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Miyauchi et al.

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(54) **DIMPLE-FORMING BURNISHING TOOL**

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B21D 1/02 (2006.01)
B21D 3/02 (2006.01)
B21D 1/08 (2006.01)
B21C 37/30 (2006.01)
B24B 39/02 (2006.01)

(52) **U.S. Cl.**
CPC ***B24B 39/023*** (2013.01)
USPC **72/75**; 72/112; 72/113; 29/90.01

(58) **Field of Classification Search**
USPC 72/67, 74, 75, 77, 78, 97, 112, 113, 72/120, 122, 123, 126, 199, 208, 209, 224, 72/225, 283, 370.1; 451/462; 29/90.01, 29/90.2, 90.3, 90.5, 90.6, 90.7, 90.1
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,934,443 A * 1/1976 Keen 72/75
4,527,929 A * 7/1985 Dickinson et al. 407/1
4,542,565 A * 9/1985 Berstein et al. 29/90.01

FOREIGN PATENT DOCUMENTS

JP A-2007-301645 11/2007

* cited by examiner

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(57) **ABSTRACT**

A dimple-forming burnishing tool allowing easy adjustment of a dimple shape is provided. The dimple-forming burnishing tool has a mandrel attached on a rear-end side thereof to a processing machine for rotation, and a cylindrical frame rotatably externally fitted on a tip side of the mandrel and holding a rolling element and a pressing element that are driven by rotation of the mandrel, for forming dimples in an inner surface of a workpiece by rotating the mandrel with the frame disposed inside the inner surface of the workpiece. In the dimple-forming burnishing tool, the mandrel includes a dimple adjusting mechanism. The dimple adjusting mechanism includes: a rolling element rotating portion causing the rolling element to rotate without moving in and out radially of the frame; and a pressing element in-and-out rotating portion causing the pressing element to rotate while moving in and out radially of the frame.

12 Claims, 12 Drawing Sheets

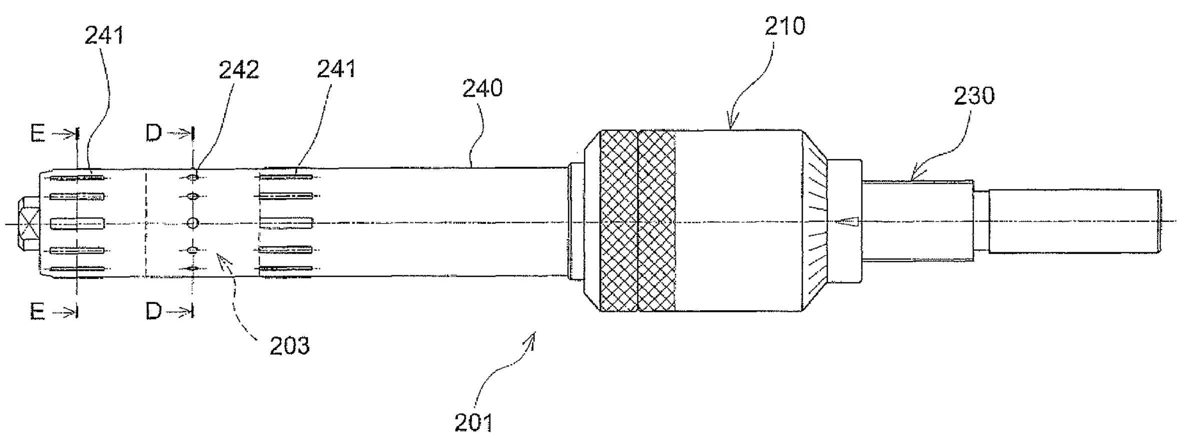
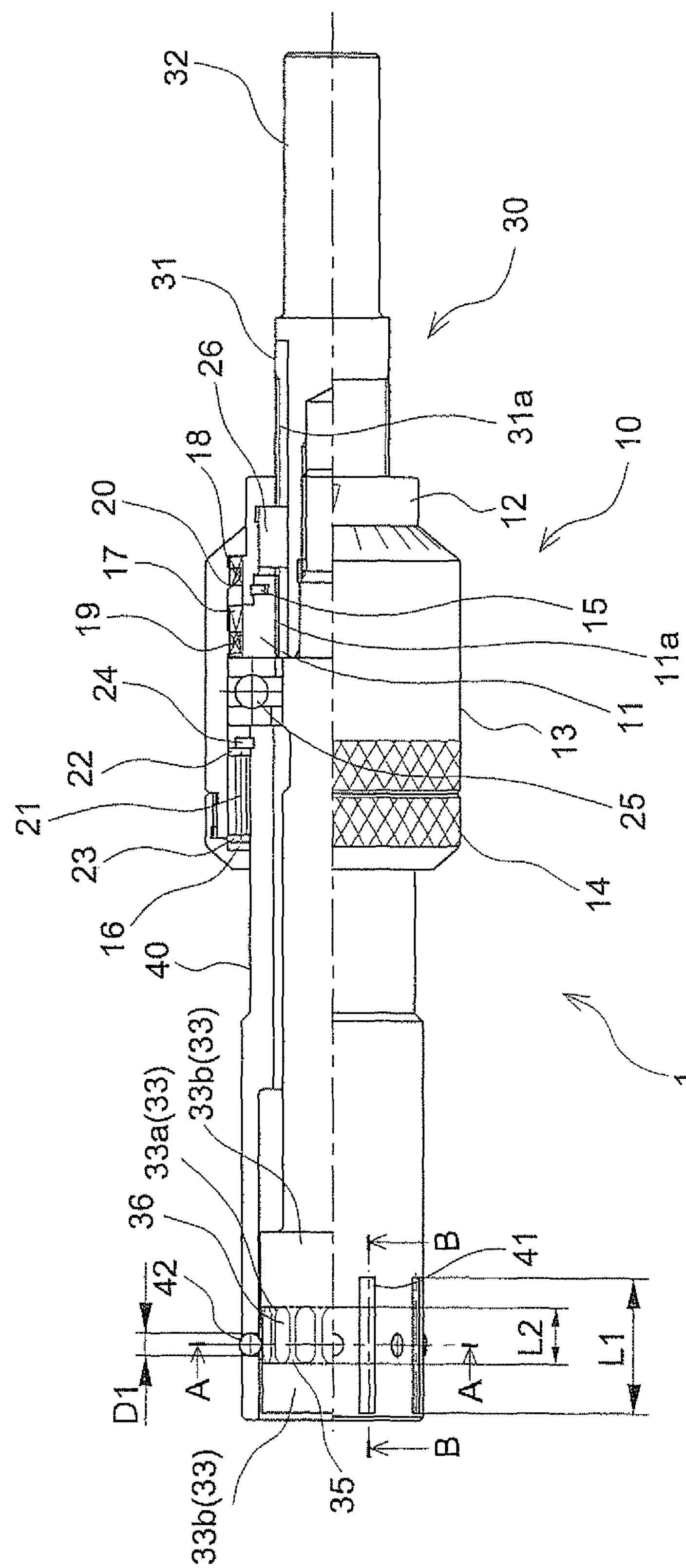


FIG. 1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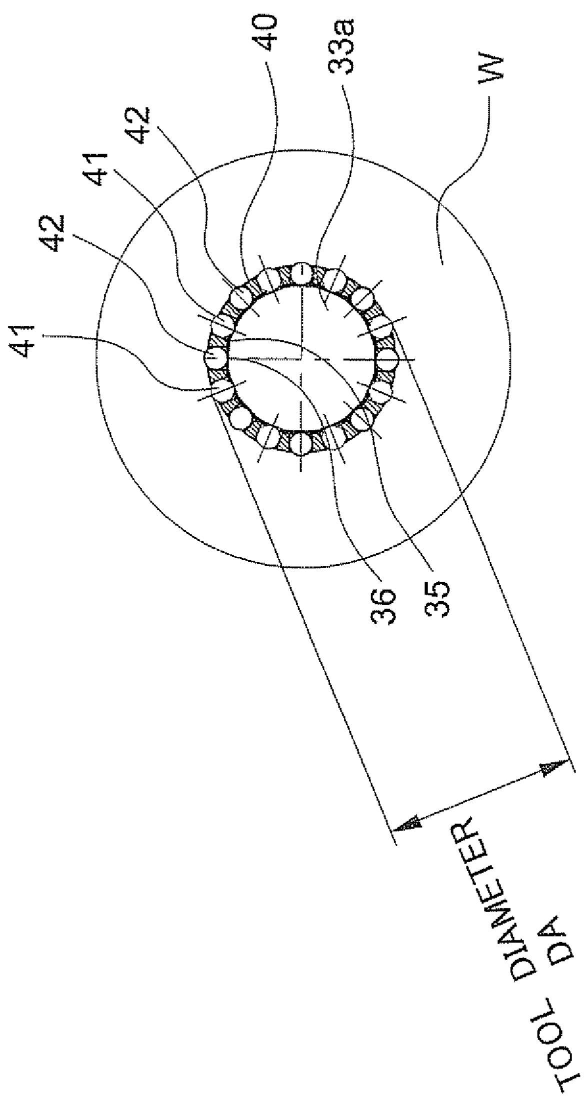
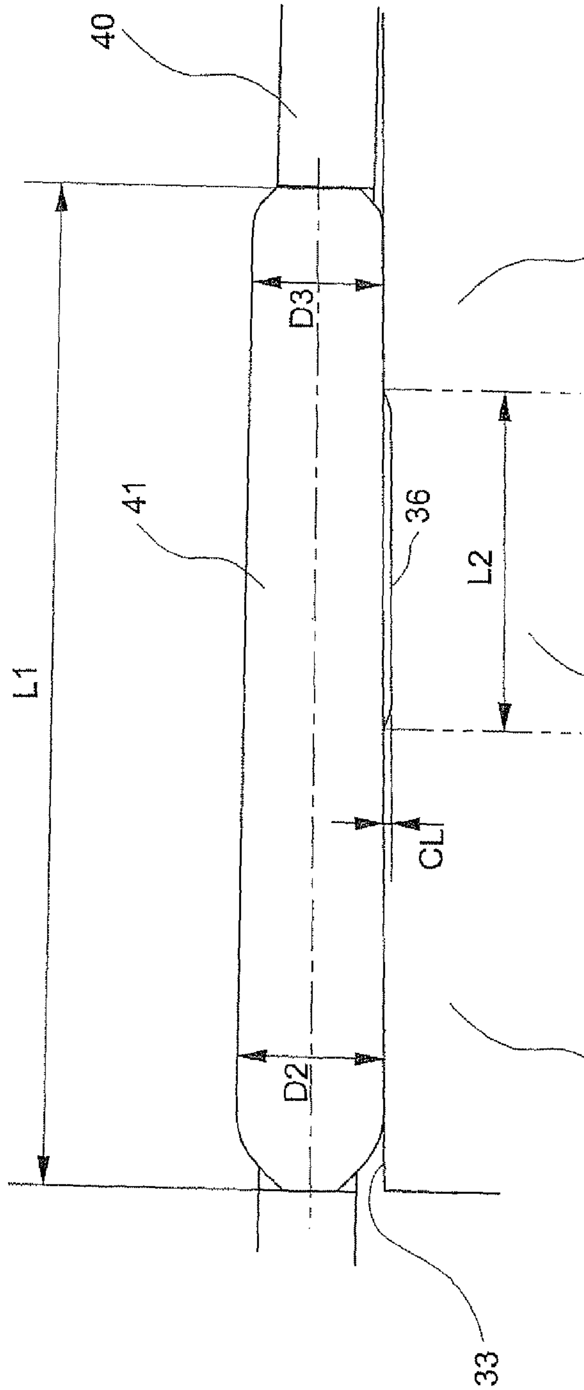
33b(33)

FIG. 2



SECTION ALONG LINE A—A

FIG. 3



ENLARGED SECTION OF ESSENTIAL PARTS ALONG LINE B—B

FIG. 4

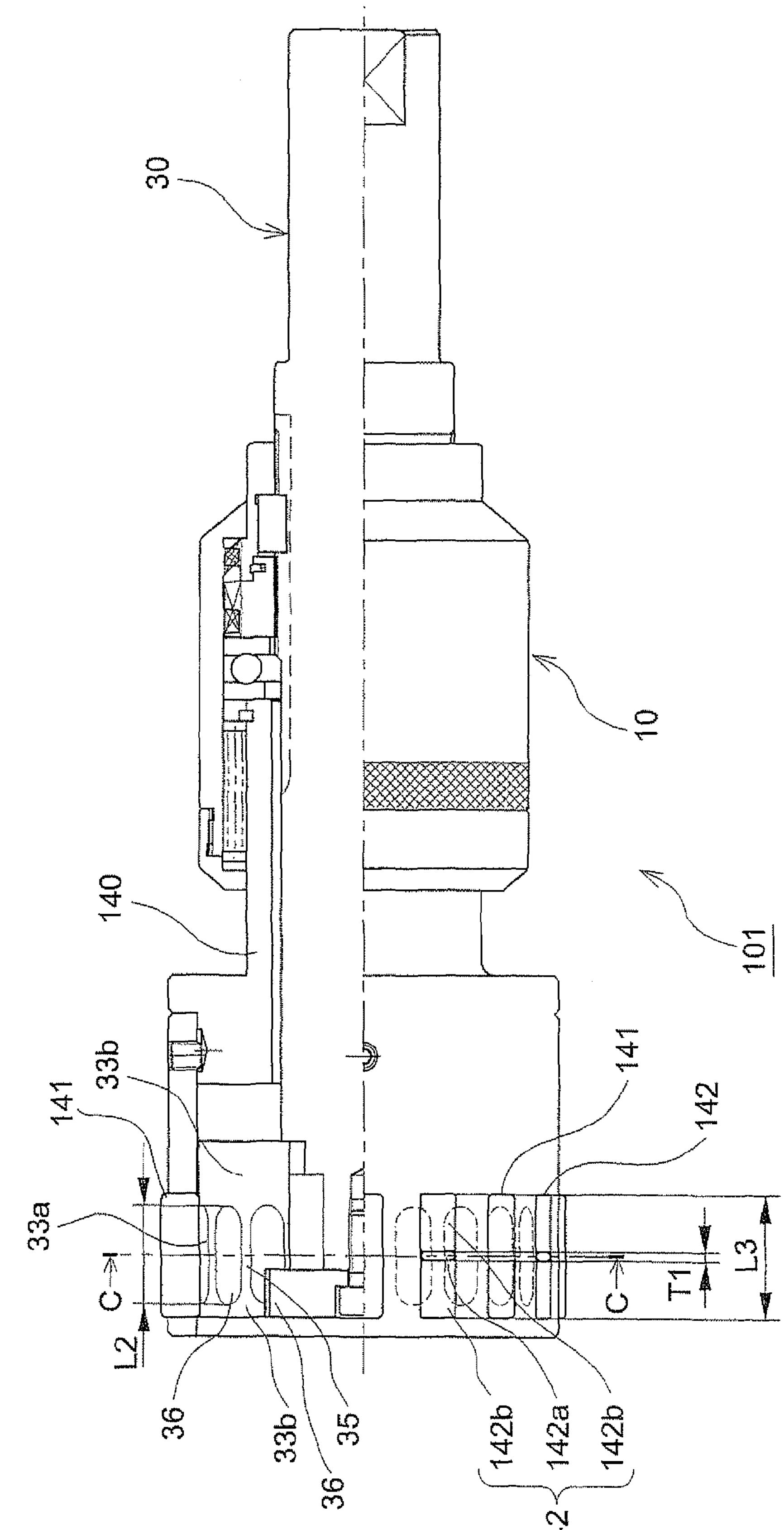

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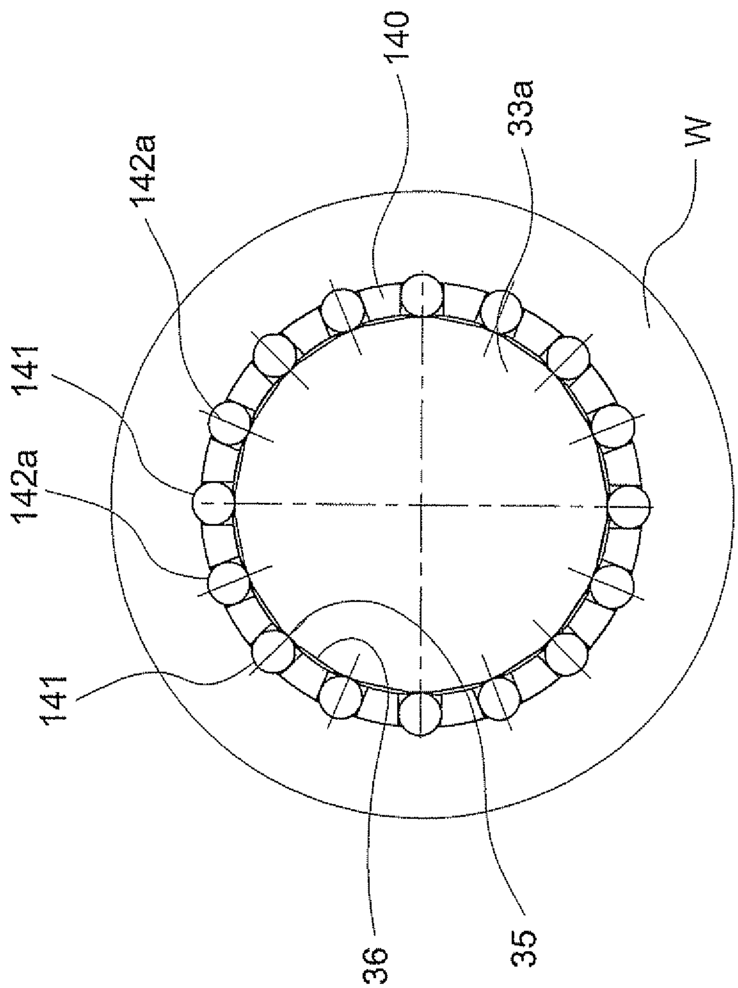
FIG. 5



SECTION ALONG LINE C—C

FIG. 6

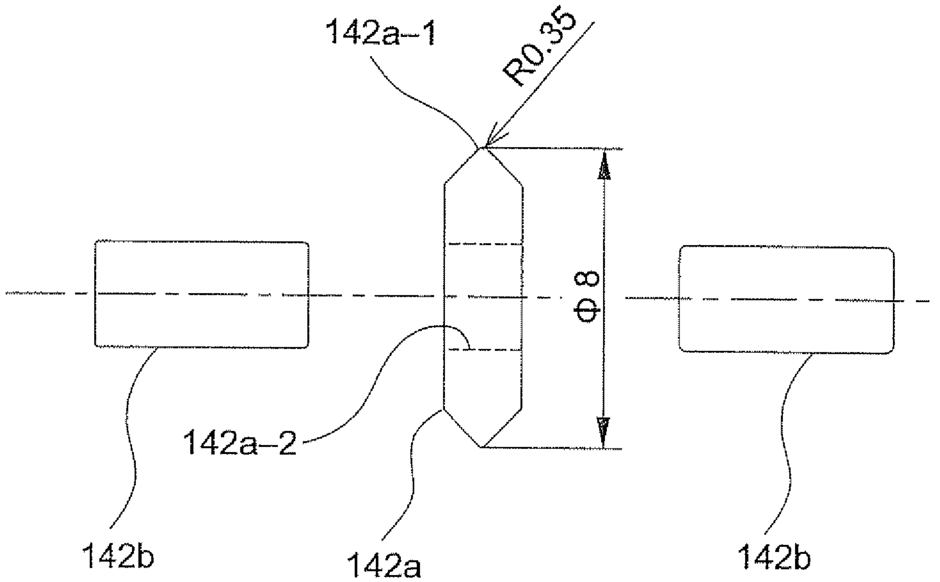


FIG. 7A

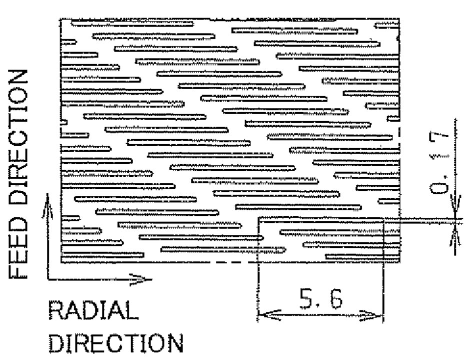


FIG. 7B

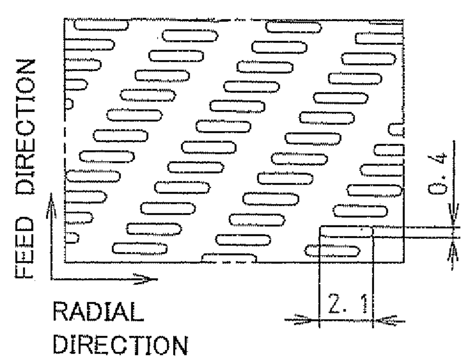


FIG.8

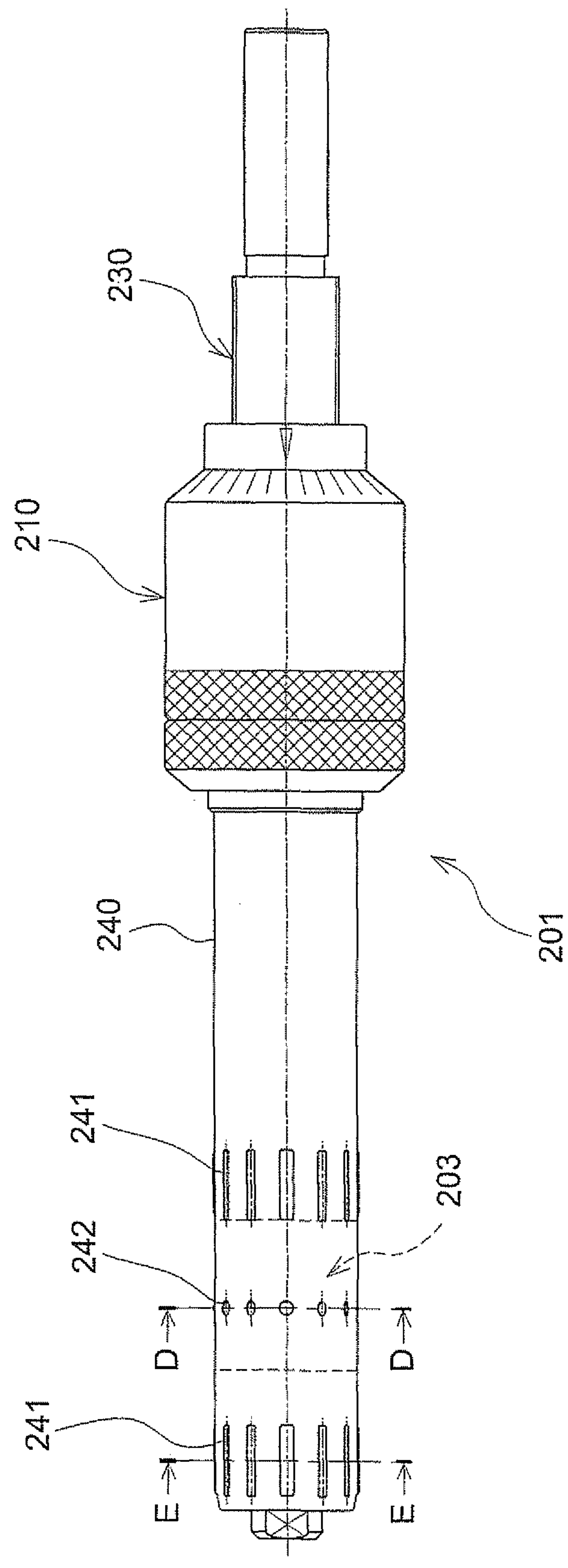
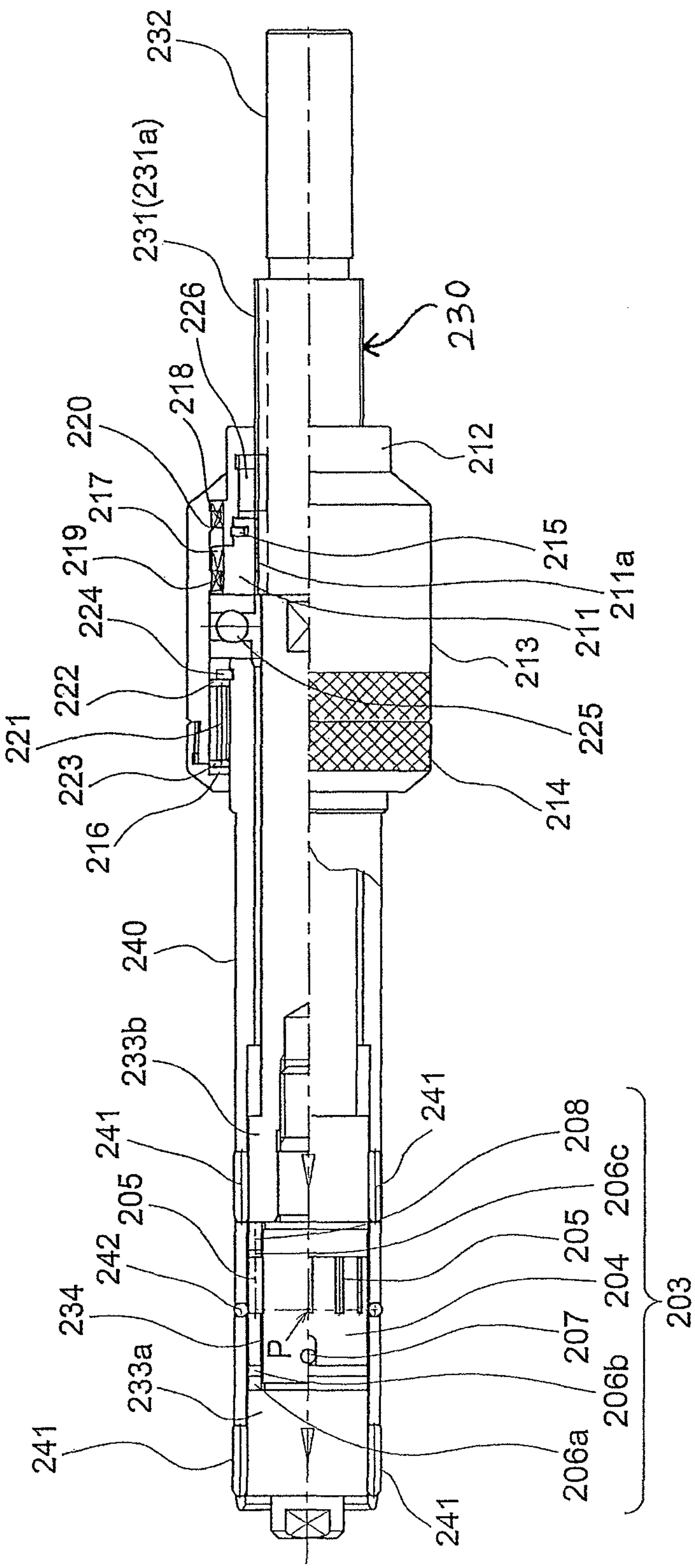


FIG.9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206a
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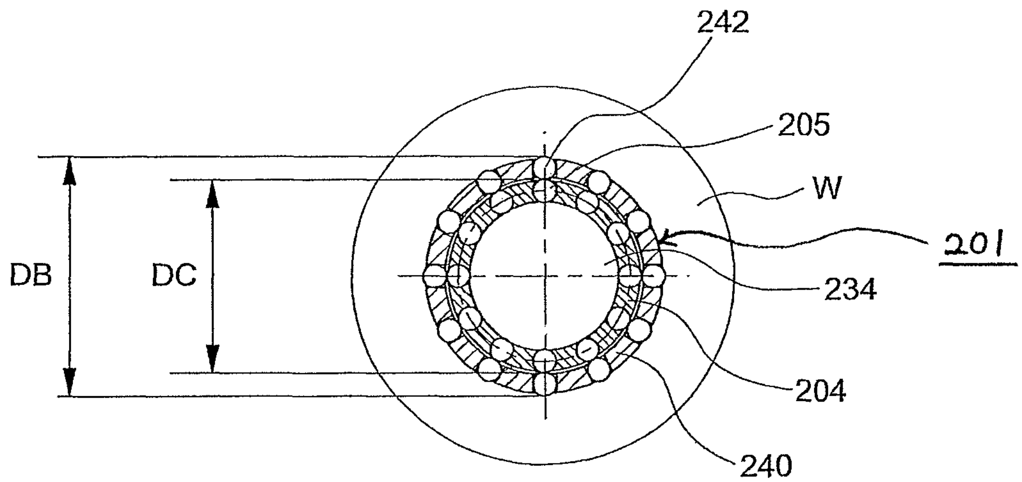
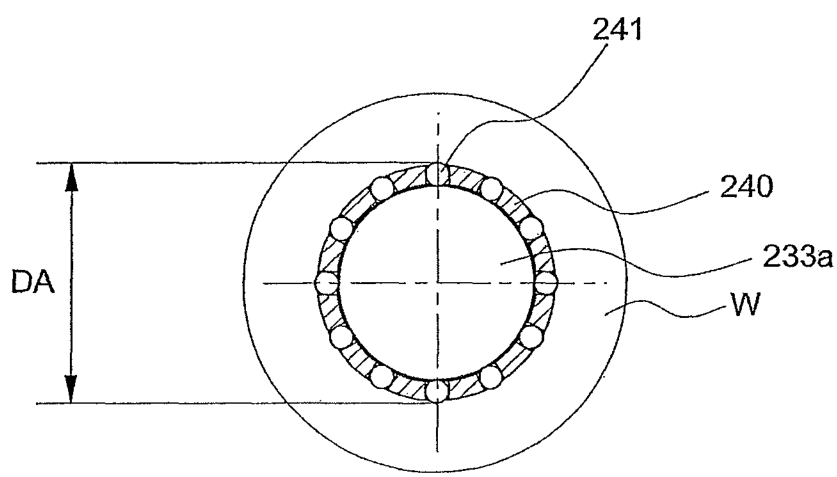
FIG.10



SECTION ALONG LINE D—D

FIG.11



SECTION ALONG LINE E—E

FIG.12A

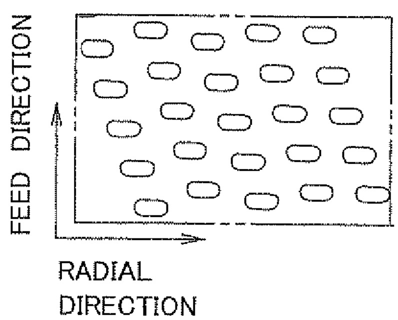
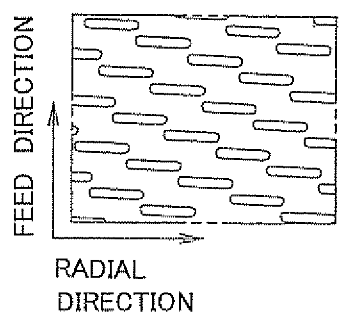


FIG.12B



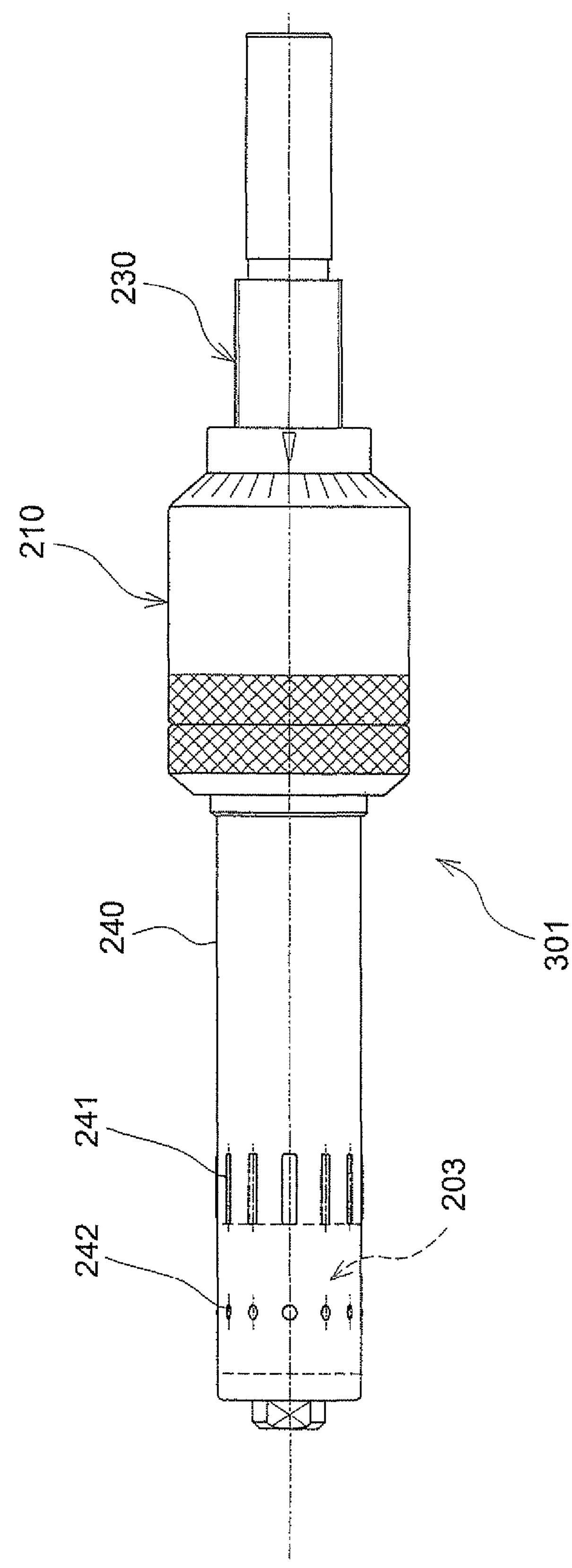


FIG. 13

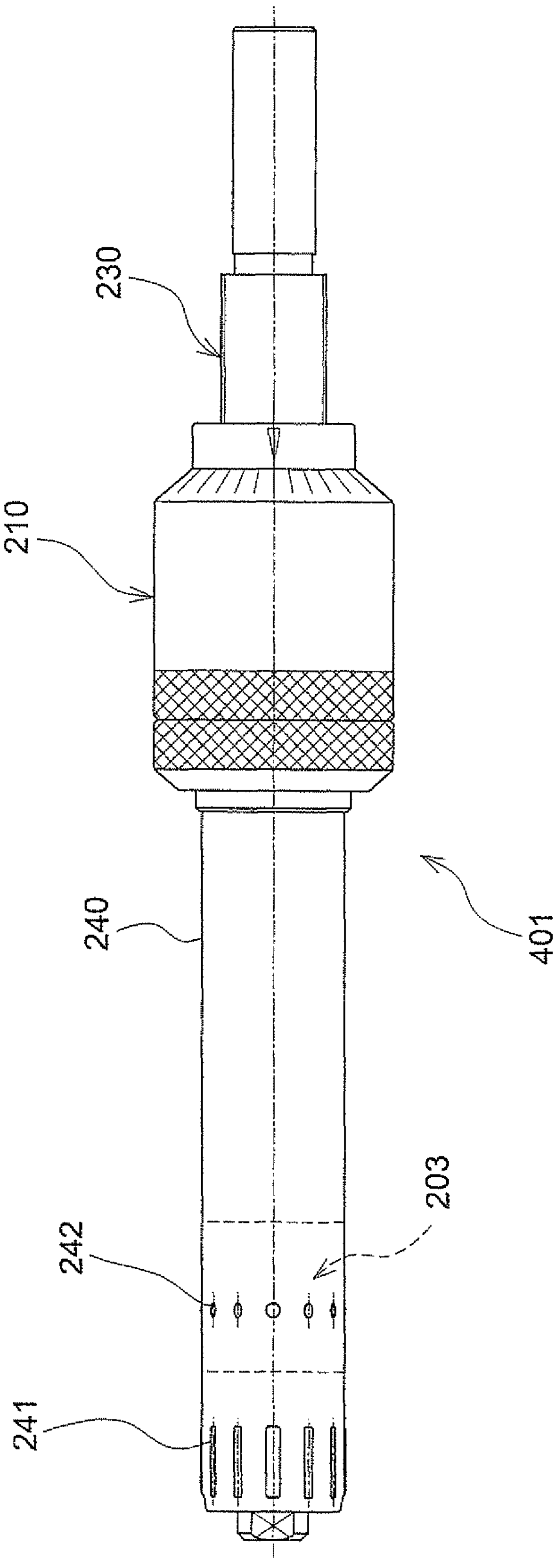


FIG. 14

DIMPLE-FORMING BURNISHING TOOL

BACKGROUND

1. Technical Field

The present invention relates to a burnishing tool, and more particularly, to a dimple-forming burnishing tool.

2. Related Art

Generally, for slide elements (sliders) used under severe conditions of high rotational speed and heat, such as fluid dynamic bearing surfaces typified by engines and hard disk drives, there is known a technology in which, in order to improve the lubricating performance, microgrooves or dimples are formed in a sliding surface to reduce the frictional resistance of the sliding surface. Examples of the known technologies for forming dimples in a sliding surface include technologies using so-called WPC treatment (fine particle shot peening), laser beam machining, barrel polishing, etc.

On the other hand, burnishing is categorized in plastic deformation in which a work surface of a workpiece is crushed and deformed by rotating a hard roller while pressing the hard roller against the workpiece to enhance the surface hardness and surface roughness. Burnishing can greatly improve the durability, wear resistance, and reliability of the sliding surface.

As a tool of burnishing and forming dimples in an inner surface of a workpiece, known is a technique disclosed, for example, in Japanese Published Unexamined Patent Application No. 2007-301645. The dimple-forming burnishing tool disclosed in Japanese Published Unexamined Patent Application No. 2007-301645 includes a mandrel attached to a processing machine for rotation, and a retainer (a frame) externally fitted to the mandrel in a rotatable manner. The retainer rotatably holds plural rollers (rolling elements) and plural balls (pressing elements) in such a manner that the plural rollers and balls can move radially in and out of an outer surface of the retainer. Also, when the mandrel rotates, protrusions formed on an outer surface of the mandrel is brought into engagement with the rollers and the balls, thereby causing the rollers and the balls to roll while vibrating on the inner surface of the workpiece. In this manner, dimples are formed in the inner surface of the workpiece.

According to Japanese Published Unexamined Patent Application No. 2007-301645, however, a problem still exists that adjustment of a dimple shape (such as groove width, groove length, or groove depth) is difficult, due to a polygonal cross-sectional shape of the mandrel, rotation of the mandrel causes the rollers and the balls both to move radially in and out of the outer surface of the retainer at the same time. Specifically, a failure to precisely locate the tool on the inner surface of the workpiece causes a change in the distance that the rollers and the balls move radially in and out at the start of dimple formation. Therefore, stable forming processing becomes impossible, so that adjustment of the dimple shape becomes more difficult. Further, according to the tool disclosed in Japanese Published Unexamined Patent Application No. 2007-301645, a problem also still exists that dimples are redundantly formed in a tool retraction process (or at the time of tool retraction) because the tool diameter is not reduced at the time of retracting the tool after processing the inner surface of the workpiece.

SUMMARY

Accordingly, the present invention has been made in view of the problems described above, and an object of the present invention is to provide a dimple-forming burnishing tool that allows easy adjustment of a dimple shape. In addition, another object of the invention is to provide a dimple-forming burnishing tool that prevents dimple formation during retraction of the tool from the workpiece.

In order to achieve the above-described objects, according to an aspect of the present invention, there is provided a dimple-forming burnishing tool having: a mandrel attached on a rear-end side thereof to a processing machine for rotation; and a cylindrical frame rotatably externally fitted on a tip side of the mandrel and holding a rolling element and a pressing element that are driven by rotation of the mandrel, for forming dimples in an inner surface of a workpiece by rotating the mandrel with the frame disposed inside the inner surface of the workpiece. The mandrel includes a dimple adjusting mechanism. The dimple adjusting mechanism includes: a rolling element rotating portion causing the rolling element to rotate without moving in and out radially of the frame; and a pressing element in-and-out rotating portion causing the pressing element to rotate while moving in and out radially of the frame.

According to the aspect of the present invention, the mandrel includes the dimple adjusting mechanism that is composed of the rolling element rotating portion and the pressing element in-and-out rotating portion. This structure causes the rolling element to rotate without moving in and out radially of the frame, thereby allowing stable burnishing of the inner surface of the workpiece. Further, a desired dimple can be formed by causing the pressing element to rotate while moving in and out radially of the frame. In this manner, according to the aspect of the present invention, even when the mandrel rotates, the rolling element can be prevented from moving in and out radially of the frame along with the pressing element, thereby allowing easier adjustment in the dimple shape (such as groove width, groove length, or groove depth) than the related art.

Here, if the balls are used as plural pressing elements, an advantage is obtained that, in a case where holes or grooves, such as connecting rod oil holes or intersecting holes, are formed in a direction crossing the inner surface of the workpiece, the balls abut or press against edge portions around the oil holes or the like, thereby allowing removal of burrs on the edge portions of the oil holes or the like at the same time. Further, if the rollers are used as plural rolling elements, an advantage is also obtained that the pressing area at the time of the rolling processing can be increased, so that a machined surface with excellent surface roughness can be obtained.

Furthermore, the above-described structure preferably includes the following. The rolling element includes plural rollers and the pressing element includes plural balls. The plural rollers and balls are alternately spaced on the same circumference of the frame. Each roller is arranged with its axis parallel to an axis of the frame. The rollers have a length greater than a diameter of each ball. The mandrel has on the tip side thereof a tapered portion gradually decreasing in diameter toward a tip of the mandrel. The tapered portion has a first area and a second area on an outer surface thereof. The first area serves as the pressing element in-and-out rotating portion. The second area is disposed on both sides of the first area in an axial direction of the mandrel, and serves as the rolling element rotating portion. The first area has plural circumferentially spaced-apart flat portions. The first area has a polygonal cross section, while the second area has a circular cross section. The flat portions have a length greater than the diameter of each ball and smaller than the length of each roller. When the frame is attached to the mandrel, the rollers are brought into contact with the second area without making contact with the flat portions of the first area, while the balls are only brought into contact with the first area.

The first area, serving as the pressing element in-and-out rotating portion of the present invention, has the plural flat portions and the polygonal cross section. If the rollers are only brought into contact with the first area, by the rotation of the mandrel, the rollers are protruded radially of the frame when the rollers are brought into contact with portions between the flat portions of the first area (that is, the portions corresponding to the angles of the polygonal cross section). On the other hand, the rollers are retracted radially of the frame when the rollers are brought into contact with the flat portions (that is, the portions corresponding to the sides of the polygonal cross section). However, in this structure, the rollers are brought into contact with the second area serving as the rolling element rotating portion, without making contact with the flat portions of the first area. Also, the second area is of a tapered shape without any rough areas on its surface. By the rotation of the mandrel, the rollers can be rotated without being influenced by the flat portions formed in the first area. In other words, the rollers of the present invention are brought into contact with the second area without making contact with the flat portions of the first area. Thus, even when the first area includes the flat portions, with the rotation of the mandrel, the rollers can rotate without retracting radially. On the other hand, the balls of the present invention are only brought into contact with the first area. Thus, the bails move in and out radially while rotating with the rotation of the mandrel.

With this structure, therefore, in the dimple formation with the balls, the radial in-and-out movement of the rollers is prevented, thereby easily adjusting the dimple shape. Also, the rollers and the balls can be arranged on the same circumference, thereby allowing a further reduction in size of the tool as compared with a case where the rollers and the balls are separately arranged axially of the frame.

Also, the above-described structure preferably includes the following. The rolling element includes plural rollers and the pressing element includes plural special rollers. The plural rollers and special rollers are alternately spaced on the same circumference of the frame. Each roller and each special roller are both arranged with their respective axes parallel to an axis of the frame. Each of the special rollers has a ring rotating about an axis thereof and a pin holding the ring. The ring has an outer surface of a sharp-pointed shape. The rollers have a length greater than a thickness of the ring. The mandrel has on the tip side thereof a tapered portion gradually decreasing in diameter toward a tip of the mandrel. The tapered portion has a first area and a second area on an outer surface thereof. The first area serves as the pressing element in-and-out rotating portion. The second area is disposed on both sides of the first area in an axial direction of the mandrel and serves as the rolling element rotating portion. The first area has a plurality of circumferentially spaced-apart flat portions. The first area has a polygonal cross section, while the second area has a circular cross section. The flat portions have a length greater than the thickness of the ring and smaller than the length of each roller. When the frame is attached to the mandrel, the rollers are brought into contact with the second area without making contact with the flat portions of the first area, while the ring is only brought into contact with the first area.

The first area, serving as the pressing element in-and-out rotating portion of the present invention, has the plural flat portions and the polygonal cross section. If the rollers are only brought into contact with the first area, by the rotation of the mandrel, the rollers are protruded radially of the frame when the rollers are brought into contact with portions between the flat portions of the first area (that is, the portions corresponding to the angles of the polygonal cross section). On the other hand, the rollers are retracted radially of the frame when the rollers are brought into contact with the flat portions (that is, the portions corresponding to the sides of the polygonal cross section). However, in this structure, the rollers are brought into contact with the second area serving as the rolling element rotating portion, without making contact with the flat portions of the first area. Also, the second area is of a tapered shape without any rough areas on its surface. By the rotation of the mandrel, the rollers can be rotated without being influenced by the flat portions formed in the first area. In other words, the rollers of the present invention are brought into contact with the second area without making contact with the flat portions of the first area. Thus, even when the first area includes the flat portions, with the rotation of the mandrel, the rollers can rotate without retracting radially. On the other hand, the rings of the present invention are only brought into contact with the first area. Thus, the rings move in and out radially while rotating with the rotation of the mandrel.

With this structure, therefore, in the dimple formation with the rings, the radial in-and-out movement of the rollers is prevented, thereby easily adjusting the dimple shape. Also, the rollers and the rings can be on the same circumference, thereby allowing a further reduction in size of the tool as compared with a case where the rollers and the rings are separately arranged axially of the frame. Additionally, in this structure, the ring is used as the pressing element. The ring rotates about the axis and has an outer surface of a sharp-pointed shape, thereby allowing a further reduction in the dimple width as compared with a case where the ball is used as the pressing element.

Moreover, the above-described structure may further include a tool diameter adjusting mechanism for adjusting a tool diameter that is a diameter of a first enveloping circle connecting peripheries of the plural rollers. This structure is convenient because the processing dimension of the inner surface of the workpiece can be adjusted. In addition, preferably, the tool diameter adjusting mechanism includes a mechanism in which, at the time of retracting the dimple-forming burnishing tool from the inner surface of the workpiece, the burnishing tool receives the resistance from the inner surface of the workpiece, thereby relatively moving the frame and the mandrel in the axial direction to automatically reduce the tool diameter. This is because it is possible to prevent redundant dimples from being formed at the time of retracting the dimple-forming burnishing tool from the inner surface of the workpiece.

Also, the above-described structure preferably includes the following. The rolling element includes plural rollers. The plural rollers are spaced from one another on a first circumference of the frame. Each roller is arranged with its axes parallel to an axis of the frame. The pressing element includes plural balls. The plural balls are spaced from one another on a second circumference of the frame. The second circumference is apart axially of the frame from the first circumference. The mandrel gradually decreases in diameter toward a tip thereof. The mandrel has a tapered portion serving as the rolling element rotating portion and a stepped shaft portion lower than the tapered portion. The stepped shaft portion is externally fitted with a retainer. The retainer holds plural rotators that are driven by the rotation of the mandrel and serves as the pressing element in-and-out rotating portion. The retainer holds the plural rotators such that the rotators are spaced from one another on the same circumference of the retainer and such that each of the rotators protrudes partially through an outer surface of the retainer. When the frame is attached to the mandrel, the rollers are brought into contact with the tapered portion, while the balls are brought into contact with the retainer holding the plural rotators.

With this structure, since the tapered portion serving as the rolling element rotating portion has contact with the rollers, the rollers rotate with the rotation of the mandrel, while the rollers are prevented from moving in and out radially. On the other hand, the retainer serving as the pressing element in-and-out rotating portion holds the plural rotators, and the balls are brought into contact with the retainer. Thus, when the retainer rotates to bring the balls into contact with the rotators held by the retainer, the balls is protruded radially of the frame. On the other hand, when the balls are brought into contact with portions in between the rotators held by the retainer, the balls are retracted radially of the frame.

In this manner, with this structure, in the dimple formation with the balls, the radial in-and-out movement of the rollers is prevented, thereby easily adjusting the dimple shape. Also, the roller and the ball are arranged apart axially of the frame from each other (in a longitudinally-displaced manner). Therefore, even in a case where there is a notch in the inner surface of the workpiece, the roller can be brought into contact with the notch. Thus, an advantage is also obtained that the sun-and-planet motion of the frame is maintained, thereby stabilizing the dimple formation.

Additionally, the above-described structure preferably further includes a tool diameter adjusting mechanism and a protrusion amount adjusting mechanism. The tool diameter adjusting mechanism adjusts a tool diameter that is a diameter of a first enveloping circle connecting peripheries of the plurality of rollers. The protrusion amount adjusting mechanism adjusts a protrusion amount that is an amount of a second enveloping circle connecting peripheries of the plurality of balls which protrudes radially of the frame beyond the first enveloping circle. The protrusion amount adjusting mechanism is preferably designed to adjust the protrusion amount to a different value without change in the tool diameter.

This structure is provided with the tool diameter adjusting mechanism, thereby allowing adjustment of the tool diameter to a desired value. Also, the protrusion amount adjusting mechanism adjusts the protrusion amount to a different value without change in the tool diameter, thereby allowing the dimple depth. In other words, with this structure, even when the inner surface of the workplace is the same in finished diameter, dimples having different depths can be formed. Therefore, an optimum dimple shape to meet the conditions of use can be formed. In addition, preferably, the tool diameter adjusting mechanism includes a mechanism in which, at the time of retracting the dimple-forming burnishing tool from the inner surface of the workplace, the burnishing tool receives the resistance from the inner surface of the workpiece, thereby relatively moving the frame and the mandrel in the axial direction to automatically reduce the tool diameter. This is because it is possible to prevent redundant dimples from being formed at the time of retracting the dimple-forming burnishing tool from the inner surface of the workplace.

It should be noted that the protrusion amount described herein refers to the amount of the second enveloping circle connecting the peripheries of the plural balls which protrudes radially of the frame beyond the first enveloping circle connecting the peripheries of the plural rollers. Therefore, obviously, the protrusion amount is determined by (second enveloping circle diameter−first enveloping circle diameter)/2.

Furthermore, in the above-described structure, the tool diameter adjusting mechanism is preferably designed to simultaneously move the plural rollers and balls radially of the frame and adjust the tool diameter without change in the protrusion amount.

With this structure in which the protrusion amount is not changed at the time of adjusting the tool diameter, the diameter of the second enveloping circle connecting the peripheries, of the plural balls decreases with decrease of the tool diameter, while the diameter of the second enveloping circle increases with increase of the tool diameter. Consequently, in a case, as for example where the inner surface of the workpiece is processed by the dimple-forming burnishing tool according to the present invention, as the tool diameter is decreased by the tool diameter adjusting mechanism at the time of returning the burnishing tool to an initial position, the diameter of the second enveloping circle also decreases. Consequently, the redundant dimple formation in the inner surface of the workpiece in the process of returning the burnishing tool is avoided.

Moreover, the above-described structure preferably includes the following. The protrusion amount adjusting mechanism is externally fitted to the stepped shaft portion, and has plural adjustable rings. The plural adjustable rings adjust an axial position of the retainer to a predetermined position. The rotators have an outer surface of a tapered shape gradually decreasing in diameter toward a tip thereof. A diameter of a third enveloping circle connecting peripheries of the plural rotators changes according to the axial position of the retainer. Also, the protrusion amount is adjusted by change of the axial position of the retainer.

With this structure, the protrusion amounts of the balls can be adjusted by easily rearranging the adjustable rings and setting the axial position of the retainer to a predetermined position. More specifically, according to this structure, by changing the axial position of the retainer, the diameter of the third enveloping circle is changed at one position in the axial direction (for example, at a position corresponding to the intersection of a vertical line drawn from a center point of the ball toward a central axis of the retainer and the central axis of the retainer). With a change in the diameter of the third enveloping circle, the engaging position in the radial direction between the ball and the rotator changes. That is to say, the engaging position between the ball and the rotator moves outward in the radial direction (in other words, the radially protruding amount of the ball increases) with increasing diameter of the third enveloping circle. Consequently, the protrusion amounts of the balls can be adjusted by adjusting the axial position of the retainer.

Also, the balls are moved in and out radially by engagement with the rotators, thereby allowing a reduction in a distance that the pressing element is pressed, as compared with the related art structure in which protrusions of the mandrel having the polygonal cross section cause the pressing element to move radially in and out. Therefore, the dimple length can be also reduced.

In addition, preferably, the tapered portion and the rotators have the same taper angle.

With this structure, because the taper angles are the same, when the tool diameter adjusting mechanism adjust the tool diameter, the diameter of the first enveloping circle connecting the peripheries of the plural rollers and the diameter of the second enveloping circle connecting the peripheries of the plural balls increase or decrease by the same value. Consequently, the tool diameter adjustment is facilitated.

According to the present invention, there is provided the dimple adjusting mechanism that allows the only pressing element to move in and out radially of the frame while preventing the rolling element from moving in and out radially of the frame. Thus, the dimple shape can be easily adjusted.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will be described in detail based on the following drawings, wherein:

FIG. **1** illustrates, in a partially-sectioned view, the general structure of a dimple-forming burnishing tool according to a first embodiment of the present invention;

FIG. **2** is a sectional view taken along line A-A of FIG. **1**, with the dimple-forming burnishing tool shown in FIG. **1** disposed inside an inner surface of a workpiece;

FIG. **3** is an enlarged sectional view of the essential parts taken along line B-B of FIG. **1**;

FIG. **4** is illustrates, in a partially-sectioned view, the general structure of a dimple-forming burnishing tool according to a second embodiment of the present invention;

FIG. **5** is a sectional view taken along line C-C of FIG. **4**, with the dimple-forming burnishing tool shown in FIG. **4** disposed inside the inner surface of the workpiece;

FIG. **6** is a detail view of a special roller shown in FIG. **4**;

FIGS. **7**A and **7**B respectively illustrate the shape of dimples formed by the dimple-forming burnishing tool shown in FIG. **4**, and the shape of dimples formed by a dimple-forming burnishing tool according to the related art;

FIG. **8** is a general front view of a dimple-forming burnishing tool according to a third embodiment of the present invention;

FIG. **9** illustrates, in a partially-sectioned view, the general structure of the dimple-forming burnishing tool shown in FIG. **8**;

FIG. **10** is a sectional view taken along line D-D of FIG. **8**, with the dimple-forming burnishing tool shown in FIG. **8** disposed inside the inner surface of the workpiece;

FIG. **11** is a sectional view taken along line E-E of FIG. **8**, with the dimple-forming burnishing tool shown in FIG. **8** disposed inside the inner surface of the workpiece;

FIGS. **12**A and **12**B respectively illustrate the shape of dimples formed by the dimple-forming burnishing tool shown in FIG. **8**, and the shape of dimples formed by a dimple-forming burnishing tool according to the related art;

FIG. **13** is a general front view of a dimple-forming burnishing tool according to a first modification; and

FIG. **14** is a general front view of a dimple-forming burnishing tool according to a second modification.

DETAILED DESCRIPTION

Hereinafter, a dimple-forming burnishing tool according to embodiments of the present invention will be described in detail with reference to the accompanying drawings as appropriate. For the sake of convenience, the dimple-forming burnishing tool will be just referred to as "burnishing tool". Firstly, a burnishing tool according to a first embodiment of the present invention will be described with reference to FIGS. **1** to **3**. As shown in FIG. **1**, the burnishing tool **1** according to the first embodiment is composed of: a mandrel **30** attached to a processing machine, such as a lathe, not shown, for rotation; a frame **40** externally fitted to the mandrel **30**; and a tool diameter adjusting mechanism **10** to adjust a tool diameter.

As shown in FIG. **1**, the mandrel **30** is generally formed into a round-bar shape. The mandrel **30** has: on a rear-end side thereof a shank **32** attached to a processing machine (not shown), such as a lathe; on a tip side thereof a tapered portion **33**; and in a substantially central portion thereof a main body **31**. The tapered portion **33** has a tapered shape gradually decreasing in diameter toward the tip thereof (the left side in FIG. **1**). The tapered portion **33** includes a first area **33***a* formed in a substantially central portion thereof, and a second area **33***b* formed in front and in the rear (i.e., left and right in FIG. **1**) of the first area **33***a* in an axial direction of the mandrel **30**.

The second area **33***b* is circular in an arbitrary section and shaped like a circular-truncated cone. The outer surface of the second area **33***b* has no rough areas. On the other hand, the outer surface of the first area **33***a* is formed with plural flat portions **36** each having a flat surface and slightly recessed in an outer surface thereof. More specifically, the sixteen flat portions **36** are closely spaced apart circumferentially of the mandrel **30**. Therefore, the portions of the outer surface of the first area **33***a* which corresponds to the flat portions **36** are slightly recessed. Also, the portions in between the flat portions **36** correspond to protrusions **35** protruding slightly through the flat portions **36**. Consequently, as shown in FIG. **2**, the cross section of the first area **33***a* is of a polygonal shape (namely, a nearly regular hexadecagon) with the protrusions **35** as angles and the flat portions **36** as sides. It should be noted that a surface of slight curvature is formed between the flat portions **36** and the protrusions **35** so as to allow a ball **42** to roll smoothly.

As will be described in more detail later, it should be noted that, when the frame **40** is externally fitted to the mandrel **30**, a roller (a rolling element) **41** is disposed in such a manner as to extend across the first area **33***a* and the second areas **33***b* so that the roller **41** is brought into contact with the second areas **33***b* without making contact with the flat portion **36**. On the other hand, the ball (the pressing element) **42** is only brought into contact with the first area **33***a*. Also note that the shank **32** may have various shapes, including a tapered shape, of fitting a processing machine to be attached thereto, in addition to a straight shape such as is shown in this embodiment.

Next, the frame **40** is of a cylindrical shape. The frame **40** rotatably holds the plural rollers **41**, and also rotatably holds the plural balls **42** in such a manner that the balls **42** can move radially in and out of an outer surface of the frame **40**. More specifically, the eight rollers **41** and the eight balls **42** are alternately spaced on the same circumference of the frame **40**. It should be noted that the rollers **41** are mounted to the frame **40**, with their axes parallel to an axis of the frame **40**.

Note that: the length L**1** of the roller **41** is larger than diameter D**1** of the ball **42**; the length L**2** of the flat portion **36** is larger than the diameter D**1** of the ball **42**; and the length L**1** of the roller **41** is larger than the length L**2** of the flat portion **36**. Hence, the relationship of $D1<L2<L1$ is established. Therefore, as shown in FIG. **3**, both ends of the roller **41** are brought into contact with the second areas **33***b*, so that slight clearance CL is made between a substantially central portion of the roller **41** and the flat portion **36**. In other words, both end portions of the roller **41** are supported by the second areas **33***b* so that the central portion of the roller **41** is prevented from contact with the surface of the flat portion **36**.

It should be noted that the length L**1** of the roller **41** is always of such length as to straddle the flat portion **36** even when the relative positions in the axial direction of the mandrel **30** and the frame **40** are changed by the tool diameter adjusting mechanism **10** (described in detail later). That is to say, even if the tool diameter adjusting mechanism **10** is operated, the roller **41** is always prevented from contact with the surface of the flat portion **36**. Also, the roller **41** is of a tapered shape gradually slightly decreasing in diameter from one end (the left end in FIG. **3**) toward the other end (the right end in FIG. **3**). That is, the roller **41** has diameter D**2** of the left end slightly larger than diameter D**3** of the right end. As for the direction that the roller **41** is mounted to the frame **40**, one end (the end having the larger diameter) of the roller **41** corresponds to the tip side of the burnishing tool **1**, and the other end (the end having the smaller diameter) corresponds to the rear-end side of the burnishing tool **1**.

As shown in FIG. **2**, when the burnishing tool **1** is inserted into a workpiece W, the rollers **41** and the balls **42** are interposed between the outer surface of the tapered portion **33** of the mandrel **30** and the inner surface of the workpiece W.

It should be noted that, because the mandrel **30**, the rollers **41**, the balls **42**, and the frame **40** are required to have high durability, special alloy steel is used. The special alloy steel undergoes heat treatment to improve the hardness and tenacity. Also, according to the conditions of use, the surface coating processing, such as DLC, TIN, or TICN, may be performed, thereby allowing further improvement in the durability.

Next, the tool diameter adjusting mechanism **10** is designed to adjust the diameter (diameter DA in FIG. **2**) of a first enveloping circle connecting the peripheries of the rollers **41**. As shown in FIG. **1**, the inside of the tool diameter adjusting mechanism **10**, covered with a housing **13**, a front cap **14**, and a thick adjustable ring **12**, is provided with an adjustable nut **11**, a key **26**, a bearing **25**, a spring **21** and the like. The adjustable nut **11** is provided with an internal thread **11***a* to engage a threaded portion **31***a*, and also provided around its periphery with external teeth **17**. Also, an abutting surface to abut on the bearing **25** is formed on a front end of the adjustable nut **11**. The thick adjustable ring **12** is rotatably and non-removably supported on the adjustable nut **11** by a snap ring **15**. The thick adjustable ring **12** is freely fitted to the main body **31** of the mandrel **30** with a predetermined clearance therebetween, and provided on its periphery with external teeth **18** similar to the external teeth **17** of the adjustable nut **11**. It should be noted that the thick adjustable ring **12** is restrained by the key **26** from moving circumferentially of the mandrel **30**.

The housing **13** is formed in a cylindrical shape. Within the housing **13**, there are provided internal teeth **19** and internal teeth **20** which engage the external teeth **17** and the external teeth **18**, respectively. Also, the front cap **14** is disposed in front of the housing **13**. The spring **21** is interposed between a retaining ring **24** attached to the vicinity of a rear end of the frame **40** and an inner surface of the front cap **14**. Note that reference signs **22** and **23** denote spring seats, which are designed to effectively hold the spring **21**. Also, reference sign **16** denotes a thrust ring, which is disposed so as to allow the smooth sliding between the spring seat **23** and the front cap **14** when the housing **13** rotates.

In order to adjust the tool diameter with the tool diameter adjusting mechanism **10** constructed in this manner, firstly, the housing **13** is grasped to move the housing **13** rearward against the force of the spring **21**. The housing **13** moves with the internal teeth **19** and **20** of the housing **13** in engagement with the external teeth **17** of the adjustable nut **11** and the external teeth **18** of the thick adjustable ring **12**, respectively. When the housing **13** further moves, the engagement between the internal teeth **20** and the external teeth **18** is released. In this state, the external teeth **17** remain in engagement with the internal teeth **19** because the internal teeth **19** are provided in wide widths.

And then the housing **13** is rotated while being pressed rearward. The internal teeth **19** and the external teeth **17** remain in engagement. Also, the internal teeth **20**, removed from engagement with the external teeth **18**, are free to rotate. Therefore, when the housing **13** turns, the housing **13** and the adjustable nut **11** are rotated together, so that the adjustable nut **11** moves forward or rearward along a thread lead with respect to the threaded portion **31***a* of the mandrel **30**. At this time, since the adjustable nut **11** and the thick adjustable ring **12** are turnably locked by the snap ring **15**, the thick adjustable ring **12** moves along the mandrel **30** with the key **26** as the adjustable nut **11** moves longitudinally while rotating.

The longitudinal movement of the adjustable nut **11** is relatively the equivalent of longitudinally moving the mandrel **30**. Therefore, this movement causes the contact position between the tapered portion **33** of the mandrel **30** and the rollers **41** to move to a tip or a base (a rear end) of the burnishing tool **1**. Thus, according to changes in diameter of the tapered portion **33**, the diameter (the diameter DA in FIG. **2**) of the first enveloping circle connecting the peripheries of the rollers **41** changes to a desired value.

After the rollers **41** are set to a desired value, the housing **13** is released to cause the spring **21** previously under compression to expand and force the front cap **14** forward. Thus, the housing **13** is unitarily moved forward, and stopped by abutting the thick adjustable ring **12**. In this state, the internal teeth **19** and **20** of the housing **13** are in engagement with the external teeth **17** of the adjustable nut **11** and the external teeth **18** of the thick adjustable ring **12**, respectively. Also, the rotation of the thick adjustable ring **12** is prevented by the key **26** and a keyway. Thus, the relative rotation of the housing **13** with respect to the mandrel **30** is avoided. In this manner, the tool diameter adjustment is completed.

Next, processes for forming dimples in the inner surface of the workpiece W will be described using the burnishing tool **1**, constructed as described above.

<Adjustment process>

In an adjustment process, firstly, the tool diameter of the rollers **41** is adjusted. More specifically, in order to adjust the tool diameter, the housing **13** is moved to a driving side of the mandrel **30**, i.e., the side of the shank **32**. Then, since the tool diameter is increased by turning the housing **13** to the right and decreased by turning the housing **13** to the left, the housing **13** is turned to the right or left to set a desired tool diameter. After the housing **13** has been turned to a position corresponding to a desired tool diameter, releasing the housing **13** causes the housing **13** to return to an initial position under the restoring force of the spring **21**, and the housing **13** is automatically locked against rotation. Thus, the tool diameter is set. And then tips of the rollers **41** are measured by a micrometer to check whether the tool diameter is properly set.

<Machining process>

In a machining process, firstly, the shank **32** is attached to a processing machine. Then the burnishing tool **1** is moved to a dimple forming location of the inner surface of the workpiece W. It should be noted that the machining length of the workpiece W using the burnishing tool **1** can be arbitrarily set by simply changing the stroke control settings of the processing machine. Next, the processing machine is driven to start the rotation of the mandrel **30**. For example, when the mandrel **30** is rotated clockwise as seen from the tip side thereof, each of the rollers **41** rotates counterclockwise (on its axis) along the outer surface of the mandrel **30**. At this time, since the workpiece W is fixed, the counterclockwise rotation of the rollers **41** causes the rollers **41** to revolve clockwise around the inner surface of the workpiece W and the outer surface of the tapered portion **33** of the mandrel **30**.

As described above, each of the rollers **41** is disposed in contact with the outer surface of the second areas **33***b* in a manner straddling the flat portion **36**, thereby preventing the roller **41** from contact with the flat portion **36** of the first area **33***a* in all rotational positions of the mandrel **30**. Consequently, although the roller **41** is rotated by the rotation of the mandrel **30**, the roller **41** is prevented from moving radially of the frame **40**, thereby allowing an operator to stably perform burnishing of the inner surface of the workpiece W with the rollers **41**.

On the other hand, as for the balls **42**, its movement caused by the rotation of the mandrel **30** is slightly different from the rollers **41**. In the same manner as the rollers **41**, with the rotation of the mandrel **30**, each of the balls **42** revolves clockwise while rotating counterclockwise on its axis along the outer surface of the tapered portion **33** of the mandrel **30**. However, when the ball **42** revolves around the mandrel **30** while rotating in a state of being sandwiched between the inner surface of the workpiece W and the outer surface of the tapered portion **33**, the ball **42** moves through the flat portions **36** formed on the first area **33***a* and the protrusions **35** alternately. Therefore, the ball **42** rolls along the inner surface of the workpiece W while vibrating radially of the frame **40** due to the differences in height (the clearance CL in FIG. **3**) between the flat portions **36** and the protrusions **35**. This radial in-and-out movement of the ball **42** forms dimples in the inner surface of the workpiece W.

It should be noted that the first area **33***a*, having the function of causing the balls **42** to rotate while moving in and out radially of the frame **40**, corresponds to a pressing element in-and-out rotating portion of the present invention. Also, the second area **33***b*, having the function of causing the rollers **41** to rotate without moving in and out radially of the frame **40**, corresponds to a rolling element rotating portion of the present invention. Additionally, the tapered portion **33** having the first area **33***a* and the second area **33***b* corresponds to a dimple adjusting mechanism of the present invention.

<Tool retraction/removal process>

In a tool retraction/removal process, firstly, the burnishing tool **1** is moved out of the inner surface of the workpiece W. At this time, in the burnishing tool **1**, the spring **21** is moved into an extended position due to the frictional force (resistance) between the spring **21** and the inner surface of the workpiece W to thereby relatively move the frame **40** forward of the mandrel **30**. Then the value of the diameter DA of the first enveloping circle connecting the peripheries of the rollers **41**, i.e., the tool diameter, is automatically reduced. Thus, formation of redundant dimples in the process of returning the burnishing tool **1** to an initial position is avoided. Thereafter, when the burnishing tool **1** is returned to the initial position and removed from the processing machine, the dimple formation processes end.

In this manner, in the burnishing tool **1** according to the first embodiment, the rollers **41** are prevented from moving radially of the frame **40**, thereby stabilizing the rotational motion in the workpiece W of the rollers **41**. Thus, in the dimple formation, a proper dimple shape to meet the conditions of use can be formed simply by adjusting the shape, machining conditions, etc., of the balls **42** as appropriate. As a result, excellent lubricating properties are imparted to the inner surface of the workpiece W.

Also, in the burnishing tool **1** according to the first embodiment, the peening effect can increase the surface hardness of the inner surface of the workpiece W and apply compressive residual stress to the work surface, thereby improving the fatigue strength of the work surface. In addition, with the structure in which the balls **42** are used as pressing elements, in a case as for example where oil holes are formed in a direction crossing the inner surface of the workpiece W, the balls **42** abut or press against edge portions around the oil holes, thereby allowing removal of burrs on the edge portions of the oil holes at the same time.

Furthermore, in the burnishing tool **1** according to the first embodiment, the balls **42** and the rollers **41** can be arranged on the same circumference, thereby allowing a reduction in size of the tool **1**.

Next, a burnishing tool **101** according to a second embodiment of the present invention will be described with reference to FIGS. **4** to **7**. It is to be noted that the same elements as those of the burnishing tool **1** according to the foregoing first embodiment are designated by the same reference signs, and a description thereof will not be repeated.

A major feature of the burnishing tool **101** according to the second embodiment is that special rollers **142** are used as pressing elements in place of the balls **42**. As shown in FIG. **4**, the burnishing tool **101** is constructed in such a manner that rollers (rolling elements) **141** and the special rollers (pressing elements) **142** are alternately arranged on the same circumference of a cylindrical frame **140**. More specifically, as shown in FIG. **5**, the eight rollers **141** and the eight special rollers **142**, alternately arranged with equal spacing, are rotatably held by the frame **140**. Furthermore, the rollers **141** and the special rollers **142** are both directed parallel to an axis of the frame **140**. Also, the rollers **141** and the special rollers **142** are both of same length L**3**.

As shown in FIG. **6**, each of the special rollers **142** is composed of a pair of pins **142***b* and a ring **142***a* which are coaxially arranged. The ring **142***a* is supported in such a manner as to be free to rotate about the axis. The ring **142***a* is provided with a through hole **142***a*-**2**, and has an outer surface of a sharp-pointed shape **142***a*-**1**. It should be noted that, when the frame **140** is attached to the mandrel **30**, the ring **142***a* is disposed in a position corresponding to the first area **33***a* of the mandrel **30**. Thus, the ring **142***a* engages the flat portions **36** and the protrusions **35** alternately while rotating with the rotation of the mandrel **30**, and thereby moves in and out radially of the frame **140**. The radial in-and-out movement of the ring **142***a* forms dimples in the inner surface of the workpiece W.

Note that: thickness T**1** of the ring **142***a* is smaller than the length L**3** of the roller **141**, and smaller than the length L**2** of the flat portion **36** formed on the first area **33***a* of the mandrel **30**; and the length L**3** of the roller **141** is larger than the length L**2** of the flat portion **36**. Hence, the relationship of T**1**<L**2**<L**3** is established. Therefore, while not shown in the figure, in the same manner as the first embodiment, both ends of the roller **141** are brought into contact with the second areas **33***b* of the tapered portion **33** of the mandrel **30**, so that the slight clearance CL (see FIG. **3**) is formed between a substantially central portion of the roller **141** and the flat portion **36**. In other words, both ends of the roller **141** are supported by the second areas **33***b* so that the central portion of the roller **141** is prevented from contact with the surface of the flat portion **36**. Consequently, although the roller **141** is rotated by the rotation of the mandrel **30**, the roller **141** is prevented from moving in and out radially of the frame **140**.

It should be noted that the length L**3** of the roller **141** is always of such length as to straddle the flat portion **36** even when the relative positions in the axial direction of the mandrel **30** and the frame **140** are changed by the tool diameter adjusting mechanism **10**. That is to say, even if the tool diameter adjusting mechanism **10** is operated, the roller **141** is always prevented from contact with the surface of the flat portion **36**. Also, the roller **141** is of a tapered shape gradually slightly decreasing in diameter from one end (the left end in FIG. **4**) toward the other end (the right end in FIG. **4**).

As shown in FIG. **5**, when the burnishing tool **101** is inserted into the workpiece W, the rollers **141** and the rings **142***a* are interposed between the outer surface of the tapered portion **33** of the mandrel **30** and the inner surface of the workpiece W.

It should be noted that, because the mandrel **30**, the rollers **141**, the rings **142***a*, the pins **142***b*, and the frame **140** are required to have high durability, special alloy steel is used. The special alloy steel undergoes heat treatment to improve the hardness and tenacity. Also, according to the conditions of use, the surface coating processing, such as DLC, TIN, or TICN, may be performed, thereby allowing further improvement in the durability.

In the burnishing tool **101** constructed in this manner, dimples can be formed by the same processes as the above-described burnishing tool **1**. FIG. **7**A illustrates the shape of actually-formed dimples. On the other hand, FIG. **7**B illustrates the shape of dimples formed by a dimple-forming burnishing tool according to the related art. As is clear from a comparison between FIG. **7**A and FIG. **7**B, according to the burnishing tool **101**, since the sharp-pointed shape **142***a***-1** of the ring **142***a* is pressed against the inner surface of the workpiece W to form dimples, the dimple width can be made smaller than the case in dimple formation using the balls. In other words, simply by employing the rings **142***a*, the dimple width can be suitably adjusted.

Next, a burnishing tool **201** according to a third embodiment of the present invention will be described with reference to FIGS. **8** to **12**. As shown in FIG. **8**, the burnishing tool **201** according to the third embodiment is composed of: a mandrel **230** attached to a processing machine, such as lathes, not shown, for rotation; a frame **240** externally fitted to the mandrel **230**; a tool diameter adjusting mechanism **210** to adjust a tool diameter; and a protrusion amount adjusting mechanism **203** to adjust a protrusion amount. Hereinafter, respective structures of the burnishing tool **201** will be described in detail with reference to FIGS. **9** to **11**.

As shown in FIG. **9**, the mandrel **230** is generally formed into a round-bar shape. The mandrel **230** has: on a rear-end side thereof a shank **232** attached to a processing machine (not shown), such as a lathe; on a tip side thereof, a first tapered portion **233***a*, a stepped shaft portion **234**, and a second tapered portion **233***b* in that order; and in a substantially central portion thereof a main body **231**. The first tapered portion **233***a* and the second tapered portion **233***b* are of the same shape, namely, a tapered shape gradually decreasing in diameter toward a tip thereof. Also, outer surfaces thereof are formed of smooth surfaces without any rough areas.

On the other hand, the stepped shaft portion **234** is of a solid round-bar shape having a diameter smaller than those of the first tapered portion **233***a* and the second tapered portion **233***b*, and forms a stepped portion lower than the first tapered portion **233***a* and the second tapered portion **233***b*. Also, a threaded portion **231***a* is formed in an outer surface of the main body **231**, and a keyway to fit a key **226** is provided along an axial direction of the main body **231**.

As will be described in more detail later, it should be noted that, when the frame **240** is externally fitted to the mandrel **230**, the first tapered portion **233***a* and the second tapered portion **233***b* are disposed in positions corresponding to rollers (rolling elements) **241**, while the stepped shaft portion **234** is disposed in a position corresponding to balls (pressing elements) **242**. Also, note that the shank **232** may have various shapes, including a tapered shape, capable of fitting a processing machine to be attached thereto, in addition to a straight shape such as is shown in this embodiment.

The frame **240** is of a cylindrical shape. The frame **240** rotatably holds the plural rollers **241** and the plural balls **242**. More specifically, the two rollers **241** and the single ball **242** are arranged in a row, spaced apart from one another, in order from the tip side, the roller **241**, the ball **242**, and the roller **241**. This row of the two rollers **241** and the single ball **242** is taken as a pair, and twelve pairs are evenly spaced circumferentially of the frame **240**. Also, the roller **241** is of a tapered shape gradually slightly decreasing in diameter from one end toward the other end. As for the direction that the roller **241** is mounted to the frame **240**, one end (the end having the larger diameter) of the roller **241** corresponds to the tip side of the burnishing tool **201**, and the other end (the end having the smaller diameter) corresponds to the rear-end side of the burnishing tool **201**.

As shown in FIG. **10**, when the burnishing tool **201** is inserted into the workpiece W, the balls **242** are interposed between an outer surface of a retainer **204** (described in detail later) externally fitted to the stepped shaft portion **234** of the mandrel **230** and the inner surface of the workpiece W. Also, as shown in FIG. **11**, the rollers **241** are interposed between the outer surface of the first tapered portion **233***a* of the mandrel **230** and the inner surface of the workpiece W. While not shown in the figure, the rollers **241** are interposed between the outer surface of the second tapered portion **233***b* of the mandrel **230** and the inner surface of the workpiece W.

It should be noted that, because the mandrel **230**, the rollers **241**, the balls **242**, and the frame **240** are required to have high durability, special alloy steel is used. The special alloy steel undergoes heat treatment to improve the hardness and tenacity. Also, according to the conditions of use, the surface coating processing, such as DLC, TIN, or TION, may be performed, thereby allowing further improvement in the durability.

Next, the tool diameter adjusting mechanism **210** is designed to adjust the diameter (diameter DA in FIG. **11**) of a first enveloping circle connecting the peripheries of the rollers **241**. The tool diameter adjusting mechanism **210** is the same as the tool diameter adjusting mechanism **10** mentioned above, i.e. reference numerals **211**, **211***a*, **212**, **214**, **215**, **216**, **217**, **218**, **219**, **220**, **222**, **223**, **224**, and **225** are the same as #**11**, **11***a*, **12**, **14**, **15**, **16**, **17**, **18**, **19**, **20**, **22**, **23**, **24**, and **25**, respectively. Therefore, the detailed description of the tool diameter adjusting mechanism **210** will not be repeated.

The protrusion amount adjusting mechanism **203** is designed to adjust a protrusion amount, that is, the amount of the diameter of the second enveloping circle connecting the peripheries of the balls **242** which protrudes radially beyond the diameter of the first enveloping circle connecting the peripheries of the rollers **241**. As shown in FIGS. **9** and **10**, the protrusion amount adjusting mechanism **203** is composed of: the retainer **204** that rotatably holds twelve rotators **205**; thin adjustable rings **206***a*, **206***b*, and **206***c* (corresponding to adjustable rings of the present invention) that are designed to adjust an axial position of the retainer **204**; a detent pin **207**; and a spacer **208**.

The retainer **204** is formed of a cylindrical member having a diameter slightly larger than that of the stepped shaft portion **234** of the mandrel **230**. The twelve rotators **205** are circumferentially arranged with equal spacing on an outer surface of the retainer **204**. Each of the rotators **205** is of a tapered shape gradually decreasing in diameter toward a tip thereof. Thus, when the retainer **204** is axially moved on the stepped shaft portion **234**, the diameter (diameter DC in FIG. **10**) of a third enveloping circle connecting the peripheries of the rotators **205** changes at position P in FIG. **9**. More specifically, when the retainer **204** is moved to the tip side (the left side in FIG. **9**) of the burnishing tool **201**, the diameter DC at the position P increases. When the retainer **204** is moved to the rear-end side (the right side in FIG. **9**) of the burnishing tool **201**, on the other hand, the diameter DC at the position P decreases. It should be noted that the position P corresponds to the intersection of a vertical line, drawn from the center point of the ball **242** to the central axis of the retainer **204**, and the central axis of the retainer **204**.

As is clear from FIG. **10**, the rotators **205** held by the retainer **204** are designed to engage the balls **242** held by the frame **240**. With this structure, as the diameter DC of the third enveloping circle connecting the peripheries of the rotators **205** increases, the protrusion amounts of the balls **242** that are radially protruded (pushed) by the rotators **205** increase. Thus, the diameter DB of the second enveloping circle connecting the peripheries of the balls **242** increases. On the other hand, since the diameter DA of the first enveloping circle connecting the peripheries of the rollers **241** is unchanged, the difference between the diameter DA and the diameter DB increases with the increase of the diameter DC. In other words, the protrusion amounts of the balls **242** increase. On the contrary, as the diameter DC decreases, the amounts of the balls **242** that are radially pushed by the rotators **205** decrease. Thus, the diameter DB decreases, so that the difference between the diameter DA and the diameter DB decreases. Consequently, the protrusion amounts of the balls **242** decrease. In this manner, the protrusion amounts of the balls **242** are adjusted.

It should be noted that the rotators **205** have the same taper angle as the first tapered portion **233***a* and the second tapered portion **233***b*. For this reason, when the mandrel **230** is axially moved, the diameter DA of the first enveloping circle connecting the peripheries of the rollers **241** and the diameter DB of the second enveloping circle connecting the peripheries of the balls **242** are simultaneously changed by the same value. Also, the retainer **204** is integrally mounted to the stepped shaft portion **234** through the detent pin **207** so that the retainer **204** is rotated within the frame **240** by the rotation of the mandrel **230**.

Also, the axial position of the retainer **204** can be changed by changing of mounting positions between the thin adjustable rings **206***a*, **206***b*, and **206***c*. Note that, in this embodiment, the thin adjustable ring **206***a* is ring-width t=1 mm; the thin adjustable ring **206***b*, ring-width t=1.5 mm; and the thin adjustable ring **206***c*, ring-width t=2 mm. For example, when the protrusion amount of the ball **242**, i.e., a value determined by (diameter DB−diameter DA)/2, is desired to be 20 μm, the thin adjustable ring **206***a* of t=1 mm is mounted on a rear-end side of the retainer **204**, and the remaining thin adjustable rings **206***b* and **206***c* are mounted on a tip side of the retainer **204**.

Alternatively, when the protrusion amount of the ball **242** is desired to be 22.5 μm, the thin adjustable ring **206***b* of t=1.5 mm is mounted on the rear-end side of the retainer **204**, and the remaining thin adjustable rings **206***a* and **206***c* are mounted on the tip side of the retainer **204**. Also, when the protrusion amount of the ball **242** is desired to be 25 μm, the thin adjustable ring **206***c* of t=2 mm is mounted on the rear-end side of the retainer **204**, and the remaining thin adjustable rings **206***a* and **206***b* are mounted on the tip side of the retainer **204**.

Alternatively, when the protrusion amount of the ball **242** is desired to be 27.5 μm, the thin adjustable ring **206***a* of t=1.0 mm and the thin adjustable ring **206***b* of t=1.5 mm are mounted on the rear-end side of the retainer **204**, and the remaining thin adjustable ring **206***c* is mounted on the tip side of the retainer **204**. Also, when the protrusion amount of the ball **242** is desired to be 30 μm, the thin adjustable ring **206***a* of t=1.0 mm and the thin adjustable ring **206***c* of t=2 mm are mounted on the rear-end side of the retainer **204**, and the remaining thin adjustable ring **206***b* is mounted on the tip side of the retainer **204**. Obviously, the number and ring widths of the thin adjustable rings may be set as appropriate depending on required specifications.

Processes for forming dimples in the inner surface of the workplace W will be described using the burnishing tool **201** constructed as described above.

<Adjustment process>

In an adjustment process, firstly, in order to adjust the protrusion amount of the ball **242**, the axial position of the retainer **204** is adjusted. More specifically, the thin adjustable rings **206***a*, **206***b*, and **206***c* are appropriately disposed in front and in the rear in the axial direction of the retainer **204** according to a selection of the above-described protrusion amounts of the ball **242**, that is, 20 μm, 22.5 μm, 25 μm, 27.5 μm, and 30 μm. By this process, adjustment of the protrusion amount of the ball **242** is completed.

Next, the tool diameter of the rollers **241** is adjusted. More specifically, in order to adjust the tool diameter, the housing **213** is moved to a driving side of the mandrel **230**, i.e., the side of the shank **232**. Then, since the tool diameter is increased by turning the housing **213** to the right and decreased by turning the housing **213** to the left, the housing **213** is turned to the right or left to set a desired tool diameter. After the housing **213** has been turned to a position corresponding to a desired tool diameter, releasing the housing **213** causes the housing **213** to return to an initial position under the restoring force of the spring **221**, and the housing **213** is automatically locked against rotation. Thus, the tool diameter is set. And then tips of the rollers **241** are measured by a micrometer to check whether the tool diameter is properly set.

<Machining process>

In a machining process, firstly, the shank **232** is attached to a processing machine. Then the burnishing tool **201** is moved to a dimple forming location of the inner surface of the workpiece W. It should be noted that the machining length of the workpiece W using the burnishing tool **201** can be arbitrarily set simply by changing the stroke control settings of the processing machine. Next, the processing machine is driven to start the rotation of the mandrel **230**. For example, when the mandrel **230** is rotated clockwise as seen from the tip side thereof, each of the rollers **241** rotates counterclockwise (on its axis) along the outer surface of the mandrel **230**. At this time, since the workpiece W is fixed, the counterclockwise rotation of the rollers **241** causes the roller **241** to revolve clockwise around the inner surface of the workpiece W and the outer surface of the mandrel **230**. At this time, the rollers **241** are prevented from moving in and out radially of the frame **240** because the outer surfaces of the first tapered portion **233***a* and the second tapered portion **233***b* have no rough areas. This allows an operator to stably perform burnishing of the inner surface of the workpiece W with the rollers **241**.

On the other hand, as for the balls **242**, its movement caused by the rotation of the mandrel **230** is slightly different from the rollers **241**. Each of the balls **242** revolves clockwise while rotating counterclockwise on its axis along the outer surface of the retainer **204** (in other words, along the third enveloping circle connecting the peripheries of the rotators **205**). When the ball **242** revolves around the mandrel **230** while rotating in a state of being sandwiched between the inner surface of the workpiece W and the outer surface of the retainer **204**, the ball **242** moves through the rotators **205** held by the retainer **204** and the outer surface of the retainer **204** alternately. Therefore, the ball **242** rolls along the inner surface of the workpiece W while vibrating radially of the frame **240** due to the differences in height between the outer surface of the retainer **204** and the rotators **205**. This radial in-and-out movement of the ball **242** forms dimples in the inner surface of the workpiece W.

It should be noted that the retainer **204** holding the plural rotators **205**, which has the function of causing the balls **242** to rotate while moving in and out radially of the frame **240**, corresponds to a pressing element in-and-out rotating portion of the present invention. Also, the first tapered portion **233***a* and the second tapered portion **233***b*, having the function of causing the rollers **241** to rotate without moving in and out radially of the frame **240**, correspond to a rolling element rotating portion of the present invention. Additionally, a dimple adjusting mechanism of the present invention is made up of the retainer **204** holding the rotators **205**, the first tapered portion **233***a*, and the second tapered portion **233***b*.

<Tool retraction/removal process>

In a tool retraction/removal process, firstly, the burnishing tool **201** is moved out of the inner surface of the workpiece W. At this time, in the burnishing tool **201**, the spring **221** is moved into an extended position due to the frictional force (resistance) between the spring **221** and the inner surface of the workpiece W to thereby relatively move the frame **240** forward of the mandrel **230**. Then the value of the diameter DA of the first enveloping circle connecting the peripheries of the rollers **241**, i.e., the tool diameter, is automatically reduced. Thus, formation of redundant dimples in the process of returning the burnishing tool **201** to an initial position is avoided. Thereafter, when the burnishing tool **201** is returned to the initial position and removed from the processing machine, the dimple formation processes end.

FIG. **12**A illustrates the shape of dimples formed in this manner. On the other hand, FIG. **12**B illustrates the shape of dimples formed by a burnishing tool according to the related art. As is clear from a comparison between FIGS. **12**A and **12**B, in the burnishing tool **201** according to the third embodiment, the protrusion amounts of the balls **242** can be adjusted without change in the tool diameter, thereby allowing adjustment of the dimple depth.

That is to say, in the burnishing tool **201** according to the third embodiment, a proper dimple shape to meet the conditions of use can be formed by adjusting the protrusion amounts of the balls **242**. As a result, excellent lubricating properties are imparted to the inner surface of the workpiece W.

Also, in the burnishing tool **201** according to the third embodiment, the peening effect can increase the surface hardness of the inner surface of the workpiece W and apply compressive residual stress to the work surface, thereby improving the fatigue strength of the work surface. In addition, with the structure in which the balls **242** are used as pressing elements, in a case as for example where oil holes are formed in a direction crossing the inner surface of the workpiece W, the balls **242** abut or press against edge portions around the oil holes, thereby allowing removal of burrs on the edge portions of the oil holes at the same time.

Furthermore, in the burnishing tool **201** according to the third embodiment, the rollers **241** are provided on the tip side and the rear-end side of the ball **242**. Therefore, even in a case, as for example where there is a notch in the inner surface of the workpiece W, at least one of the roller **241** on the tip side and the roller **241** on the rear-end side can be brought into contact with the inner surface of the workpiece W, thereby maintaining the sun-and-planet motion of the frame **240** and enabling the dimple formation.

Next, first and second modifications of the burnishing tool **201** according to the third embodiment will be described. It is to be noted that the same elements as those of the burnishing tool **201** are designated by the same reference signs, and a description thereof will not be repeated. Firstly, FIG. **13** illustrates a burnishing tool **301** according to the first modification. The main feature of the burnishing tool **301** is that the rollers **241** are not provided on the tip side further than the balls **242**. Even with this structure, in a case where there is a notch in the inner surface of the workpiece W, the rollers **241** disposed on the rear-end side further than the balls **242** can be brought into contact with the inner surface of the workpiece W, thereby maintaining the sun-and-planet motion of the frame **240** and enabling the dimple formation.

Also, FIG. **14** illustrates a burnishing tool **401** according to the second modification. The main feature of the second modification is that the rollers **241** are not provided on the rear-end side further than the balls **242**. Even with this structure, in a case where there is a notch in the inner surface of the workpiece W, the rollers **241** disposed on the tip side further than the balls **242** can be brought into contact with the inner surface of the workpiece W, thereby maintaining the sun-and-planet motion of the frame **240** and enabling the dimple formation.

Although embodiments and modifications of the present invention have been described above, it should be understood that the invention is not limited to the above-described embodiments and modifications, but may be practiced with various changes.

What is claimed is:

1. A dimple-forming burnishing tool comprising:

a mandrel; and

a cylindrical frame rotatably externally fitted on a tip side of the mandrel, the frame holding a rolling element and a pressing element, the rolling element and the pressing element being driven by rotation of the mandrel, for forming dimples in an inner surface of a workpiece by rotating the mandrel with the frame disposed inside the inner surface of the workpiece,

wherein:

the mandrel has a dimple adjusting mechanism, the dimple adjusting mechanism including:

a pressing element in-and-out rotating portion causing the pressing element to rotate while moving in and out radially of the frame; and

a rolling element rotating portion causing the rolling element to rotate without moving in and out radially of the frame,

the rolling element comprises a plurality of rollers and the pressing element comprises a plurality of balls, the plurality of rollers and balls being alternately spaced on the same circumference of the frame, each roller being arranged with its axis parallel to an axis of the frame;

the rollers have a length greater than a diameter of each ball;

the mandrel has on the tip side thereof a tapered portion gradually decreasing in diameter toward a tip of the mandrel;

the tapered portion has a first area and a second area on an outer surface thereof, the first area serving as the pressing element in-and-out rotating portion, the second area being disposed on both sides of the first area in an axial direction of the mandrel, the second area serving as the rolling element rotating portion;

the first area has a plurality of circumferentially spaced-apart flat portions, the first area having a polygonal cross section, while the second area having a circular cross section;

the flat portions have a length greater than the diameter of each ball and smaller than the length of each roller; and

when the frame is attached to the mandrel, the rollers are brought into contact with the second area without making contact with the flat portions of the first area, while the balls are only brought into contact with the first area.

2. The dimple-forming burnishing tool according to claim **1**, further comprising:

a tool diameter adjusting mechanism, the tool diameter adjusting mechanism adjusting a tool diameter, the tool diameter being a diameter of a first enveloping circle connecting peripheries of the plurality of rollers.

3. A dimple-forming burnishing tool comprising:

a mandrel; and

a cylindrical frame rotatably externally fitted on a tip side of the mandrel, the frame holding a rolling element and a pressing element, the rolling element and the pressing element being driven by rotation of the mandrel, for forming dimples in an inner surface of a workpiece by rotating the mandrel with the frame disposed inside the inner surface of the workpiece,

wherein:

the mandrel has a dimple adjusting mechanism, the dimple adjusting mechanism including:

a pressing element in-and-out rotating portion causing the pressing element to rotate while moving in and out radially of the frame; and

a rolling element rotating portion causing the rolling element to rotate without moving in and out radially of the frame;

the rolling element comprises a plurality of rollers and the pressing element comprises a plurality of special rollers, the plurality of rollers and special rollers being alternately spaced on the same circumference of the frame, each roller and each special roller being both arranged with their respective axes parallel to an axis of the frame;

each of the special rollers has a ring rotating about an axis thereof and a pin holding the ring, the ring having an outer surface of a sharp-pointed shape;

the rollers have a length greater than a thickness of the ring;

the mandrel has on the tip side thereof a tapered portion gradually decreasing in diameter toward a tip of the mandrel;

the tapered portion has a first area and a second area on an outer surface thereof, the first area serving as the pressing element in-and-out rotating portion, the second area being disposed on both sides of the first area in an axial direction of the mandrel, the second area serving as the rolling element rotating portion;

the first area has a plurality of circumferentially spaced-apart flat portions, the first area having a polygonal cross section, while the second area having a circular cross section;

the flat portions have a length greater than the thickness of the ring and smaller than the length of each roller; and

when the frame is attached to the mandrel, the rollers are brought into contact with the second area without making contact with the flat portions of the first area, while the ring is only brought into contact with the first area.

4. The dimple-forming burnishing tool according to claim **3**, further comprising:

a tool diameter adjusting mechanism, the tool diameter adjusting mechanism adjusting a tool diameter, the tool diameter being a diameter of a first enveloping circle connecting peripheries of the plurality of rollers.

5. A dimple-forming burnishing tool comprising:

a mandrel; and

a cylindrical frame rotatably externally fitted on a tip side of the mandrel, the frame holding a rolling element and a pressing element, the rolling element and the pressing element being driven by rotation of the mandrel, for foaming dimples in an inner surface of a workpiece by rotating the mandrel with the frame disposed inside the inner surface of the workpiece,

wherein:

the mandrel has a dimple adjusting mechanism, the dimple adjusting mechanism including:

a pressing element in-and-out rotating portion causing the pressing element to rotate while moving in and out radially of the frame; and

a rolling element rotating portion causing the rolling element to rotate without moving in and out radially of the frame,

the rolling element comprises a plurality of rollers, the plurality of rollers being spaced from one another on a first circumference of the frame, each roller being arranged with its axes parallel to an axis of the frame;

the pressing element comprises a plurality of balls, the plurality of balls being spaced from one another on a second circumference of the frame, the second circumference being apart axially of the frame from the first circumference;

the mandrel gradually decreases in diameter toward a tip thereof, the mandrel having a tapered portion serving as the rolling element rotating portion and a stepped shaft portion lower than the tapered portion;

the stepped shaft portion is externally fitted with a retainer, the retainer holding a plurality of rotators and serving as the pressing element in-and-out rotating portion, the plurality of rotators being driven by the rotation of the mandrel;

the retainer holds the plurality of rotators such that the rotators are spaced from one another on the same circumference of the retainer and such that each of the rotators protrudes partially through an outer surface of the retainer; and

when the frame is attached to the mandrel, the rollers are brought into contact with the tapered portion, while the balls are brought into contact with the retainer holding the plurality of rotators.

6. The dimple-forming burnishing tool according to claim **5**, further comprising:

a tool diameter adjusting mechanism that adjusts a tool diameter, the tool diameter being a diameter of a first enveloping circle connecting peripheries of the plurality of rollers; and

a protrusion amount adjusting mechanism that adjusts a protrusion amount, the protrusion amount being an amount of a second enveloping circle connecting peripheries of the plurality of balls which protrudes radially of the frame beyond the first enveloping circle,

wherein the protrusion amount adjusting mechanism adjusts the protrusion amount to a different value without change in the tool diameter.

7. The dimple-forming burnishing tool according to claim **6**,

wherein: the protrusion amount adjusting mechanism is externally fitted to the stepped shaft portion and has a plurality of adjustable rings, the plurality of adjustable rings adjusting an axial position of the retainer to a predetermined position;

the rotators have an outer surface of a tapered shape gradually decreasing in diameter toward a tip thereof;

a diameter of a third enveloping circle connecting peripheries of the plurality of rotators changes according to the axial position of the retainer; and

the protrusion amount is adjusted by change of the axial position of the retainer.

8. The dimple-forming burnishing tool according to claim **7**, wherein the tapered portion and the rotators have the same taper angle.

9. The dimple-forming burnishing tool according to claim **6**, wherein the tool diameter adjusting mechanism simultaneously moves the plurality of rollers and balls radially of the frame to adjust the tool diameter without change in the protrusion amount.

10. The dimple-forming burnishing tool according to claim **9**,

wherein: the protrusion amount adjusting mechanism is externally fitted to the stepped shaft portion and has a plurality of adjustable rings, the plurality of adjustable rings adjusting an axial position of the retainer to a predetermined position;

the rotators have an outer surface of a tapered shape gradually decreasing in diameter toward a tip thereof;

a diameter of a third enveloping circle connecting peripheries of the plurality of rotators changes according to the axial position of the retainer; and

the protrusion amount is adjusted by change of the axial position of the retainer.

11. The dimple-forming burnishing tool according to claim **10**, wherein the tapered portion and the rotators have the same taper angle.

12. A dimple-forming burnishing tool comprising:

a mandrel; and

a cylindrical frame rotatably externally fitted on a tip side of the mandrel, the frame holding a rolling element and a pressing element, the rolling element and the pressing element being driven by rotation of the mandrel, for forming dimples in an inner surface of a workpiece by rotating the mandrel with the frame disposed inside the inner surface of the workpiece,

wherein:

the mandrel has a dimple adjusting mechanism, the dimple adjusting mechanism including:

a pressing element in-and-out rotating portion causing the pressing element to rotate while moving in and out radially of the frame; and

a rolling element rotating portion causing the rolling element to rotate and to be fixed radially to the frame such that the rolling element rotates without moving in and out radially to the frame, and

the rolling element comprises a plurality of rollers and the pressing element comprises a plurality of balls, the plurality of rollers and balls being alternately spaced on the same circumference of the frame, and each roller being arranged with its axis parallel to an axis of the frame.

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