

Machine tool for and method of providing a surface which is not rotationally symmetrical on a workpiece, and control for such a machine tool.

The invention relates to a machine tool with a spindle which extends parallel to a Z-direction and a tool holder which is movable relative to the spindle, this spindle being rotatable about an axis of rotation which is directed parallel to the Z-direction
5 and being provided with a holder for a workpiece, while a displacement of the tool holder has at least a component which is parallel to an X-direction directed perpendicularly to the Z-direction, and the spindle and tool holder are mutually displaceable parallel to the Z-direction as a function of an angle of rotation of the spindle so as to provide the workpiece with a surface which is not rotationally symmetrical relative to an axis of the workpiece which
10 coincides with the axis of rotation.

The invention also relates to a method whereby a workpiece is provided with a surface which is not rotationally symmetrical relative to an axis of the workpiece, the workpiece being mounted on a spindle which extends parallel to a Z-direction, and the spindle being rotated about an axis of rotation directed parallel to the Z-direction and
15 coinciding with the axis of the workpiece, whereupon a tool is displaced relative to the workpiece in a direction which has at least a component which is parallel to an X-direction directed perpendicularly to the Z-direction, and the spindle and the tool are mutually displaced parallel to the Z-direction as a function of an angle of rotation of the spindle.

The invention also relates to a control suitable for use in a machine tool
20 according to the invention.

A machine tool and a method of the kind mentioned in the opening paragraphs are known from EP-A-0 370 788. The spindle of the known machine tool is fastened in a bush by means of two elastically deformable membranes, the bush being
25 rotatably supported in a bearing block by means of ball bearings. The spindle is supported parallel to the Z-direction by means of a further ball bearing of which a stationary part is fastened to the bearing block by means of a further elastically deformable membrane. The known machine tool further comprises an electromagnetic actuator of which a magnetic circuit is fastened to the bearing block and of which an electric coil is fastened to the

stationary part of the further ball bearing. The spindle is displaceable over a limited distance parallel to the Z-direction by means of the electromagnetic actuator under elastic deformation of said membranes. The tool holder of the known machine tool is fastened to a carriage which is rotatable about a Y-axis which extends at right angles to the X-direction and Z-direction.

The known machine tool and the method which can be carried out with the known machine tool are used for the application of a so-called astigmatic surface on a lens such as, for example, a contact lens or spectacle glass. Such an astigmatic surface has a spherical basic surface with an astigmatic correction which is not rotationally symmetrical relative to an optical axis of the lens. For this purpose, the tool is rotated about the Y-axis by means of the carriage, so that the tool is displaced along the lens in accordance with a circular arc of a defined radius and the lens is provided with the spherical basic surface, while at the same time the spindle is displaced parallel to the Z-direction by the actuator as a function of the angle of rotation of the spindle, so that the spherical basic surface is simultaneously provided with the astigmatic correction. The spherical basic surface thus has a radius which corresponds to the radius of the circular arc. The limited distance over which the spindle is displaceable parallel to the Z-direction by means of the actuator under elastic deformation of said membranes is sufficient, because the displacements of the spindle parallel to the Z-direction, which are necessary for applying the astigmatic correction, are comparatively small in relation to the displacements of the tool parallel to the Z-direction, which are necessary for applying the spherical basic surface and are achieved by rotation of the tool about the Y-axis.

It is a disadvantage of the known machine tool and the known method that the tool is displaceable exclusively along a circular arc with a previously defined radius, so that exclusively workpieces can be manufactured by the known machine tool and method which have a spherical basic surface of a previously defined radius. If a series of lenses is to be manufactured by the known machine tool or known method, the basic surfaces of which have mutually different radii adapted to the relevant users of the lenses, the tool must be readjusted for each lens or the carriage must be provided with a large number of tools each fastened at a different distance from the Y-axis. In addition, it is not possible with the known machine tool or known method to provide a workpiece with a rounded edge which merges fluently into a rear side of the workpiece from the surface of the workpiece to be manufactured. The application of such a rounded edge in a contact lens considerably improves the wearing comfort of the contact lens. It is furthermore practically impossible in

the known machine tool or known method to provide a workpiece with a different type of basic surface, so that the known machine tool or known method does not allow for, for example, the manufacture of a dynamic groove bearing with a pattern of grooves which is present on a plane basic surface.

5

It is an object of the invention to provide a machine tool and a method of the kind mentioned in the opening paragraphs with which the disadvantages mentioned above are avoided as much as possible, so that it is possible to manufacture workpieces with different basic surfaces by means of the machine tool or method, and the number of machining possibilities of the machine tool and the method is increased.

10

According to the invention, the machine tool is for this purpose characterized in that the spindle and the tool holder are mutually displaceable parallel to the Z-direction in that exclusively the spindle is displaceable parallel to the Z-direction.

15

The method according to the invention is for this purpose characterized in that the spindle and the tool are mutually displaced parallel to the Z-direction in that exclusively the spindle is displaced parallel to the Z-direction.

20

Since it is exclusively the spindle which is displaced parallel to the Z-direction, while the tool is displaced exclusively parallel to the X-direction, the surface to be applied on the workpiece is determined exclusively by the displacements carried out by the spindle parallel to the Z-direction during an operation as a function of the angle of rotation of the spindle and the X-position of the tool. Thus it is possible by means of the machine tool or by the method, for example, to manufacture a series of astigmatic lenses whose basic surfaces have mutually differing radiuses adapted to the relevant users of the lenses in that the Z-position of the spindle is controlled in a suitable manner as a function of the X-position of the tool and the angle of rotation of the spindle. For example, when a tool having a bent rod is used, it is also possible by means of the machine tool or by the method to machine a portion of a rear side of the workpiece, so that, for example, contact lenses can be provided with rounded edges. In addition, the machine tool or method also allows for the manufacture of workpieces having a plane or aspherically curved basic surface such as, for example, a dynamic groove bearing with a pattern of grooves present on a plane basic surface, which pattern is not rotationally symmetrical relative to an axis of rotation of the groove bearing.

25

30

A further advantage of the machine tool and the method according to the invention is that the Z-position of the spindle is controllable as a function of the X-position of the tool and the angle of rotation of the spindle in accordance with a comparatively simple

mathematical relation. Since the Z-position of the tool relative to the workpiece is dependent exclusively on the Z-position of the spindle, the calculated Z-position need not be corrected as a function of the X-position of the tool, as is necessary in the machine tool disclosed by EP-A-0 370 788. Calculation times required by a control unit for the calculation of the Z-position of the spindle are reduced thereby.

A special embodiment of a machine tool according to the invention is characterized in that the spindle is a hollow shaft which is supported perpendicularly to the Z-direction by a radial fluid bearing, which fluid bearing is bounded by a circular-cylindrical outer wall of the hollow shaft. Owing to the use of the hollow shaft, the spindle has a comparatively small mass, so that a comparatively high frequency and a comparatively great stroke of the spindle displacements parallel to the Z-direction are achieved. Such a comparatively great axial stroke of the radially supported spindle is constructionally possible owing to the use of the radial fluid bearing. As a result of its comparatively small mass, the spindle has a great mechanical bandwidth as regards displacements parallel to the Z-direction, so that the displacements of the spindle parallel to the Z-direction are particularly accurate.

A further embodiment of a machine tool according to the invention is characterized in that the spindle is supported parallel to the Z-direction by means of an axial fluid bearing with two cooperating bearing surfaces which extend perpendicularly to the Z-direction, a first of the two bearing surfaces being coupled to the spindle and a second of the two bearing surfaces being coupled to an actuator by means of which the spindle is displaceable parallel to the Z-direction. The use of the axial fluid bearing couples the spindle to the actuator in a constructionally simple manner, while a linear drive unit which is known and usual *per se* may be used as the actuator.

A yet further embodiment of a machine tool according to the invention is characterized in that the spindle is supported and displaceable parallel to the Z-direction by means of only one electromagnetic actuator, which actuator is provided with a permanent magnet fastened to the spindle and with an electric coil fastened to a frame of the machine tool. The electromagnetic actuator thus has a dual function, so that the machine tool is of a particularly simple construction. When the electromagnetic actuator is controlled in a suitable manner, a particularly small rotation error and a particularly high axial stiffness of the spindle are provided by the electromagnetic actuator. Owing to these favourable properties, the workpiece can be provided by means of the machine tool with a surface of optical quality which requires no aftertreatment. When the machine tool is used, for example, for the

manufacture of lenses, lenses manufactured by the machine tool need not be polished any more, so that the manufacturing process of the lenses is strongly simplified.

A particular embodiment of a machine tool according to the invention is characterized in that the machine tool comprises a control provided with a control unit for
5 supplying a first electrical output signal which corresponds to a desired X-position of the tool, and a second electrical output signal which corresponds to a Z-position of the spindle calculated by the control unit in accordance with a mathematical algorithm as a function of the X-position of the tool, so as to provide the workpiece with a desired basic surface which is rotationally symmetrical relative to the axis of the workpiece, while the control is further
10 provided with a processor for supplying an electrical output signal which corresponds to a correction of the Z-position of the spindle which is stored in table form in the processor as a function of the X-position of the tool and the angle of rotation of the spindle so as to provide the workpiece with a desired correction on the basic surface which is not rotationally symmetrical relative to the axis of the workpiece, and the control is further provided with an
15 electronic adder circuit for supplying an electrical output signal which is the sum of the second output signal of the control unit and the output signal of the processor.

A special embodiment of a method according to the invention is characterized in that a desired Z-position of the spindle is calculated through addition of a Z-position calculated in accordance with a mathematical algorithm as a function of an X-
20 position of the tool, whereby the workpiece is provided with a desired basic surface which is rotationally symmetrical relative to the axis of the workpiece, and a correction of the Z-position which is laid down in table form as a function of the X-position of the tool and the angle of rotation of the spindle, whereby the basic surface is provided with a desired correction which is not rotationally symmetrical relative to the axis of the workpiece.

25 The control unit of said control controls the X-position of the tool and the Z-position of the spindle necessary for providing the desired basic surface, and carries out a new calculation of said X-position and Z-position once or a limited number of times per revolution. The correction of the Z-position necessary for applying the desired non-rotationally-symmetrical correction of the basic surface is to be carried out a great number of
30 times, for example, a hundred times per spindle revolution. Since the correction of the Z-position of the spindle is stored in the processor of the said control in table form as a function of the X-position of the tool and the angle of rotation of the spindle, a fast determination of the Z-position correction is possible, so that also at a comparatively high spindle speed the correction can be carried out a sufficient number of times per spindle

revolution.

A further embodiment of a machine tool according to the invention is characterized in that the angle of rotation of the spindle, as a function of which the processor determines the correction of the Z-position of the spindle, is the sum of a measured angle of rotation of the spindle and a rotation angle correction calculated by the processor as a function of a rotation speed of the spindle. Owing to the required calculation time of the processor and the inertia of the actuator by means of which the spindle is displaceable parallel to the Z-direction, a difference will occur between the measured angle of rotation of the spindle, for which the processor determines the desired correction of the spindle Z-position, and the angle of rotation of the spindle at which the desired correction of the spindle Z-position is actually carried out by the actuator. Owing to this difference, which increases with an increase in the spindle speed, an undesirable distortion of the correction of the spindle Z-position about the workpiece axis will take place relative to a reference axis of the workpiece. Since the angle of rotation of the spindle as a function of which the processor determines the correction of the Z-position of the spindle is the sum of the measured angle of rotation of the spindle and said rotation angle correction, said difference is compensated by the rotation angle correction, so that said undesirable distortion of the correction of the spindle Z-position relative to the reference axis is avoided.

It is noted that EP-A-0 602 724 discloses a machine tool provided with a spindle extending parallel to a Z-direction with a workpiece holder and a tool holder which is displaceable parallel to an X-direction perpendicular to the Z-direction, while the spindle and the tool holder are mutually displaceable parallel to the Z-direction in that exclusively the spindle is displaceable parallel to the Z-direction. The spindle of the machine tool known from EP-A-0 602 724, however, is not displaceable relative to the tool as a function of the angle of rotation of the spindle, so that the known machine tool is not used for providing a workpiece with a surface which is not rotationally symmetrical relative to an axis of the workpiece which coincides with the axis of rotation.

The invention will be explained in more detail below with reference to the drawing, in which

Fig. 1 is a plan view of a first embodiment of a machine tool according to the invention for carrying out a method according to the invention,

Fig. 2 in cross-section shows a spindle, an axial fluid bearing, a coupling member, and a rotation angle sensor of the machine tool of Fig. 1,

Fig. 3 diagrammatically shows a control for the machine tool of Fig. 1,

Fig. 4a shows an astigmatic contact lens manufactured by the machine tool of Fig. 1,

Fig. 4b is a cross-section of the contact lens taken on the line IVb-IVb in
5 Fig. 4a,

Fig. 4c diagrammatically shows the manufacture of a rounded edge of the contact lens of Fig. 4a,

Fig. 4d shows a surface of a dynamic groove bearing manufactured by the machine tool of Fig. 1,

10 Fig. 5 is a plan view of a second embodiment of a machine tool according to the invention for carrying out a method according to the invention,

Fig. 6 diagrammatically shows a spindle, an electromagnetic actuator, and a rotation angle sensor of the machine tool of Fig. 5,

Fig. 7 shows in cross-section the spindle, the electromagnetic actuator, .
15 and the rotation angle sensor of Fig. 6, and

Fig. 8 diagrammatically shows a control for the machine tool of Fig. 5.

The first embodiment of a machine tool 1 according to the invention shown in Figs. 1 to 3 is provided with a frame 3 which can be placed on a support surface.

20 A guide block 5 with a straight guide 7 extending parallel to an X-direction is present on the frame 3. The machine tool 1 comprises a carriage 9 which is displaceably guided along the guide 7 by means of a static fluid bearing which is not visible in Fig. 1. A holder 11 for a tool such as, for example, a cutting tool 13, is present on the carriage 9. The carriage 9 is displaceable along the guide 7 by means of a drive unit 15, so that the holder 11 with the
25 cutting tool 13 is displaceable parallel to the X-direction. The drive unit 15 comprises a drive rod 17 which extends parallel to the X-direction, is coupled to the carriage 9, and is guided in a housing 19 fastened to the frame 3 by means of a number of guide wheels 21 which are indicated diagrammatically only in Fig. 1. A friction wheel 23, which has its rotation
30 bearings in the housing 19 and can be driven by an electric motor 25 fastened to the housing 19, bears with prestress on the drive rod 17, so that the carriage 9 is displaceable by means of the motor 25 parallel to the X-direction *via* the drive rod 17 and the friction wheel 23.

As Fig. 1 further shows, the machine tool 1 comprises a spindle 27 which extends parallel to a Z-direction directed perpendicularly to the X-direction and which is rotatable about an axis of rotation 29 directed parallel to the Z-direction. The spindle 27 is

provided with a holder 33, to which a workpiece 35 can be fastened, adjacent an end 31. As Fig. 2 shows, the spindle 27 comprises a hollow shaft 37 which is supported perpendicularly to the Z-direction by a radial static fluid bearing 39. The radial fluid bearing 39 comprises a feed channel 41 for the supply of a fluid, such as *e.g.* air, from a pressure source not shown in the Figures to an annular bearing gap 43 of the radial fluid bearing 39 which is bounded by a circular-cylindrical inner wall 45 of a bearing block 47 and by a circular-cylindrical outer wall 49 of the hollow shaft 37.

As Fig. 1 further shows, the spindle 27 is coupled to a drive unit 55 via an axial static fluid bearing 51 and an elastically deformable coupling member 53. As Fig. 2 shows, the axial fluid bearing 51 comprises a central bearing plate 57 which is fastened to an end 61 of the hollow shaft 37 and is provided with a central opening 63. The bearing plate 57 is provided with a bearing surface 65, 67 at either side, these surfaces extending perpendicularly to the axis of rotation 29. The axial fluid bearing 51 further comprises a first aerostatically supported foot 69 which is arranged in the hollow shaft 37 and is provided with a bearing surface 71 extending perpendicularly to the axis of rotation 29 for cooperation with the bearing surface 65 of the bearing plate 57, and a second aerostatically supported foot 73 which is provided with a bearing surface 75 which extends perpendicularly to the axis of rotation 29 for cooperation with the bearing surface 67 of the bearing plate 57. Between the bearing surfaces 65 and 71 there is a bearing gap 77, while a bearing gap 79 is present between the bearing surfaces 67 and 75. The bearing gaps 77 and 79 are each connected through a feed channel 81, 83 to a pressure source (not shown) for a fluid, such as *e.g.* air, the feed channel 81 for the bearing gap 77 extending through the central opening 63 of the bearing plate 57. The first aerostatically supported foot 69 is coupled to the second aerostatically supported foot 73 by means of a flexible tension rod 85 which also extends through the central opening 63 of the bearing plate 57 and through an opening 87 in the first aerostatically supported foot 69 and an opening 89 in the second aerostatically supported foot 73. The spindle 27 is supported and pretensioned parallel to the Z-direction by means of the axial fluid bearing 51.

The coupling member 53 shown in Fig. 2 and mentioned above is of a kind known from EP-A-0 602 724 and is provided with a first fastening part 91, which is fastened to the second aerostatically supported foot 73, and a second fastening part 93, which is fastened to a drive rod 95 of the drive unit 55. The fastening parts 91 and 93 are interconnected by an elastically deformable bridge 97 which is rigid in a direction parallel to the Z-direction and is provided with a number of incision-defined hinges 99. The incision-

defined hinges 99 are so provided in the bridge 97 that the first fastening part 91 is pivotable relative to the second fastening part 93 through limited angles about a first virtual pivot axis 101 shown in Fig. 2 which extends through a point of intersection 103 between the axis of rotation 29 and the bearing surface 75 of the second aerostatically supported foot 73 and which extends perpendicularly to the axis of rotation 29, and a second virtual pivot axis 105 not visible in Fig. 2 which also extends through said point of intersection 103 and which extends perpendicularly to the axis of rotation 29 and the first pivot axis 101. The use of the elastically deformable bridge 97 achieves that the second aerostatically supported foot 73 is self-adjusting relative to the bearing surface 67 of the bearing plate 57, so that inaccuracies in the perpendicularity of the cooperating bearing surfaces 67 and 75 relative to the axis of rotation 29 have no influence on the Z-position of the spindle 27 during the rotation of the spindle 27 about the axis of rotation 29. The use of the flexible tension rod 85 mentioned above achieves that also the first aerostatically supported foot 69 is self-adjusting relative to the bearing surface 65 of the bearing plate 57, so that also inaccuracies in the perpendicularity of the cooperating bearing surfaces 65 and 71 relative to the axis of rotation 29 have no influence on the Z-position of the spindle 27 during rotation of the spindle 27 about the axis of rotation 29.

The drive rod 95 of the drive unit 55 shown in Fig. 2 and mentioned above extends parallel to the Z-direction and is guided along a number of guide wheels 107 which are shown diagrammatically only in Fig. 1 and which have their rotation bearings in a housing 109 fastened to the frame 3. The drive unit 55 further comprises a friction wheel 111 which also has its rotation bearings in the housing 109 and can be driven by an electric motor 113 fastened to the housing 109. The friction wheel 111 bears with prestress on the drive rod 95, so that the spindle 27 is displaceable parallel to the Z-direction via the drive rod 95, the coupling member 53, and the axial fluid bearing 51. As Fig. 1 further shows, the spindle 27 is rotatable about the axis of rotation 29 by means of a further electric motor 115, which is also fastened to the frame 3 and is coupled to the hollow shaft 37 via a pulley 117, a rope 119, and a pulley 121 integrated with the bearing plate 57 of the hollow shaft 37. The rope 119 has sufficient elasticity for being capable of following a displacement of the hollow shaft 37 and the pulley 121 parallel to the Z-direction.

The control 123 of the machine tool 1 as shown in Fig. 3 shows a numerical control unit 125 which is usual and known *per se*, with a first electrical input 127 for receiving a first electrical input signal u_{xx} which corresponds to a measured X-position of the cutting tool 13, and a second electrical input 129 for receiving a second electrical input

signal u_{zz} which corresponds to a measured Z-position of the workpiece 35. The first input signal u_{xx} is supplied by a first optical position sensor 131 which is usual and known *per se* and which is shown diagrammatically only in Figs. 1 and 3. As Fig. 1 shows, the first position sensor 131 is provided with an optical source 133 and an optical detector 135 which are fastened to the housing 19 of the drive unit 15, and a reflecting surface 137 fastened to the carriage 9. The second input signal u_{zz} is supplied by a second optical position sensor 139 which is usual and known *per se* and which again is shown diagrammatically only in Figs. 1 and 3. As Fig. 1 shows, the second position sensor 139 also comprises an optical source 141 and an optical detector 143, which are fastened to the housing 109 of the drive unit 55, and a reflecting surface 145 fastened to the drive rod 95 of the drive unit 55. The reflecting surface 145 of the second position sensor 139 is also visible in Fig. 2.

As Fig. 3 further shows, the control unit 125 comprises a contour generator 147 which generates a first signal u_x in accordance with a previously defined program, which signal corresponds to a desired X-position of the cutting tool 13, and a second signal U_{z0} , which corresponds to a desired Z_0 -position of the workpiece 35 and is calculated by the contour generator 147 in accordance with a mathematical algorithm as a function of the desired X-position of the cutting tool 13. Since the desired Z_0 -position of the workpiece 35 is calculated exclusively as a function of the desired X-position of the cutting tool 13, the workpiece 35 as a result of the displacements of the cutting tool 13 and of the workpiece 35 in accordance with the desired X-position and the desired Z_0 -position, respectively, is provided with a basic surface which is rotationally symmetrical relative to an axis 149 of the workpiece 35 coinciding with the axis of rotation 29 and shown in Figs. 4a, 4b and 4d.

As Fig. 3 further shows, the control unit 125 comprises a first comparator 151 which compares the signal u_x of the desired X-position of the cutting tool 13 with the input signal u_{xx} of the measured X-position of the cutting tool 13. The first comparator 151 supplies an output signal $u_{cx} = u_x - u_{xx}$, which is multiplied by a factor K_x by a first multiplier 153. The control unit 125 comprises a first electrical output 155 for supplying a first electrical output signal $u_{kx} = K_x * u_{cx} = K_x * (u_x - u_{xx})$. As Fig. 3 shows, the output signal u_{kx} is offered to a first electrical amplifier 157 which supplies the electric motor 25 of the drive unit 15. The amplifier 157, the motor 25, the drive unit 15, and the first position sensor 131 together have a transmission factor H_x , so that the first input signal $u_{xx} = H_x * u_{kx} = H_x * K_x * (u_x - u_{xx})$, and $u_{xx} = u_x * H_x * K_x / (1 + H_x * K_x)$. It is achieved through a suitable adjustment and choice of the factors H_x and K_x that $H_x * K_x \gg 1$, so that u_{xx} , i.e.

the measured X-position of the cutting tool 13, is substantially equal to u_x , i.e. the desired X-position of the cutting tool 13, and an accurate control of the X-position of the cutting tool 13 is obtained.

As Fig. 3 further shows, the control unit 125 comprises a second comparator 159 which compares the signal u_{z0} of the desired Z_0 -position of the workpiece 35 with the input signal u_{zz} of the measured Z-position of the workpiece 35. The second comparator 159 supplies an output signal $u_{cz} = u_{z0} - u_{zz}$, which is multiplied by a factor K_z by a second multiplier 161. The control unit 125 comprises a second electrical output 163 for supplying a second electrical output signal $u_{kz} = K_z * u_{cz} = K_z * (u_{z0} - u_{zz})$.

As Fig. 3 shows, the control 123 further comprises a processor 165, which is usual and known *per se*, with a first electrical input 167 for receiving said first electrical input signal u_{xx} , which corresponds to the X-position of the cutting tool 13 measured by the first position sensor 131, and a second electrical input 169 for receiving a second electrical input signal u_{ϕ} , which corresponds to a measured angle of rotation ϕ of the spindle 27 about the axis of rotation 29. The second input signal u_{ϕ} is supplied by an optical rotation angle sensor 171 which is diagrammatically depicted in Fig. 2. The rotation angle sensor 171 comprises an annular collar 173 which extends concentrically around the axis of rotation 29 and which is integrated with the bearing plate 57. In the collar 173 there is a raster of slots 175 which are provided at mutually equal distances in the collar 173, while a single reference slot 177 is provided next to the slots 175, defining a zero value of the angle of rotation ϕ . The rotation angle sensor 171 further comprises a furcate holder 179 fastened to the second fastening part 93 of the coupling member 53. Two optical sources 181, 183 and two optical detectors 185, 187 are mounted in the furcate holder 179. The source 183 and the detector 187 are positioned next to the raster of slots 175 and detect the passage of the reference slot 177 during rotation of the spindle 27, ϕ being zero then. The source 181 and the detector 185 are positioned on either side of the raster of slots 175 and detect the passage of the slots 175 during the rotation of the spindle 27, the measured angle of rotation ϕ increasing by a value $\delta\phi = 2\pi/N$ (N being the number of slots 175) each time upon the passage of a slot 175. Since the sources 181, 183 and the detectors 185, 187 are mounted on the holder 179, and the holder 179 is displaced parallel to the Z-direction simultaneously with the spindle 27, it is achieved that the position of the sources 181, 183 and the detectors 185, 187 relative to the collar 173 does not change as seen in the Z-direction, so that the rotation angle sensor 171 can function during the full stroke of the spindle 27.

The processor 165 has an electrical output 189 for supplying an electrical

output signal u_{pr} generated by the processor 165 as a function of the input signals u_{xx} and $u_{\phi\phi}$. The output signal u_{pr} corresponds to a correction of the Z-position of the workpiece 35, which is previously determined as a function of the X-position of the cutting tool 13 and the angle of rotation ϕ of the spindle 27, as stored in table form in the processor 165. Said

5 correction of the Z-position of the workpiece 35 is performed so as to provide said basic surface of the workpiece 35 with a correction which is not rotationally symmetrical relative to the axis 149 of the workpiece 35 shown in Figs. 4a, 4b and 4d. The output signal u_{pr} of the processor 165 for this purpose forms a first input signal for an adder circuit 191 of the control 123 which has the second output signal u_{kz} of the control unit 125 as its second input

10 signal. As Fig. 3 shows, an output signal $u_{z+\delta z} = u_{kz} + u_{pr}$ of the adder circuit 191 is applied to a second electrical amplifier 193 which supplies the electric motor 113 of the drive unit 55. The amplifier 193, the motor 113, the drive unit 55, and the second position sensor 139 together have a transmission factor H_z , so that the second input signal $u_{zz} = H_z * u_{z+\delta z} = H_z * (u_{kz} + u_{pr}) = H_z * K_z * (u_{z0} - u_{zz}) + H_z * u_{pr}$ and $u_{zz} = u_{z0} * H_z * K_z / (1 + H_z * K_z) +$

15 $u_{pr} * H_z / (1 + H_z * K_z)$. Through programming of the processor 165 such that $u_{pr} = K_z * u_{\delta z}$, where $u_{\delta z} = \delta Z * u_{z0} / Z_0$ (Z_0 and δZ are the Z-positions of the basic surface and the correction of the basic surface, respectively), it is achieved that $u_{zz} = (u_{z0} + u_{\delta z}) * H_z * K_z / (1 + H_z * K_z)$. It is achieved by a suitable adjustment and choice of the factors H_z and K_z that $H_z * K_z \gg 1$, so that u_{zz} , i.e. to the measured Z-position of the workpiece 35, is

20 substantially equal to $u_{z0} + u_{\delta z}$, i.e. the sum of the desired Z_0 -position of the workpiece 35 and the desired correction δZ of the Z-position of the workpiece 35, and the rotationally symmetrical basic surface and the non-rotationally-symmetrical correction are provided on the workpiece 35 in an accurate manner.

It is noted that owing to the inertia of the processor 165, the adder circuit

25 191, the amplifier 193, the drive unit 55, and the rotation angle sensor 171, there will be a difference between the measured angle of rotation $u_{\phi\phi}$ of the spindle 27, as a function of which the processor 165 determines the desired correction δZ of the Z-position of the spindle 27, and the angle of rotation ϕ of the spindle 27 at which the desired correction δZ of the Z-position of the spindle 27 is actually realised by the drive unit 55. Said difference increases

30 with an increase in the speed of the spindle 27 and causes an undesirable distortion of the correction δZ about the axis 149 of the workpiece 35 relative to the reference slot 177 of the rotation angle sensor 171. To prevent said undesirable distortion, a corrector 195 is connected between the rotation angle sensor 171 and the second electrical input 169 of the processor 165. The corrector 195 comprises a first electrical input 197 for receiving the

signal $u_{\phi\phi}$ and a second electrical input 199 for receiving a signal u_r which is supplied by a differentiator 201 for the signal $u_{\phi\phi}$ and corresponds to the speed of the spindle 27. The differentiator 201 supplies an output signal $u_{\phi\phi}' = u_{\phi\phi} + u_{\delta\phi}$, where $u_{\delta\phi}$ corresponds to a rotation angle correction $\delta\phi = r \cdot \delta t$ of the spindle 27 determined by the differentiator 201 as a function of the speed r of the spindle 27 and the total, previously determined time delay δt of the processor 165, adder circuit 191, amplifier 193, drive unit 55, and rotation angle sensor 171. Since the angle of rotation $\phi + \delta\phi$, as a function of which the processor 165 determines the correction δZ of the Z-position of the spindle 27, is the sum of the measured angle of rotation ϕ and said rotation angle correction $\delta\phi$, the desired correction δZ is realised at an angle rotation of the spindle 27 which corresponds to the corrected angle of rotation $\phi + \delta\phi$, so that said undesirable distortion of the correction δZ about the axis 149 of the workpiece 35 is avoided.

It was described above how the basic surface and the non-rotationally-symmetrical correction are provided on the workpiece 35 through a displacement of the cutting tool 13 parallel to the X-direction and through a mutual displacement of the cutting tool 13 and the workpiece 35 parallel to the Z-direction in a suitable manner as a function of the X-position of the cutting tool 13 and the angle of rotation ϕ of the spindle 27. Since the cutting tool 13 is displaceable exclusively parallel to the X-direction, the workpiece 35 and the cutting tool 13 are mutually displaced parallel to the Z-direction in that exclusively the spindle 27 is displaced parallel to the Z-direction. Since the non-rotationally-symmetrical correction is provided as a function of the angle of rotation ϕ of the spindle 27, the displacements of the spindle 27 parallel to the Z-direction have a frequency which is at least equal to the frequency of the rotational movement of the spindle 27. The spindle 27 has a comparatively small mass because it is provided with a hollow shaft 37, so that a comparatively high frequency in combination with a comparatively great stroke of the displacements of the spindle 27 parallel to the Z-direction are achieved. Since there is no mechanical contact between the spindle 27 and the bearing block 47 of the radial fluid bearing 39, such a great stroke of the spindle 27 is not hampered constructionally by the radial fluid bearing 39. In addition, the control 123 of the Z-position of the spindle 27 has a great mechanical bandwidth owing to the comparatively small mass of the spindle 27, so that the displacements of the spindle 27 parallel to the Z-direction are particularly accurate. The control unit 125 generates the X-position of the cutting tool 13 and the Z_0 -position of the workpiece 35 which are necessary for providing the desired basic surface. The calculation of said X-position and Z_0 -position is carried out only once or a comparatively small number of

times per revolution of the spindle 27, so that said calculation by the control unit 125 can be carried out in accordance with an accurate mathematical algorithm. The correction of the Z-position of the workpiece 35 necessary for applying the desired non-rotationally-symmetrical correction on the basic surface, however, is to be carried out a comparatively large number of times per revolution of the spindle 27. Since the calculation speed of the control unit 125 is limited, the calculations for the non-rotationally-symmetrical correction cannot be carried out by the control unit 125. Since the correction of the Z-position of the workpiece 35 is stored in the processor 165 in table form as a function of the X-position of the cutting tool 13 and the angle of rotation ϕ of the spindle 27, a fast calculation of the correction of the Z-position of the workpiece 35 is possible by means of the processor 165, so that said correction can also be carried out at comparatively high speeds of the spindle 27.

Figs. 4a and 4b show a first example of a workpiece 35 manufactured with the machine tool 1 by the method according to the invention. The workpiece 35 is a contact lens 203 manufactured, for example, from a transparent, oxygen-permeable medical synthetic resin. The contact lens 203 comprises a spherical, concave contact surface 205 by means of which the contact lens 203 can be placed on an eye, and an outer surface 207 provided with an astigmatic surface 209 and a spherical, convex positioning surface 211 which surrounds the astigmatic surface 209. The astigmatic surface 209 forms the effective optical part of the contact lens 203, which is present in front of the eye pupil during use, while the positioning surface 211 is partly covered by the eyelids during use. In the manufacture of the contact lens 203, a circular-cylindrical initial product is fastened to the holder 33 of the spindle 27, and the initial product is first provided with the hollow contact surface 205 by means of the cutting tool 13. Then the contact lens 203 is provided with a rounded edge 213 and with a small portion of the positioning surface 211, the rounded edge 213 merging fluently from the contact surface 205 into the positioning surface 211. Such a rounded edge 213 leads to a considerable improvement in the wearing comfort of the contact lens 203. As Fig. 4c shows, a further cutting tool 215, placed at an acute angle relative to the Z-direction, is used for the application of the rounded edge 213. Since the spindle 27 is displaceable parallel to the Z-direction over a comparatively great distance, the further cutting tool 215 can partly reach the positioning surface 211, so that the rounded edge 213 and a small portion of the positioning surface 211 can be provided by means of the further cutting tool 215. After the contact surface 205, said portion of the positioning surface 211, and the rounded edge 213 have been provided, the contact lens 203 is glued with its contact surface 205 to a spherical carrier 217 of the holder 33 visible in Fig. 2, after which the

astigmatic surface 209 and the remaining portion of the positioning surface 211 are provided by the cutting tool 13. As Figs. 4a and 4b show, the positioning surface 211 exclusively comprises a spherical basic surface with a radius R_p , while the astigmatic surface 209 comprises a spherical basic surface with a radius R_A and a correction δZ which is not rotationally symmetrical relative to the axis 149 of the contact lens 203. The non-rotationally-symmetrical correction δZ of the contact lens 203 has two maximum positive corrections δZ_{POS} , which are present on a centreline 219, and two maximum negative corrections δZ_{NEG} , which are present on a centreline 221. The corrections δZ decrease from a circumference of the astigmatic surface 209 linearly along a radius towards the centre of the astigmatic surface 209, where the correction δZ is zero. Between the maximum positive and negative corrections δZ_{POS} and δZ_{NEG} , the corrections δZ have a fluent gradient, for example, in accordance with a sine shape. Since it is exclusively the spindle 27 with the contact lens 203 which is displaced parallel to the Z-direction, the basic surfaces of the positioning surface 211 and the astigmatic surface 209 as well as the non-rotationally-symmetrical correction δZ of the astigmatic surface 209 can be provided by the cutting tool 13 in a single operation in that the Z-position of the spindle 27 is controlled by the control 123 in a suitable manner. In addition, the cutting tool 13 is capable of manufacturing a series of astigmatic contact lenses whose basic surfaces of the positioning surface and astigmatic surface have mutually differing radii adapted to relevant users of the contact lenses, and whose non-rotationally-symmetrical corrections of the astigmatic surfaces are mutually different.

Fig. 4d shows a second example of a workpiece 35 manufactured with a machine tool 1 by the method according to the invention. The workpiece 35 is a bearing surface 223 of a dynamic fluid bearing which is usual and known *per se* and which is provided with a pattern of grooves 225. The bearing surface 223 has a plane basic surface 226, while the grooves 225 constitute the correction δZ of the basic surface 226 provided by the machine tool 1 as a function of the X-position of the cutting tool 13, *i.e.* the radius r shown in Fig. 4d, and as a function of the angle of rotation ϕ of the spindle 27. It is noted that the frequency of the Z-displacements of the spindle 27 necessary for the manufacture of the bearing surface 223 and dependent on the number of grooves 225 is greater than the frequency of the Z-displacements of the spindle 27 necessary for the manufacture of the contact lens 203 discussed above, while the stroke of the Z-displacements for manufacturing the bearing surface 223 is smaller than the stroke of the Z-displacements for manufacturing the contact lens 203. It is further noted that the bearing surface 223 may be provided with a spherical basic surface instead of a plane basic surface, so that the bearing surface 223 in

combination with a smooth ball has a radial as well as an axial bearing function.

The second embodiment of a machine tool 227 according to the invention shown in Figs. 5 to 7 is identical to the first embodiment of the machine tool 1 in a number of respects. Corresponding components of the machine tools 1 and 227 have been given the same reference numerals in the Figures. The differences only between the machine tools 1 and 227 will be discussed below.

As Fig. 5 shows, the machine tool 227, like the machine tool 1, has a spindle 229 which extends parallel to the Z-direction and which is rotatable about an axis of rotation 231 directed parallel to the Z-direction. Adjacent a first end 233, the spindle 229 is provided with a holder 235 for fastening a workpiece 237. As Fig. 7 shows, the spindle 229 is provided with a hollow shaft 239, as is the spindle 27 of the machine tool 1, which shaft is supported perpendicularly to the Z-direction by a radial static fluid bearing 241. The radial fluid bearing 241 is of a kind similar to the radial fluid bearing 39 of the machine tool 1.

As Figs. 6 and 7 further show, the machine tool 227 has an electromagnetic actuator 243. The actuator 243 comprises an annular magnetic circuit 245 which is fastened to the spindle 229 and is provided with a permanent magnet 247, a magnetizable closing yoke 249, and an annular gap 251. An annular electrical coil 253 is present inside the annular gap 251 and is fastened to a bearing block 255 of the radial fluid bearing 241. The spindle 229 is supported by the electromagnetic actuator 243 parallel to the Z-direction, while the spindle 229 is displaceable parallel to the Z-direction also by means of the electromagnetic actuator 243. As Fig. 7 further shows, a pulley 257 is fastened near the actuator 243, and the spindle 229 can be driven into rotation by an electric motor 263 visible in Fig. 5 via the pulley 257, a rope 259, and a pulley 261. The rope 259 has a sufficient elasticity for following a displacement of the spindle 229 parallel to the Z-direction.

The Z-position of the spindle 229 is controlled by means of a control 265 of the machine tool 227 shown diagrammatically in Fig. 8, which control in the main is identical to the control 123 of the machine tool 1. The differences between the controls 123 and 265 only will be discussed below. As Figs. 6, 7 and 8 show, the Z-position of the spindle 229 of the machine tool 227 is measurable by means of an optical position sensor 267 provided with an optical source 269 and an optical detector 271 which are fastened to a carrier 273 fastened to the bearing block 255, and provided with a reflecting surface 275 which is provided on a second end 277 of the spindle 229. The angle of rotation ϕ of the spindle 229 of the machine tool 227 is further measurable by means of an optical rotation angle sensor 279. As Fig. 6 shows, the rotation angle sensor 279 comprises an annular raster

of reflecting marks 281 which are provided with equal interspacings around the hollow shaft 239 near the second end 277 of the spindle 229, and a single reflecting reference mark 283 provided next to the marks 281 and defining a zero value for the angle of rotation of the spindle 229. The rotation angle sensor 279 further comprises a first optical source 285 and a first optical detector 287, which are provided in the bearing block 255 and detect the passage of the marks 281 during rotation of the spindle 229, and a second optical source 289 and a second optical detector 291, also provided in the bearing block 255 and detecting the passage of the reference mark 283 during rotation of the spindle 229.

As Figs. 6, 7 and 8 further show, the control 265 of the machine tool 227 also comprises a speed sensor 293 for measuring a speed of the spindle 229 directed parallel to the Z-direction. The speed sensor 293 comprises an annular magnetic circuit 295 which is fastened to the spindle 229 and is provided with a permanent magnet 297, a magnetizable closing yoke 299 and an annular gap 301. In the annular gap 301 there is an annular electrical coil 303 which is fastened to said carrier 273. When the spindle 229 is displaced parallel to the Z-direction, an electric current is induced in the coil 303 of the speed sensor 293 by the magnetic field present in the gap 301, which current is proportional to the speed of the spindle 229 parallel to the Z-direction. An output signal u_{vv} of the speed sensor 293 accordingly corresponds to said speed of the spindle 229. As Fig. 8 shows, the control 265 of the machine tool 227 comprises a control member 305 with a first electrical input 307 for receiving the output signal u_{vv} of the speed sensor 293 and a second electrical input 309 for receiving the output signal $U_{z+\delta z}$ of the adder circuit 191. The control member 305 has an electrical output 311 for supplying an electrical output signal $U_D = C_1 * u_{z+\delta z} + C_2 * u_{vv} = C_1 * U_{z+\delta z} + C_2 * u'_{zz}$, where $u'_{zz} = \delta u_{zz} / \delta t$. As Fig. 8 shows, the signal u_D is applied to the amplifier 193. Owing to the use of the control member 305, the electromagnetic actuator 243 exerts not only the force necessary for reaching a desired Z-position but also a damping force on the spindle 229, so that a particularly stable control of the Z-position of the spindle 229 is achieved by the control 265. The electromagnetic actuator 243 provides a particularly accurate support and positioning of the spindle 229 parallel to the Z-direction. The axial stiffness of the actuator 243 is particularly great. In addition, the so-called rotation error of the spindle 229, i.e. the undesirable axial displacements of the spindle 229 caused by axial forces arising from the rotation of the actuator 243 about the axis of rotation 231 and from cutting forces, are negligibly small. The machine tool 227 is thus eminently suitable for the manufacture of products with an accuracy in the sub-micron range or for the manufacture of surfaces of optical quality. When the machine tool 227 is used, for example, for the

manufacture of the astigmatic contact lens 203 shown in Fig. 4a, an optical surface quality of the contact lens 203 is achieved such that the contact lens 203 requires no aftertreatment and the manufacturing process of the contact lens 203 is strongly simplified.

It is noted that instead of the spindle 27, 229 with the hollow shaft 37, 339 supported by a static fluid bearing 39, 241 an alternative type of spindle may also be used in the machine tool 1, 227 such as, for example, a solid spindle or a spindle provided with two bearing parts coupled by a connecting rod. Instead of the radial static fluid bearings 39, 241, it is also possible to use, for example, dynamic groove bearings or electromagnetic bearings. The invention is also applicable to machine tools provided with spindles supported by radial ball bearings. The axial stroke of a machine tool with such a spindle, however, is limited so that only a limited number of different basic surfaces can be manufactured by means of such a machine tool. The invention is equally applicable to machine tools provided with an axial ball bearing or an axial dynamic groove bearing. The stiffness of such bearings, however, is comparatively low, while the rotation accuracy of axial ball bearings is limited.

It is further noted that instead of the drive unit 55 or the electromagnetic actuator 243, an alternative type of actuator may be used for displacing the spindle 27, 229 parallel to the Z-direction. When the machine tool 1, 227 is used for the manufacture of workpieces for which only a limited stroke of the workpiece is required, such as, for example, in the manufacture of bearing surfaces of dynamic groove bearings, it is possible, for example, to use a piezoelectric actuator.

It is further noted that instead of the controls 123 and 265 discussed above a different type of control may alternatively be used. Instead of the numerical control unit 125 and the processor 165, for example, a microprocessor may be used which generates both the basic surface and the correction which is not rotationally symmetrical. With the use of the conventional numerical control unit 125 in combination with the processor 165, however, the machine tool 1, 227 is controlled by the numerical control unit 125 in a known and usual manner for conventional rotationally-symmetrical operations, whereby a desired rotationally symmetrical basic surface can be programmed in a practical manner by means of a mathematical relation, while the use of the processor 165 for non-rotationally-symmetrical operations renders it possible to calculate a non-rotationally-symmetrical correction of the basic surface in a fast and effective manner. Furthermore, the control 123 just as the control 265 may be provided with a feedback of the speed of the spindle 27 parallel to the Z-direction. Moreover, the controls 123 and 265 may be provided with a feedback of the speed

of the carriage 9 parallel to the X-direction.

In the machine tools 1, 227 described above, examples mentioned for the workpiece 35, 237 were an astigmatic contact lens, whose basic surface is spherical, and a bearing surface for a dynamic groove bearing, whose basic surface is plane. It is finally
5 noted that basic surfaces of different shapes may also be provided with the machine tool 1, 227 and by the method according to the invention, for example, basic surfaces having an ellipsoidal or other aspherical contour, in the case of aspherical lenses, or basic surfaces having a sawtooth contour, in the case of so-called fresnel lenses. It is also possible with the machine tool 1, 227 and by the method according to the invention to apply non-rotationally-
10 symmetrical corrections other than the corrections described above, for example, corrections of a decorative nature.

CLAIMS:

1. A machine tool with a spindle which extends parallel to a Z-direction and a tool holder which is movable relative to the spindle, this spindle being rotatable about an axis of rotation which is directed parallel to the Z-direction and being provided with a holder for a workpiece, while a displacement of the tool holder has at least a component which is parallel to an X-direction directed perpendicularly to the Z-direction, and the spindle and tool holder are mutually displaceable parallel to the Z-direction as a function of an angle of rotation of the spindle so as to provide the workpiece with a surface which is not rotationally symmetrical relative to an axis of the workpiece which coincides with the axis of rotation, characterized in that the spindle and the tool holder are mutually displaceable parallel to the Z-direction in that exclusively the spindle is displaceable parallel to the Z-direction.
2. A machine tool as claimed in Claim 1, characterized in that the spindle is a hollow shaft which is supported perpendicularly to the Z-direction by a radial fluid bearing, which fluid bearing is bounded by a circular-cylindrical outer wall of the hollow shaft.
3. A machine tool as claimed in Claim 1 or 2, characterized in that the spindle is supported parallel to the Z-direction by means of an axial fluid bearing with two cooperating bearing surfaces which extend perpendicularly to the Z-direction, a first of the two bearing surfaces being coupled to the spindle and a second of the two bearing surfaces being coupled to an actuator by means of which the spindle is displaceable parallel to the Z-direction.
4. A machine tool as claimed in Claim 1 or 2, characterized in that the spindle is supported and displaceable parallel to the Z-direction by means of only one electromagnetic actuator, which actuator is provided with a permanent magnet fastened to the spindle and with an electric coil fastened to a frame of the machine tool.
5. A machine tool as claimed in any one of the preceding Claims, characterized in that the machine tool comprises a control provided with a control unit for supplying a first electrical output signal which corresponds to a desired X-position of the tool, and a second electrical output signal which corresponds to a Z-position of the spindle calculated by the control unit in accordance with a mathematical algorithm as a function of the X-position of the tool, so as to provide the workpiece with a desired basic surface which

is rotationally symmetrical relative to the axis of the workpiece, while the control is further provided with a processor for supplying an electrical output signal which corresponds to a correction of the Z-position of the spindle which is stored in table form in the processor as a function of the X-position of the tool and the angle of rotation of the spindle so as to provide the workpiece with a desired correction on the basic surface which is not rotationally symmetrical relative to the axis of the workpiece, and the control is further provided with an electronic adder circuit for supplying an electrical output signal which is the sum of the second output signal of the control unit and the output signal of the processor.

6. A machine tool as claimed in Claim 5, characterized in that the angle of rotation of the spindle, as a function of which the processor determines the correction of the Z-position of the spindle, is the sum of a measured angle of rotation of the spindle and a rotation angle correction calculated by the processor as a function of a rotation speed of the spindle.

7. A control suitable for use in a machine tool as claimed in Claim 5 or 6.

8. A method whereby a workpiece is provided with a surface which is not rotationally symmetrical relative to an axis of the workpiece, the workpiece being mounted on a spindle which extends parallel to a Z-direction, and the spindle being rotated about an axis of rotation directed parallel to the Z-direction and coinciding with the axis of the workpiece, whereupon a tool is displaced relative to the workpiece in a direction which has at least a component which is parallel to an X-direction directed perpendicularly to the Z-direction, and the spindle and the tool are mutually displaced parallel to the Z-direction as a function of an angle of rotation of the spindle, characterized in that the spindle and the tool are mutually displaced parallel to the Z-direction in that exclusively the spindle is displaced parallel to the Z-direction.

9. A method as claimed in Claim 8, characterized in that a desired Z-position of the spindle is calculated through addition of a Z-position calculated in accordance with a mathematical algorithm as a function of an X-position of the tool, whereby the workpiece is provided with a desired basic surface which is rotationally symmetrical relative to the axis of the workpiece, and a correction of the Z-position which is laid down in table form as a function of the X-position of the tool and the angle of rotation of the spindle, whereby the basic surface is provided with a desired correction which is not rotationally symmetrical relative to the axis of the workpiece.

