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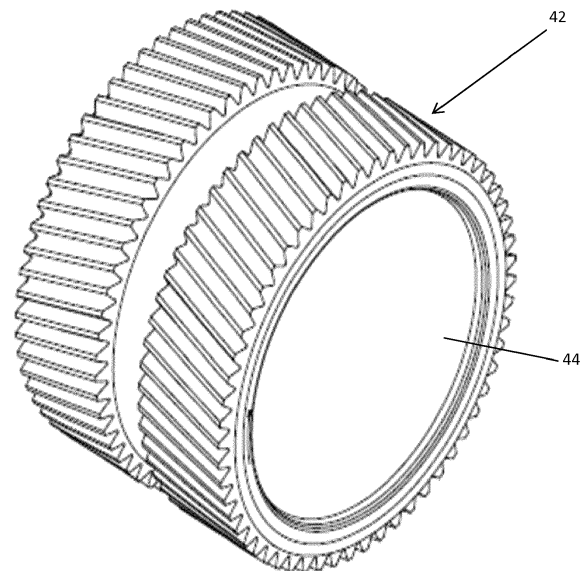
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(54) **GRINDING CYLINDRICAL BORES**

(57) Method of reducing the thickness of a bore of a cylindrical workpiece for use as a gear, with the method comprising the steps of: mounting a cylindrical workpiece having a horizontal central axis and an outer diameter in a grinding machine; and grinding the bore of the cylindrical workpiece to reduce its thickness using a grinding wheel that has a diameter that is from 40% to 80% of the outer diameter of the cylindrical bore and has a direction of rotation about an axis of rotation that is parallel to the horizontal central axis of the cylindrical workpiece. The axis of rotation of the grinding wheel may be located from 90 degrees to 180 degrees, in the direction of rotation of the grinding wheel, from a plane that extends vertically through the workpiece when it is mounted in the grinding machine. The gear may be one of a planetary, sun, parallel axis or helical gear.



**Fig. 4**

## Description

### Field of the Disclosure

**[0001]** The present disclosure relates to a method of grinding the internal bore of a gear, for example a gear for use in a gas turbine engine.

### Background of the Disclosure

**[0002]** Current gas turbine engines typically do not spin at optimal speeds as they are limited by the speed of the fan system. It is known that the use of a gearbox placed in between the fan and the compressors can overcome this problem. The gears of such a gear box have to be manufactured to exacting standards to achieve the performance criteria required in such an engine. This is because the gears are required to be strong enough in use to withstand the forces acting upon them and yet light enough so that they do not add drastically to the mass of the engine. To overcome the issues relating to strength, the gear systems typically employ double helical planet and sun gearing, i.e. both sides of the gear have helices running in perpendicular directions. However, a gear of this type requires a gap to be manufactured in the centre of the gear. This gap in turn adds weight and complexity to the gearbox. Consequently, there is a driver to reduce the weight of the gears and thus reduce the centrifugal force associated with the gears in the system.

**[0003]** A known method of reducing the mass of the gears involves grinding the internal bore to reduce its thickness. This, grinding also increases the bore accuracy, which provides an improved surface for the bearings to run on. Achieving accurate bearing surfaces results in an improved fit for the bearings themselves, which in turn reduces any imbalance in the system. Cylindrical grinders are able to perform this process. However, using cylindrical grinding machines results in a large number of manufacturing steps; this in turn increases the complexity of manufacturing the part. This is because cylindrical grinders are limited to a single function, but are much stiffer than other tools as typically they have fewer axes of movement. This conflicting set of features results in cylindrical grinders having the advantage of high conformance, but being limited in their use, as other machines are required to produce the other parts of the gear, such as the teeth.

**[0004]** The use of standard 5-axis machines, which are known for grinding the teeth of gears, however, typically they are not feasible for grinding the internal bore as they are usually dedicated for turning and milling operations. These operations can be the grinding of the gear faces, so that they are perpendicular to an outer surface of the gear. Certain 5-axis machines are nonetheless able to perform grinding operations; however, the grinding wheels in such instruments are susceptible to wear and are not as stable due to the slow speed of operation.

## Summary of the Disclosure

**[0005]** The present disclosure provides a method of reducing the thickness of a bore of a cylindrical workpiece for use as a gear, and a gas turbine engine including a gear that has a central bore ground by that method, as set out in the appended claims.

**[0006]** In a first aspect the present disclosure provides a method of reducing the thickness of a bore of a cylindrical workpiece for use as a gear; the method comprising the steps of:

mounting a cylindrical workpiece having a horizontal central axis and an outer diameter in a grinding machine; and  
grinding the bore of the cylindrical workpiece to reduce its thickness using a grinding wheel that has a diameter that is from 40% to 80% of the outer diameter of the cylindrical bore and has a direction of rotation about an axis of rotation that is parallel to the horizontal central axis of the cylindrical workpiece.

**[0007]** Utilising this method means that the internal bore may be ground on a standard 5-axis machine. This also means that the external teeth of the gear can be ground on the same machine; this reduces the number of set up steps that are required for the gear, which reduces production time. As well as this the other operations such as turning and milling can be performed all on the same machine. Importantly, this leads to a greater conformance as the errors created by changing and re-setting equipment are not present when performing multiple stages on the same piece of equipment. This is because the operator does not have to setup the datums again for each of the different pieces of equipment.

**[0008]** The axis of rotation of the grinding wheel may be located from 90 degrees to 180 degrees, in the direction of rotation of the grinding wheel, from a plane that extends vertically through the workpiece when it is mounted in the grinding machine.

**[0009]** The grinding machine for grinding the bore of the cylindrical workpiece may be performed on a 5-axis machining centre.

**[0010]** The bore may be rotated about a C-axis of the machine whilst the grinding wheel position is maintained stationary.

**[0011]** Gear teeth may be ground on an external surface of the cylindrical workpiece using the same grinding machining centre.

**[0012]** The faces of the cylindrical workpieces may be ground using the same grinding machining.

**[0013]** The gear may be one of a planetary, sun, parallel axis or helical gear.

**[0014]** Coolant may be provided to the grinding wheel and/or workpiece whilst in use to cool the grinding wheel.

**[0015]** Coolant may be applied to the grinding wheel and/or workpiece via a flat head nozzle.

**[0016]** Coolant may be applied to the grinding wheel

and/or workpiece in a range from 50 to 150 bar.

**[0017]** The internal bore may be reduced in thickness in three stages: a roughing stage; a semi-finishing stage; and a finishing stage.

**[0018]** The grinding process may be completed in fewer than 20 roughing steps within the roughing stage, fewer than 10 semi finishing steps within the semi finishing stage, and fewer than 5 finishing steps in the finishing stage.

**[0019]** In a second aspect the present disclosure provides a gas turbine engine that includes a gear that has a central bore ground by the above method.

**[0020]** As noted elsewhere herein, the present disclosure may relate to a gas turbine engine. Such a gas turbine engine may comprise an engine core comprising a turbine, a combustor, a compressor, and a core shaft connecting the turbine to the compressor. Such a gas turbine engine may comprise a fan (having fan blades) located upstream of the engine core.

**[0021]** Arrangements of the present disclosure may be particularly, although not exclusively, beneficial for fans that are driven via a gearbox. Accordingly, the gas turbine engine may comprise a gearbox that receives an input from the core shaft and outputs drive to the fan so as to drive the fan at a lower rotational speed than the core shaft. The input to the gearbox may be directly from the core shaft, or indirectly from the core shaft, for example via a spur shaft and/or gear. The core shaft may rigidly connect the turbine and the compressor, such that the turbine and compressor rotate at the same speed (with the fan rotating at a lower speed).

**[0022]** The gas turbine engine as described and/or claimed herein may have any suitable general architecture. For example, the gas turbine engine may have any desired number of shafts that connect turbines and compressors, for example one, two or three shafts. Purely by way of example, the turbine connected to the core shaft may be a first turbine, the compressor connected to the core shaft may be a first compressor, and the core shaft may be a first core shaft. The engine core may further comprise a second turbine, a second compressor, and a second core shaft connecting the second turbine to the second compressor. The second turbine, second compressor, and second core shaft may be arranged to rotate at a higher rotational speed than the first core shaft.

**[0023]** In such an arrangement, the second compressor may be positioned axially downstream of the first compressor. The second compressor may be arranged to receive (for example directly receive, for example via a generally annular duct) flow from the first compressor.

**[0024]** The gearbox may be arranged to be driven by the core shaft that is configured to rotate (for example in use) at the lowest rotational speed (for example the first core shaft in the example above). For example, the gearbox may be arranged to be driven only by the core shaft that is configured to rotate (for example in use) at the lowest rotational speed (for example only be the first core shaft, and not the second core shaft, in the example

above). Alternatively, the gearbox may be arranged to be driven by any one or more shafts, for example the first and/or second shafts in the example above.

**[0025]** In any gas turbine engine as described and/or claimed herein, a combustor may be provided axially downstream of the fan and compressor(s). For example, the combustor may be directly downstream of (for example at the exit of) the second compressor, where a second compressor is provided. By way of further example, the flow at the exit to the combustor may be provided to the inlet of the second turbine, where a second turbine is provided. The combustor may be provided upstream of the turbine(s).

**[0026]** The or each compressor (for example the first compressor and second compressor as described above) may comprise any number of stages, for example multiple stages. Each stage may comprise a row of rotor blades and a row of stator vanes, which may be variable stator vanes (in that their angle of incidence may be variable). The row of rotor blades and the row of stator vanes may be axially offset from each other.

**[0027]** The or each turbine (for example the first turbine and second turbine as described above) may comprise any number of stages, for example multiple stages. Each stage may comprise a row of rotor blades and a row of stator vanes. The row of rotor blades and the row of stator vanes may be axially offset from each other.

**[0028]** Each fan blade may be defined as having a radial span extending from a root (or hub) at a radially inner gas-washed location, or 0% span position, to a tip at a 100% span position. The ratio of the radius of the fan blade at the hub to the radius of the fan blade at the tip may be less than (or on the order of) any of: 0.4, 0.39, 0.38, 0.37, 0.36, 0.35, 0.34, 0.33, 0.32, 0.31, 0.3, 0.29, 0.28, 0.27, 0.26, or 0.25. The ratio of the radius of the fan blade at the hub to the radius of the fan blade at the tip may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds). These ratios may commonly be referred to as the hub-to-tip ratio. The radius at the hub and the radius at the tip may both be measured at the leading edge (or axially forwardmost) part of the blade. The hub-to-tip ratio refers, of course, to the gas-washed portion of the fan blade, i.e. the portion radially outside any platform.

**[0029]** The radius of the fan may be measured between the engine centreline and the tip of a fan blade at its leading edge. The fan diameter (which may simply be twice the radius of the fan) may be greater than (or on the order of) any of: 250 cm (around 100 inches), 260 cm, 270 cm (around 105 inches), 280 cm (around 110 inches), 290 cm (around 115 inches), 300 cm (around 120 inches), 310 cm, 320 cm (around 125 inches), 330 cm (around 130 inches), 340 cm (around 135 inches), 350cm, 360cm (around 140 inches), 370 cm (around 145 inches), 380 (around 150 inches) cm or 390 cm (around 155 inches). The fan diameter may be in an inclusive range bounded by any two of the values in the previous

sentence (i.e. the values may form upper or lower bounds).

**[0030]** The rotational speed of the fan may vary in use. Generally, the rotational speed is lower for fans with a higher diameter. Purely by way of non-limitative example, the rotational speed of the fan at cruise conditions may be less than 2500 rpm, for example less than 2300 rpm. Purely by way of further non-limitative example, the rotational speed of the fan at cruise conditions for an engine having a fan diameter in the range of from 250 cm to 300 cm (for example 250 cm to 280 cm) may be in the range of from 1700 rpm to 2500 rpm, for example in the range of from 1800 rpm to 2300 rpm, for example in the range of from 1900 rpm to 2100 rpm. Purely by way of further non-limitative example, the rotational speed of the fan at cruise conditions for an engine having a fan diameter in the range of from 320 cm to 380 cm may be in the range of from 1200 rpm to 2000 rpm, for example in the range of from 1300 rpm to 1800 rpm, for example in the range of from 1400 rpm to 1600 rpm.

**[0031]** In use of the gas turbine engine, the fan (with associated fan blades) rotates about a rotational axis. This rotation results in the tip of the fan blade moving with a velocity  $U_{tip}$ . The work done by the fan blades on the flow results in an enthalpy rise  $dH$  of the flow. A fan tip loading may be defined as  $dH/U_{tip}^2$ , where  $dH$  is the enthalpy rise (for example the 1-D average enthalpy rise) across the fan and  $U_{tip}$  is the (translational) velocity of the fan tip, for example at the leading edge of the tip (which may be defined as fan tip radius at leading edge multiplied by angular speed). The fan tip loading at cruise conditions may be greater than (or on the order of) any of: 0.3, 0.31, 0.32, 0.33, 0.34, 0.35, 0.36, 0.37, 0.38, 0.39 or 0.4 (all units in this paragraph being  $Jkg^{-1}K^{-1}/(ms^{-1})^2$ ). The fan tip loading may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds).

**[0032]** Gas turbine engines in accordance with the present disclosure may have any desired bypass ratio, where the bypass ratio is defined as the ratio of the mass flow rate of the flow through the bypass duct to the mass flow rate of the flow through the core at cruise conditions. In some arrangements the bypass ratio may be greater than (or on the order of) any of the following: 10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5, 14, 14.5, 15, 15.5, 16, 16.5, or 17. The bypass ratio may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds). The bypass duct may be substantially annular. The bypass duct may be radially outside the core engine. The radially outer surface of the bypass duct may be defined by a nacelle and/or a fan case.

**[0033]** The overall pressure ratio of a gas turbine engine as described and/or claimed herein may be defined as the ratio of the stagnation pressure upstream of the fan to the stagnation pressure at the exit of the highest pressure compressor (before entry into the combustor). By way of non-limitative example, the overall pressure

ratio of a gas turbine engine as described and/or claimed herein at cruise may be greater than (or on the order of) any of the following: 35, 40, 45, 50, 55, 60, 65, 70, 75. The overall pressure ratio may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds).

**[0034]** Specific thrust of an engine may be defined as the net thrust of the engine divided by the total mass flow through the engine. At cruise conditions, the specific thrust of an engine described and/or claimed herein may be less than (or on the order of) any of the following: 110  $Nkg^{-1}s$ , 105  $Nkg^{-1}s$ , 100  $Nkg^{-1}s$ , 95  $Nkg^{-1}s$ , 90  $Nkg^{-1}s$ , 85  $Nkg^{-1}s$  or 80  $Nkg^{-1}s$ . The specific thrust may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds). Such engines may be particularly efficient in comparison with conventional gas turbine engines.

**[0035]** A gas turbine engine as described and/or claimed herein may have any desired maximum thrust.

Purely by way of non-limitative example, a gas turbine as described and/or claimed herein may be capable of producing a maximum thrust of at least (or on the order of) any of the following: 160kN, 170kN, 180kN, 190kN, 200kN, 250kN, 300kN, 350kN, 400kN, 450kN, 500kN, or 550kN. The maximum thrust may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds). The thrust referred to above may be the maximum net thrust at standard atmospheric conditions at sea level plus 15 degrees C (ambient pressure 101.3kPa, temperature 30 degrees C), with the engine static.

**[0036]** In use, the temperature of the flow at the entry to the high pressure turbine may be particularly high. This temperature, which may be referred to as TET, may be measured at the exit to the combustor, for example immediately upstream of the first turbine vane, which itself may be referred to as a nozzle guide vane. At cruise, the TET may be at least (or on the order of) any of the following: 1400K, 1450K, 1500K, 1550K, 1600K or 1650K. The TET at cruise may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds). The maximum TET in use of the engine may be, for example, at least (or on the order of) any of the following: 1700K, 1750K, 1800K, 1850K, 1900K, 1950K or 2000K. The maximum TET may be in an inclusive range bounded by any two of the values in the previous sentence (i.e. the values may form upper or lower bounds). The maximum TET may occur, for example, at a high thrust condition, for example at a maximum take-off (MTO) condition.

**[0037]** A fan blade and/or aerofoil portion of a fan blade described and/or claimed herein may be manufactured from any suitable material or combination of materials. For example at least a part of the fan blade and/or aerofoil may be manufactured at least in part from a composite, for example a metal matrix composite and/or an organic matrix composite, such as carbon fibre. By way of further example at least a part of the fan blade and/or aerofoil

may be manufactured at least in part from a metal, such as a titanium based metal or an aluminium based material (such as an aluminium-lithium alloy) or a steel based material. The fan blade may comprise at least two regions manufactured using different materials. For example, the fan blade may have a protective leading edge, which may be manufactured using a material that is better able to resist impact (for example from birds, ice or other material) than the rest of the blade. Such a leading edge may, for example, be manufactured using titanium or a titanium-based alloy. Thus, purely by way of example, the fan blade may have a carbon-fibre or aluminium based body (such as an aluminium lithium alloy) with a titanium leading edge.

**[0038]** A fan as described and/or claimed herein may comprise a central portion, from which the fan blades may extend, for example in a radial direction. The fan blades may be attached to the central portion in any desired manner. For example, each fan blade may comprise a fixture which may engage a corresponding slot in the hub (or disc). Purely by way of example, such a fixture may be in the form of a dovetail that may slot into and/or engage a corresponding slot in the hub/disc in order to fix the fan blade to the hub/disc. By way of further example, the fan blades may be formed integrally with a central portion. Such an arrangement may be referred to as a blisk or a bling. Any suitable method may be used to manufacture such a blisk or bling. For example, at least a part of the fan blades may be machined from a block and/or at least part of the fan blades may be attached to the hub/disc by welding, such as linear friction welding.

**[0039]** The gas turbine engines described and/or claimed herein may or may not be provided with a variable area nozzle (VAN). Such a variable area nozzle may allow the exit area of the bypass duct to be varied in use. The general principles of the present disclosure may apply to engines with or without a VAN.

**[0040]** The fan of a gas turbine as described and/or claimed herein may have any desired number of fan blades, for example 16, 18, 20, or 22 fan blades.

**[0041]** As used herein, cruise conditions may mean cruise conditions of an aircraft to which the gas turbine engine is attached. Such cruise conditions may be conventionally defined as the conditions at mid-cruise, for example the conditions experienced by the aircraft and/or engine at the midpoint (in terms of time and/or distance) between top of climb and start of decent.

**[0042]** Purely by way of example, the forward speed at the cruise condition may be any point in the range of from Mach 0.7 to 0.9, for example 0.75 to 0.85, for example 0.76 to 0.84, for example 0.77 to 0.83, for example 0.78 to 0.82, for example 0.79 to 0.81, for example on the order of Mach 0.8, on the order of Mach 0.85 or in the range of from 0.8 to 0.85. Any single speed within these ranges may be the cruise condition. For some aircraft, the cruise conditions may be outside these ranges, for example below Mach 0.7 or above Mach 0.9.

**[0043]** Purely by way of example, the cruise conditions

may correspond to standard atmospheric conditions at an altitude that is in the range of from 10000m to 15000m, for example in the range of from 10000m to 12000m, for example in the range of from 10400m to 11600m (around 38000 ft), for example in the range of from 10500m to 11500m, for example in the range of from 10600m to 11400m, for example in the range of from 10700m (around 35000 ft) to 11300m, for example in the range of from 10800m to 11200m, for example in the range of from 10900m to 11100m, for example on the order of 11000m. The cruise conditions may correspond to standard atmospheric conditions at any given altitude in these ranges.

**[0044]** Purely by way of example, the cruise conditions may correspond to: a forward Mach number of 0.8; a pressure of 23000 Pa; and a temperature of -55 deg C.

**[0045]** As used anywhere herein, "cruise" or "cruise conditions" may mean the aerodynamic design point. Such an aerodynamic design point (or ADP) may correspond to the conditions (comprising, for example, one or more of the Mach Number, environmental conditions and thrust requirement) for which the fan is designed to operate. This may mean, for example, the conditions at which the fan (or gas turbine engine) is designed to have optimum efficiency.

**[0046]** In use, a gas turbine engine described and/or claimed herein may operate at the cruise conditions defined elsewhere herein. Such cruise conditions may be determined by the cruise conditions (for example the mid-cruise conditions) of an aircraft to which at least one (for example 2 or 4) gas turbine engine may be mounted in order to provide propulsive thrust.

**[0047]** The skilled person will appreciate that except where mutually exclusive, a feature or parameter described in relation to any one of the above aspects may be applied to any other aspect. Furthermore, except where mutually exclusive, any feature or parameter described herein may be applied to any aspect and/or combined with any other feature or parameter described herein.

## Brief description of the drawings

**[0048]** Embodiments will now be described by way of example only, with reference to the Figures, in which:

**Figure 1** is a sectional side view of a gas turbine engine;

**Figure 2** is a close-up sectional side view of an upstream portion of a gas turbine engine;

**Figure 3** is a partially cut-away view of a gearbox for a gas turbine engine;

**Figure 4** is an example of a planetary gear;

**Figure 5** is an embodiment of the invention showing

a diagram of the setup for the grinding process.

### Detailed Description

**[0049]** Aspects and embodiments of the present disclosure will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art.

**[0050]** **Figure 1** illustrates a gas turbine engine 10 having a principal rotational axis 9. The engine 10 comprises an air intake 12 and a propulsive fan 23 that generates two airflows: a core airflow A and a bypass airflow B. The gas turbine engine 10 comprises a core 11 that receives the core airflow A. The engine core 11 comprises, in axial flow series, a low pressure compressor 14, a high-pressure compressor 15, combustion equipment 16, a high-pressure turbine 17, a low pressure turbine 19 and a core exhaust nozzle 20. A nacelle 21 surrounds the gas turbine engine 10 and defines a bypass duct 22 and a bypass exhaust nozzle 18. The bypass airflow B flows through the bypass duct 22. The fan 23 is attached to and driven by the low pressure turbine 19 via a shaft 26 and an epicyclic gearbox 30.

**[0051]** In use, the core airflow A is accelerated and compressed by the low pressure compressor 14 and directed into the high pressure compressor 15 where further compression takes place. The compressed air exhausted from the high pressure compressor 15 is directed into the combustion equipment 16 where it is mixed with fuel and the mixture is combusted. The resultant hot combustion products then expand through, and thereby drive, the high pressure and low pressure turbines 17, 19 before being exhausted through the core exhaust nozzle 20 to provide some propulsive thrust. The high pressure turbine 17 drives the high pressure compressor 15 by a suitable interconnecting shaft 27. The fan 23 generally provides the majority of the propulsive thrust. The epicyclic gearbox 30 is a reduction gearbox.

**[0052]** An exemplary arrangement for a geared fan gas turbine engine 10 is shown in **Figure 2**. The low pressure turbine 19 (see **Figure 1**) drives the shaft 26, which is coupled to a sun wheel, or sun gear, 28 of the epicyclic gear arrangement 30. Radially outwardly of the sun gear 28 and intermeshing therewith is a plurality of planet gears 32 that are coupled together by a planet carrier 34. The planet carrier 34 constrains the planet gears 32 to precess around the sun gear 28 in synchronicity whilst enabling each planet gear 32 to rotate about its own axis. The planet carrier 34 is coupled via linkages 36 to the fan 23 in order to drive its rotation about the engine axis 9. Radially outwardly of the planet gears 32 and intermeshing therewith is an annulus or ring gear 38 that is coupled, via linkages 40, to a stationary supporting structure 24.

**[0053]** Note that the terms "low pressure turbine" and "low pressure compressor" as used herein may be taken to mean the lowest pressure turbine stages and lowest pressure compressor stages (i.e. not including the fan

23) respectively and/or the turbine and compressor stages that are connected together by the interconnecting shaft 26 with the lowest rotational speed in the engine (i.e. not including the gearbox output shaft that drives the fan 23). In some literature, the "low pressure turbine" and "low pressure compressor" referred to herein may alternatively be known as the "intermediate pressure turbine" and "intermediate pressure compressor". Where such alternative nomenclature is used, the fan 23 may be referred to as a first, or lowest pressure, compression stage.

**[0054]** The epicyclic gearbox 30 is shown by way of example in greater detail in **Figure 3**. Each of the sun gear 28, planet gears 32 and ring gear 38 comprise teeth about their periphery to intermesh with the other gears. However, for clarity only exemplary portions of the teeth are illustrated in **Figure 3**. There are four planet gears 32 illustrated, although it will be apparent to the skilled reader that more or fewer planet gears 32 may be provided within the scope of the claimed invention. Practical applications of a planetary epicyclic gearbox 30 generally comprise at least three planet gears 32.

**[0055]** The epicyclic gearbox 30 illustrated by way of example in **Figures 2** and **3** is of the planetary type, in that the planet carrier 34 is coupled to an output shaft via linkages 36, with the ring gear 38 fixed. However, any other suitable type of epicyclic gearbox 30 may be used. By way of further example, the epicyclic gearbox 30 may be a star arrangement, in which the planet carrier 34 is held fixed, with the ring (or annulus) gear 38 allowed to rotate. In such an arrangement the fan 23 is driven by the ring gear 38. By way of further alternative example, the gearbox 30 may be a differential gearbox in which the ring gear 38 and the planet carrier 34 are both allowed to rotate.

**[0056]** It will be appreciated that the arrangement shown in **Figures 2** and **3** is by way of example only, and various alternatives are within the scope of the present disclosure. Purely by way of example, any suitable arrangement may be used for locating the gearbox 30 in the engine 10 and/or for connecting the gearbox 30 to the engine 10. By way of further example, the connections (such as the linkages 36, 40 in the **Figure 2** example) between the gearbox 30 and other parts of the engine 10 (such as the input shaft 26, the output shaft and the fixed structure 24) may have any desired degree of stiffness or flexibility. By way of further example, any suitable arrangement of the bearings between rotating and stationary parts of the engine (for example between the input and output shafts from the gearbox and the fixed structures, such as the gearbox casing) may be used, and the disclosure is not limited to the exemplary arrangement of **Figure 2**. For example, where the gearbox 30 has a star arrangement (described above), the skilled person would readily understand that the arrangement of output and support linkages and bearing locations would typically be different to that shown by way of example in **Figure 2**.

**[0057]** Accordingly, the present disclosure extends to a gas turbine engine having any arrangement of gearbox styles (for example star or planetary), support structures, input and output shaft arrangement, and bearing locations.

**[0058]** Optionally, the gearbox may drive additional and/or alternative components (e.g. the intermediate pressure compressor and/or a booster compressor).

**[0059]** Other gas turbine engines to which the present disclosure may be applied may have alternative configurations. For example, such engines may have an alternative number of compressors and/or turbines and/or an alternative number of interconnecting shafts. By way of further example, the gas turbine engine shown in **Figure 1** has a split flow nozzle 18, 20 meaning that the flow through the bypass duct 22 has its own nozzle that is separate to and radially outside the core exhaust nozzle 20. However, this is not limiting, and any aspect of the present disclosure may also apply to engines in which the flow through the bypass duct 22 and the flow through the core 11 are mixed, or combined, before (or upstream of) a single nozzle, which may be referred to as a mixed flow nozzle. One or both nozzles (whether mixed or split flow) may have a fixed or variable area. Whilst the described example relates to a turbofan engine, the disclosure may apply, for example, to any type of gas turbine engine, such as an open rotor (in which the fan stage is not surrounded by a nacelle) or turboprop engine, for example.

**[0060]** The geometry of the gas turbine engine 10, and components thereof, is defined by a conventional axis system, comprising an axial direction (which is aligned with the rotational axis 9), a radial direction (in the bottom-to-top direction in **Figure 1**), and a circumferential direction (perpendicular to the page in the **Figure 1** view). The axial, radial and circumferential directions are mutually perpendicular.

**[0061]** The gears for such engines and those for use for other purposes can be manufactured using a number of different processes such as casting, forging, blanking and extrusion. In many of these cases once the gear has been formed further machining will be required so that the part conforms to the specific design criteria required for its operation. The further machining can be milling of the edges for size conformance; or milling or grinding of the teeth; and grinding the bore of the gear. Recently, as the technology has improved and the accuracy of the machining has increased, it has been discovered that the milling of the teeth and the surfaces can be performed using a 5-axis milling machine. These machines employ computer numerical controls (CNC) to perform this accurate machining of the component. 5-axis machines also allow for greater conformity of the final component as either the workpiece - the component to be machined - or the tooling head can be moved along 5 different axes simultaneously. These movement axes are the standard X, Y and Z axis, as well as two rotational axes: the A-axis, which rotates around the X axis; and a C-axis which

rotates around the Z-axis. This movement of the workpiece and of the tooling enables the machining of highly complex components. It also allows for more than one process to be carried out on a single machine tool, which minimises the number of tools used in a production process. Furthermore, they can limit the number of machines required in a factory.

**[0062]** Grinding of the bore of the workpiece is typically performed on a dedicated cylindrical grinder. In this an abrasive grinding wheel is rotated within the internal bore of the cylindrical workpiece, which is in turn rotated in the opposite direction, or alternatively the grinding wheel can move relative to the workpiece. Cylindrical grinders can also be used for finishing the external surface of a cylinder or gear as well. These machines can produce high conformance components, but are limited as they are only able to grind and cannot be used to manufacture the teeth of the gear. As such when making a gear from its initial forming, if a cylindrical grinder is used then another machine is required to grind the teeth or to finish them. One of the issues of using multiple machines is in errors resulting from the changing equipment between processing steps. Each time the workpiece is moved to a new piece of equipment it needs to be set-up, as such there is a need to parameterise its location within the computer controlling the CNC machining. This adds an extra degree of imprecision on the machining of the component, which is not desirable. It also increases the production time for each of the components.

**[0063]** As such there are a number of means of producing the gears. Any of these processes can be used in the manufacture of the gears for gas turbine engines. The gears used in a gas turbine engine are of a particularly high specification due to the forces that they are configured to take. As such, precision manufacturing is employed in order to achieve this, which is not just limited to the gear teeth themselves, but also to the grinding of the internal bore of the gear, such that it meets the weight and conformance targets required to use in a gas turbine engine. **Figure 4** shows an example of a typical planetary gear for use in the gearbox of a gas turbine engine. This is shown featuring an internal bore 44, which requires grinding down to increase the internal diameter and consequently, to reduce the mass of the gear. On the outer surface of the gear are shown featuring double helical gear teeth 42, with a space between the helices of the gear. These two features can as discussed above be manufactured in a number of different ways.

**[0064]** **Figure 5** shows the setup employed in the bore grinding process. In this the workpiece has an outer edge onto which the gear teeth 52 are to be positioned either before or after the cylindrical bore 54 extending through the gear has been ground. The bore is positioned in the centre of the cylindrical workpiece that is to be machined. The internal bore comprises a cylindrical section 56 that requires grinding in order to reduce its thickness. To achieve this, the internal bore is ground using grinding wheel 58. In the grinding process the grinding wheel is

rotated about an axis that is horizontal to that of the centre of the workpiece. At the same time that the workpiece is rotated to grind the surface the workpiece can be rotated in the same or opposite direction to that of the grinding wheel. In the grinding process the grinding wheel employed covers a substantial portion of the external diameter of the tube; this can be between 40%-80% of the external diameter of the pipe. Although the figure presents a planetary gear the method may also be applied to any type of gears having a central bore. The same grinding machines can also be used for grinding the end faces of the cylindrical workpiece. This can be to ensure that the end faces are perpendicular to the outer surface of the workpiece. Additionally, the machine can be used to grind an outer face of the workpiece, that is to say the face whose axis runs parallel to the central bore. In doing so, it can be used to ground the gap between the helices of a double helical gear.

**[0065]** In order to perform the method of grinding the internal bore of a cylinder for use as a gear the grinding wheel can be positioned anywhere in the workpiece.

**[0066]** However, it is desirable that the grinding wheel is positioned in a lower quadrant. In this case the quadrants are taken relative to the standard orientation of the workpiece, such that 0° is considered to be at the top dead centre of the cylinder then the upper quadrants would cover this and the range of angles between 270°-90°. Similarly, the lower quadrants would cover the range of angles between 90°-270°- incorporating 180° from top dead centre. The grinding wheel may have an axis of rotation that is parallel to the central axis of the workpiece and may be positioned anywhere on the workpiece. In an example it can be positioned anywhere from 90° to 180° from the top dead centre of the cylindrical bore with respect to the direction of rotation of the grinding wheel. In the example shown in **figure 5** the grinding wheel is positioned at 135° around the arc of the bore with respect to the direction of rotation of the grinding wheel. However, it may be suitably positioned at 95°, 100°, 105°, 110°, 115°, 120°, 125°, 130°, 140°, 145°, 150°, 155°, 160°, 165°, 170° or 175°.

**[0067]** A coolant may also be applied to the grinder wheel and/or workpiece whilst the grinding process is taking place. The positioning of the grinding wheel in a lower quadrant has been found to allow for better access of the coolant. This in turn makes it better enabled to extract the swarf generated from grinding the workpiece and to reduce the temperature at the grind surface, thus reducing the amount of grind burn. This also has the beneficial effect of improving the surface finish and reducing the wear on the grinding wheel. This coolant therefore reduces the amount of damage that the workpiece suffers during its processing and consequently improves the strength of the final component. The coolant can be supplied to the grinding interface from above the workpiece. This can be supplied in a variety of ways such as through a flat head slit nozzle or any suitable nozzle shape, such as round, oval, or square and at any suitable pressure.

The use of high pressure coolant may further reduce the chance of grind burn on the workpiece.

**[0068]** The grinding may be performed as discussed above on a multi-axis grinding machine or on a dedicated cylindrical grinder. The use of a multi-axis grinding machine could reduce the number of different setups required during the grinding process. In particular, certain 5-axis machines having a Very Impressive Performance Extreme Removal (VIPER) grinding capability have been found to be particularly suitable for this purpose. VIPER grinding employs aluminium oxide grinding wheels which are able to move around the work piece. The speed of rotation of the wheel and the use of coolant results in less thermal damage to workpiece during the manufacturing process. For this, it is desirable to operate the grinding wheel at high speeds. Machines employing VIPER grinding are advantageous as they are not limited by the maximum size of the grind wheel, which is a limitation of a dedicated cylindrical bore grinder. The use of smaller wheels was found not to achieve the same surface speed as that of larger wheels. They are also not as desirable for use in this operation as they are less stable and more prone to wear. Consequently, it is desirable for the grinder to employ a large grinding wheel relative to the external diameter of the workpiece to mitigate these issues. In a 5-axis machine the workpiece may be rotated in its c-axis (i.e. rotation around the translation Z-axis), whilst the position of the grinding wheel remains stationary, translational movement along the z-axis may be performed to grind the depth of the bore. The use of a 5-axis machine may also enable the gear teeth 42 to be made in the same setup as the bore, thus allowing for greater conformance. This greater conformance results from the workpiece not having to be moved between machines for different operations, and therefore, removes the need for repeated alignment steps. The combination of both the bore grind and the gear manufacturing on a single machine produces better alignment between the gear teeth 42 and the bore 44. It could also lead to a reduction in production time as the number of set-up steps is minimized.

**[0069]** The grind reduction in the cylindrical bore may be performed in a three stage process. This involves an initial roughing pass, followed by semi finishing pass and completed via finishing pass. In a trial example 16 roughing passes, 8 semi-finishing passes and 2 finishing passes were used for the completed workpiece. However, the skilled person would appreciate the exact number of these steps for each stages could vary depending upon the operational configuration, and the desired final parameters of the bore grind. For example, this could be 20 or fewer roughing, semi-finishing or finishing steps, for example; 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1 for each stage. For the different stages different grits on the grinding wheels may be used. Coarser grit may be used for the roughing step and semi-finish finishing steps and a finer grit may be used for the finishing step. The present disclosure also provides a gas tur-



bine that has a gar that has a central bore ground by the method as described above.

**[0070]** Although the disclosure focuses on the machining of a gear for use in a gas turbine engine, the skilled person will appreciate that such a method may be used for any other suitable gear. For example this could be for the gears used in wind turbine gear boxes, marine gear boxes, or car gear boxes. The process can be applied to any type of power transmission gear requiring a high accuracy bore and teeth on the outside. Furthermore, the disclosure can also be used for components that require a smooth interior bore as well as machining on the outer face. Examples of such components are turbocharger rotors.

**[0071]** It will be understood that the invention is not limited to the embodiments above-described and various modifications and improvements can be made without departing from the concepts described herein but within the scope of the following claims. Except where mutually exclusive, any of the features may be employed separately or in combination with any other features and the disclosure extends to and includes all combinations and sub-combinations of one or more features described herein.

## Claims

1. A method of reducing the thickness of a bore of a cylindrical workpiece for use as a gear; the method comprising the steps of:

mounting a cylindrical workpiece having a horizontal central axis and an outer diameter in a grinding machine; and  
grinding the bore of the cylindrical workpiece to reduce its thickness using a grinding wheel that has a diameter that is from 40% to 80% of the outer diameter of the cylindrical bore and has a direction of rotation about an axis of rotation that is parallel to the horizontal central axis of the cylindrical workpiece.

2. The method according to claim 1, wherein the axis of rotation of the grinding wheel is located from 90 degrees to 180 degrees, in the direction of rotation of the grinding wheel, from a plane that extends vertically through the workpiece when it is mounted in the grinding machine.
3. The method according to claim 1, wherein the grinding machine for grinding the bore of the cylindrical workpiece is performed on a 5-axis machining centre.
4. The method according to claim 3, wherein the bore is rotated about a C-axis of the machine whilst the grinding wheel position is maintained stationary.

5. The method according to claim 3 or 4, wherein gear teeth are ground on an external surface of the cylindrical workpiece using the same grinding machine as is used for claim 1.

6. The method according to any one of claims 3 to 5, wherein the faces of the cylindrical workpieces are be ground using the same grinding machining.

7. The method according to claim 5 or 6, wherein the gear is one of a planetary, sun, parallel axis or helical gear.

8. The method according to claim 1, wherein a coolant is provided to the grinding wheel and/or workpiece whilst in use to cool the grinding wheel.

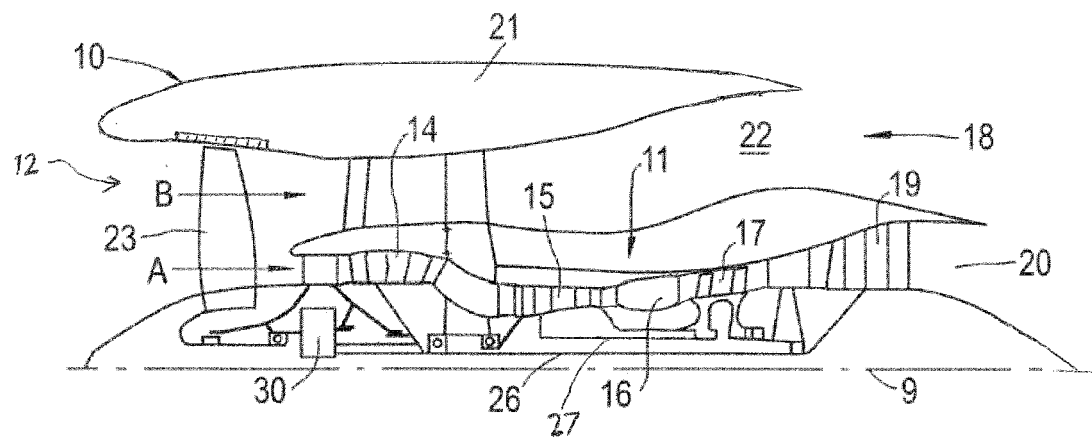
9. The method according to claim 8, wherein the coolant is applied to the grinding wheel and/or workpiece via a flat head nozzle.

10. The method according to claim 8 or 9, wherein the coolant is applied to the grinding wheel and/or workpiece in a range from 50 to 150 bar.

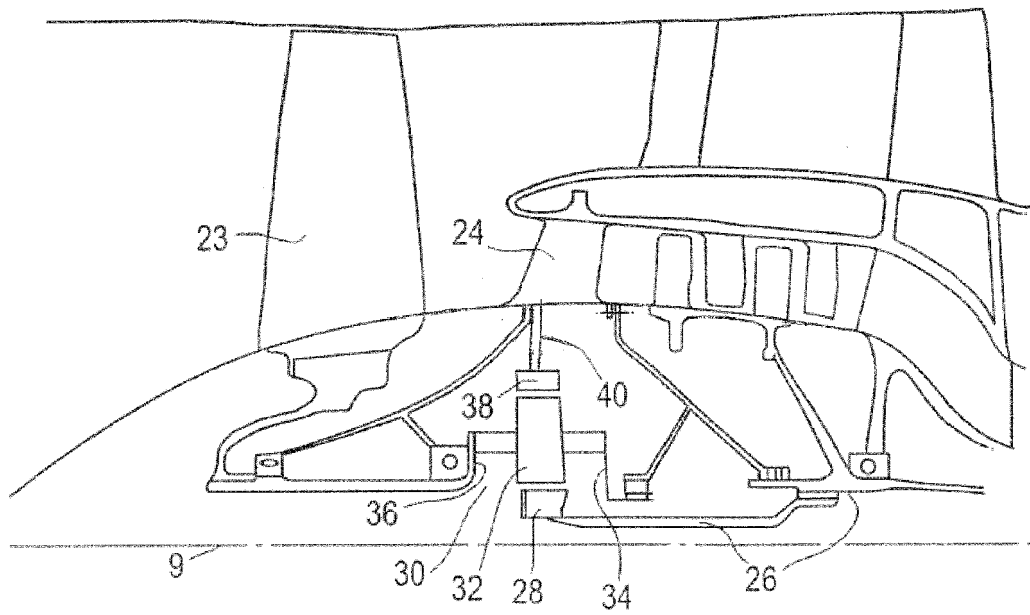
11. The method according to claim 1, wherein the internal bore is reduced in thickness in three stages: a roughing stage; a semi-finishing stage; and a finishing stage.

12. The method according to claim 11, wherein the grinding process is completed in fewer than 20 roughing steps within the roughing stage, fewer than 10 semi finishing steps within the semi finishing stage, and fewer than 5 finishing steps in the finishing stage.

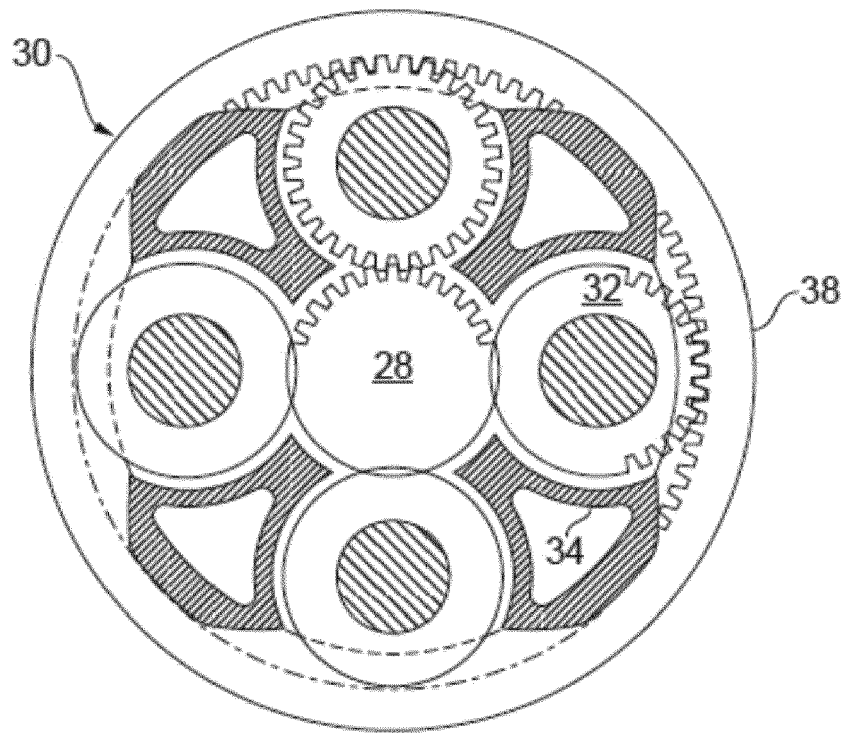
13. A gas turbine engine including a gear that has a central bore ground by the method of any one of claims 1 to 12.



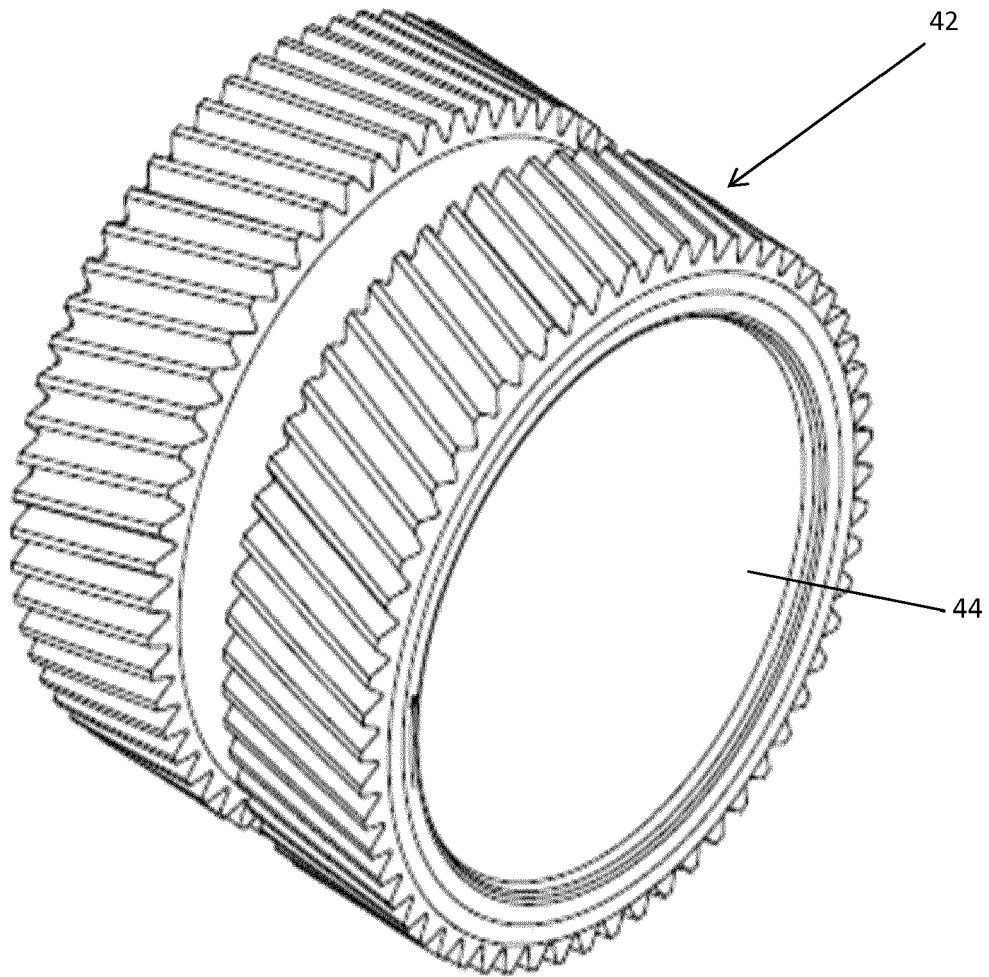
**Fig. 1**



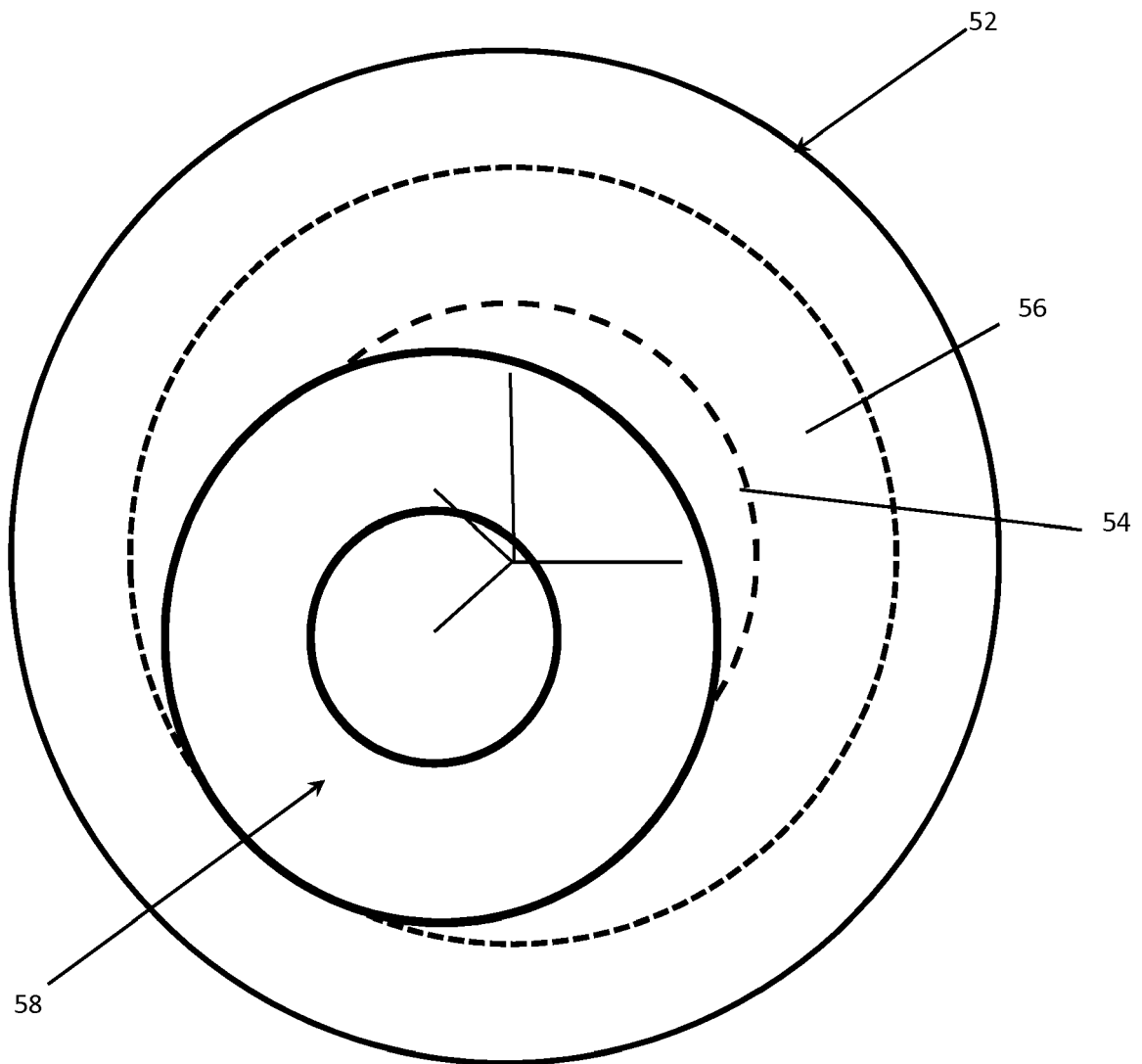
**Fig. 2**



**Fig. 3**



**Fig. 4**



**Fig. 5**



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