la pièce à travailler (14) est en rotation, de manière à : entrer en prise avec une première surface (16) de la pièce à travailler (14) ; et pousser la pièce à travailler (14), d'une géométrie initiale de la pièce à travailler, vers la géométrie cible (40) et au-delà de celle-ci dans une géométrie intermédiaire (120) ; et
- déplacer le second outil de formage (12b), pendant que la pièce à travailler (14) est en rotation, de manière à : entrer en prise avec une seconde surface (18) de la pièce à travailler (14), opposée à la première surface (16) de la pièce à travailler (14) ; et pousser la pièce à travailler (14) de la géométrie intermédiaire (120) vers la géométrie cible (40) ;
- dans lequel le premier outil de formage (12a) est déplacé pour pousser la pièce à travailler (14) vers l'intérieur, le long d'un axe de rotation du point de montage (4) et vers celui-ci, de la géométrie initiale de la pièce à travailler vers la géométrie intermédiaire (120), et le second outil de formage (12b) est déplacé pour pousser la pièce à travailler (14) vers l'extérieur, de la géométrie intermédiaire (120) vers la géométrie cible (40). 55

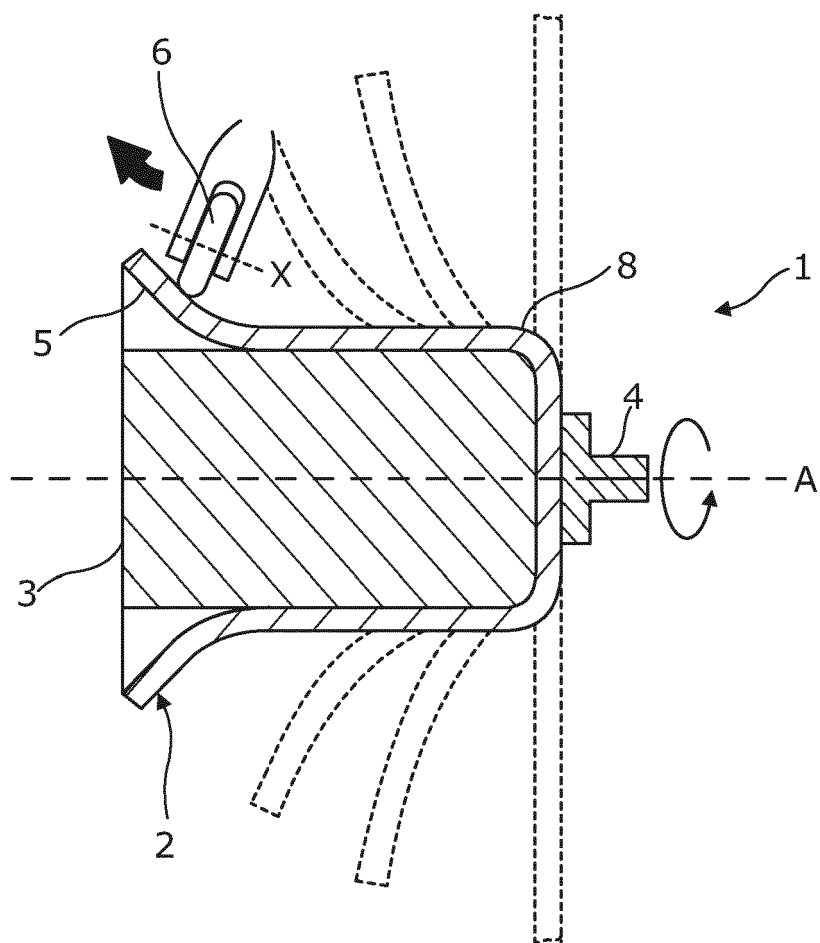


Fig. 1

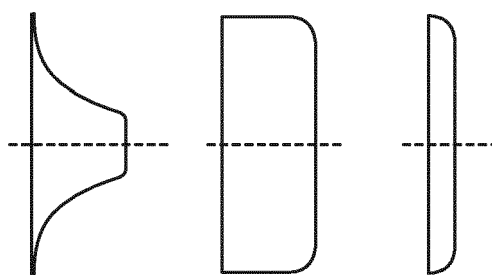


Fig. 2

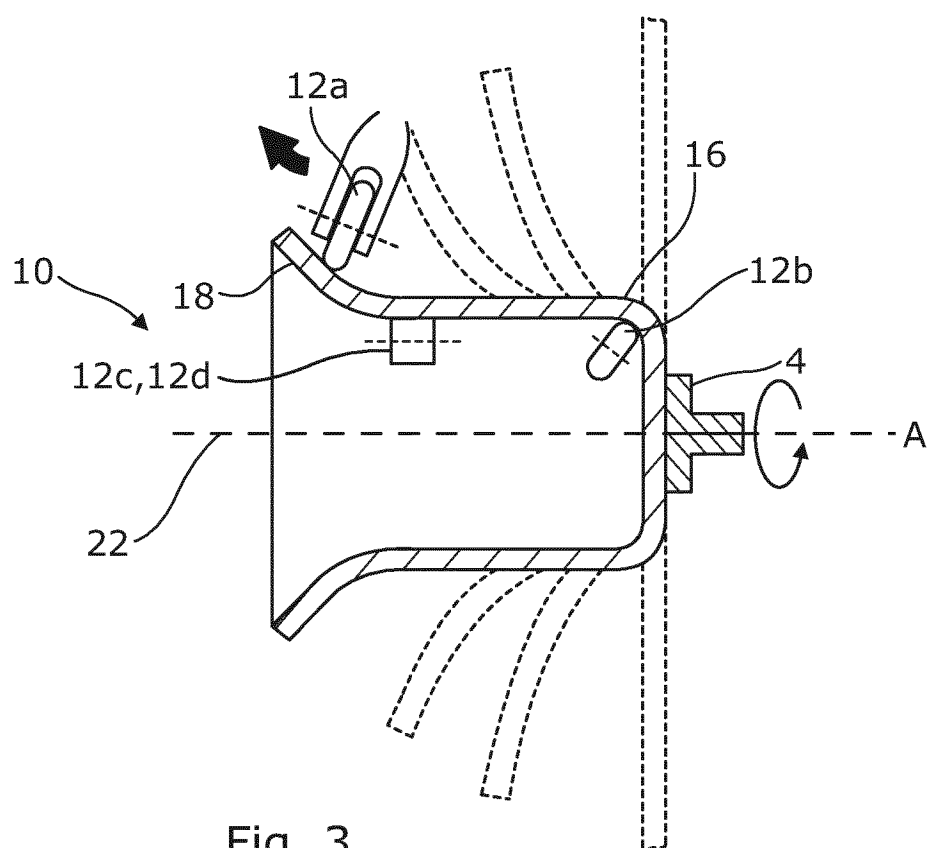


Fig. 3

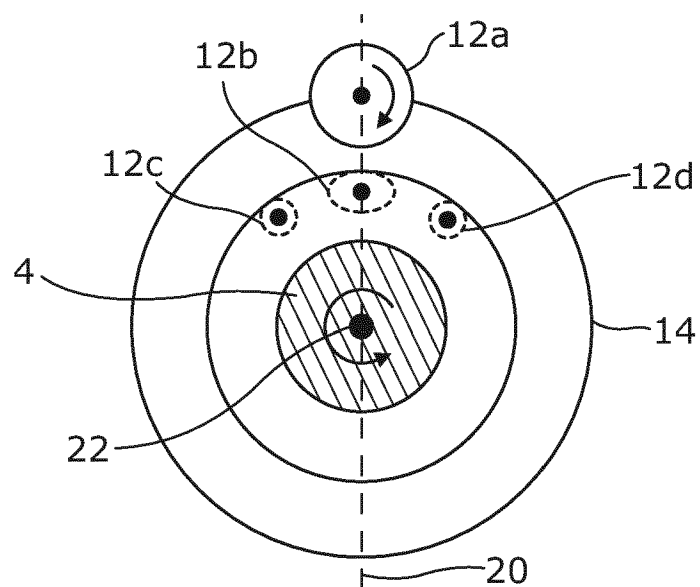
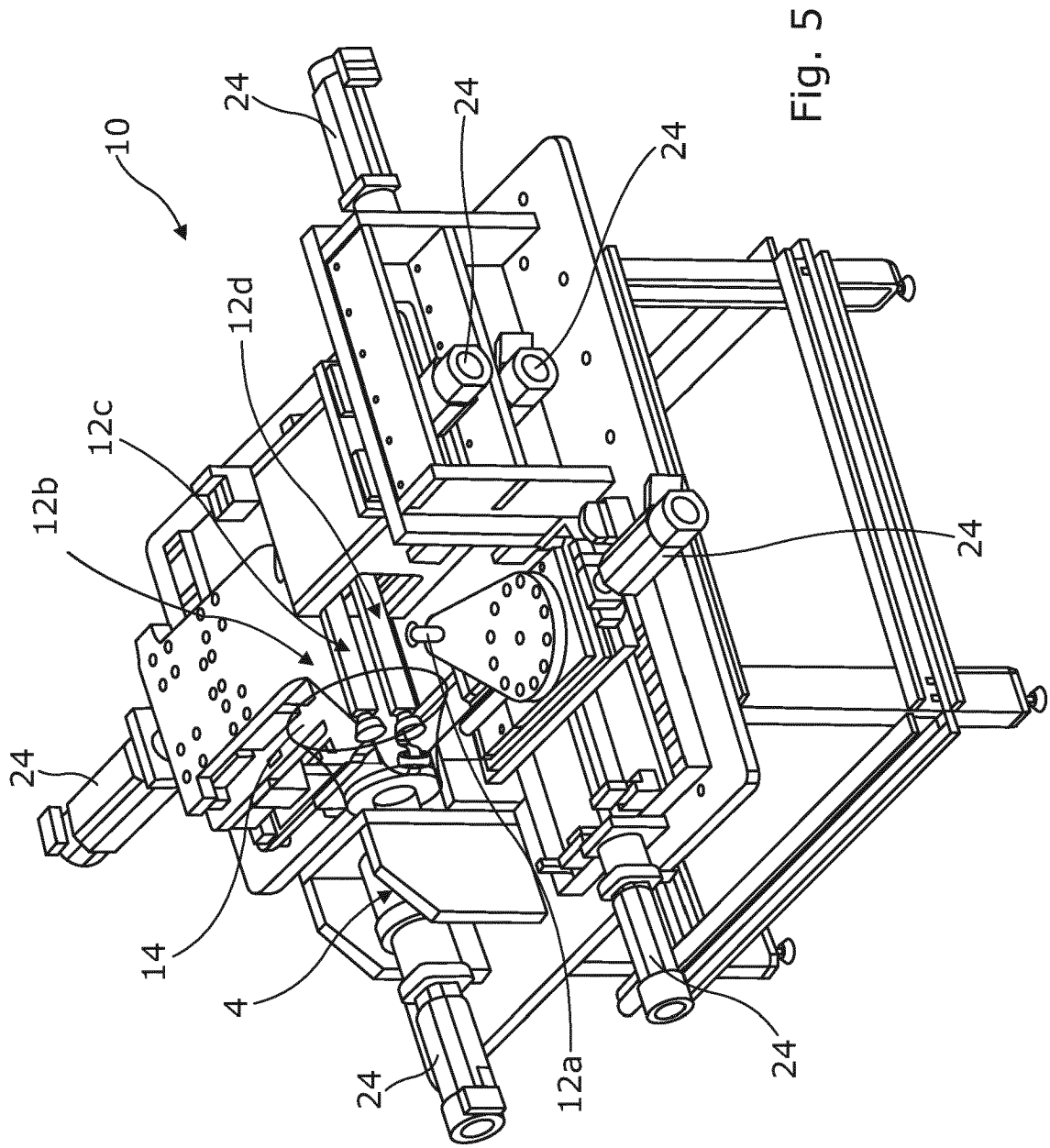


Fig. 4



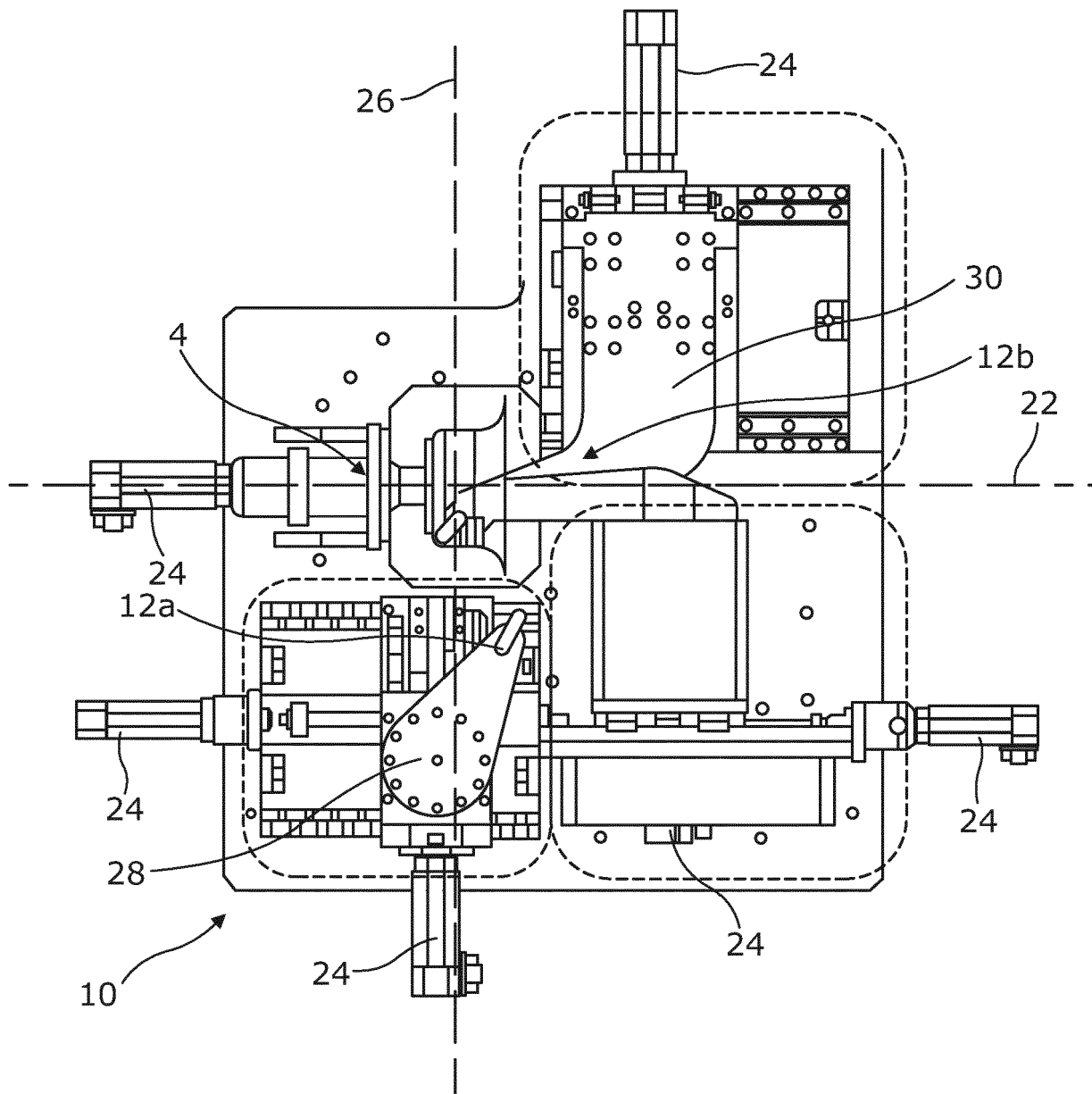


Fig. 6

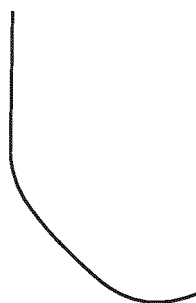
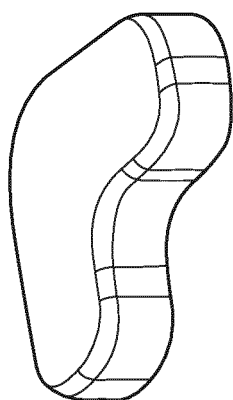


Fig. 7

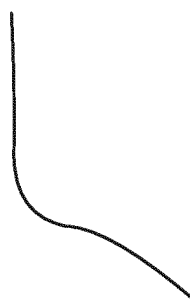
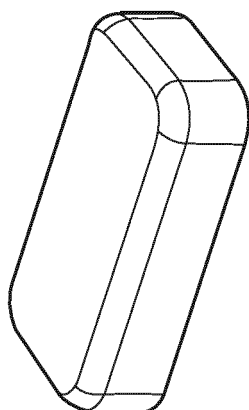


Fig. 8

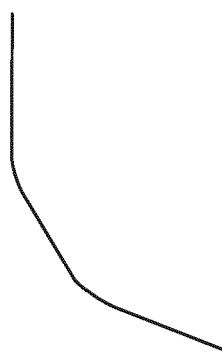
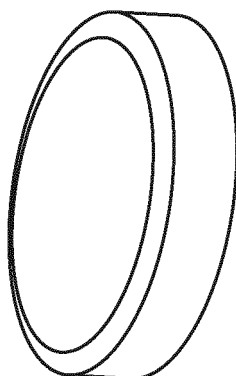


Fig. 9

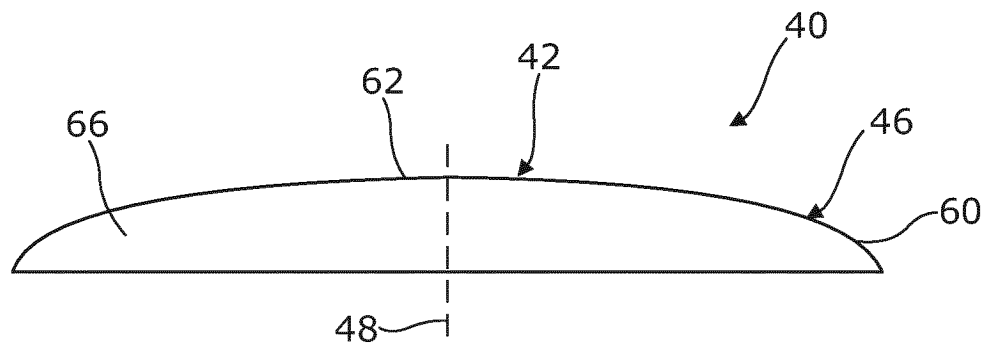


Fig. 10

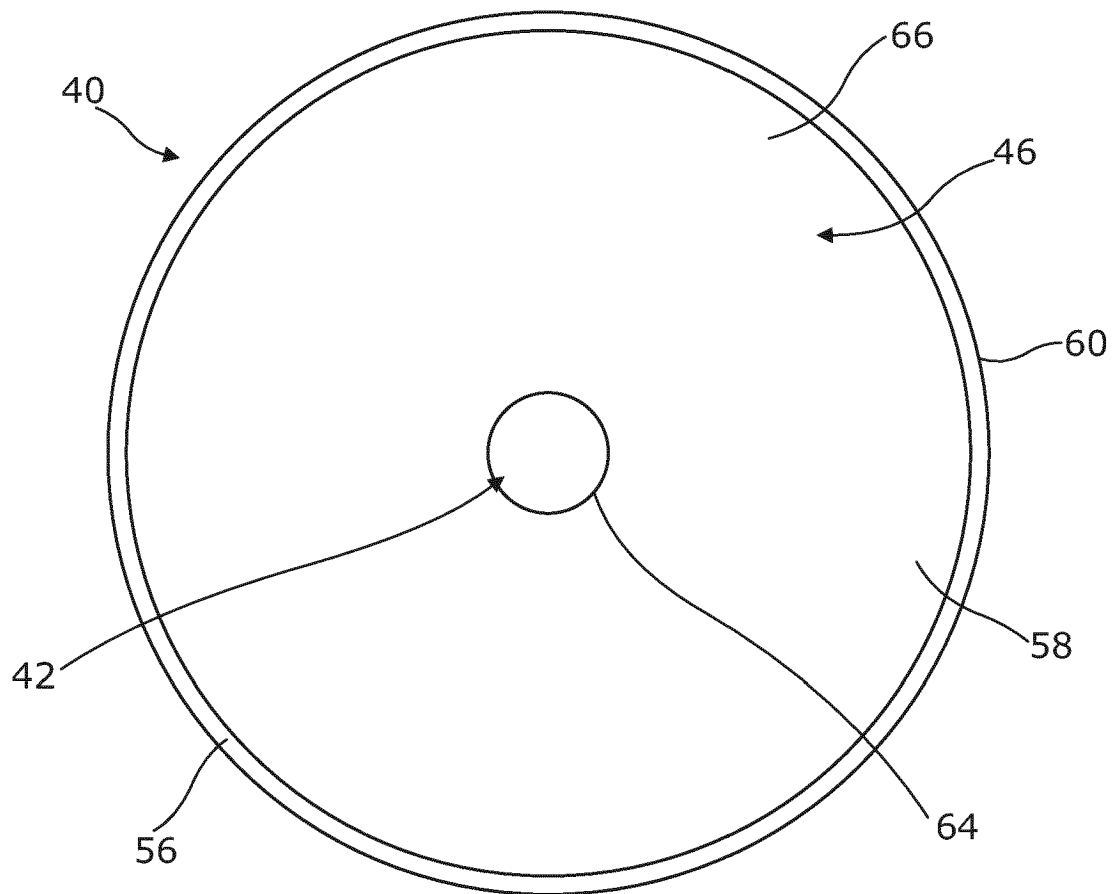


Fig. 11

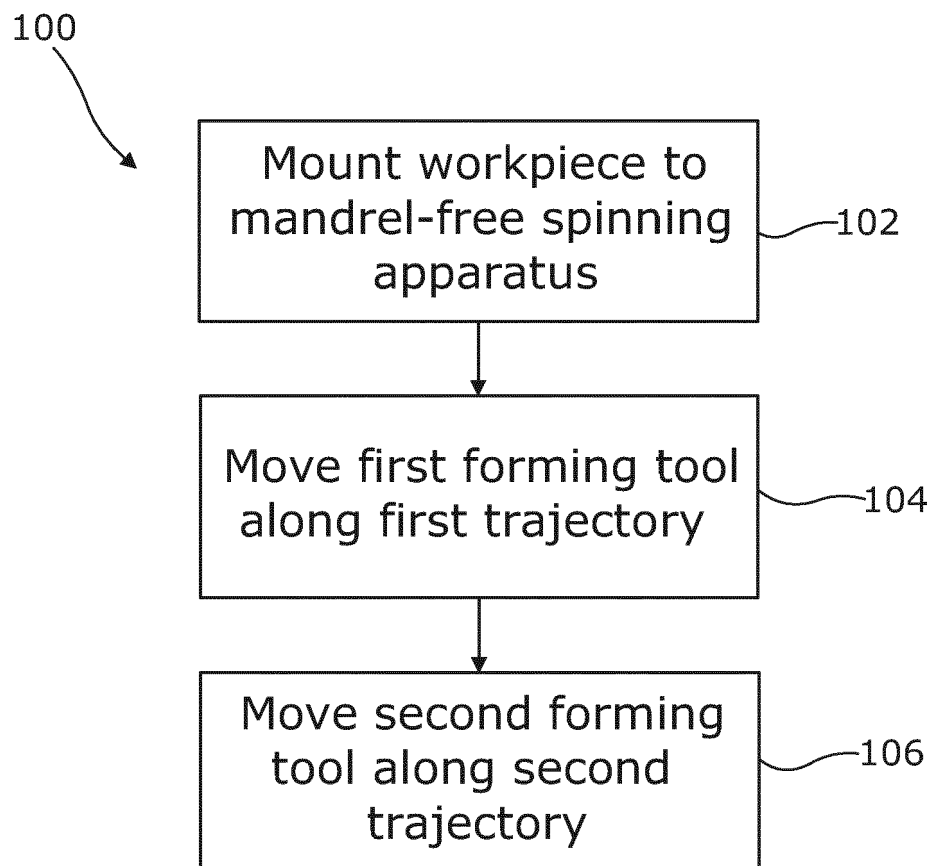


Fig. 12

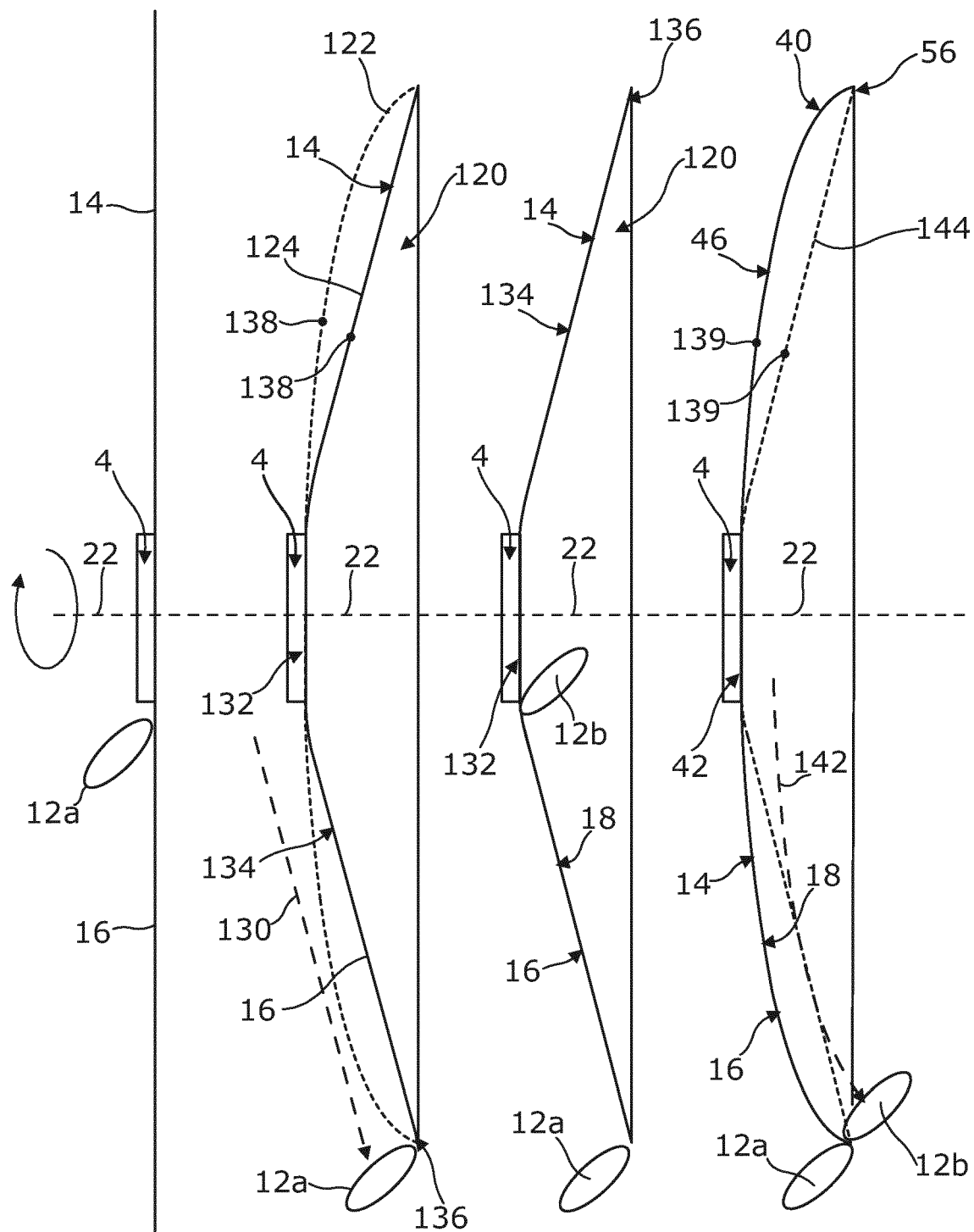


Fig. 13

Fig. 14

Fig. 15

Fig. 16

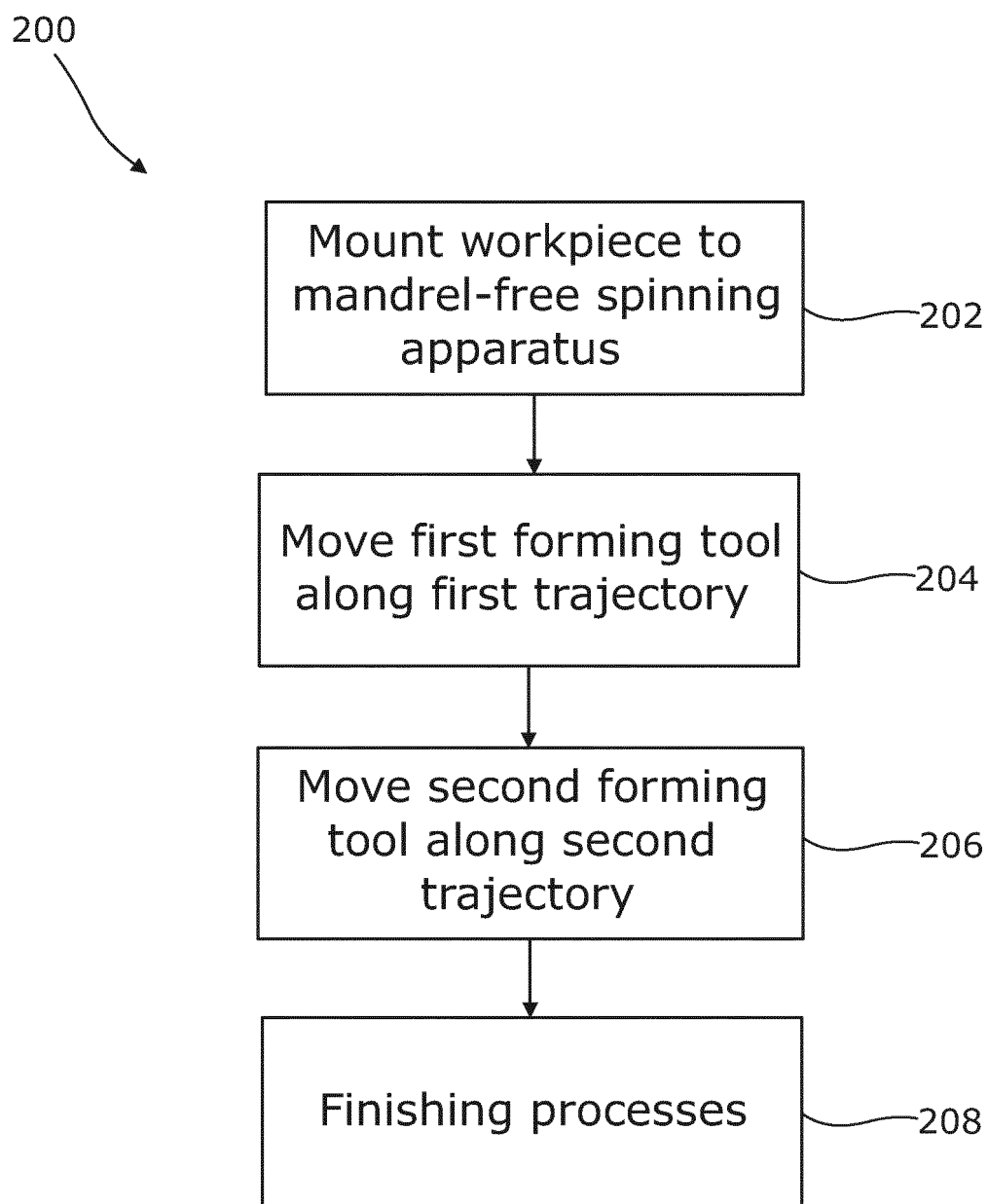


Fig. 17

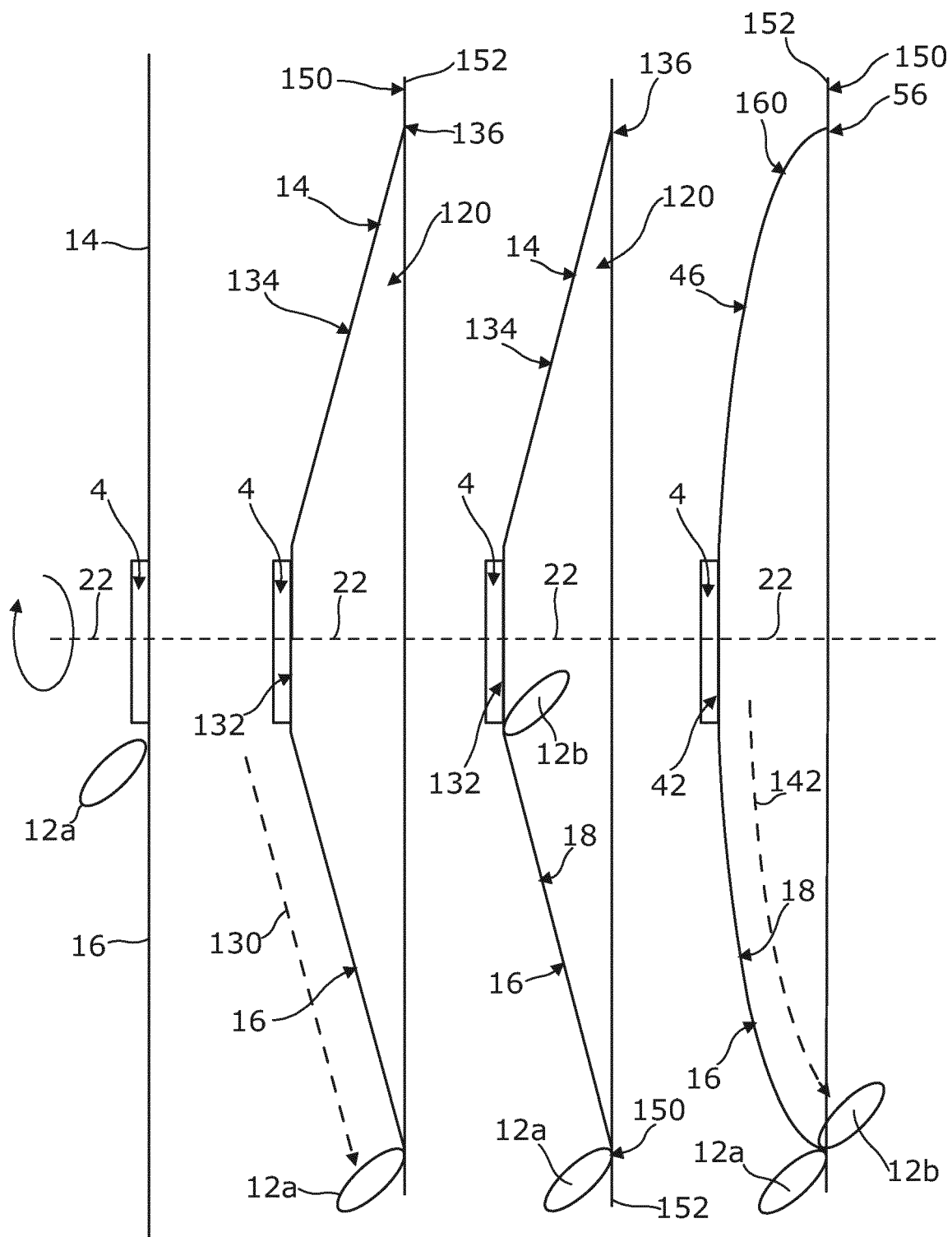


Fig. 18

Fig. 19

Fig. 20

Fig. 21

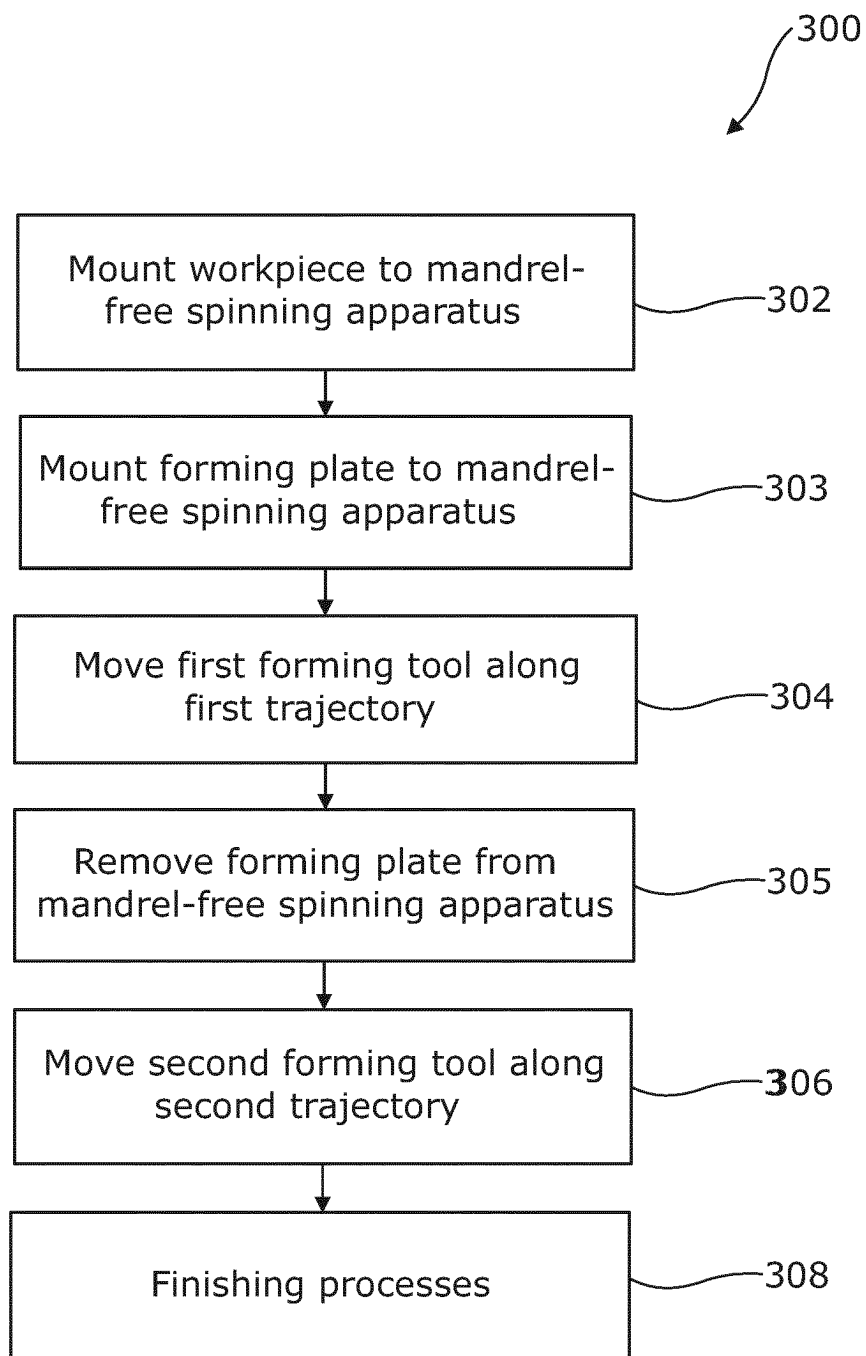


Fig. 22

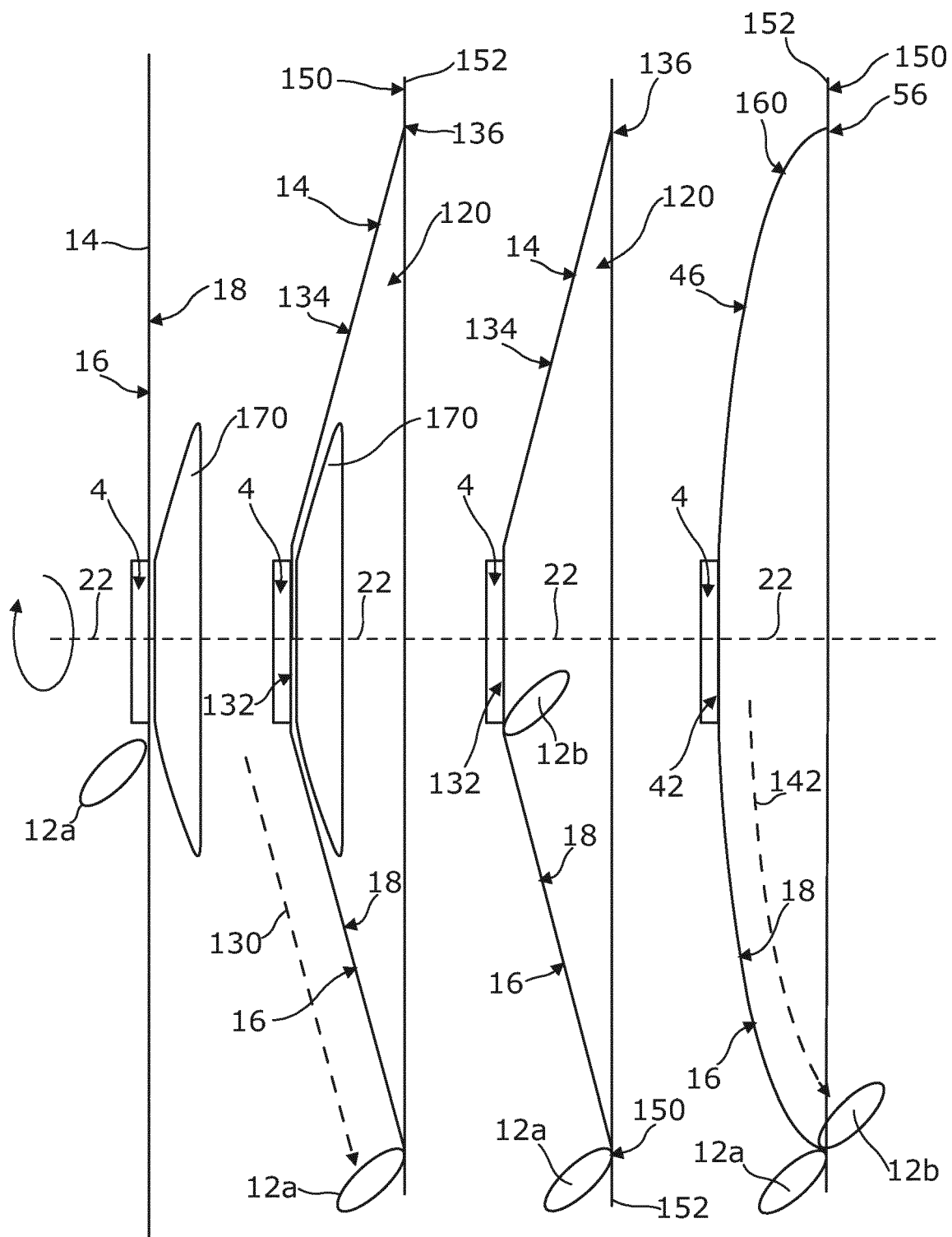


Fig. 23

Fig. 24

Fig. 25

Fig. 26

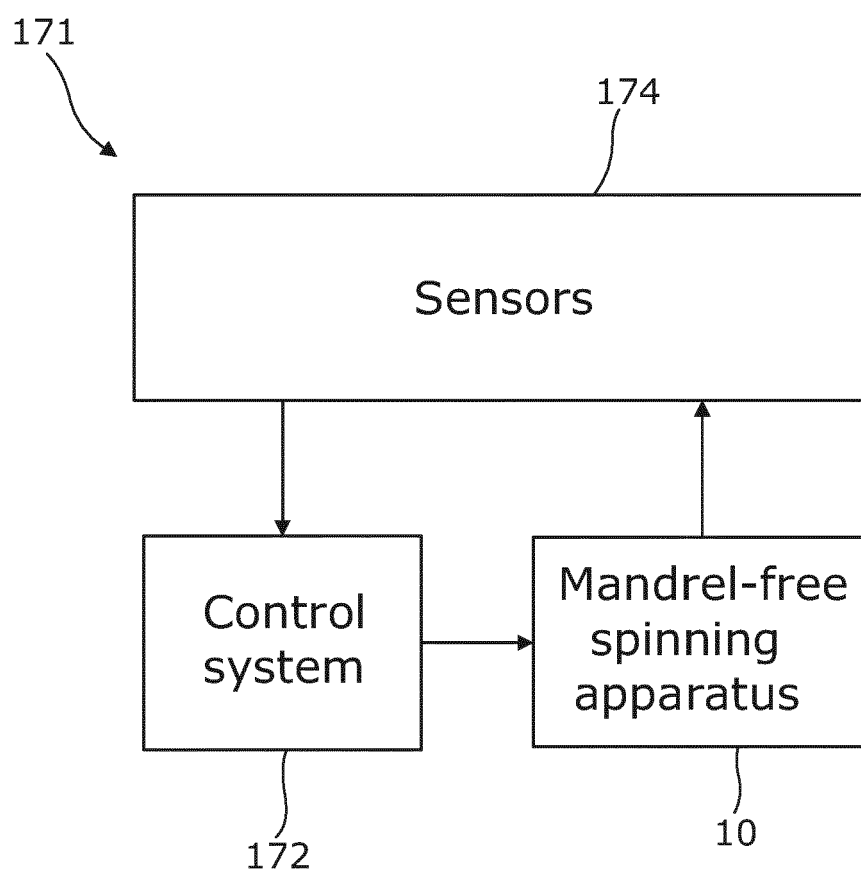


Fig. 27

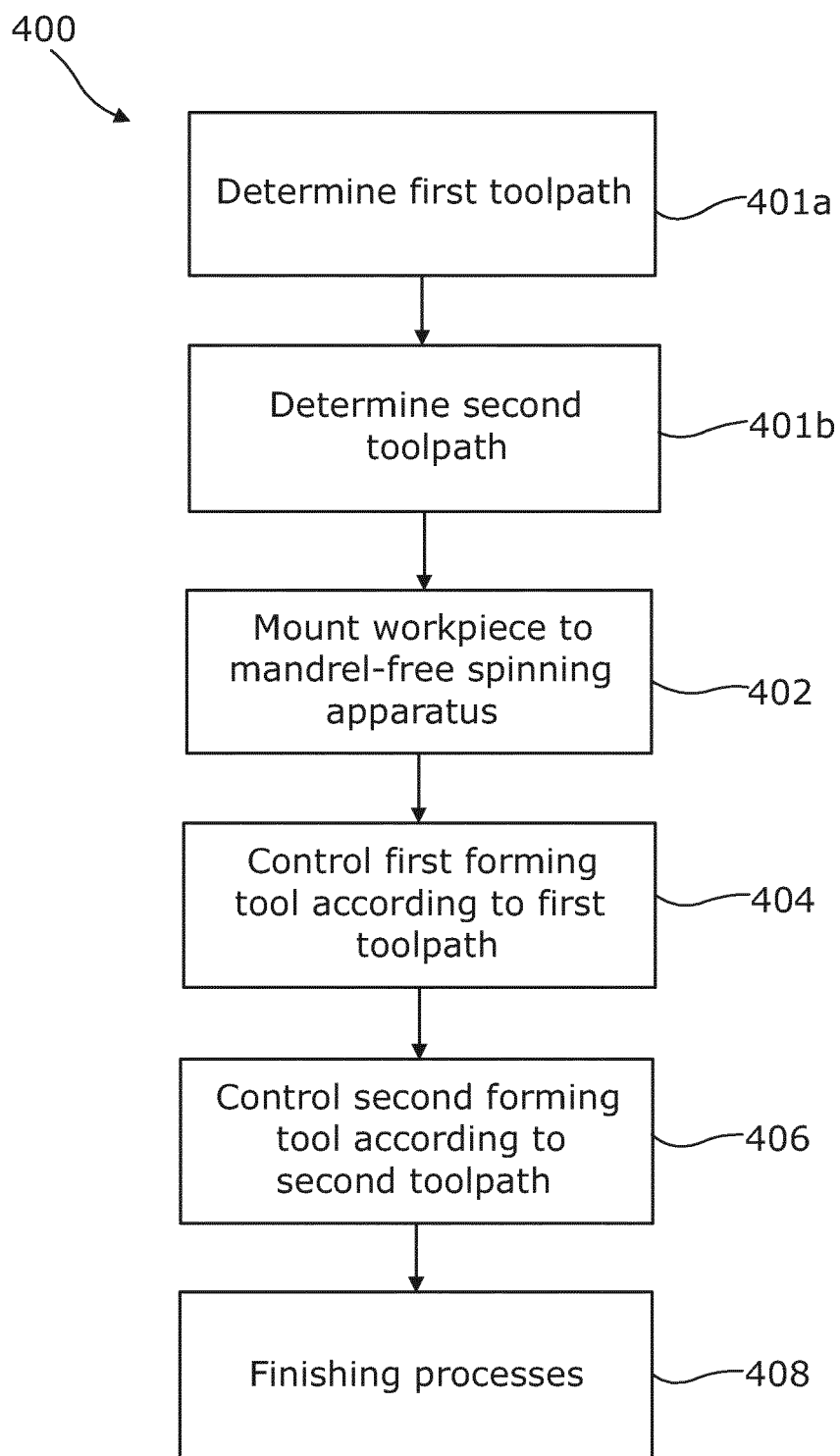


Fig. 28

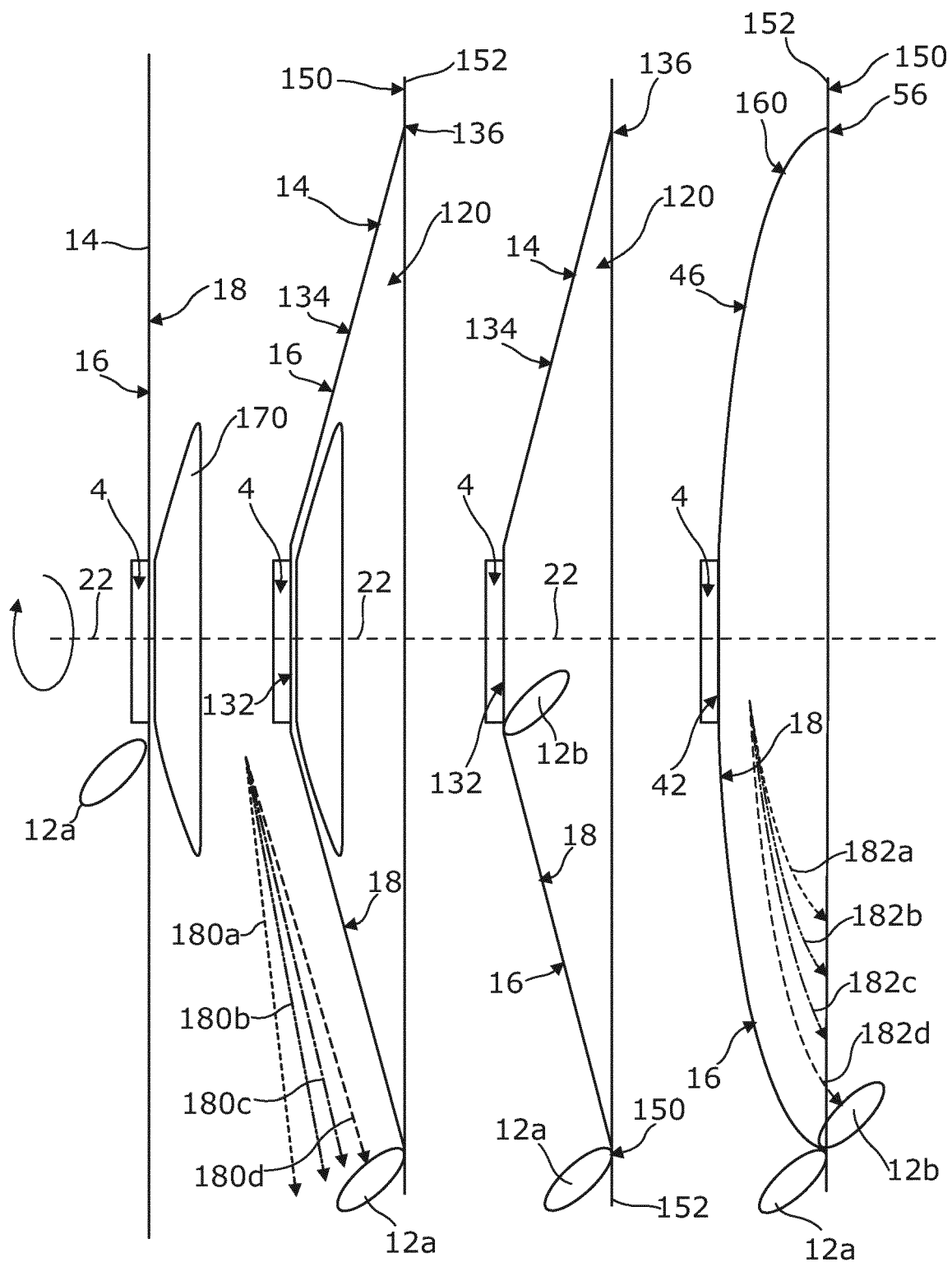


Fig. 29

Fig. 30

Fig. 31

Fig. 32

REFERENCES CITED IN THE DESCRIPTION

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