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Title:	**Polishing Tools, Polishing Machines and Methods for Polishing a Workpiece**
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POLISHING TOOLS, POLISHING MACHINES AND METHODS OF POLISHING A WORKPIECE

FIELD OF THE INVENTION

The invention relates to polishing tools and polishing machines incorporating said polishing tool. Methods of polishing a workpiece are also provided. Both full-aperture and sub-aperture apparatus and techniques are disclosed.

BACKGROUND TO THE INVENTION

Many processes for manufacturing objects across a range of technological fields involve polishing parts of the artefact being manufactured. For example, lenses, mirrors and other optical components, medical surfaces such as those of ophthalmic devices and prosthetics, and engineering components such as jet engine turbine blades are all typically polished so as to provide the finished product with a smooth surface with minimal defects and aberrations. Likewise, moulding dies for the production of moulded parts requiring a highly smooth surface finish, for example for moulding curved glass screens for consumer products such as mobile telephones, wearable technology such as watches, and tablet and computer screens, must be similarly highly polished. The polishing process may be a “full-aperture” polishing process, in which the whole surface to be polished is contacted by a polishing tool simultaneously, or a “sub-aperture” polishing process, in which the polishing tool is smaller than the surface to be polished. In the latter case, portions of the surface are polished sequentially by moving the polishing tool across the workpiece surface (in addition to rotating, oscillating or vibrating the tool to effect the polishing action).

Before being polished, the workpiece from which the article is to be formed is typically ground to the required shape with an abrasive surface or substance that is capable of removing material from the workpiece when moved against its surface under pressure. The material used to subsequently polish the surface is finer than the abrasive used for grinding and does not remove material from the workpiece at a significant rate. Thus, in theory, the overall shape of the surface of the workpiece surface is determined by the grinding phase of the process whereas the subsequent polishing removes defects and smooths the surface without significantly altering its macroscopic form.

However, since the polishing action cannot distinguish between different features of the workpiece surface – that is, treat undesired surface roughness whilst not removing intended shape features – the desired outcome is frequently hard to achieve. For example, the macroscopic shape of the workpiece may become distorted and/or desired small-scale features may be lost. These problems are felt particularly (though not exclusively) in sub-aperture polishing processes, where the dimensions of the working surface of the polishing tool (i.e. the part or parts of the surface of the tool that is capable of polishing the surface of the workpiece) are less than those of the surface being polished. Sub-aperture polishing techniques are useful as they allow a limited set of tools to be used for polishing surfaces of virtually any shape (sometimes referred to as “free-form” surfaces, in contrast to surfaces that are symmetric or otherwise of a regular shape), but it is particularly difficult to accurately polish the kinds of surface to which sub-aperture techniques are often applied (for example those that are irregular, have sharp features, are strongly-curved or are non-symmetric). There is hence a need to provide polishing tools which enable improved control of the polishing process.

SUMMARY OF THE INVENTION

A first aspect of the invention provides a sub-aperture polishing tool, comprising:

a support member including an attachment feature for attachment to a sub-aperture polishing machine; and

at an end of the support member, a polishing head comprising:

a base structure attached to or integral with the support member, the base structure being arranged to provide a non-flat surface;

an outer shell, at least part of the outer surface of which defines the working surface of the polishing tool, the outer shell being affixed to the base structure so as to enclose a cavity between the outer shell and the non-flat surface; and a viscoelastic material filling the cavity, located between the outer shell and the base structure.

Viscoelastic materials are non-Newtonian, meaning that they do not have a constant viscosity (if the material is a fluid) or stiffness (if the material is a solid). Rather, the parameter varies in dependence on the applied shear or strain rate, or on the amount of applied stress. As a result, the polishing tool responds differently to different features encountered as it moves over the workpiece surface. Relatively small or closely spaced features, such as sharp edges, will impact the working surface of a tool with a relatively high shear or strain rate, whereas relatively low-curvature features will do the opposite. The viscoelastic material backing the working surface will thus vary in its apparent viscosity or stiffness and apply a different polishing pressure to different types of feature on the workpiece surface. As a result, the process can be better controlled.

Depending on the nature of the workpiece, the viscoelastic material which is sealed inside the cavity may be one which increases in viscosity/stiffness with increasing shear/strain rate (or applied stress), or it may be one which does the opposite. Some viscoelastic materials are capable of exhibiting either behaviour, depending on the range of shear/strain rate (or applied stress) at which they are operating. Examples of applications in which each behaviour is useful will be explained below.

The non-flat surface of the base structure plays an important role in the effectiveness of the tool since it enables better control over the viscoelastic material and hence its behaviour. For instance, the non-flat surface can be configured to force the viscoelastic material into better contact with the outer shell during use. In addition, the amount of viscoelastic material located between the non-flat surface and the outer shell at any given location on the working surface (i.e. the thickness of the layer measured in the direction normal to the working surface at that point) influences the response of the tool to shearing caused by contact with the workpiece surface. Typically, where the layer of viscoelastic material is thinner, the thickness and/or stiffness of the material when the respective part of the working surface is in contact with a feature that causes shearing will be greater in absolute terms. Since the viscoelastic material fills the cavity enclosed by the outer shell and the non-flat surface, it forms a layer whose thickness at each position on the working surface depends on the distance separating the outer shell and non-flat surface. In some embodiments the non-flat surface may therefore be configured to define a macro-structure which allows the thickness of the viscoelastic material at each position on the workpiece surface to be controlled when designing the tool without constraining the form of the outer shell. Examples will be given below. Alternatively or in addition, the non-flat surface can be used to define a micro-structure (which would be on a smaller scale than any macro-structure present), resulting in a surface texture which "grips" the viscoelastic material thereby transferring rotation from the support member to the material more efficiently during use.

The non-flat surface, as part of the base structure, will be relatively rigid as compared with the outer shell (i.e. non-deformable), at least during any polishing procedure. However, as explained below it could be formed in a number of alternative ways including some where the non-flat surface may not become rigid until configured ready for use. The outer shell will typically be relatively flexible compared to the non-flat surface so that the working surface of the tool can conform to the general shape of the workpiece surface in use. It should be appreciated that the non-flat surface could include one or more regions which are locally flat. However, it will not be flat (planar) all the way from one periphery to the other.

As noted above, the term "sub-aperture" means that the dimensions of the working surface of the polishing tool are smaller than the surface of the workpiece that the tool is used to polish. A "sub-aperture polishing tool" is thus suitable for polishing workpieces with surfaces of greater dimensions those of the working surface of the polishing tool. Typically the working surface of the polishing tool will be much smaller than the surface to be polished, e.g. less than half of its surface area (often much smaller). The tool is moved across the workpiece surface, typically while being spun about the tool axis at high speed, so that all points of the workpiece surface requiring polishing are treated sequentially (rather than simultaneously).

Polishing tools of the above-described type in which the viscoelastic material is a shear-thickening and/or stress-stiffening material (i.e. its viscosity/stiffness increases with increasing shear/strain rate (or applied stress)) have been found by the present inventors to be particularly useful for the removal of so-called "mid-spatial defects" on workpiece surfaces.

While techniques have been developed that are capable of grinding and polishing the surfaces of such workpieces with high levels of precision, the grinding phase of these manufacturing processes is highly prone to producing these "mid-spatial defects" in the surfaces being worked. Mid-spatial defects (or simply "mid-spatials") are defects that manifest as waves or undulations in the surface of the workpiece with a spatial periodicity typically in the range of 0.1 to 10 millimetres (mm). Mid-spatials can be detrimental for a variety of reasons: in the case of optical components (whether formed by the workpiece itself or subsequently moulded from it), for example, these defects can reduce the quality of the images formed by the component, and in the case of prosthetics can undermine the adhesion of the component to tissues in the body. Typical polishing tools are ineffective at removing features on the scale of mid-spatials and so tend to simply smooth the surfaces of these defects while preserving their undulating profiles.

Conventional approaches to removing mid-spatials involve intensively polishing the workpiece using a polishing tool. While this can eventually result in a reduction in the amplitude of the mid-spatials, it often also results in the macroscopic shape of the surface being distorted since the difference between the rates at which material is removed from the 'peaks' of the mid-spatials as compared to the 'troughs' is typically small. An undesirably large amount of material must therefore be removed during the polishing phase in order to supress the mid-spatial defects.

Thus in a particularly preferred embodiment, the cavity enclosed by the outer shell and non-flat surface is filled with a shear-thickening and/or stress-stiffening viscoelastic material. "Shear-thickening" means that the viscosity of a (fluid) material increases with the shear rate experienced by the material. Similarly, "stress-stiffening" means that the stiffness of a (solid) material increases with the stress experienced by the material. The material may be both shear-thickening and stress-stiffening, but it is not essential that the material possesses both of these properties. Shear-thickening materials may also be referred to as “dilatants”. Examples of suitable materials will be given below.

Polishing tools of this sort have been found to be capable of efficiently removing mid-spatial defects in the course of normal polishing without the need for the kind of intensive application that results in distortion of the workpiece surface as described above. It is believed that because the shear-thickening and/or stress-stiffening viscoelastic material becomes more resistant to deformation where it is subject to greater shear rates, the parts of the working surface coming repeatedly into contact with the peaks of mid-spatial defects on the surface (where the surface elevation varies over much smaller distances than does the overall surface profile, resulting in a high frequency of impacts between the material and each subsequent peak) are caused to thicken and/or stiffen in the vicinity of these features, while the working surface still conforms generally to the overall shape of the area to which the tool is applied. This selective thickening and/or stiffening of the working surface causes the peaks of the mid-spatial defects to be preferentially removed by the polishing in comparison to the troughs between them and any surrounding, non-defective parts of the surface.

In preferred implementations, the outer shell comprises a layer of polishing material forming the outer surface and being suitable for sub-aperture polishing of a workpiece. This may commonly be referred to as a “polishing pad” in the art, and could itself carry abrasive particles or may be designed to be used with an abrasive slurry. In preferred examples the polishing material comprises at least one of polyurethane, poromeric cloth, a tar based viscoelastic polymer and/or another compliant material. By “compliant material” we mean a material that is capable of conforming to the surface of a workpiece when in contact with it. Polyurethane, poromeric cloth and tar based viscoelastic polymers are examples of compliant materials. The polishing material may optionally be porous. An additional layer of pitch or similar could be provided on the outside of the layer of polishing material if desired.

In some preferred embodiments, the polishing material is in direct contact with the viscoelastic material in the cavity. The outer shell could for instance consist of the polishing material and nothing else. This can be the case where, for example, the viscoelastic material is a highly viscous substance that will not leak through the polishing material during polishing. Pitch is an example of such a viscoelastic material. It may also be the case where the polishing material is a non-porous material capable of retaining the viscoelastic material. In other preferred embodiments, however, the outer shell may further comprise an elastic layer located between the layer of polishing material and the viscoelastic material, wherein preferably the elastic layer is in direct contact with the viscoelastic material. The elastic layer can improve the strength of the outer shell, preventing tearing, for example, and can serve as a barrier that prevents leakage of the viscoelastic material. The elastic layer also helps to return the shell to its intended shape after it has been deformed in use. In preferred embodiments, the elastic layer comprises at least one of rubber, silicone, neoprene and a polymeric elastomer. The elastic layer preferably has a thickness in the range of 0.1 to 5 mm. It should be noted that where the outer shell includes an elastic layer, the polishing material need not have the same lateral extent as the elastic layer. For instance, the polishing material could be disposed on all or only part of the external surface of the elastic layer, as necessary to form the desired working surface.

As noted above, the construction of the tool is such that the viscoelastic material forms a layer between the non-flat surface of the base structure and the outer shell. In some preferred embodiments, the non-flat surface defines a macro-structure which is rigid in use and has a surface profile which varies on a scale of the same order of magnitude as that of the outer shell, the macro-structure being shaped so as to determine the thickness of the viscoelastic material between the outer shell and the non-flat surface at each location on the outer surface. The surface profile of the macro-structure varies (i.e. follows a path which deviates from some flat reference plane by a varying distance) on a similar scale to that of the profile of the outer shell, e.g. having a similar lateral spatial frequency. The deviation could for instance be monotonous in one direction over approximately half of the lateral dimension of the tool and then monotonous in the opposite direction over the other half. The amount of deviation (e.g. maximum height of the macrostructure) may be at least a tenth of the height of the outer shell relative to a notional flat reference plane drawn through the base structure. Advantageously, the macro-structure is rotationally symmetric about an axis about which the outer shell is also rotationally symmetric. This helps to avoid introducing any eccentricity to the tool. The presence of a macro-structure can improve the performance of the tool either through control of the thickness of the viscoelastic material and/or by controlling the direction in which it flows/distorts during use, encouraging good contact between it and the outer shell.

In some preferred implementations, the macro-structure and the outer shell are configured such that the viscoelastic material forms a layer having a substantially constant thickness between the non-flat surface and the outer shell, the surface profile of the macro-structure preferably including a region which follows the shape of the outer shell. “Constant thickness” here means that the thickness of the viscoelastic material between the outer shell and the non-flat surface is substantially the same at all locations on the working surface (measured normal to the working surface). This ensures that the behaviour of the tool when applied to the workpiece being treated (which, as noted above, depends on the thickness of the viscoelastic material) is the same irrespective of which part of the tool is in contact with the workpiece, or at which angle.

In other preferred embodiments, however, the macro-structure and the outer shell are shaped differently relative to one another such that the thickness of the viscoelastic material between varies across different locations on the working surface. For example, the outer shell may include a part-spherical section while the macro-structure is aspherical. This allows the behaviour of the tool to be controlled by placing different parts of the working surface in contact with the workpiece (and/or changing the orientation of the tool relative to the workpiece), and the variation in thickness may for example be designed such that different parts of the tool are optimised for removing mid-spatial defects of different wavelengths as described previously, or to help preserve intentional sharp edges. By controlling the underlying thickness of semi-compliant material, the polishing pressure can be actively adjusted to yield the processing conditions most adapted to the specific spatial contents found on the workpiece surface. Preferably the greatest value of the thickness of the viscoelastic material is in the range of 2 to 200 mm.

It is particularly advantageous if the macro-structure has at least in part a convex or concave curved shape, preferably part-spherical, part-ellipsoidal, part-parabolic or part-toroidal. It has been found that at the parts of the working surface close to where the outer shell meets the base structure, the behaviour of the viscoelastic material as it undergoes deformation can be influenced by the presence of the base structure underneath. Forming the macro-structure with a concave shape (such that at least part of the non-flat surface has a form of a depression in the direction away from the outer shell) can reduce this effect, since it causes the non-flat surface to be curved (or sloped) away from the outer shell and hence reduces the extent to which it interferes with the properties of the working surface. The concavity (depression) can also be used to counter the natural tendency for a tool with a part-spherical outer shape to push fluids towards the equator. As a tool is rotated about its axis, the non-Newtonian material will attempt to climb up the slope of the concave macro-structure to balance the similar and opposite effect from the part-spherical outer working surface. In other embodiments, convex cores, e.g. with part- spherical, ellipsoidal or parabolic shapes have also been found particularly suitable for controlling the thickness of the layer formed by the viscoelastic material, since these shapes can be arranged to project into the space enclosed by the outer shell and hence cause the cavity to form a well-defined layer between the outer shell and non-flat surface.

The non-flat surface can be configured in various different ways. In preferred implementations, the macro-structure is formed at least in part by a core which extends towards the outer shell and is configurable to be rigid in use. As will be shown later, this core may be formed by a variety of structures, and may or may not be integral with the rest of the non-flat surface. In the simplest cases, the core may simply be a solid body – for example a metal hemisphere – which could be machined into a surface of the base structure. However, other more complex structures, examples of which will be described later, may be employed. Hence, in preferred embodiments, the core comprises one or more of a solid body, an inflatable structure, and an adjustable piston. The inflatable structure could be a non-porous bladder, for example, which may be adapted to be filled with a fluid such as air, oil or water using a hydraulic system in use in order to confer the required rigidity to the structure. In the case of an inflatable structure, the support member may advantageously comprise a conduit for delivering, in use, a fluid to the inflatable structure. The provision of an adjustable piston as part of the core can allow the shape of the working surface and/or the thickness of the layer of viscoelastic material between the outer shell and non-flat surface to be varied.

In most cases, the macro-structure will not directly contact the outer shell (other than at the periphery of the non-flat surface if it extends to the point at which the outer shell joins to the base structure). However, in some embodiments the core could extend continuously from the base structure to a part of the outer shell (which part may or may not coincide with a portion of the working surface). This may be the case for certain shapes of tool: for example, where the tool has the form of a truncated cone intended to be rotated about its axis of symmetry in use, the core may extend continuously from the base structure to the end of the truncated cone. It will be appreciated that the cavity will still exist, e.g. in an annular form located around the core. Macro-structures which contact the outer shell at at least one point in this way are also useful since the tool can then be used to probe the workpiece before, during or after the polishing operation. That is, this portion of the outer shell (which will be rigid due to its direct contact with the base structure) can be used to measure the position and/or shape of the workpiece surface.

Where a core of the kind described above is provided as part of the macro-structure, the non-flat surface may further comprise a peripheral region adjacent to the core, wherein preferably the peripheral region is relatively flat (relative to the core). For example, the macro-structure could include a hemispherical core surrounded by a relatively flat, disc-shaped peripheral region. In that case, the outer shell could meet the base structure at the outside edge of the disc-shaped peripheral region.

Whilst in many embodiments it is desirable to use the non-flat surface of the base structure to control the thickness of the viscoelastic material layer (i.e. the amount of it between the base structure and the outer shell at any one point), as mentioned above the non-flat surface can be utilised for other purposes. In some preferred embodiments, the non-flat surface defines a micro-structure in the form of a surface texture arranged to grip the viscoelastic material when the sub-aperture polishing tool is rotated in use. By “micro-structure” it is meant a surface relief profile on a scale much smaller than that of the outer shell (and as compared with any macro-structure which might also be present). It should be noted that “micro” in this context should not be held to impose any particular size limit (e.g. having a spatial frequency of less than a millimetre) and/or that the structure is too small to be seen by the naked eye, but either of these characteristics may well be the case in practice. As such, the presence of this surface relief on the base structure makes only a negligible difference (if any) to the thickness of the viscoelastic material layer at different points on the working surface. However, the micro-structure engages the viscoelastic material layer and therefore improves the transmission of torque from the support member to the material, to ensure the material spins with the tool during use. Any shape of surface relief could be utilised for this purpose, including regular or irregular patterns, such as grooves or a grid of lines. In preferred examples, the surface texture comprises a plurality of raised and/or depressed features in the non-flat surface, the raised and/or depressed features preferably forming a studded and/or pitted texture. If the non-flat surface also defines a macro-structure, the surface texture may be present on all or part of the macro-structure. For instance, in the case where the macro-structure includes a core and a peripheral region, the micro-structure could be provided on the surface of the core only and not in the peripheral region, or vice versa.

Preferably, the micro-structure is defined integrally in the base structure and/or is defined in part by a plurality of protrusions affixed to the base structure. Thus, the micro-structure could be formed by appropriate shaping of the base structure itself, e.g. machining into a solid material or moulding that material to form the desired relief. Alternatively the micro-structure could be formed by locally affixing one or more materials to the base structure to form protrusions of the relief as desired. The material(s) forming such protrusions could be compliant or non-compliant material(s) but preferably will be rigid in use (compared to the outer shell), like the rest of the non-flat surface. For instance, the protrusions could be formed from a viscoelastic material provided that it remains in place and does not change its shape or frictional properties considerably in use. The protrusions could also be formed from an elastomer such as rubber and bonded to the rest of the base structure using adhesive. In preferred cases, the protrusions will be at least as rigid as the rest of the material forming the non-flat surface (e.g. steel). For instance, the protrusions (or depressions) could be machined directly into the base structure material. Therefore the micro-structure can be formed by an additive manufacturing technique and/or a subtractive manufacturing technique.

In preferred embodiments, the profile of the micro-structure may have an amplitude (i.e. peak to trough height) in the range of 0.1 mm to 10 mm, or possibly greater in large tools. The amplitude will be small relative to the thickness of viscoelastic material filling the cavity. The protrusions could have any shape, e.g. cylindrical protrusions or elongate grooves, and can be arranged either pseudo-randomly or in a regular pattern in one or two dimensions, e.g. a line grid, a hexagonal arrangement, concentric circles etc. The lateral size of each protrusion (e.g. line width or diameter) is preferably in the range 0.1 mm to 10 mm although again could be larger in large tools. The average centre to centre spacing (or periodicity, if arranged in a regular array) may be between 0.1 mm and 10 mm, or larger in large tools. All of these dimensional considerations would apply equally to depressions, in the case where the surface texture comprises depressions formed into the base structure.

The working surface could be flat or substantially flat, when not pressed against the workpiece surface. However, preferably the working surface of the tool is non-flat when not pressed against a surface. In other words, the outer shell, viscoelastic material and base structure are arranged such that the working surface is not flat when the tool is at rest and the materials are free to relax to their equilibrium states. Typically, the outer shell will be manufactured so as to hold the desired shape in its rest state, although is conformable to the workpiece in use.

For example, the working surface of the tool could be shaped as a section of a sphere. Curved working surfaces (whether convex, concave or otherwise non-flat) are particularly suitable for sub-aperture polishing since they are typically able to be applied to surfaces with a greater range of shapes and curvatures than are flat working surfaces. For example, a working surface in the shape of a section of a sphere is in principle capable of polishing any concave surface whose radius of curvature is greater than that of the working surface.

In preferred implementations, at least part of the working surface is part-spherical, part-ellipsoidal, part-cylindrical, part-conical or toroidal. These shapes have been found to be suitable for polishing surfaces having a range of topologies and are thus particularly suited to polishing of free-form surfaces. Working surfaces including a plurality of laterally-offset regions each of a different shape (such as any one of those mentioned above) are also possible.

Preferably the working surface has a lateral width in the range of 0.5 millimetres (mm) to 1 metre (m), preferably 0.5 mm to 0.5 m, more preferably 0.5 mm to 200 mm, most preferably 0.5 to 5 mm. A range of such polishing tools with different dimensions and/or shapes may be made available, to suit different workpieces or for polishing of different parts of one workpiece.

Whilst preferred implementations of the viscoelastic material have been described above as either: (i) "shear-thickening and/or stress-stiffening", or (ii) "shear-thinning and/or stress-weakening", it should be noted that the two are not mutually exclusive. That is, as noted above, some viscoelastic materials can exhibit both types of behaviour in different ranges of applied shear/strain rate (or applied stress). Hence each of the above terms encompasses any viscoelastic material which exhibits the respective property under at least one range of shear/strain rates (or applied stresses), even if it exhibits the opposite property at some other range. As an example, some mixtures of corn starch and water exhibit shear-thickening behaviour at one range of shear rate, and shear-thinning at a different range of shear-rate, and would therefore be considered to meet both definitions (i) and (ii). Of course, in practice the polishing tool will be controlled such that the shear/strain rate (or applied stress) experienced by the material will be in the necessary range in order to elicit the desired viscoelastic behaviour – i.e. either (i) or (ii). In some preferred embodiments, the viscoelastic material will be selected such that it only exhibits behaviour (i) or (ii), i.e. its response type is the same at all shear/strain rates (or applied stress levels). In preferred examples, the viscoelastic material comprises at least one of: pitch, a non-Newtonian fluid, a polymer, a silicone polymer, starch, clay, a meta-material, a suspension of particles in a solvent or any combination thereof (e.g. in a homogeneous mix). Preferred examples of shear-thickening and/or stress-stiffening viscoelastic materials comprises at least polydimethylsiloxane (PDMS). For example, the material could be a suspension of dimethylsiloxane, silicon dioxide, castor oil and polydimethylsiloxane. Preferred examples of shear-thinning and/or stress-weakening viscoelastic materials include: soaps, shampoo compositions, mixtures of corn starch and water, and mixtures of fine particles (e.g. talc) with a solvent. For instance, some paints exhibit shear-thinning behaviour if their constituent particles are sufficiently small (e.g. 5 micron particles). An example of a suitable commercial product is Carbopol 940 gel (available from The Lubrizol Corporation, of Ohio USA), which contains carbomer and carboxypolymethylene

The first aspect of the invention further provides a sub-aperture polishing machine comprising:

the sub-aperture polishing tool as described above;

a workpiece holder for holding, in use, a workpiece; and

an actuating mechanism in mechanical communication with the attachment feature, wherein the actuating mechanism is configured to rotate, in use, the sub-aperture polishing tool about a first rotational axis passing through the tool while at least a portion of the working surface is in contact with a surface of the workpiece such that the working surface moves against the surface of the workpiece.

This provides all the advantages already explained above with reference to the polishing tool.

Preferably, the actuating mechanism is further controllable so as to vary, in use, the position and/or orientation of the sub-aperture polishing tool with respect to the workpiece. Desirably, the actuating mechanism is controllable so as to move the polishing tool along three orthogonal spatial directions. The actuating mechanism may also be controllable so as to vary the orientation of the polishing tool about a second rotational axis and/or a third rotational axis each orthogonal to the first rotational axis and one another. For example, a 3-, 4- or 5- axis CNC machine could be utilised. Alternatively, the polishing machine could be a machining centre (e.g. FANUC Robodrill) an industrial robot (e.g. FANUC LR Mate) or a belt-driven mechanism (i.e. a system of gears and pulleys used to move a tool across the surface in some repeating pattern).

Advantageously, the actuating mechanism is further controllable so as to drive the movement of the tool against surface of the workpiece such that the viscoelastic material exhibits either: (i) shear-thickening and/or stress-stiffening behaviour, or (ii) shear-thinning and/or stress-weakening behaviour. If the viscoelastic material of the tool can exhibit both types of behaviour, it is also possible to configure the machine such that the movement of the tool is driven differently (e.g. at different speeds) in different areas of the workpiece, to elicit each type of behaviour (i) and (ii) from the same tool, sequentially.

The first aspect of the invention also provides a method of polishing a workpiece, the method comprising:

(a) providing a sub-aperture polishing tool as described above;

(b) placing the working surface of the sub-aperture polishing tool in contact with a surface of the workpiece; and

(c) moving the working surface against the surface of the workpiece so as to polish the workpiece surface.

Preferably, moving the working surface against the surface of the workpiece comprises rotating the sub-aperture polishing tool about a first rotational axis which passes through the sub-aperture polishing tool. This will typically be an axis about which the outer shell (and working surface) has 360 degree rotational symmetry. In advantageous implementations, steps (b) and (c) are performed a plurality of times at different locations on the workpiece surface, wherein the orientation of the sub-aperture tool with respect to the workpiece surface is different at at least some of the locations. This can be used to obtain different polishing behaviours at different locations on the workpiece surface, so as to account for different types of surface feature.

In some preferred embodiments, the viscoelastic material is a shear-thickening and/or stress-stiffening viscoelastic material, and, the working surface is moved against the surface of the workpiece so as to reduce and/or remove mid-spatial defects from the surface of the workpiece. The movement of the tool relative to the working surface is preferably controlled (e.g. in terms of its speed) such that the viscoelastic material exhibits shear-thickening and/or stress-stiffening behaviour.

The tool could be moved across the workpiece surface in such a way that the polishing conditions are constant at all points, e.g. constant relative orientation of the tool and workpiece surface, constant pressure etc. This will be desirable where the surface defects are similar across the whole surface. However in other preferred implementations, steps (b) and (c) may be repeated sequentially at two or more different locations on the workpiece surface, each of the plurality of locations comprising mid-spatial defects having a respective wavelength different to those of at least some of the other locations, wherein step (b) is performed at each location under polishing conditions selected in dependence on the wavelength of the respective mid-spatial defects. That is, the nature of the polishing can be varied across the workpiece surface so that it is “tuned” to remove the particular type of defect present at each point. Advantageously, the polishing conditions that vary in dependence on the wavelength of the mid-spatial defects comprise at least one of: the rotational speed of the sub-aperture polishing tool, the pressure between the working surface of the sub-aperture polishing tool and the workpiece surface, and the orientation of the sub-aperture polishing tool with respect to the workpiece surface.

It has been found particularly useful if the orientation of the sub-aperture tool with respect to the workpiece surface is different at at least some of the locations. Preferably the orientation of the sub-aperture polishing tool with respect to the workpiece surface at each location is selected in dependence on the wavelength of the respective mid-spatial defects. This is especially effective when using a tool in which the viscoelastic material is arranged such that the thickness of said material between the surface of the workpiece and the core varies between the two or more different orientations. In this way the properties of the polishing head will be different when applied to the workpiece in different orientations, since the contact between the two will involve different point(s) of the tool's working surface.

In other preferred embodiments, the viscoelastic material is a shear-thinning and/or stress-weakening viscoelastic material, and the working surface is moved against the surface of the workpiece so as to preferentially smooth relatively flat regions while retaining sharp features of the workpiece surface (e.g. edges). The movement of the tool relative to the working surface is preferably controlled (e.g. in terms of its speed) such that the viscoelastic material exhibits shear-thinning and/or stress-weakening behaviour. Exemplary applications for such processes include polishing of Fresnel lenses, diffractive optics or semiconductor wafers.

Preferably, the surface of the workpiece has a different shape and/or surface profile to that of the working surface of the sub-aperture polishing tool at least when the sub-aperture polishing tool is not in contact with the surface of the workpiece. Advantageously, the working surface of the sub-aperture polishing tool has a surface area that is less than the surface area of the surface of the workpiece, preferably less than half, more preferably less than 10%. In preferred examples, the working surface of the sub-aperture polishing tool has a greatest lateral dimension that is smaller than the greatest lateral dimension of the surface of the workpiece, preferably less than half, more preferably less than 10%. Desirably, at least a portion of the working surface of the sub-aperture polishing tool has a radius of curvature less than the smallest radius of curvature of the surface of the workpiece. This enables the same tool to be used to polish the whole surface of the workpiece, if wished. The disclosed polishing tool and method is particularly well suited for cases in which the workpiece is not rotationally symmetric and/or wherein the surface of the workpiece comprises at least one convex region and at least one concave region, or where both convex and concave curvature is present in the same region (e.g. "saddle" shaped surfaces).

In further preferred implementations, moving the working surface against the surface of the workpiece comprises rotating the sub-aperture polishing tool at a first rotational speed when in contact with a first location on the surface of the workpiece and rotating the sub-aperture polishing tool at a second rotational speed when in contact with a second location of the surface of the workpiece such that the shape of the working surface is different when at the second location to when at the first location. Due to the flexible nature of the outer shell and the compliant nature of the viscoelastic material, when the tool is rotated at high speed, centrifugal forces may cause the shape of the working surface to change, which can be made use of to change the polishing properties of the tool.

The present invention also provides an article polished by the method disclosed above, wherein the article is preferably any of: an optical element such as a lens or prism, a semiconductor wafer, a screen for an electronic device, a medical prosthetic, or a mould. For instance, the apparatus and methods disclosed here could be used for ultra-precision polishing of: precision optics (lenses and mirrors for imaging, microscopy, spectroscopy…), precision moulds (for replication by plastic injection or glass pressing), medical surfaces (ophthalmic, prosthetics), as well as the consumer mass-markets including precision polished surfaces of smartphones, smartwatches, spectacles, etc.

As mentioned above, some types of workpiece have high spatial frequency features which need to be retained during the polishing process. These include Fresnel lenses, diffractive optics and semiconductor wafers. Traditional polishing tools risk polishing out sharp edges in these cases, which is detrimental to the finished product. This problem is encountered in both sub-aperture and full-aperture settings.

Hence, a second aspect of the present invention provides a polishing tool, comprising a support member including an attachment feature for attachment to a polishing machine; and at an end of the support member, a polishing head comprising: a base structure attached to or integral with the support member; an outer shell, at least part of the outer surface of which defines the working surface of the polishing tool, the outer shell being affixed to the base structure so as to enclose a cavity between the outer shell and the base structure; and a shear-thinning and/or stress-weakening viscoelastic material filling the cavity, located between the outer shell and the base structure.

By “shear-thinning and/or stress-weakening” it is meant that the viscoelastic material sealed inside the cavity exhibits this type of behaviour at at least a range of shear/strain rates (or applied stress), as before – preferably at all shear/strain rates (or applied stress levels). As already explained, viscoelastic materials of this sort will thin or weaken in response to increased shear/strain rates (or increased stress). This has the result of preserving sharp edges and other high-frequency features on a workpiece surface during polishing. The polishing tool could be a sub-aperture polishing tool or a full-aperture polishing tool, designed to polish the whole surface of the workpiece (or more than one workpiece) simultaneously.

It should be noted that, unlike the first aspect of the invention, it is not essential to provide a non-flat surface of the base structure. However, this can optionally be included and provides all the same attendant benefits as hereinbefore described, especially in the case of a sub-aperture tool. Such a non-flat surface could define a macro-structure and/or a micro-structure having any of the preferred features already described in relation to the first aspect. The non-flat surface could alternatively be configured to match contours of the workpiece surface to be polished, particularly in the case of a full-aperture polishing tool.

The outer shell can be constructed in any of the ways already described in relation to the first aspect of the invention. Likewise, the working surface can have any of the shapes described in relation to the first aspect of the invention. The working surface may also be flat or substantially flat, when not pressed against the workpiece surface.

The second aspect of the invention further provides a polishing machine, comprising the polishing tool of the second aspect; a workpiece holder for holding, in use, a workpiece; and an actuating mechanism in mechanical communication with the attachment feature, wherein the actuating mechanism is configured to move, in use, the polishing tool relative to the workpiece, while at least a portion of the working surface is in contact with a surface of the workpiece. The nature of the actuating mechanism may depend on whether the machine is configured to perform sub-aperture or full-aperture polishing. In preferred embodiments, the actuating mechanism is configured to rotate the polishing tool about a first rotational axis passing through the tool.

Advantageously, the actuating mechanism is further controllable so as to drive the movement of the tool against surface of the workpiece such that the viscoelastic material exhibits shear-thinning and/or stress-weakening behaviour. This may be necessary if a viscoelastic material is selected which exhibits shear-thinning and/or stress-weakening behaviour at one range of shear/strain rates (or applied stress) and not others. This may involve controlling the rotational speed of the tool, for instance.

The second aspect of the invention further provides a method of polishing a workpiece, comprising: a) providing a polishing tool in accordance with the second aspect; (b) placing the working surface of the polishing tool in contact with a surface of the workpiece; and (c) moving the working surface against the surface of the workpiece so as to polish the workpiece surface. In preferred implementations, the working surface is moved against the surface of the workpiece so as to preferentially smooth relatively flat regions while retaining sharp edges of the workpiece surface, such as the sharp peaks of a Fresnel lens or diffractive optical element, or the sharp edges of a semiconductor wafer. The movement of the tool relative to the working surface is preferably controlled (e.g. in terms of its speed) such that the viscoelastic material exhibits shear-thinning and/or stress-weakening behaviour (if this is not always the case).

In some preferred embodiments, the polishing tool is a sub-aperture polishing tool and the surface of the workpiece has a different shape and/or surface profile to that of the working surface of the sub-aperture polishing tool at least when the sub-aperture polishing tool is not in contact with the surface of the workpiece.

Alternatively, the polishing tool may be a full-aperture polishing tool and the surface of the workpiece to be polished is substantially the same size as the working surface of the polishing tool, or smaller than the working surface of the polishing tool. Full aperture tools can be used to polish the whole of a workpiece surface simultaneously, or even multiple workpieces simultaneously.

The second aspect of the invention further provides an article polished by the above method, wherein the article is preferably any of: an optical element such as a lens or prism, a diffractive optical element, a semiconductor wafer, a screen for an electronic device, a medical prosthetic, or a mould.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of polishing tools, polishing machines and methods in accordance with the present invention will now be described and contrasted with known techniques, with reference to the accompanying drawings, in which:

Figures 1 to 4 show an example of a sub-aperture polishing machine in accordance with an embodiment of the present invention;

Figures 5(a) to 5(g) show examples of sub-aperture polishing tools of different geometries in accordance with embodiments of the invention;

Figures 6(a) to 6(i) show further examples of sub-aperture polishing tools in accordance with embodiments of the invention;

Figures 7(a), 7(b) and 7(c) show examples of sub-aperture polishing tools in accordance with the invention in use polishing workpieces;

Figure 8(a) is a photograph showing a first exemplary sub-aperture polishing tool in accordance with the invention;

Figure 8(b) is a photograph showing the interior structure of the sub-aperture polishing tool of Figure 8(a);

Figures 9(a), 9(b) and 9(c) are photographs showing a second exemplary polishing tool in accordance with the invention;

Figures 10(a) and 10(b) show further examples of sub-aperture polishing tools in accordance with embodiments of the invention;

Figure 11(a) shows schematically the behaviour of a shear-thickening and/or stress-stiffening viscoelastic material suitable for use in embodiments of the invention;

Figures 11(b) and 11(c) show measurements of the properties of exemplary shear-thickening and/or stress-stiffening viscoelastic materials suitable for use in embodiments of the invention;

Figure 12(a) is a graph showing the behaviour of three exemplary material compositions, of which one exhibits shear-thinning and/or stress-weakening behaviour;

Figure 12(b) is a graph showing the behaviour of an exemplary viscoelastic material suitable for use in embodiments of the invention, which exhibits a shear-thickening and/or stress-stiffening response under some conditions, and a shear-thinning and/or stress-weakening response under other conditions;

Figure 13(a) shows an example of a sub-aperture polishing in accordance with an embodiment of the invention during polishing of an exemplary workpiece, Figures 13(b) and 13(c) showing an enlarged detail of the workpiece: (b) overpolished using a conventional polishing tool, and (c) polished using the polishing tool of Figure 13(a);

Figure 14(a) shows parts of an embodiment of a full-aperture polishing apparatus in accordance with an embodiment of the invention, in use, Figure 14(b) showing a schematic cross-section through the polishing head thereof; and

Figure 15 is a graph showing the material removal rate versus radial distance from the workpiece centre, for an exemplary polishing process of the sort shown in

Figure 14, for two different polishing heads (a) and (b), polishing head (a) being conventional and polishing head (b) being in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

Figures 1 to 4 show an exemplary sub-aperture polishing machine in accordance with an embodiment of the invention. The sub-aperture polishing machine comprises a robust table 1 resistant to vibrations. On the table 1 there is mounted an X-slide mechanism 2 for movement in the x direction. On the X-slide mechanism 2 there is mounted a Y-slide mechanism 3 for movement in the y direction. On the Y-slide mechanism 3 there is mounted a turntable 4 for rotation about the axis labelled c. The turntable 4 is mounted on the Y-slide mechanism 3 via a z movement mechanism (not shown) for movement of the turntable 4 in the z direction. The turntable 4 has a workpiece holder onto which a workpiece may be mounted for polishing. This arrangement provides for motion of the workpiece in four axes, namely linear movement in the x, y and z directions, and rotation about the c axis. It will be appreciated that in the arrangement shown, the rotation axis c is parallel to the movement axis z.

Also mounted to the table 1 is an arm 6 which is generally "L" shaped, having a generally horizontal base part 6a and a generally vertical upright 6b. The arm 6 is mounted to the table 1 at the end of the base part 6a remote from the upright 6b for rotation about a vertical axis A. At the upper end of the upright 6b a tool holder 7 is mounted to the upright, so as to be rotatable relative to the upright about horizontal axis B. In the tool holder 7, a sub-aperture polishing tool 8 is mounted by a support member thereof for rotation relative to the tool holder, about a rotational axis H which is set at an angle to the axis B about which the tool holder 7 rotates relative to the upright 6b.

The sub-aperture polishing tool 8 of this example has a part-spherical working surface, which is arranged so that the rotation axes A, B and H coincide at the centre of the part-spherical surface. As noted above, however, sub-aperture polishing tools in accordance with the invention may have a range of geometries, some of which are not spherical or part-spherical, and several examples of sub-aperture polishing tools with such geometries will be discussed later. The sub-aperture polishing tool 8 of this example could be replaced with any of the embodiments of sub-aperture polishing tools described in the examples that follow.

In this example, the arrangement of the sub-aperture polishing machine is such that rotation of the tool arm 6 about the axis A rotates the part-spherical surface without moving the sub-aperture polishing tool in translation, and rotation of the tool holder 7 about the axis H likewise does not move the sub-aperture polishing tool in translation but merely alters the plane of the precession angle between the tool rotation axis B and the tool holder axis H.

Control of the movement of the workpiece in the x, y and z directions and rotation about the c axis, and control of the rotations of the tool arm 6, the tool holder 7 and the sub-aperture polishing tool 8 are affected by an actuating mechanism, which may comprise actuators and drives controlled by a processor apparatus 9, schematically illustrated in Figure 4. The processor apparatus 9 may include input means 10 such as a keyboard, a port for external input signals or a disk drive, to receive process parameters and control instructions for controlling the motions of the workpiece and the tool. A display means 11, for example a screen, may be provided to display information to the machine operator.

By controlling the motions of the workpiece and the tool, the sub-aperture polishing tool 8 may be positioned in contact with any part of the workpiece, and by controlling the rotation of the tool holder 7 about the axis H, the relative direction of movement of the tool relative to the workpiece at the area of contact between the tool and the workpiece may be selected. The movement of the working surface of the sub-aperture polishing tool 8 across the workpiece surface within the area of contact is controlled by varying the precession angle, which is the angle between a normal to the workpiece surface at the area of contact and the axis about which the tool is rotated. As will be shown later, some sub-aperture polishing tools are adapted such that the thickness of the viscoelastic material at the points of the working surface in contact with the workpiece varies in dependence on the precession angle.

The sub-aperture polishing tool 8 has an outer shell that is deformable, so the area of contact between the working surface of the sub-aperture polishing tool and the workpiece may be increased by urging the sub-aperture polishing tool towards the part of the workpiece surface being polished.

In methods in accordance with embodiments of the invention, a workpiece can be mounted in the workpiece holder of the polishing machine described above. The sub-aperture polishing tool 8 is then rotated by the aperture and its working surface is brought into contact with the surface of the workpiece such that it moves against the workpiece surface, thereby polishing the workpiece. An alternative machine which can be used with polishing tools as disclosed herein to perform polishing operations is disclosed in WO-A-0032353, Figures 1 to 3.

Examples of sub-aperture polishing tools in accordance with embodiments of the invention will now be described with reference to Figures 5(a) to 6(i). The examples in Figures 5(a) to 5(f) illustrate a (non-exhaustive) selection of exemplary geometries with which sub-aperture polishing tools in accordance with the inventions may be constructed, while Figures 6(a) to 6(i) illustrate various other features that may be present in tools in accordance with certain preferred embodiments of the invention.

It will be appreciated that all of the exemplary tools are shown and described in their “rest” state – that is, when stationary and not in contact with anything else. In use, the shape of the tool may differ from that when the tool is at rest. In particular, when the tool is in contact with a workpiece surface, it will deform and become locally conformed to the shape of the workpiece surface. The elongation of a (e.g.) spherical tool into an ellipsoidal or toroidal shape offers advantages in the smoothing of surfaces, as it can maximize the area of contact between the tool and workpiece within folded areas of the work surface, such as rolled edges (indeed, the area of contact is an important factor in the removal of mid-to-high spatial frequencies whereby more contact area leads to faster smoothing).

Further, when the tool is rotated at high speed, centrifugal forces may also cause its shape to change. In many cases, the tool relies on its rotational speed to generate the forces that make the surface of the tool the right shape. It is preferably soft enough that the viscoelastic material forms the sack of the tool into a conformal shape. Then as explained below it relies on the movement of the tool across the features of the workpiece surface (e.g. mid-spatials or sharp edges) to either harden or soften its working surface (depending on the type of viscoelastic material used) in order to remove or preserve those features.

Figure 5(a) is a cross-sectional view of an exemplary sub-aperture polishing tool 501a in accordance with an embodiment of the invention. The tool 501a has a support member 503, which is adapted for attachment to a polishing machine such as that shown in Figures 1-4, and a base structure comprising a cylindrical base plate 505, which is oriented with its axis of revolution aligned along the rotational axis H and is connected to (or integral with) an end of the support member 503. The support member 503 and base structure may typically be formed of a metal or alloy, such as stainless steel. In this example, the base plate 505 has a generally flat surface 505’ on the side opposite the support member 503. A hemispherical core 511a is affixed to the base plate 505 on the same side as the flat surface 505’ such that the flat surface 505’ and the surface of the solid core 511a together define a non-flat surface. Alternatively, the core 511a could be formed integrally with the base plate 505, e.g. by machining its shape into surface 505’ or by casting the base plate 505 accordingly. The central part of this non-flat surface is thus hemispherical (due to the presence of the hemispherical core 511a) and is surrounded by a flat, ring-shaped peripheral region.

In combination, the shapes of the surface of the hemispherical core 511a and the surrounding part of the flat surface 505’ determine the macro-structure of the non-flat surface, i.e. its variation over distances of the same or similar order of magnitude to the dimensions of the sub-aperture polishing tool 501a as a whole. In particularly, the macro-structure has a surface profile which varies in height on a similar scale to that of the outer shell 507’. The macro-structure in this example also has full rotational symmetry about the rotational axis H of the sub-aperture polishing tool (like the outer shell 507). In some implementations, the non-flat surface could also define a micro-structure as a result of, for example, a texture formed in the flat surface 505’ and/or the surface of the core 511a. The core 511a in this example is configured to be rigid in use so that it does not deform when subject to stresses induced during its use when the tool 501a is applied to a workpiece. In this simplest case, the core 511a could be a solid structure formed of a rigid material such as a metal, a rigid polymer or ceramics. However, more complex structures can be used to form a core with the required rigidity, examples of which will be described later.

An outer shell 507 is affixed to the base plate 505 at its periphery (preferably only at the periphery, and along the full length of the periphery). In this example, the outer shell 507 is hemispherical in shape and arranged concentrically with the hemispherical core 511a. The outer shell 507 includes at least a layer of a polishing material (frequently termed a “polishing pad” in the industry), for example comprising polyurethane, poromeric cloth, a tar based viscoelastic polymer or any other suitable compliant material, which forms a working surface 507’ of the outer shell 507 suitable for polishing a workpiece in use. The polishing material may or may not be porous. In some embodiments the polishing material may include abrasive particles, whereas in others it may be designed for use with an abrasive slurry.

The outer shell 507 and the non-flat surface formed by the core 511a and base plate 505 together enclose a cavity, which is filled with a (non-Newtonian) viscoelastic material 509. In this example, the cavity is shaped (as a result of the shapes and arrangement of the core 511a, base plate 505 and outer shell 507) such that the viscoelastic material forms a layer which has the same thickness between the core 511a and outer shell 507 at all locations on the working surface 507’. By “thickness” of the layer here we mean the distance between the outer shell 507 and the surface of the core 511a along the direction normal to the working surface 507’ at the location in question. As a result of this configuration, when the tool 501a is rotated about the rotational axis H in use and applied to workpiece, its behaviour is substantially the same regardless of which part of the working surface 507’ is placed in contact with the workpiece surface. Suitable viscoelastic materials 509 for use in this tool 501a exhibit behaviours falling into two general categories: (i) shear-thickening and/or stress-stiffening; and (ii) shear-thinning and/or stress-weakening. Viscoelastic materials exhibiting the first category of behaviour will be selected for applications where the workpiece includes relatively high frequency features which need to be polished out (e.g. mid-spatial defects), whereas viscoelastic materials exhibiting the second category of behaviour will be selected where the relatively high frequency features on the workpiece need to be retained (e.g. sharp edges). As noted above, some viscoelastic materials can exhibit both categories of behaviour, at different ranges of applied shear/strain rate (or applied stress and an example of this will be given below. If this type of material is selected, the type of behaviour it exhibits can be controlled via changing the movement parameters of the tool against the workpiece, e.g. its rotational speed.

Exemplary viscoelastic materials include: pitch, a non-Newtonian fluid, a polymer, a silicone polymer, starch, clay, a meta-material, a suspension of particles in a solvent or any combination thereof (e.g. in a homogeneous mix). Preferred examples of shear-thickening and/or stress-stiffening viscoelastic materials comprise at least polydimethylsiloxane (PDMS). For example, the material could be a suspension of dimethylsiloxane, silicon dioxide, castor oil and polydimethylsiloxane. Preferred examples of shear-thinning and/or stress-weakening viscoelastic materials include: soaps, toothpastes, shampoo compositions, mixtures of corn starch and water, and mixtures of fine particles (e.g. talc) with a solvent. For instance, some paints exhibit shear-thinning behaviour if their constituent particles are sufficiently small (e.g. 5 micron particles). An example of a suitable commercial product is Carbopol 940 gel (available from The Lubrizol Corporation, of Ohio USA), which contains carbomer and carboxypolymethylene. More details of suitable viscoelastic materials 509 will be given below.

Optionally, the outer shell 507 may also include a layer of an elastic material such as rubber, silicone, neoprene or another polymeric elastomer, in which case the layer of polishing material would be arranged on the outside of this elastic layer. The provision of an elastic layer can confer several advantages. Firstly, it can help to restore the shape of the outer shell 507 after being deformed in the course of polishing a workpiece. It can also help to retain the viscoelastic material 509, preventing leakage, which is advantageous where the polishing material forming the working surface 507' is porous. The outer shell can optionally have an additional layer of a material such as pitch applied to its external surface if desired.

The outer shell 507 can be affixed to the base structure in a variety of ways. For example, it could be adhered or clamped to the base plate 505 at its periphery. Alternatively, outer shell 507 could be fitted around a portion of the base plate 505 and held in place by its own elasticity, and/or could be heat-shrunk onto the base structure.

The tool could be made to any size as suited to the workpiece to be polished. For instance, the diameter of the outer shell could be in the range 0.5mm to 1m, preferably 0.5 mm to 0.5 m, more preferably 0.5 mm to 200 mm, most preferably 0.5 to 5 mm. A range of such polishing tools with different dimensions and/or shapes may be made available, to suit different workpieces or for polishing of different parts of one workpiece. Preferably, the minimum radius of curvature of the tool is selected such that it may contact freely with every possible location on the workpiece surface (e.g. both convex and concave sides of a curved smartphone or smartwatch screen, sun glasses, etc.). The same dimensional considerations apply to all the embodiments disclosed herein.

Figure 5(b) shows a second example of a sub-aperture polishing tool 501b in accordance with the invention. This tool 501b has the same support member 503, base plate 505 and hemispherical outer shell 507 as the tool 501a of Figure 5(a). In this example, however, the tool 501b has a core 511b that is aspherical – for example it may have the shape of part of a prolate spheroid (or in other words, a sphere that has been stretched along the direction of the rotational axis H) and thus has an elliptical cross-section. Because the shape of this core 511b does not match that of the hemispherical outer shell 507, the cavity between the non-flat surface of the base structure (formed by the flat surface 505' of the base plate 505 and the surface of the core 511b) and the outer shell is shaped such that the thickness of the viscoelastic material varies between locations on the working surface 507'. For example, the thickness is smallest at a point L1 on the working surface 507’ corresponding to the ‘tip’ of the tool 501b. Where the viscoelastic material layer is thinner, the working surface tends to be more resistant to deformation for a given rate of shearing. This is useful since the polishing behaviour of the tool depends on the orientation in which it is applied to the workpiece, which can be varied.

For example, in a tool designed for use in removing mid-spatial defects (where the viscoelastic material 509 will be selected to exhibit shear-thickening and/or stress-stiffening viscoelastic properties),the parts of the working surface 507’ where the viscoelastic material layer is thinner are therefore suited to removing mid-spatial defects of smaller spatial frequencies. For the same reasons, parts where the viscoelastic layer is thinner (for example point L2) are best suited to removing mid-spatial defects of comparatively greater spatial frequencies. In this example, since the core 511b and the outer shell 507 have full rotational symmetry about the rotational axis H, the thickness of the viscoelastic material layer at the part of the workpiece surface in contact with the working surface 507’ can be controlled simply by changing the angle between the rotational axis H and the part of the workpiece surface to which the tool 501b is applied, as will be demonstrated below. The tool 501b of this example is therefore suitable for polishing workpieces that are known or expected to contain mid-spatial defects of different spatial frequencies. By contrast, the sub-aperture polishing tool 501a of Figure 5(a) behaves in the same way irrespective of which part of the working surface 507’ is in contact with the workpiece surface, so it is suitable for polishing workpieces (or a part of a workpiece) with complex geometries, containing mid-spatial defects that do not vary significantly in spatial frequency (if it too comprises a shear-thickening and/or stress-stiffening viscoelastic material 509).

To illustrate the functional differences between the sub-aperture polishing tools of Figures 5(a) and 5(b), Figure 7(a) shows the sub-aperture polishing tool 501a of Figure 5(a) in use at two different locations on a curved surface of a workpiece 701. The surface 701’ of the workpiece has a ‘wavy’ profile due to the mid-spatial defects that are present on it (it should be appreciated that the Figures are not to scale in this respect: the mid-spatial defects are shown much larger than they will generally be in reality, for clarity). At both the first location C1 and the second location C2, the thickness of the viscoelastic material layer between the part of the working surface 507’ in contact with the workpiece 701 and the core 511a is the same. Figure 7(b) shows the sub-aperture polishing tool 501b of Figure 5(b) applied to two different locations on the surface of a different workpiece 703’. At a first position C3 on this surface 703’, there are mid-spatial defects having a first spatial period P1. Because the parts of the tool 501b where the viscoelastic layer is thicker are best suited to removing mid-spatial defects of larger spatial periods (and hence smaller spatial frequencies), the tool 501b is applied to the surface at the first position C3 at an oblique angle to the plane of the surface 703’. At a second position C4 on the same surface 703’, where the mid-spatial defects present have a smaller spatial period P2 less than P1, the tool 501b is applied such that its rotational axis H is substantially normal to the surface 703’. Hence, at the second position C4, the thickness of the viscoelastic layer between the part of the working surface 701’ in contact with the workpiece surface 703’ of the workpiece reduced in comparison to the first position C3 and the tool 501b removes the higher-frequency mid-spatial defects in the most efficient possible manner.

Returning to the examples of tool geometries, Figure 5(c) shows a third exemplary sub-aperture polishing tool 501c in accordance with an embodiment of the invention. Again, this tool 501c has the same support member 503 and outer shell 507 as the foregoing examples, but in this case the tool 501c has a base structure 513 shaped to define a concave surface 513’, herein the shape of an inverted cone. Whereas in the previous examples the non-flat surface of the base structure is non-flat due to the presence of a core, in this case the non-flat surface is simply provided by the concave surface 513’ and the macro-structure of the non-flat surface is, accordingly, concave. Because of the concave shape of the non-flat surface 513’, the thickness of the viscoelastic material between working surface 507’ and the base structure varies less between locations on the working surface 507’ than it would if the same surface were flat. This ensures that the behaviour of the tool 501c behaves in a relatively uniform manner irrespective of the angle at which it is applied to the workpiece being polished. As noted previously, however, some variation in behaviour may be desirable in order to treat mid-spatial defects (or other features) of different frequencies and the precise form of the convex surface 513’ may be chosen so as to allow for some variation.

Figure 5(d) shows a fourth exemplary sub-aperture polishing tool 501d in accordance with an embodiment of the invention. This tool 501d is similar to that of Figure 5(a), but in this case the core 515 is shaped with a cylindrical portion 515a, which extends from the base plate 517 along the direction of the rotational axis H, and a hemispherical section 515b forming the end of the core 515 distal to the base plate 517. The core 519 is affixed to a flat base plate 521, which in combination with the core 519 defines a non-flat surface formed of the surface of the core 519 and the surrounding, ring-shaped part of the surface 521’ of the base plate 521.

The outer shell 519 has a shape matching that of the core 515, so that the thickness of the viscoelastic material between 509 the outer shell 519 and core 515 is constant and the working surface 519’ has a cylindrical region 519’a adjacent to the base plate 517 and a dome-shaped region 519’b forming the tip of the tool 501d. A tool of this kind, of which the working surface 519’ has differently-shaped regions, is suitable for polishing differently-shaped parts of the surface of a workpiece. For example, the cylindrical region 519’a is suited to polishing convex features while the dome-shaped region 519’b is capable of reaching into concave regions with radii of curvature greater than that of the dome-shaped region 519’b.

Figure 5(e) shows a fifth exemplary sub-aperture polishing tool 501e in accordance with an embodiment of the invention. This tool 501e has a support member 503 and a base plate 527 connected to one another. Connected to the side of the base plate 527 opposite the support member 503 is a core 523, which has the form of a truncated cone with its axis of revolution aligned with the rotational axis H of the tool. An outer shell 525 (which may be formed of the same materials used to form the outer shells described previously) is affixed to the base plate 527 at its periphery and extends circumferentially around the core 523. Like in the previous examples, the part of the outer shell 525 that extends circumferentially around the core 523 forms a working surface 525’ suitable for polishing a workpiece in use as the tool 501e is rotated about the axis of rotation H. An end part 525'' of the outer shell, which is not part of the working surface in this example, also extends across the tip of the tool 501e and is in contact with the narrower end of the core 523 (i.e. the end distal to the base plate 527). The core 523 thus extends continuously from the base plate 527 to the end part 525'' of the outer shell 525. Where the core 523 contacts the outer shell, the outer shell will be held rigid and so can be used to probe the workpiece if desired, as described further in connection with Figure 10(b) below. In this example, the outer shell 525 is shaped such that the thickness of the viscoelastic material (as measured along the direction normal to the working surface 525' at the location in question) in the cavity is greatest where the outer shell 525 meets the base plate 527 and decreases with distance from the base plate 527.

Figure 5(f) is a cross-sectional view of a sixth exemplary sub-aperture polishing tool 501f in accordance with an embodiment of the invention. Like the previous examples, this tool has a support member 503 for attachment to a polishing machine and is configured to be rotated in use about a rotational axis H. Attached to the support member 503 is a base structure 531. The base structure 531 is fully rotationally symmetric about the axis of rotation H. Its central part 533, by which it is attached to the support member 503, has the form of a disc of substantially constant thickness. Surrounding the central part 533 is an intermediate section 535, which tapers along the radial direction perpendicular to the rotational axis H. An outer section 537 of the base structure 531 is curved about the circumferential direction that extends around the rotational axis H and thus has a semi-elliptical cross-section.

An outer shell 541 is affixed to the tapering surfaces of the intermediate section 535 and extends fully around the circumference of the base structure 531. As a result, the outer shell 541 defines a toroidal working surface 541' that has full rotational symmetry about the rotational axis H. In this case, the outer section 537 and the parts of the intermediate section 535 enclosed by the cavity formed by the outer shell 541 form a non-flat surface whose macro-structure is defined by the tapering surfaces of the intermediate section 535 and the curved surface of the outer section 537.

Figure 5(g) shows a seventh example of a sub-aperture polishing tool 501g in accordance with an embodiment of the invention. This tool 501g has the same support member 503, base plate 505, outer shell 507 and viscoelastic material as example shown in Figure 5(a). In this case, however, no core is present on the generally flat surface 505’ of the base plate. Instead, the base structure is provided with an array of raised surface elements (protrusions) 551 arranged on the flat surface 505’ of the base plate 505. The surface elements 551 could be integral with the base plate 505 or formed separately and then adhered or otherwise fixed to the flat surface 505’. The surface elements 551 in combination with the flat surface 505’ of the base plate define a non-flat surface (which is non-flat by virtue of the raised surface elements 551) which has a micro-structure that corresponds to the texture formed by the surface elements 551.

This texture defines a “micro-structure” in the sense defined previously because, although they render the surface of the base structure in contact with the viscoelastic material non-flat, they do not cause any substantial variation in the thickness of the viscoelastic material layer between the outer shell and the non-flat surface of the base structure. The surface elements protrude into the viscoelastic material inside the cavity enclosed by the outer shell 507 and have the effect of engaging the viscoelastic material as the tool 501g is rotated about the rotational axis H and thus assist in the transmission of torque from the rotating tool to the viscoelastic material in the cavity. Although the surface elements 551 here are shown as being raised with respect to the flat surface 505’, there could additionally or alternatively be depressions in the non-flat surface 505’ which contribute to the non-flat character of the surface in contact with the viscoelastic material. The micro-structure could be formed integrally with the base structure 505 (e.g. machined or moulded into surface 505’), or could comprise material which is affixed to surface 505’. Such a material could be compliant or non-compliant. For instance, isolated portions of the material could be locally adhered to the surface 505’, spaced from one another as appropriate to form the desired surface texture.

The protrusions 551 could, if desired, themselves be formed from a viscoelastic material provided that it remains in place and does not change its shape or frictional properties considerably in use. The protrusions 551 could alternatively be formed from an elastomer such as rubber and bonded to the rest of the base structure using adhesive. In preferred cases, the protrusions 551 will be at least as rigid as the rest of the material forming the non-flat surface (e.g. steel). For instance, the protrusions (or depressions) could be machined directly into surface 505' of base structure 505. Therefore the micro-structure can be formed by an additive manufacturing technique and/or a subtractive manufacturing technique.

The profile of the micro-structure may have an amplitude (i.e. peak to trough height) in the range of 0.1 mm to 10 mm, or possibly greater in large tools. The amplitude will be small relative to the thickness of viscoelastic material filling the cavity. The protrusions could have any shape, e.g. cylindrical protrusions or elongate grooves, and can be arranged either pseudo-randomly or in a regular pattern in one or two dimensions, e.g. a line grid, a hexagonal arrangement, concentric circles etc. The lateral size of each protrusion (e.g. line width or diameter) is preferably in the range 0.1 mm to 10 mm although again could be larger in large tools. The average centre to centre spacing (or periodicity, if arranged in a regular array) may be between 0.1 mm and 10 mm, or larger in large tools. All of these dimensional considerations would apply equally to depressions, in the case where the surface texture comprises depressions formed into the base structure.

Figure 7(c) shows a cross-sectional view of the sub-aperture polishing tools of Figures 5(d), 5(e) and 5(f) in use polishing different features in the surface of a free-form workpiece 711. In general, sub-aperture polishing tools of the sort disclosed herein are particularly well adapted to polishing complex freeform surfaces (such as prosthetic knee joint or moulding insert for spectacles) where the curvature can vary rapidly and/or invert itself (saddle points). For instance, the part-spherical working surface of the Figure 5(d) tool 501d is suited to polishing features with relatively low curvature, while the toroidal tool 501f of Figure 5(f) is well-suited to polishing strongly-curved and difficult-to-reach regions. Due to its straight, sloping sides, the conical tool 501e of Figure 5(e) is particularly suited to polishing features that are flat or curved in a single direction (e.g. ridges having the topology of a section of a cylinder).

Having described examples of a range geometries suitable for constructing sub-aperture polishing tools in accordance with the present invention, we will now present examples of possible modifications and specific implementations of features of sub-aperture polishing tools in accordance with preferred embodiments of the invention with reference to Figures 6(a) to 6(i). It should be appreciated that any of these preferred features could be applied to tools of any shape (and/or having any form of macro-structure) including all the options shown in Figures 5(a) to 5(g), but they will be described by reference to hemispherical tools only, for brevity.

As noted above, the non-flat surface formed by the base structure may define either or both of a macro-structure and a micro-structure. Figures 6(a), 6(b) and 6(c) hence show modified versions of the sub-aperture polishing tools of Figures 5(a), 5(b) and 5(c) respectively, which in each case are provided with surface elements 651 of the kind described above that are arranged to form a micro-structure on the macro-structures of the respective base structures. These have the same advantage as in the example of Figure 5(g), i.e. they engage the viscoelastic material and thereby aid in the transmission of torque to it as the tool rotates. While in the examples shown, the micro-structure extends over the whole macro-structure, this is not essential and could be provided on only a part thereof.

Figures 6(d) and 6(e) show an example of a sub-aperture polishing tool 601d with one preferred form of core. In this example, the tool 601d includes a piston 611 that is moveable along the direction of the rotational axis H. The piston 611 has a shaft 612 that extends through a bore in the support member 613 and has a head 611' that occupies a correspondingly-shaped recess in a base plate 605. The head 611' and a peripheral surface 605' of the base plate together define a non-flat surface (which is stepped, in this example), and an outer shell 507 is fixed to the base plate 605 at its periphery. As the piston is moved towards the outer shell 507, the shape of the non-flat surface, and hence that of the cavity between the non-flat surface and the outer shell 507, changes. This causes the working surface 507' to also change shape and modifies the behaviour of the tool in response to shearing when applied to a workpiece in use. The position of the piston 611 can therefore be selected in use so as to vary the behaviour of the tool, for example in order to better conform to differently-shaped regions of the workpiece and/or to optimally remove mid-spatial defects of different spatial frequencies. The movement of the piston 611 could be actuated by, for example, a hydraulic mechanism arranged to transmit force to the piston shaft 612.

Figures 6(f) and 6(g) show a further exemplary sub-aperture polishing tool 601f, which has a core that relies on a fluid to provide its rigidity in use. The tool 601f has a support member 625 attached to a base plate 621, each similar in construction to those described previously. However, in this example, a conduit 625 extends through the support member 625 and the base plate 621 and connects to the interior of an inflatable bladder 627, which is fixed to a flat surface 621' of the base plate 621. In use, as shown in Figure 6(g), the bladder can be filled with a fluid 629 which causes the bladder to inflate and become rigid. The bladder then acts as a rigid core in a manner equivalent to the cores described previously, e.g. that shown in Figure 5(a). The fluid is introduced via the conduit 625, for example from a reservoir comprised by the polishing machine with which the tool 601f is used. The inflation of the bladder 627 causes the bladder to expand or otherwise change shape, which causes a corresponding change in shape of the viscoelastic material layer 509 and the outer shell 507. Suitable fluids for this purpose include liquids such as water or oil and gasses such as air.

As explained previously, the outer shell of the polishing tool in some embodiments can be formed simply by a layer of polishing material (a “polishing pad”) – for example polyurethane, poromeric cloth, a tar based viscoelastic polymer or some combination thereof. Figure 6(h) thus shows a sub-aperture polishing tool 601h in accordance with an embodiment of the invention that corresponds in its construction to that of Figure 5(a) and in which the outer shell 647 is formed by only a layer of polishing material that is affixed to the base plate 505 at its periphery. Embodiments of this sort, in which the layer of polishing material is in direct contact with the viscoelastic material, have been found to produce good results since the behaviour of the material is transmitted to the workpiece surface with little or no modification. This works particularly well for tools of relatively small size (e.g. radii of 5mm or less) and/or where the viscoelastic material is solid or highly viscous so cannot leak through the polishing material.

Figure 6(i) shows another sub-aperture polishing tool 601i also in accordance with an embodiment of the invention and based on that of Figure 5(a), but in which the outer shell 657 includes an elastic layer 659 that confers the outer shell 657 with its hemispherical shape and is fixed to the base plate 505 at its periphery. A region of the outer shell opposite the base plate 505 is covered by a layer of polishing material 671, which does not extend over the full area of the outer shell 657. In this embodiment the polishing material defines the working surface 671’ of the tool 601i, so here the working surface 671’ has a smaller area than the outer shell 657 as a whole. The provision of an elastic layer 659 has been found beneficial especially in mid-sized and large polishing tools, e.g. those with a radius greater than 5mm. The elastic layer assists in retaining the desired shape of the tool and in preventing leakage of the viscoelastic material. The elastic layer preferably has a thickness in the range of 0.1 to 5 mm, depending on the size of the tool. The elastic layer 659 could for instance be formed of any of: nitrile rubber, silicone rubber, polyethylene, or other non-permeable sheet materials.

Figure 8(a) is a photograph of a first sample sub-aperture polishing tool 801 that was manufactured in accordance with an embodiment of the present invention. Figure 8(b) shows the same tool 801 in a partially deconstructed state, in which part of its outer shell 807 has been cut away to reveal the interior structure. The tool 801 has an elongate support member 803 that is adapted for to attachment to a polishing machine, for example one of the kind shown in Figures 1 to 4. A base structure 805 is attached to (and in this example integral with) the support member 803. The base structure has the general form of a cylinder and its end distal to the support member 803 has a generally flat surface 805’ on which a plurality of raised surface elements (not visible) of the kind described previously are arranged. Due to the presence of the surface elements, this end of the support structure forms a non-flat surface whose micro-structure is defined by the arrangement of the surface elements. There is no macro-structure in this embodiment, similar to the example shown in Figure 5(g).

An outer shell 807 is arranged to enclose a hemispherical cavity that is bounded by the non-flat surface of the base structure 805 and filled with a viscoelastic material 809, which in this example is pitch. The outer shell 807 comprises an elastic layer 815, which extends along the length of the base structure 805 and is held in place by its own elasticity (optionally a clamp may also be provided, not shown here). On the end of the elastic layer 815 and forming a part of outer shell 807 distal to the support member 803, there is a part-spherical cap 813 made of a polishing material, in this case polyurethane. The polishing material 813 defines the working surface of the tool 801, which is adapted to be rotated in use about the rotational axis H.

Figures 9(a) to 9(c) are photographs showing a second sample sub-aperture polishing tool 901 that was manufactured in accordance with an embodiment of the present invention. Figure 9(a) shows the tool 901 in an assembled state, while Figures 9(b) and 9(c) show the tool's components while disassembled in order to reveal features of its construction.

The tool 901 has an elongate support member 903 to which a base structure 905 is attached. The base structure in this example is shaped to define a non-flat surface 905' which has a stepped profile and is fully rotationally symmetric about the rotational axis H of the tool 901. The stepped profile defines a raised annular region 905'a and a circular central mesa 905'b of greater height. The tool 901 also includes an outer shell 907, which is placed on the end of the base structure 905 when the tool 901 is assembled so as to enclose a cavity that is bounded on one side by the non-flat surface 905'. The outer shell has at its base a rigid ring 917, which is placed in contact with the non-flat surface 905' when the tool 901 is assembled. Attached to the ring 917 is an elastic layer 915 that encloses the cavity, which is filled with a shear-thickening putty 909 (which is the viscoelastic material in this example). The elastic layer has a domed end on which a polishing pad 913 formed of a polishing material (in this example polyurethane) is arranged to form the working surface 907' of the tool 901. The base structure 905 has a threaded edge 921 (visible in Figure 9(c)), onto which a collar 919 having a correspondingly threaded interior surface is screwed in order to complete the assembly of the tool 901. The collar 919 is shaped with an opening out of which the part of the outer shell 907 carrying the polishing pad 913 extends such that the working surface is available for polishing. The opening is of a smaller diameter than the ring 917 such that the outer shell 907 is held in place when the tool is in its assembled state, shown in Figure 9(a).

Once assembled, the annular region 905'a and circular mesa 905'b are in contact with the shear-thickening putty 909. The circular mesa 905'b defines in effect a cylindrical core and thus a non-flat macro-structure having the attendant benefits discussed above.

Figures 10(a) and 10(b) show two further embodiments of polishing tools. In both cases, only the polishing head is shown but in practice this will be affixed to an end of support member as previously described. In the Figure 10(a) embodiment, a polishing tool 941 is shown in which the base structure 945 is formed of an annular ring 945a within which is affixed a core 945b, e.g. by way of a screw thread fixing. Both the ring 945a and core 945b may be made from a rigid material such as steel (or another metal or alloy). The core 945b has a curved, convex surface 945' defining a macro-structure as described above. The curved surface 945' may for example be a part-spherical surface, and will be rotationally symmetric about the axis of the tool 941. An outer shell 947 is affixed to the ring 945a of the base structure 945 about its periphery. The outer shell 947 defines the working surface of the tool and may consist of a polishing material or may also comprise an elastic layer as previously described. In the latter case, the working surface may not extend across the whole of the outer shell 947. A cavity exists between the outer shell 947 and the non-flat surface 945' of the base structure defined by core 945b, which is filled with a viscoelastic material 949. In this example, the shape of the macro-structure 945' substantially matches that of the outer shell 947 such that the thickness (amount) of material 949 between the two components is substantially the same at all points on the working surface. This has the benefits described in relation to Figure 7(a) above.

The construction of the polishing tool 961 shown in Figure 10(b) is similar to that of Figure 10(a). Namely, a viscoelastic material 969 is located in a cavity formed between an outer shell 967 and a non-flat macro-structure 965' defined by core 965b of base structure 965. However, in this embodiment the non-flat surface 965' is more complex, including an extension 965'' at the centre of the tool, which contacts the outer shell 967. Thus the cavity containing material 969 is annular, the viscoelastic material 969 being absent between outer shell 967 and extension 965''. This configuration is beneficial because it enables the tool 961 to additionally be utilised as a probe – that is, it can be used to measure the shape of the workpiece, either before, during or after a polishing operation. This is achieved by placing the part of the outer shell aligned with extension 965'' in contact with the workpiece, and sensing that contact has occurred, in order to ascertain the exact position of that contact point using a CNC machine (or equivalent) carrying the tool 961. The rigidity of the tool at this point conferred by the extension 965'' being in contact with the outer shell ensures that the measurement is precise. Typically, polishing operations will be conducted with the tool in an alternative orientation such that the contact between the workpiece and the tool is away from the extension 965''.

Figure 11(a) illustrates schematically the behaviour of a viscoelastic material in a polishing tool as a point on its working surface moves across the surface of a workpiece 1001 in a direction M that is substantially parallel to the plane of the surface. In practice, this relative motion will be that due to the rotation of the tool so each point on the surface may follow a straight or curved path depending on the tilt of the tool. However, for simplicity a straight path will be assumed here. As can be seen in Figure 10, the surface of the workpiece 1001 has a 'wavy' profile due to the presence of mid-spatial defects, which could have been introduced by a grinding process as described previously. The outer shell 1007 of the tool, which could be formed simply by a layer of polishing material or some other, more complex construction as discussed previously, is compliant and thus conforms to the shape of the defects on the surface of the workpiece 1001. As the working surface 1007' tool is moved along the movement direction M, each part of the viscoelastic material in proximity to the inner surface 1007'' of the outer shell is cyclically compressed (when positioned over a 'peak' in the surface profile, such as at location M1) and expanded (when positioned over a 'trough' in the surface profile, such as at location M2), as represented schematically by springs in the Figure. Each position on the surface of the viscoelastic material 1009 is thus cyclically deformed at a frequency, f, corresponding to the speed, v_M, at which the working surface 1007’ moves relative to the surface of the workpiece 1001 divided by the spatial period, P, of the defects. Importantly, this frequency is directly dependent on the rotational speed of the sub-aperture polishing tool.

The response of the viscoelastic material 1009 to the frequency of deformation will depend on the nature of the viscoelastic material and particularly whether it exhibits shear-thickening or shear-thinning behaviour at the range of frequencies in question. If the viscoelastic material 1009 is a shear-thickening and/or stress-stiffening material under the operating conditions in use, it will harden as the frequency increases meaning that small-scale features on the workpiece surface (such as mid-spatial defects) are preferentially polished-out. In contrast, if the viscoelastic material 1009 is a shear-thinning and/or stress-weakening material under the operating conditions in use, it will soften as the frequency increases, meaning that small-scale features (such as sharp edges) are preferentially retained.

Viscoelastic materials simultaneously exhibit both viscous and elastic behaviours. The elastic component of the material’s behaviour causes it to store energy when cyclically deformed (such as in the manner shown in Figure 11(a)) and is represented by a parameter called the shear storage modulus G’, which is measured in units of Pascals (Pa). Similarly, the viscous aspect of its behaviour, which causes the material to dissipate energy when deformed, is represented by the shear loss modulus G’’, again with units of Pa. Each of G’ and G’’ can vary in dependence on the frequency of the cyclic deformation to which the material is subjected. When the value of G’ is greater than that of G’’, the elastic component of the material’s behaviour dominates (and similarly, when G’’ exceeds G’, the viscous behaviour dominates). For a given material, the frequency at which G’ and G’’ are equal is referred to as the viscoelastic transition. (It should be noted that some materials have several viscoelastic transition points.) The frequency at which the viscoelastic transition occurs is relevant to the present discussion because the material’s behaviour can be characterised as being stiffer when the elastic behaviour dominates, so the rotational speed of the sub-aperture polishing tool be can controlled to ensure that a shear-thickening and/or shear-stiffening viscoelastic material therein behaves with a sufficient stiffness for removing mid-spatial defects of a given spatial frequency. Or, conversely, in a tool comprising a shear-thinning and/or stress-weakening viscoelastic material, to ensure that it thins sufficiently to preserve features of a given spatial frequency.

Measurements of G’ and G’’ over a range of deformation frequencies for two sample shear-thickening and/or shear-stiffening viscoelastic materials are shown in Figure 11(b). The horizontal axis is the deformation frequency in units of Hertz (Hz) and the vertical axis represents the shear storage and shear loss moduli, with units of Pa. For the first sample, known as “sample C”, measurements of the shear storage modulus G’ are plotted as diamonds fitted by the line 1101a and measurements of the shear loss modulus G’’ are plotted as crosses fitted by the line 1101b. It can be seen that at lower frequencies (on the left-hand side of the graph), G’’ is significantly greater than G’. As the frequency approaches about 2 Hz, both G’ and G’’ increase, but the rate of increase of G’’ begins to fall. At 2.516 Hz, the moduli become equal, and at higher frequencies G’ exceeds G’’. Sample C thus has its viscoelastic transition point at about 2.516 Hz. Figure 11(b) also shows measurements of G’ and G’’ for a second sample, “sample D”. Measurements of G’ for sample D are plotted as diamonds fitted by the line 1103a, while measurements of G’’ are plotted as crosses fitted by the line 1103b. It can be seen that sample D has a viscoelastic transition point 1005b at a frequency slightly greater than that of the orange sample.

Figure 11(c) shows measurements of the shear loss and shear storage moduli for two further samples, “sample A” and “sample B”. For sample A, G’ is plotted as diamonds fitted by the line 1111a and G’’ is plotted as crosses fitted by the line 1111b. For sample B, G’ is plotted as diamonds fitted by the line 1113a and G’’ is plotted as crosses fitted by the line 1113b. Sample B can be seen to have a viscoelastic transition point 1115a at a frequency of about 3.981 Hz, while sample A has a viscoelastic transition point at a similar but slightly higher frequency.

All of the sample materials mentioned above are suitable for use as a shear-thickening and/or stress-stiffening viscoelastic material in embodiments of the invention. Each material is primarily composed of a suspension of dimethylsiloxane, silicon dioxide, castor oil and/or polydimethylsiloxane.

Proportions can vary to alter the characteristics as illustrated by the graphs in Figure 11. One exemplary composition is: 65% dimethylsiloxane (hydroxy-terminated polymers with boric acid), 17% silica (crystalline quartz), 9% Thixatrol ST (castor oil derivative), 4% polydimethylsiloxane, 1% decamethyl cyclopentasiloxane, 1% glycerine, and 1% titanium dioxide. Another suitable example material comprises corn starch (cornflour) mixed with water in varying proportions.

More generally, suitable shear-thickening and/or stress-stiffening viscoelastic materials for use in embodiments of the invention include dilatants (shear-thickening fluids) and pentamode metamaterials (meta-fluids). A dilatant (also termed shear thickening) material is one in which viscosity increases with the rate of shear strain. Such a shear thickening fluid is an example of a non-Newtonian fluid. This behaviour is usually not observed in pure materials, but can occur in suspensions. A dilatant is a non-Newtonian fluid where the shear viscosity increases with applied shear stress. This behaviour is only one type of deviation from Newton’s Law, and it is controlled by such factors as particle size, shape, and distribution. The properties of these suspensions depend on Hamaker theory and Van der Waals forces and can be stabilized electrostatically or sterically. Shear thickening behaviour occurs when a colloidal suspension transitions from a stable state to a state of flocculation. A large portion of the properties of these systems are due to the surface chemistry of particles in dispersion, known as colloids. This can readily be seen with a mixture of corn starch and water, which acts in counterintuitive ways when struck or thrown against a surface. Sand that is completely soaked with water also behaves as a dilatant material.

Examples of suitable shear-thinning and/or stress-weakening viscoelastic materials for use in embodiments of the invention include soaps, toothpastes, shampoo compositions, mixtures of corn starch and water, and mixtures of fine particles (e.g. talc) with a solvent. For instance, some paints exhibit shear-thinning behaviour if their constituent particles are sufficiently small (e.g. 5 micron particles). An example of a suitable commercial product is Carbopol 940 gel (available from The Lubrizol Corporation, of Ohio USA), which contains carbomer and carboxypolymethylene.

Figure 12(a) is a graph showing the apparent viscosity of three different materials (i), (ii) and (iii) across a range of applied stress levels . Material (i) is a pure solvent with no particles dispersed therein. Materials (ii) and (iii) are paint compositions based on the same solved but now carrying a suspension of talc particles. In material (ii) the paint comprises 29% coarse talc (D50 = 19 microns) whereas in material (iii) the paint comprises 29% fine talc (D50 = 5 microns). It will be seen that materials (i) and (ii) display substantially constant viscosity over the range of stress levels tested (i.e. no viscoelastic properties). However material (iii) decreases in apparent viscosity with increasing applied stress and hence is an example of a suitable shear-thinning and/or stress-weakening viscoelastic materials for use in embodiments of the invention.

As mentioned previously, some materials can exhibit shear-thickening behaviour across one range of applied shear/strain rates (or applied stress) and shear-thinning behaviour across a different range. Figure 12(b) shows the behaviour of an exemplary material of this sort, which is a mixture of corn starch and water. It will be seen that in a first region I, from shear rates of about 10^{-3} to 0.1 s^{-1}, the apparent viscosity of the material decreases with increasing shear rate, so here the material is characterised as shear-thinning. In contrast, between shear rates of about 0.1 and 1 s^{-1} (second region II), the apparent viscosity increases with increasing shear rate, so here the material is characterised as shear-thickening. Above shear rates of about 1 s^{-1} (third region III), the material exhibits shear-thinning behaviour once more. Materials such as these are considered both “shear-thickening and/or stress-stiffening” and “shear-thinning and/or stress-weakening” for the purposes of the present disclosure. The material is controlled to exhibit the desired type of behaviour via control of the movement between the tool and the workpiece surface, e.g. rotational speed, to ensure that it operates within the correct shear rate regime.

A pentamode metamaterial is an artificial three-dimensional structure which, despite being a solid, ideally behaves like a fluid. Thus, it has a finite bulk but vanishing shear modulus, or in other words it is hard to compress yet easy to deform. Speaking in a more mathematical way, pentamode metamaterials have an elasticity tensor with only one non-zero eigenvalue and five (penta) vanishing eigenvalues. According to theory, pentamode metamaterials can be used as the building blocks for materials with completely arbitrary elastic properties, and can therefore be designed to be “shear-thickening and/or stress-stiffening” or “shear-thinning and/or stress-weakening” as necessary. Anisotropic versions of pentamode structures are a candidate for transformation elastodynamics and elastodynamic cloaking.

Figures 13(a), (b) and (c) show a further embodiment of the invention, which utilises a shear-thinning and/or stress-weakening viscoelastic material. Here the polishing tool 1201 is shown in use in a sub-aperture process polishing a workpiece 1210 in the form of an optical structure, such as a Fresnel lens or diffractive optical element. The workpiece 1210 could equally be a mould for such an optical structure. The workpiece 1210 includes sharp features 1211 corresponding to peaks of the optical structure, which need to be accurately retained in the finished product. Figure 13(b) shows a polished workpiece of this sort having been treated using a typical conventional polishing tool. It will be seen that the sharp edges of the features have been removed, becoming curved, which is detrimental to the performance of the optical structure.

The polishing tool 1201, however, will preferentially polish the flanks of the optical structure and not the peaks 1211, leaving these sharp as shown in Figure 13(b). This is because the tool 1201 contains a shear-thinning and/or stress-weakening viscoelastic material 1209, which as described above will soften as the shear rate it experiences increases. The construction of the sub-aperture polishing tool 1201 is similar to those already described above, having a support member 1203 for attachment to a polishing machine (not shown, but that of Figures 1 to 4 is suitable) and a base structure 1205 of a rigid material (e.g. steel). A cavity is formed between the base structure 1205 and an outer shell 1207 which defines the working surface of the tool. In this example, the working surface will be substantially flat when the tool is not in contact with the workpiece, and then conforms to the large scale contours of the workpiece in use, as shown in Figure 13(a). The outer shell 1207 in this example comprises both an elastic layer 1207a and a polishing pad 1207b but as before, the elastic layer 1207a is optional.

Sealed within the cavity is the shear-thinning and/or stress-weakening viscoelastic material 1209, which could be any of the exemplary compositions given above.

In this example, the base structure 1205 presents a flat surface to the viscoelastic material 1209. However, in variants, the base structure could be provided with a non-flat surface as described above, defining a macro-structure and/or micro-structure of any of the sorts described above, in order to better control the movement of the viscoelastic material 1209 as previously explained.

In use, the tool 1201 is rotated about its axis H by the polishing machine to effect polishing of the region of the workpiece with which it is in contact. The tool 1201 is also moved laterally across the workpiece surface (arrow D) to polish different regions.

Figures 14(a) and (b) depict a further embodiment of a polishing tool 1301, in use in a full-aperture polishing process. Figure 14(a) shows a perspective view of the tool in use during polishing of a workpiece 1310, along with selected other parts of the polishing apparatus. The workpiece 1310, which could be a lens or a semiconductor wafer, for example, is mounted on a workpiece holder 1311. The polishing tool 1301 here takes the form of a disc with a larger diameter than that of the workpiece. This enables the tool to polish the whole of the workpiece surface simultaneously, and it could also be used to polish multiple workpieces at the same time (not shown). In variants, the tool could be of substantially the same diameter as the workpiece surface to be polished.

The polishing tool 1301 comprises a rigid base structure (or “substrate”) 1305, made for example of steel, affixed to or integral with a support member 1303 which couples with an actuator in use to rotate the polishing tool about its central axis. As shown in Figure 14(b), the base structure 1305 is joined at its peripheral edge to an outer shell 1307 with which it defines an interior cavity filled with a shear-thinning and/or stress-weakening viscoelastic material 1309. Any of the exemplary shear-thinning and/or stress-weakening viscoelastic materials mentioned above could be used for this purpose. As before, the outer shell 1307 could be single-layered, comprising a polishing material layer 1307b only, but in this example it is depicted as being formed of two layers – an elastic layer (or "membrane") 1307a and polishing pad 1307b. The outer shell 1307 can be bonded to the base structure 1305, or screwed with a flange, or any other method where the shear-thinning material is sealed inside. In this example, the working surface extends over the whole area of outer shell 1307 and is frustoconical. However, in other cases the polishing material 1307b could be constrained to the flat upper region of the outer shell, in which case the working surface would likewise be flat, if desired.

In use, the workpiece 1310 is held against the polishing pad 1307b of the tool by the workpiece holder 1311 and may or may not itself be rotated about the axis of the workpiece holder. The polishing pad 1307b may or may not itself be abrasive – in the version depicted an abrasive slurry 1314 is supplied to the working surface by conduit 1312 to effect the polishing.

As in the previous embodiment, here the base structure surface opposite the working surface is flat. However, in variants it is also possible to provide the base structure with a non-flat surface as previously described. This may be to control the movement of the viscoelastic material 1309 and/or to conform to the shape of the workpiece, which is particularly useful in the case of a full-aperture polishing tool which is of substantially the same size as the workpiece surface to be polished. For example, if the workpiece to be polished is a curved surface of a lens (or other object), the base structure may be provided with substantially the same curved shape, e.g. part-spherical or aspherical.

The use of a shear-thinning and/or stress-weakening viscoelastic material 1309 in this scenario provides the benefit that relatively flat features of the workpiece will be polished preferentially to sharp features such as edges. Figure 15 shows an example of this effect in the case of a semiconductor wafer being polished by a process of the sort shown in Figure 14, using (a) a conventional polishing tool, and (b) a polishing tool in accordance with an embodiment of the invention, containing a shear-thinning and/or stress-weakening viscoelastic material 1309 as described above. It will be seen that, using a conventional tool (a), the material removal rate sharply rises towards the edge of the wafer and then peaks at its edge, causing rounding of the edge and loss of the desired shape. In contrast, the material removal rate using the tool herein disclosed (b) is relatively constant across the whole radius of the wafer and shows no significant peak at the edge. As such, the sharp edge is preserved.

Some preferred aspects of the invention are set out in the following clauses:

Clause 1. A sub-aperture polishing tool, comprising:
a support member including an attachment feature for attachment to a sub-aperture polishing machine; and
at an end of the support member, a polishing head comprising:
a base structure attached to or integral with the support member, the base structure being arranged to provide a non-flat surface;
an outer shell, at least part of the outer surface of which defines the working surface of the polishing tool, the outer shell being affixed to the base structure so as to enclose a cavity between the outer shell and the non-flat surface; and
a viscoelastic material filling the cavity, located between the outer shell and the base structure.

Clause 2. The sub-aperture polishing tool of clause 1, wherein the outer shell comprises a layer of polishing material forming the outer surface and being suitable for sub-aperture polishing of a workpiece.

Clause 3. The sub-aperture polishing tool of clause 2, wherein the polishing material comprises at least one of polyurethane, poromeric cloth, a tar based viscoelastic polymer and/or another compliant material.

Clause 4. The sub-aperture polishing tool of clause 2 or clause 3, wherein the polishing material is in direct contact with the viscoelastic material.

Clause 5. The sub-aperture polishing tool of clause 2 or clause 3, wherein the outer shell further comprises an elastic layer located between the layer of polishing material and the viscoelastic material, wherein preferably the elastic layer is in direct contact with the viscoelastic material.

Clause 6. The sub-aperture polishing tool of clause 5, wherein the elastic layer comprises at least one of rubber, silicone, neoprene and a polymeric elastomer.

Clause 7. The sub-aperture polishing tool of clause 5 or clause 6, wherein the elastic layer has a thickness in the range of 0.1 to 5 millimetres (mm).

Clause 8. The sub-aperture polishing tool of any preceding clause, wherein the non-flat surface defines a macro-structure which is rigid in use and has a surface profile which varies on a scale of the same order of magnitude as that of the outer shell, the macro-structure being shaped so as to determine the thickness of the viscoelastic material between the outer shell and the non-flat surface at each location on the outer surface.

Clause 9. The sub-aperture polishing tool of clause 8, wherein the macro-structure is rotationally symmetric about an axis about which the outer shell is also rotationally symmetric.

Clause 10. The sub-aperture polishing tool of clause 8 or clause 9, wherein the macro-structure and the outer shell are configured such that the viscoelastic material forms a layer having a substantially constant thickness between the non-flat surface and the outer shell, the surface profile of the macro-structure preferably including a region which follows the shape of the outer shell, wherein most preferably the layer has a thickness in the range of 2 to 200 mm.

Clause 11. The sub-aperture polishing tool of any of clauses 8 to 10, wherein the macro-structure and the outer shell are shaped differently relative to one another such that the thickness of the viscoelastic material between varies between different locations on the working surface.

Clause 12. The sub-aperture polishing tool of clause 11, wherein the greatest value of the thickness of the viscoelastic material is in the range of 2 to 200 mm.

Clause 13. The sub-aperture polishing tool of any of clauses 8 to 12, wherein the macro-structure has at least in part a convex or concave curved shape, preferably part-spherical, part-ellipsoidal, part-parabolic or part-toroidal.

Clause 14. The sub-aperture polishing tool of any preceding clause, wherein the macro-structure is formed at least in part by a core which extends towards the outer shell and is configurable to be rigid in use.

Clause 15. The sub-aperture polishing tool of clause 14, wherein the core comprises one or more of a solid body, an inflatable structure, and an adjustable piston.

Clause 16. The sub-aperture polishing tool of clause 15, wherein the support member comprises a conduit for delivering, in use, a fluid to the inflatable structure.

Clause 17. The sub-aperture polishing tool of any of clauses 14 to 16, wherein the core extends continuously from the base structure to a part of the outer shell.

Clause 18. The sub-aperture polishing tool of any of clauses 14 to 17, wherein the core is moveable with respect to the support member.

Clause 19. The sub-aperture polishing tool of any of clauses 14 to 18, wherein the macro-structure of the non-flat surface further includes a peripheral region adjacent to the core, wherein preferably the peripheral region is relatively flat.

Clause 20. The sub-aperture polishing tool of any of the preceding clauses, wherein the non-flat surface defines a micro-structure in the form of a surface texture arranged to grip the shear-stiffening and/or shear-thickening material when the sub-aperture polishing tool is rotated in use, wherein preferably the micro-structure is defined integrally in the base structure and/or is defined in part by a plurality of protrusions affixed to the base structure.

Clause 21. The sub-aperture polishing tool of clause 20, wherein the surface texture comprises a plurality of raised and/or depressed features of the non-flat surface, the raised and/or depressed features preferably forming a studded and/or pitted texture.

Clause 22. The sub-aperture polishing tool of clause 20 or clause 21, when dependent on any of clauses 8 to 19, wherein the surface texture is present on all or part of the macro-structure.

Clause 23. The sub-aperture polishing tool of any preceding clause, wherein the working surface is non-flat when not pressed against a surface.

Clause 24. The sub-aperture polishing tool of clause 23, wherein at least part of the working surface is curved in at least one direction, preferably two directions.

Clause 25. The sub-aperture polishing tool of clause 23 or clause 24, wherein at least part of the working surface is part-spherical, part-ellipsoidal, part-cylindrical, part-conical or toroidal.

Clause 26. The sub-aperture polishing tool of any preceding clause, wherein the working surface has a lateral width in the range of 0.5 millimetres (mm) to 1 metre (m), preferably 0.5 mm to 0.5 m, more preferably 0.5 mm to 200 mm, most preferably 0.5 to 5 mm.

Clause 27. The sub-aperture polishing tool of any preceding clause, wherein the viscoelastic material is a shear-thickening and/or stress-stiffening viscoelastic material.

Clause 28. The sub-aperture polishing tool of any of clauses 1 to 26, wherein the viscoelastic material is a shear-thinning and/or stress-softening viscoelastic material.

Clause 29. The sub-aperture polishing tool of any preceding clause, wherein the viscoelastic material comprises at least one of pitch, a non-Newtonian fluid, a polymer, a silicone polymer, starch, clay, a meta-material, a suspension of particles in a solvent or any combination thereof.

Clause 30. A sub-aperture polishing machine comprising:
the sub-aperture polishing tool of any preceding clause;
a workpiece holder for holding, in use, a workpiece; and
an actuating mechanism in mechanical communication with the attachment feature, wherein the actuating mechanism is configured to rotate, in use, the sub-aperture polishing tool about a first rotational axis passing through the tool while at least a portion of the working surface is in contact with a surface of the workpiece such that the working surface moves against the surface of the workpiece.

Clause 31. The polishing machine of clause 30, wherein the actuating mechanism is further controllable so as to vary, in use, the position and/or orientation of the sub-aperture polishing tool with respect to the workpiece.

Clause 32. The polishing machine of clause 31, wherein the actuating mechanism is controllable so as to move the polishing tool along three orthogonal spatial directions.

Clause 33. The polishing machine of clause 30 or clause 31, wherein the actuating mechanism is controllable so as to vary the orientation of the polishing tool about a second rotational axis and/or a third rotational axis each orthogonal to the first rotational axis and one another.

Clause 34. A method of polishing a workpiece, the method comprising:
(a) providing a sub-aperture polishing tool in accordance with any of clauses 1 to 29;
(b) placing the working surface of the sub-aperture polishing tool in contact with a surface of the workpiece; and
(c) moving the working surface against the surface of the workpiece so as to polish the workpiece surface.

Clause 35. The method of clause 34, wherein moving the working surface against the surface of the workpiece comprises rotating the sub-aperture polishing tool about a first rotational axis which passes through the sub-aperture polishing tool.

Clause 36. The method of clause 34 or 35, wherein steps (b) and (c) are performed a plurality of times at different locations on the workpiece surface, and wherein the orientation of the sub-aperture tool with respect to the workpiece surface is different at at least some of the locations.

Clause 37. The method of any of clauses 34 to 36, wherein the viscoelastic material is a shear-thickening and/or stress-stiffening viscoelastic material, and the working surface is moved against the surface of the workpiece so as to reduce and/or remove mid-spatial defects from the surface of the workpiece.

Clause 38. The method of clause 37, wherein steps (b) and (c) are repeated sequentially at two or more different locations on the workpiece surface, each of the plurality of locations comprising mid-spatial defects having a respective wavelength different to those of at least some of the other locations, and wherein step (b) is performed at each location under polishing conditions selected in dependence on the wavelength of the respective mid-spatial defects.

Clause 39. The method of clause 38, wherein the polishing conditions that vary in dependence on the wavelength of the mid-spatial defects comprise at least one of the rotational speed of the sub-aperture polishing tool, the pressure between the working surface of the sub-aperture polishing tool and the workpiece surface, and the orientation of the sub-aperture polishing tool with respect to the workpiece surface.

Clause 40. The method of any of clauses 37 to 39, wherein the sub-aperture polishing tool is moved against a plurality of locations on the workpiece surface, at least some of which locations contain mid-spatial defects of different respective wavelengths to those present at other ones of the locations, and wherein the orientation of the sub-aperture polishing tool with respect to the workpiece surface at each location is selected in dependence on the wavelength of the respective mid-spatial defects.

Clause 41. The method of clause 40, wherein the viscoelastic material is arranged such that the thickness of the viscoelastic material between the surface of the workpiece and the core varies between the two or more different orientations.

Clause 42. The method of any of clauses 34 to 36, wherein the viscoelastic material is a shear-thinning and/or stress-weakening viscoelastic material, and the working surface is moved against the surface of the workpiece so as to preferentially smooth relatively flat regions while retaining sharp edges of the workpiece surface.

Clause 43. The method of any of clauses 34 to 42, wherein the surface of the workpiece has a different shape and/or surface profile to that of the working surface of the sub-aperture polishing tool at least when the sub-aperture polishing tool is not in contact with the surface of the workpiece.

Clause 44. The method of any of clauses 34 to 43, wherein the working surface of the sub-aperture polishing tool has a surface area that is less than the surface area of the surface of the workpiece, preferably less than half, more preferably less than 10%.

Clause 45. The method of any of clauses 34 to 44, wherein the working surface of the sub-aperture polishing tool has a greatest lateral dimension that is smaller than the greatest lateral dimension of the surface of the workpiece, preferably less than half, more preferably less than 10%.

Clause 46. The method of any of clauses 34 to 45, wherein at least a portion of the working surface of the sub-aperture polishing tool has a radius of curvature less than the smallest radius of curvature of the surface of the workpiece.

Clause 47. The method of any of clauses 34 to 46, wherein moving the working surface against the surface of the workpiece comprises rotating the sub-aperture polishing tool at a first rotational speed when in contact with a first location on the surface of the workpiece and rotating the sub-aperture polishing tool at a second rotational speed when in contact with a second location of the surface of the workpiece such that the shape of the working surface is different when at the second location to when at the first location.

Clause 48. The method of any of clauses 34 to 47, wherein the workpiece is not rotationally symmetric and/or wherein the surface of the workpiece comprises at least one convex region and at least one concave region.

Clause 49. An article polished by the method of any of clauses 34 to 48, wherein the article is preferably any of: an optical element such as a lens or prism, a diffractive optical element, a semiconductor wafer, a screen for an electronic device, a medical prosthetic, or a mould.

Clause 50. A polishing tool, comprising:

a support member including an attachment feature for attachment to a polishing machine; and

at an end of the support member, a polishing head comprising:

a base structure attached to or integral with the support member;

an outer shell, at least part of the outer surface of which defines the working surface of the polishing tool, the outer shell being affixed to the base structure so as to enclose a cavity between the outer shell and the base structure; and

a shear-thinning and/or stress-weakening viscoelastic material filling the cavity, located between the outer shell and the base structure.

Clause 51. The polishing tool of clause 50, wherein the outer shell comprises a layer of polishing material forming the outer surface and being suitable for polishing of a workpiece, where the polishing material preferably comprises at least one of polyurethane, poromeric cloth, a tar based viscoelastic polymer and/or another compliant material.

Clause 52. The polishing tool of clause 51, wherein the polishing material is in direct contact with the shear-thinning and/or stress-weakening viscoelastic material.

Clause 53. The polishing tool of 50 or 51, wherein the outer shell further comprises an elastic layer located between the layer of polishing material and the shear-thinning and/or stress-weakening viscoelastic material, wherein preferably the elastic layer is in direct contact with the viscoelastic material.

Clause 54. The polishing tool of clause 53, wherein the elastic layer comprises at least one of rubber, silicone, neoprene and a polymeric elastomer.

Clause 55. The polishing tool of clause 53 or clause 54, wherein the elastic layer has a thickness in the range of 0.1 to 5 millimetres (mm).

Clause 56. The polishing tool of any of clauses 50 to 55, wherein the polishing tool is a sub-aperture or full-aperture polishing tool.

Clause 57. The polishing tool of any of clauses 50 to 56, wherein the base structure is arranged to provide a non-flat surface and the cavity is enclosed between the outer shell and the non-flat surface.

Clause 58. The polishing tool of any of clauses 50 to 57, wherein the working surface is non-flat when not pressed against a surface, and preferably at least part of the working surface is curved in at least one direction, most preferably two directions.

Clause 59. The polishing tool of clause 58, wherein at least part of the working surface is frustoconical, part-spherical, part-ellipsoidal, part-cylindrical, part-conical or toroidal.

Clause 60. A polishing machine comprising:
the polishing tool of any of clauses 50 to 59;
a workpiece holder for holding, in use, a workpiece; and
an actuating mechanism in mechanical communication with the attachment feature, wherein the actuating mechanism is configured to move, in use, the polishing tool relative to the workpiece, while at least a portion of the working surface is in contact with a surface of the workpiece.

Clause 61. A polishing machine according to clause 60 wherein the actuating mechanism is configured to rotate the polishing tool about a first rotational axis passing through the tool.

Clause 62. A polishing machine according to clause 60 or 61 wherein the polishing machine is configured for sub-aperture or full-aperture polishing of the workpiece.

Clause 63. A method of polishing a workpiece, the method comprising:
(a) providing a polishing tool in accordance with any of clauses 50 to 62;
(b) placing the working surface of the polishing tool in contact with a surface of the workpiece; and
(c) moving the working surface against the surface of the workpiece so as to polish the workpiece surface.

Clause 64. A method of polishing a workpiece according to clause 63, wherein the working surface is moved against the surface of the workpiece so as to preferentially smooth relatively flat regions while retaining sharp edges of the workpiece surface.

Clause 65. A method of polishing a workpiece according to clause 63 or 64, wherein the polishing tool is a sub-aperture polishing tool and the surface of the workpiece has a different shape and/or surface profile to that of the working surface of the sub-aperture polishing tool at least when the sub-aperture polishing tool is not in contact with the surface of the workpiece.

Clause 66. A method of polishing a workpiece according to clause 63 or 64, wherein the polishing tool is a full-aperture polishing tool and the surface of the workpiece to be polished is substantially the same size as the working surface of the polishing tool, or smaller than the working surface of the polishing tool.

Clause 67. An article polished by the method of any of clauses 63 to 66, wherein the article is preferably any of: an optical element such as a lens or prism, a diffractive optical element, a semiconductor wafer, a screen for an electronic device, a medical prosthetic, or a mould.

CLAIMS

1. A sub-aperture polishing tool, comprising:
a support member including an attachment feature for attachment to a sub-aperture polishing machine; and
at an end of the support member, a polishing head comprising:
a base structure attached to or integral with the support member, the base structure being arranged to provide a non-flat surface;
an outer shell, at least part of the outer surface of which defines the working surface of the polishing tool, the outer shell being affixed to the base structure so as to enclose a cavity between the outer shell and the non-flat surface; and
a viscoelastic material filling the cavity, located between the outer shell and the base structure.

2. The sub-aperture polishing tool of claim 1, wherein the outer shell comprises a layer of polishing material forming the outer surface and being suitable for sub-aperture polishing of a workpiece.

3. The sub-aperture polishing tool of claim 2, wherein the polishing material is in direct contact with the viscoelastic material.

4. The sub-aperture polishing tool of claim 2, wherein the outer shell further comprises an elastic layer located between the layer of polishing material and the viscoelastic material, wherein preferably the elastic layer is in direct contact with the viscoelastic material.

5. The sub-aperture polishing tool of any preceding claim, wherein the non-flat surface defines a macro-structure which is rigid in use and has a surface profile which varies on a scale of the same order of magnitude as that of the outer shell, the macro-structure being shaped so as to determine the thickness of the viscoelastic material between the outer shell and the non-flat surface at each location on the outer surface.

6. The sub-aperture polishing tool of claim 5, wherein the macro-structure and the outer shell are configured such that the viscoelastic material forms a layer having a substantially constant thickness between the non-flat surface and the outer shell, the surface profile of the macro-structure preferably including a region which follows the shape of the outer shell, wherein most preferably the layer has a thickness in the range of 2 to 200 mm.

7. The sub-aperture polishing tool of claim 5 or 6, wherein the macro-structure and the outer shell are shaped differently relative to one another such that the thickness of the viscoelastic material between varies across different locations on the working surface.

8. The sub-aperture polishing tool of any of claims 5 to 7, wherein the macro-structure has at least in part a convex or concave curved shape, preferably part-spherical, part-ellipsoidal, part-parabolic or part-toroidal.

9. The sub-aperture polishing tool of any preceding claim, wherein the macro-structure is formed at least in part by a core which extends towards the outer shell and is configurable to be rigid in use.

10. The sub-aperture polishing tool of any of the preceding claims, wherein the non-flat surface defines a micro-structure in the form of a surface texture arranged to grip the shear-stiffening and/or shear-thickening material when the sub-aperture polishing tool is rotated in use, wherein preferably the micro-structure is defined integrally in the base structure and/or is defined in part by a plurality of protrusions affixed to the base structure.

11. The sub-aperture polishing tool of any preceding claim, wherein the working surface is non-flat when not pressed against a surface.

12. The sub-aperture polishing tool of any preceding claim, wherein the viscoelastic material is a shear-thickening and/or stress-stiffening viscoelastic material.

13. The sub-aperture polishing tool of any of claims 1 to 11, wherein the viscoelastic material is a shear-thinning and/or stress-softening viscoelastic material.

14. A sub-aperture polishing machine comprising:
the sub-aperture polishing tool of any preceding claim;
a workpiece holder for holding, in use, a workpiece; and
an actuating mechanism in mechanical communication with the attachment feature, wherein the actuating mechanism is configured to rotate, in use, the sub-aperture polishing tool about a first rotational axis passing through the tool while at least a portion of the working surface is in contact with a surface of the workpiece such that the working surface moves against the surface of the workpiece.

15. The polishing machine of claim 14, wherein the actuating mechanism is further controllable so as to vary, in use, the position and/or orientation of the sub-aperture polishing tool with respect to the workpiece.

16. A method of polishing a workpiece, the method comprising:
(a) providing a sub-aperture polishing tool in accordance with any of claims 1 to 13;
(b) placing the working surface of the sub-aperture polishing tool in contact with a surface of the workpiece; and
(c) moving the working surface against the surface of the workpiece so as to polish the workpiece surface.

17. The method of claim 16, wherein steps (b) and (c) are performed a plurality of times at different locations on the workpiece surface, and wherein the orientation of the sub-aperture tool with respect to the workpiece surface is different at at least some of the locations.

18. The method of any of claims 16 to 17, wherein the viscoelastic material is a shear-thickening and/or stress-stiffening viscoelastic material, and the working surface is moved against the surface of the workpiece so as to reduce and/or remove mid-spatial defects from the surface of the workpiece.

19. The method of claim 18, wherein steps (b) and (c) are repeated sequentially at two or more different locations on the workpiece surface, each of the plurality of locations comprising mid-spatial defects having a respective wavelength different to those of at least some of the other locations, and wherein step (b) is performed at each location under polishing conditions selected in dependence on the wavelength of the respective mid-spatial defects.

20. The method of claim 16 or 17, wherein the viscoelastic material is a shear-thinning and/or stress-weakening viscoelastic material, and the working surface is moved against the surface of the workpiece so as to preferentially smooth relatively flat regions while retaining sharp edges of the workpiece surface.

21. An article polished by the method of any of claims 16 to 20, wherein the article is preferably any of: an optical element such as a lens or prism, a diffractive optical element, a semiconductor wafer, a screen for an electronic device, a medical prosthetic, or a mould.

22. A polishing tool, comprising:
a support member including an attachment feature for attachment to a polishing machine; and
at an end of the support member, a polishing head comprising:
a base structure attached to or integral with the support member;
an outer shell, at least part of the outer surface of which defines the working surface of the polishing tool, the outer shell being affixed to the base structure so as to enclose a cavity between the outer shell and the base structure; and
a shear-thinning and/or stress-weakening viscoelastic material filling the cavity, located between the outer shell and the base structure.

23. The polishing tool of claim 22, wherein the outer shell comprises a layer of polishing material forming the outer surface and being suitable for polishing of a workpiece, where the polishing material preferably comprises at least

one of polyurethane, poromeric cloth, a tar based viscoelastic polymer and/or another compliant material.

24. The polishing tool of claim 23, wherein the polishing material is in direct contact with the shear-thinning and/or stress-weakening viscoelastic material.

25. The polishing tool of 23 or 24, wherein the outer shell further comprises an elastic layer located between the layer of polishing material and the shear-thinning and/or stress-weakening viscoelastic material, wherein preferably the elastic layer is in direct contact with the viscoelastic material.

26. A polishing machine comprising:
the polishing tool of any of claims 23 to 25;
a workpiece holder for holding, in use, a workpiece; and
an actuating mechanism in mechanical communication with the attachment feature, wherein the actuating mechanism is configured to move, in use, the polishing tool relative to the workpiece, while at least a portion of the working surface is in contact with a surface of the workpiece.

27. A polishing machine according to claim 26 wherein the actuating mechanism is configured to rotate the polishing tool about a first rotational axis passing through the tool.

28. A method of polishing a workpiece, the method comprising:
(a) providing a polishing tool in accordance with any of claims 23 to 25;
(b) placing the working surface of the polishing tool in contact with a surface of the workpiece; and
(c) moving the working surface against the surface of the workpiece so as to polish the workpiece surface.

29. A method of polishing a workpiece according to claim 28, wherein the working surface is moved against the surface of the workpiece so as to preferentially smooth relatively flat regions while retaining sharp edges of the workpiece surface.

30. A method of polishing a workpiece according to claim 28 or 29, wherein the polishing tool is a sub-aperture polishing tool and the surface of the workpiece has a different shape and/or surface profile to that of the working surface of the sub-aperture polishing tool at least when the sub-aperture polishing tool is not in contact with the surface of the workpiece.

31. A method of polishing a workpiece according to claim 28 or 29, wherein the polishing tool is a full-aperture polishing tool and the surface of the workpiece to be polished is substantially the same size as the working surface of the polishing tool, or smaller than the working surface of the polishing tool.

32. An article polished by the method of any of claims 28 to 31, wherein the article is preferably any of: an optical element such as a lens or prism, a diffractive optical element, a semiconductor wafer, a screen for an electronic device, a medical prosthetic, or a mould.

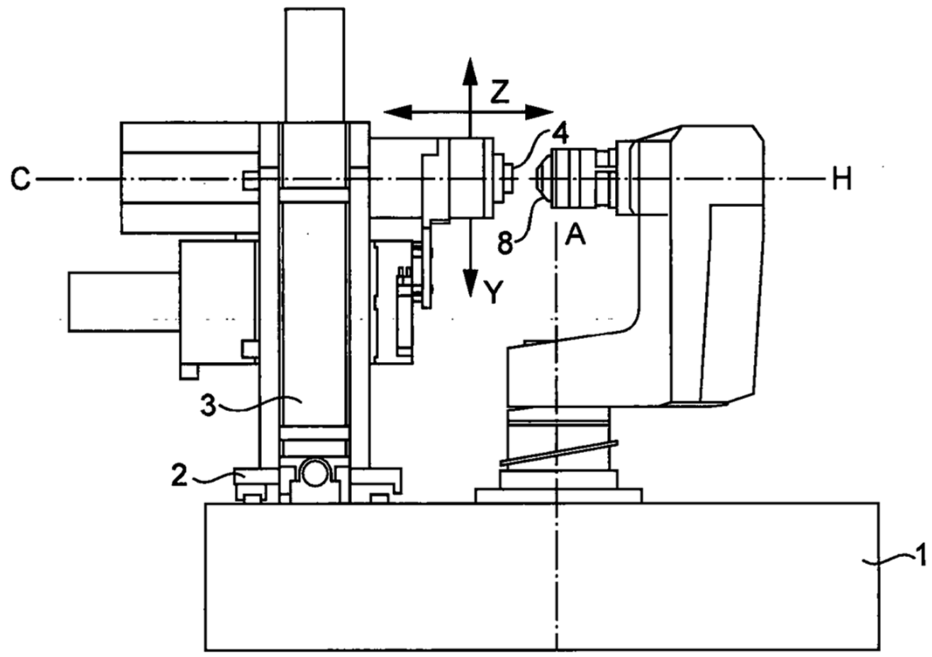

FIG. 1

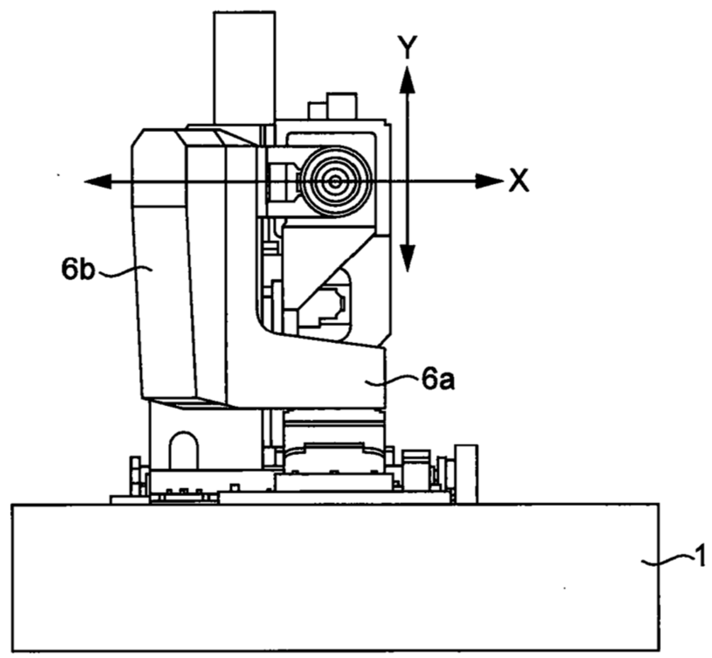

FIG. 2

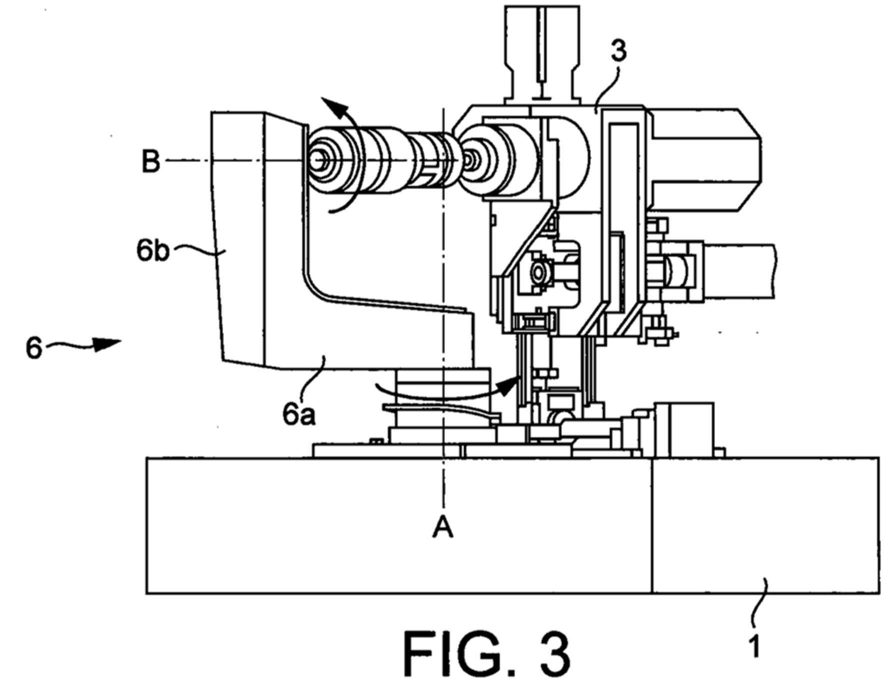

FIG. 3

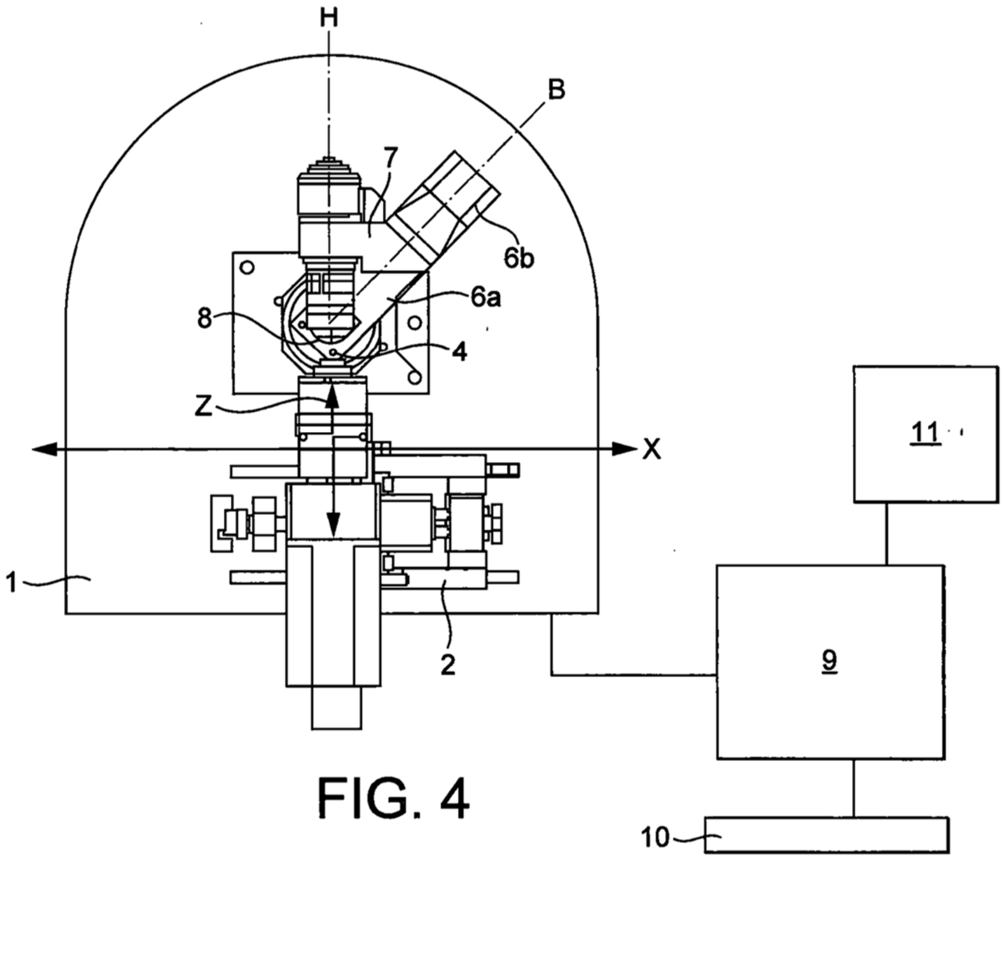

FIG. 4

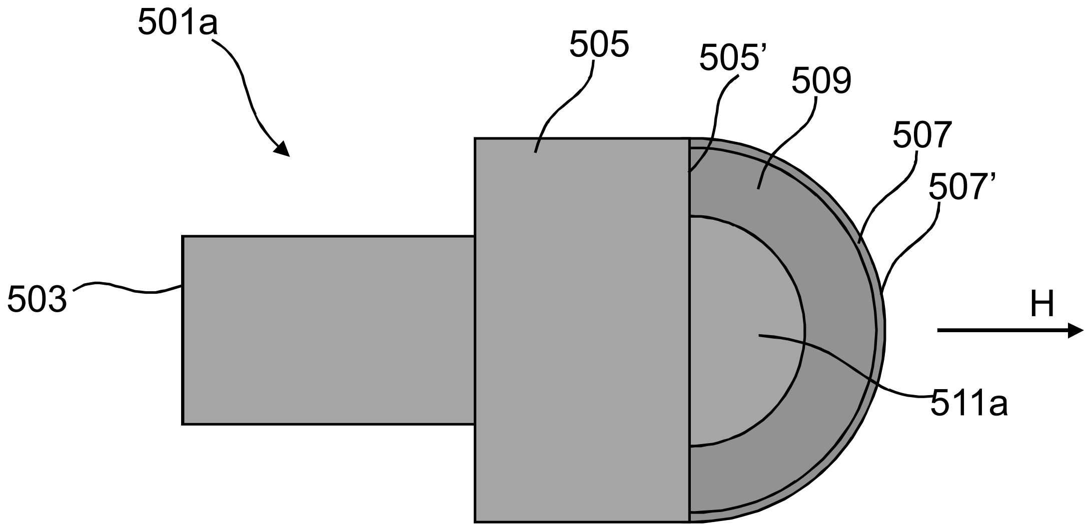

Fig. 5(a)

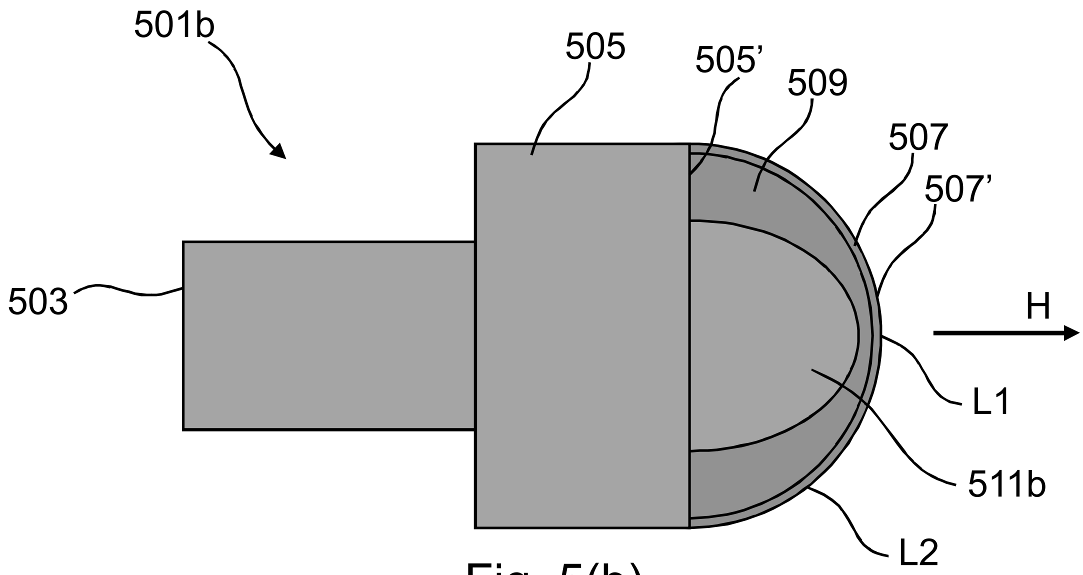

Fig. 5(b)

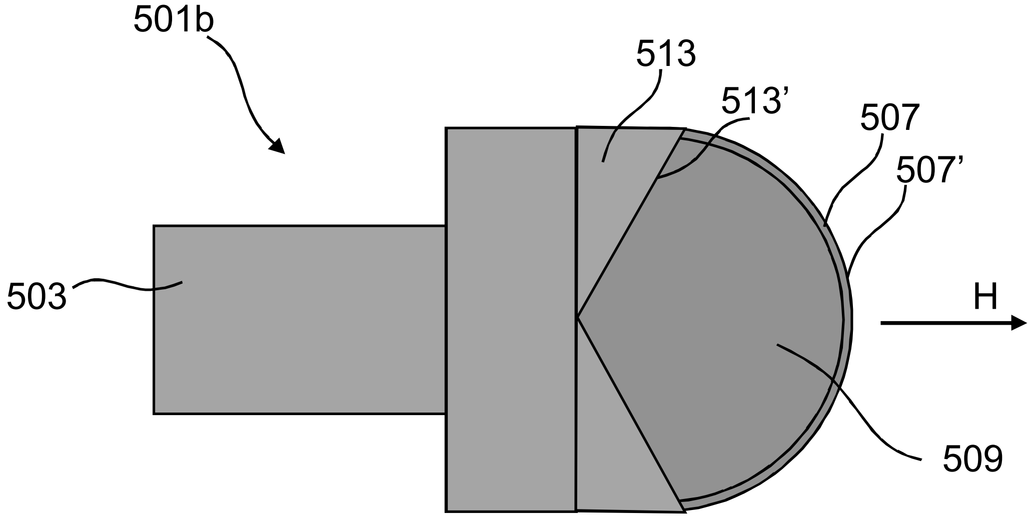

Fig. 5(c)

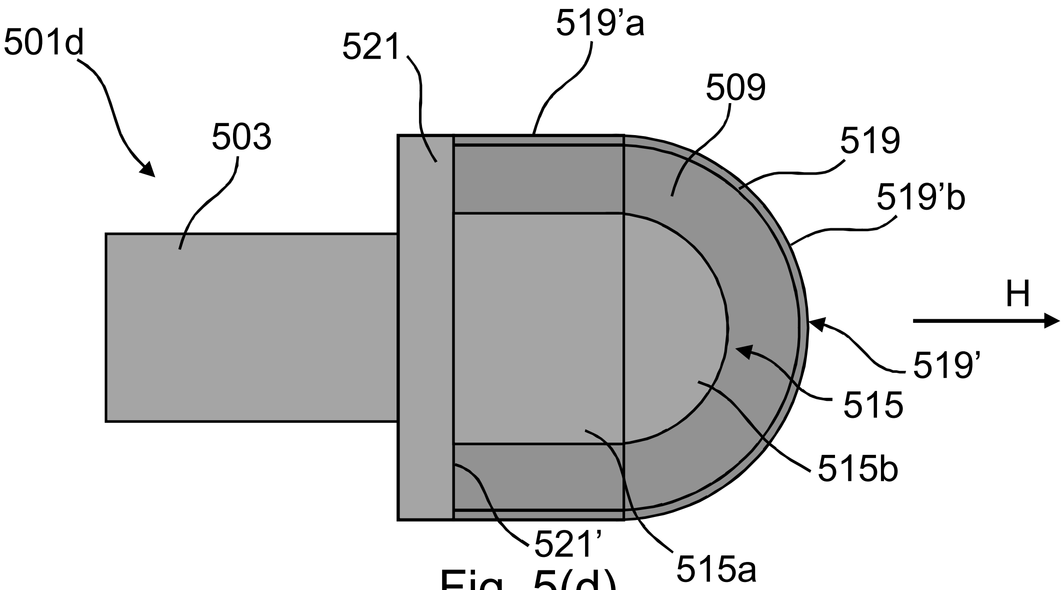
501d
521
519'a
509
519
519'b
503
H
519'
515
515b
521'
515a

Fig. 5(d)

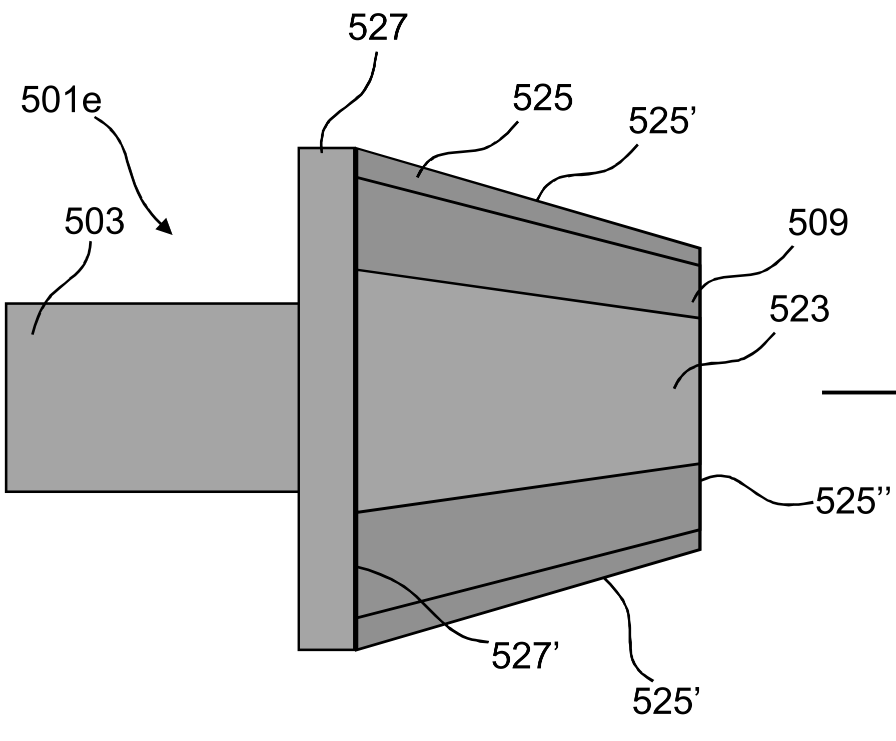
527
501e
525
525'
503
509
523
H
525''
527'
525'

Fig. 5(e)

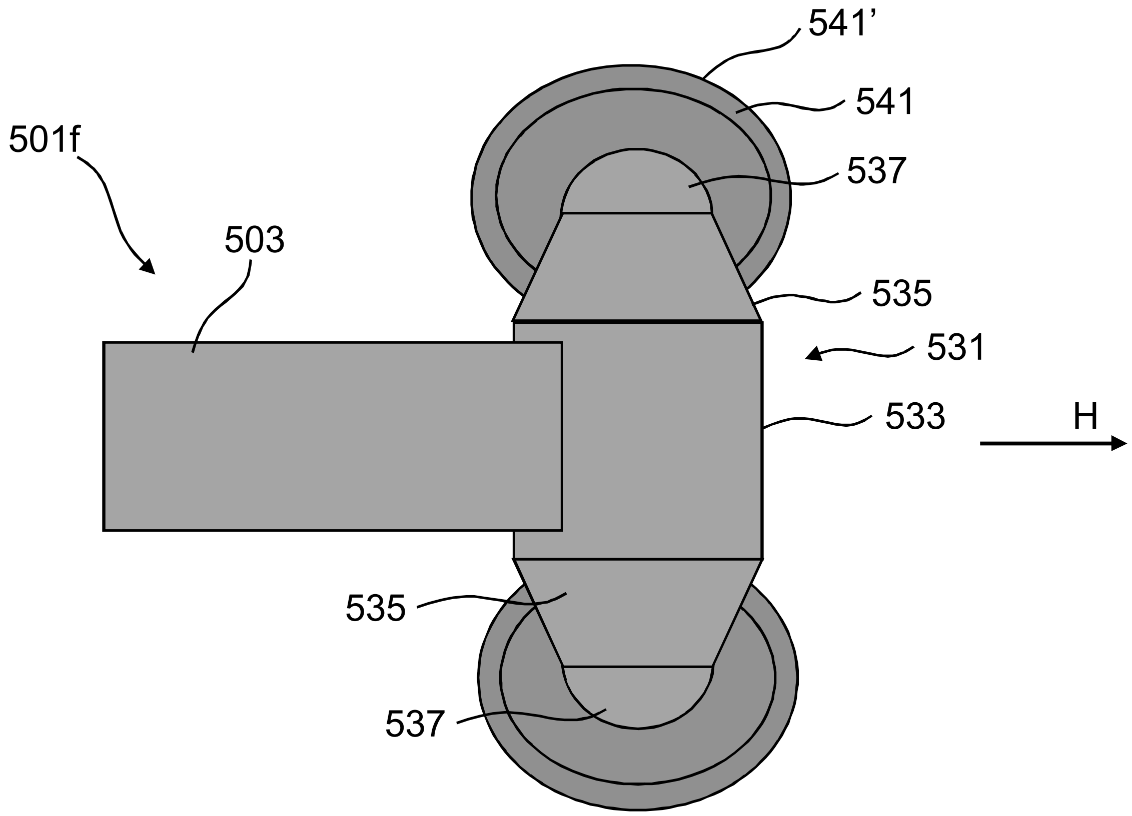
541’
541
501f
537
503
535
531
533
H
535
537

Fig. 5(f)

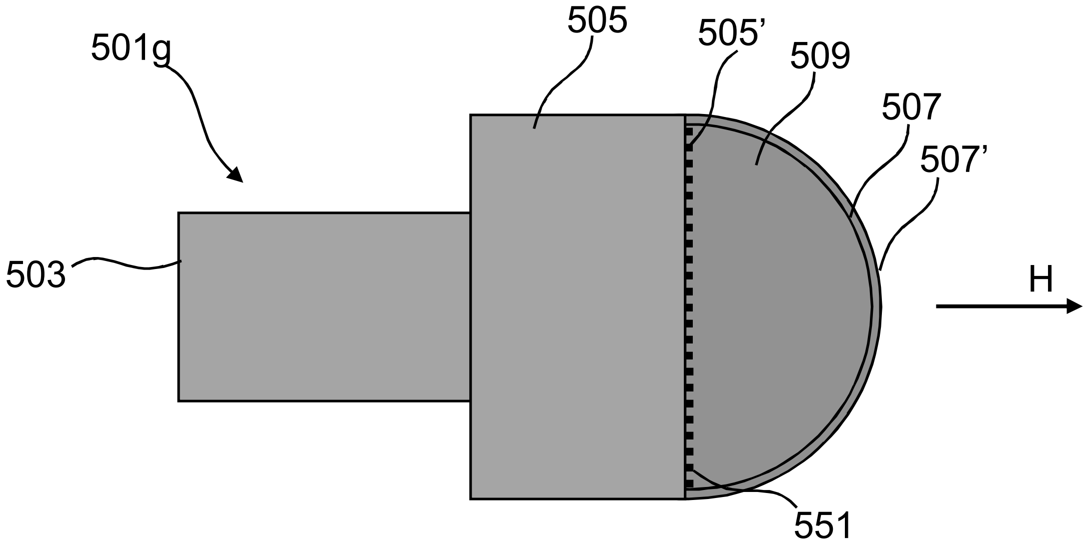
505
505’
501g
509
507
507’
503
H
551

Fig. 5(g)

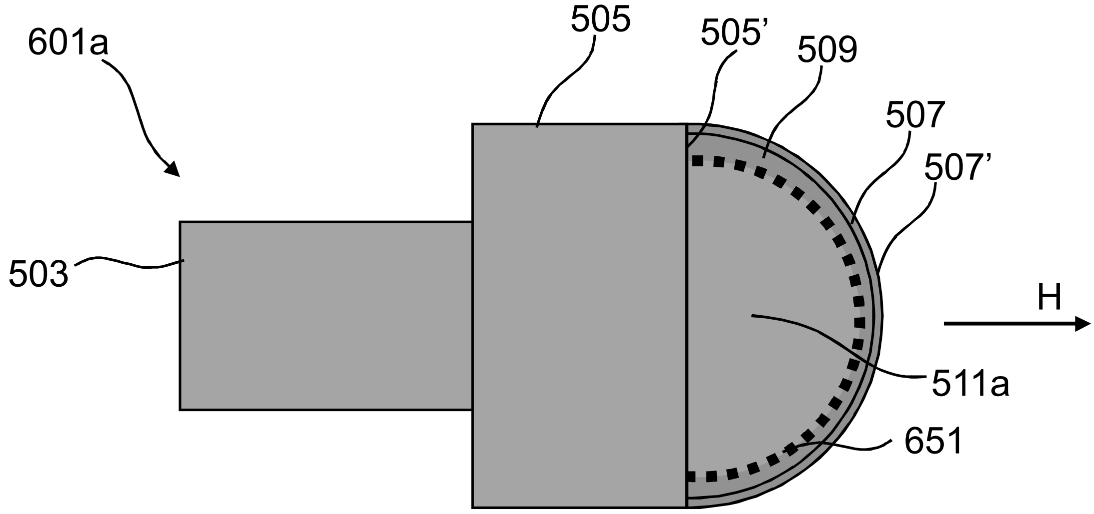

Fig. 6(a)

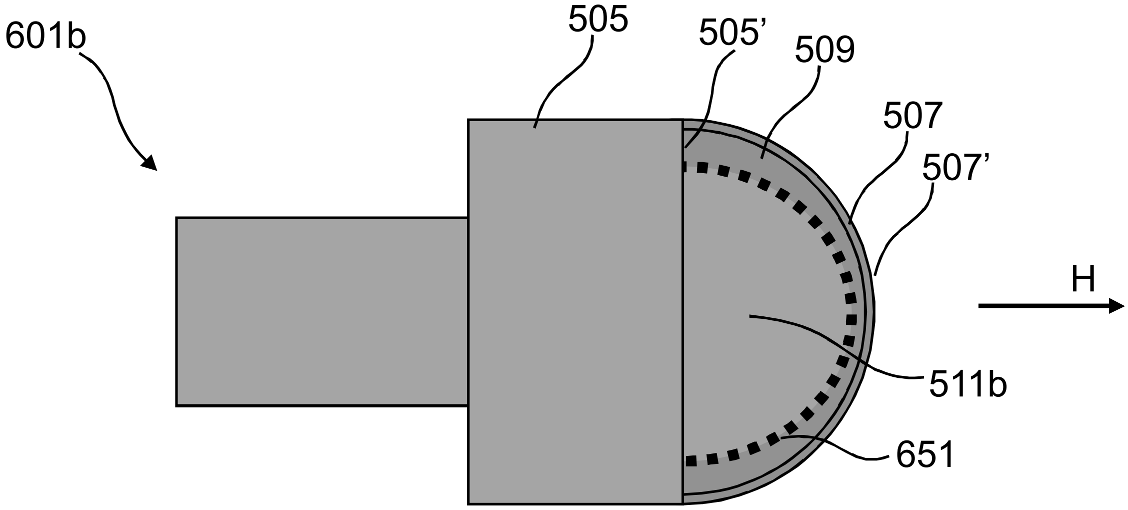

Fig. 6(b)

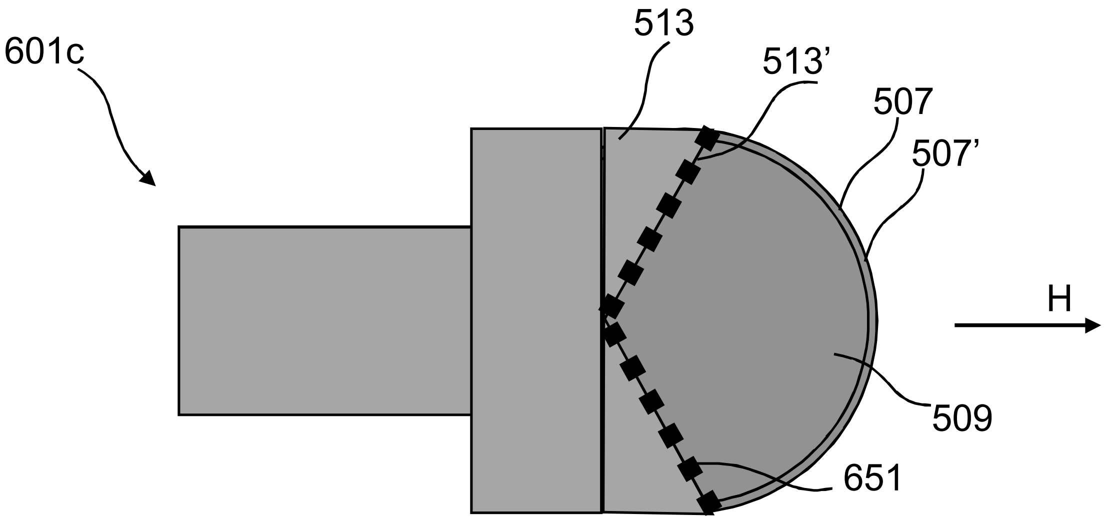

Fig. 6(c)

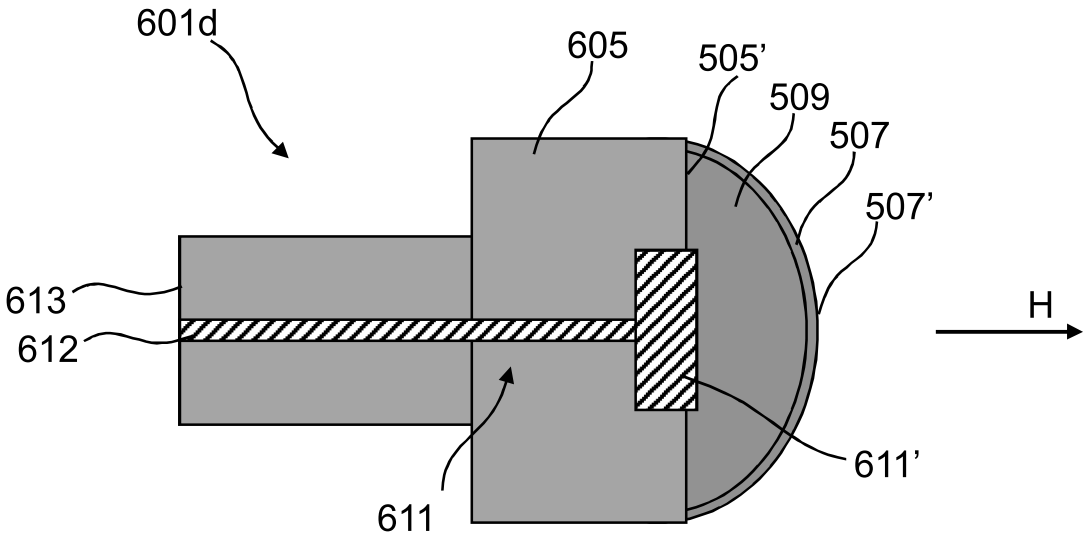

Fig. 6(d)

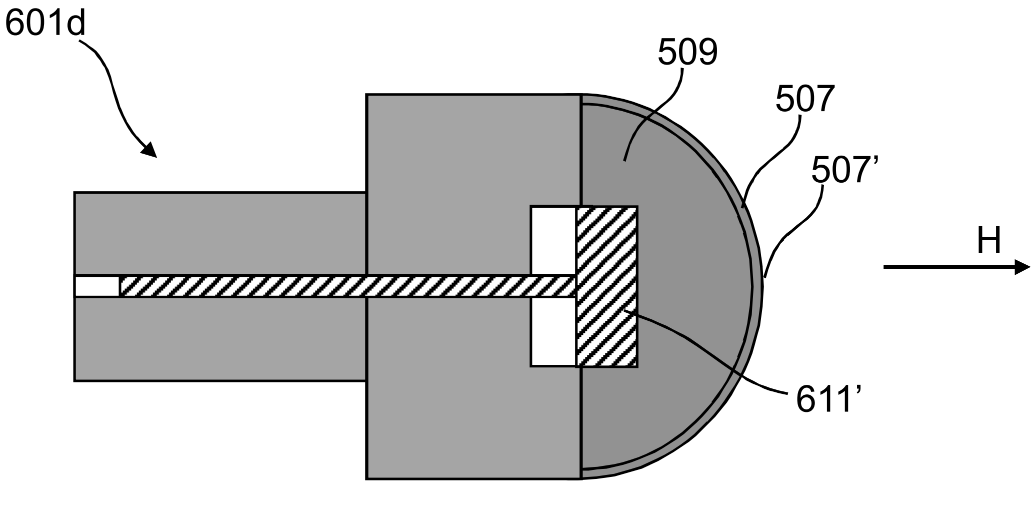

Fig. 6(e)

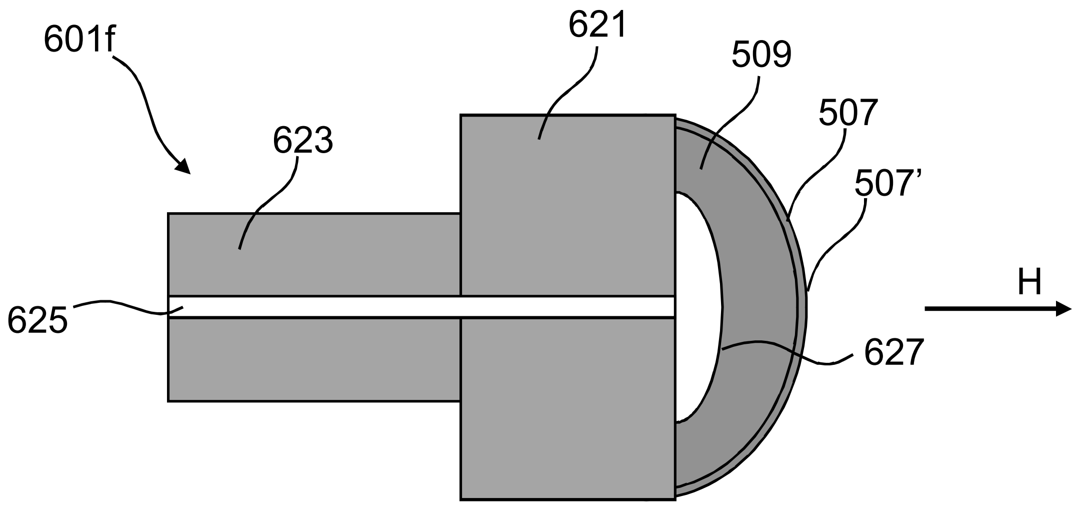

Fig. 6(f)

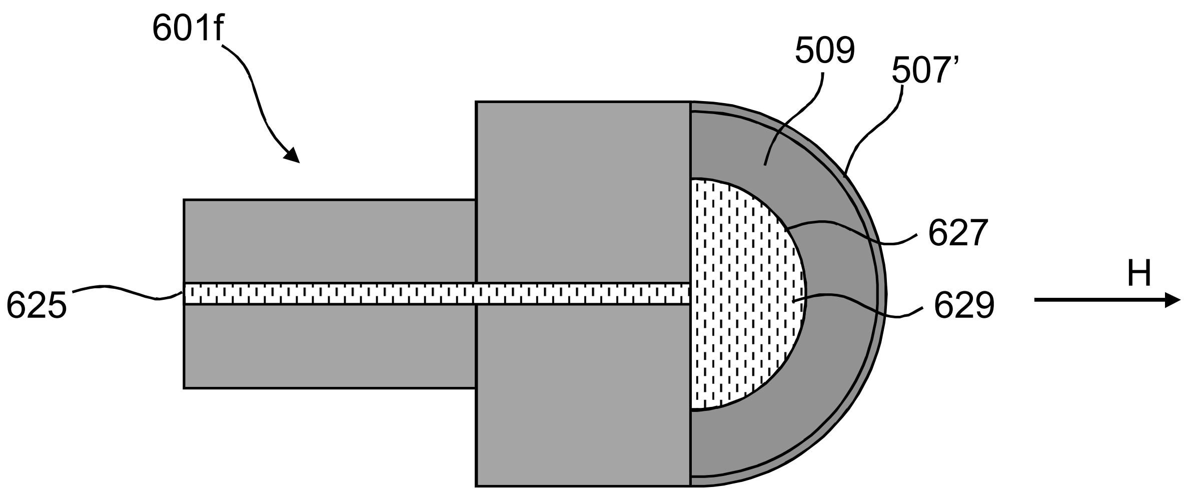

Fig. 6(g)

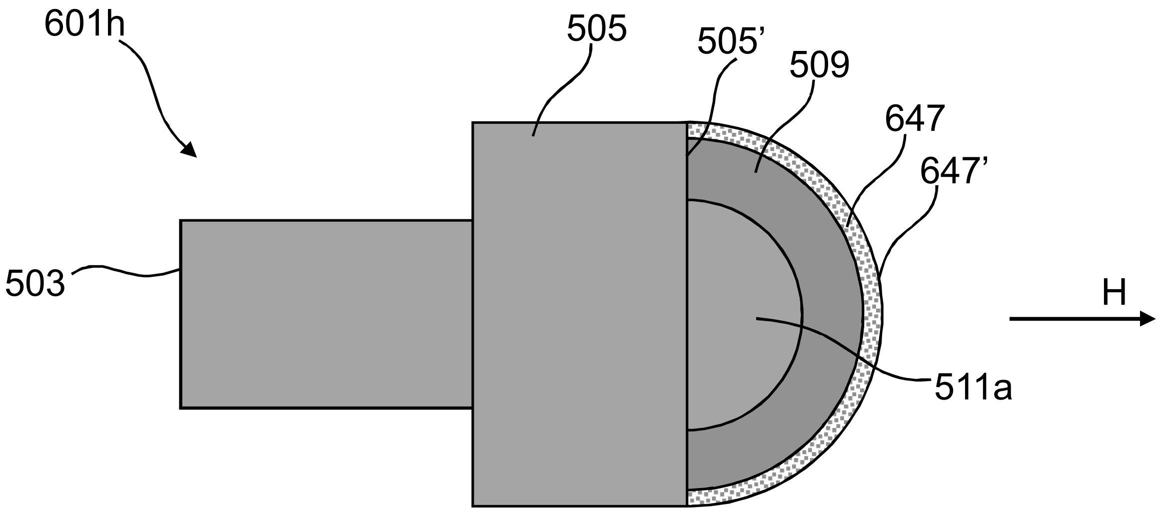
601h
505
505'
509
647
647'
503
H
511a

Fig. 6(h)

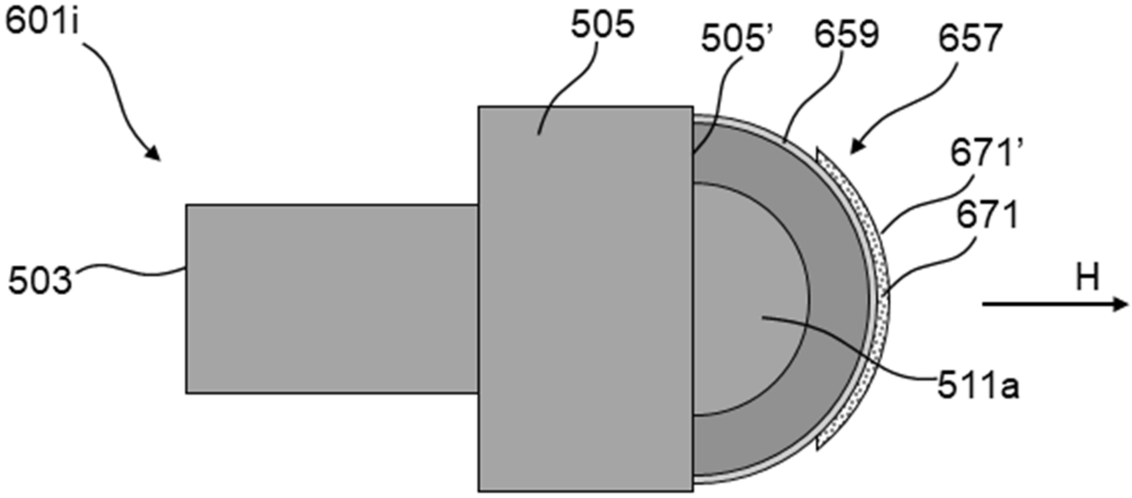
601i
505
505'
659
657
671'
671
503
H
511a

Fig. 6(i)

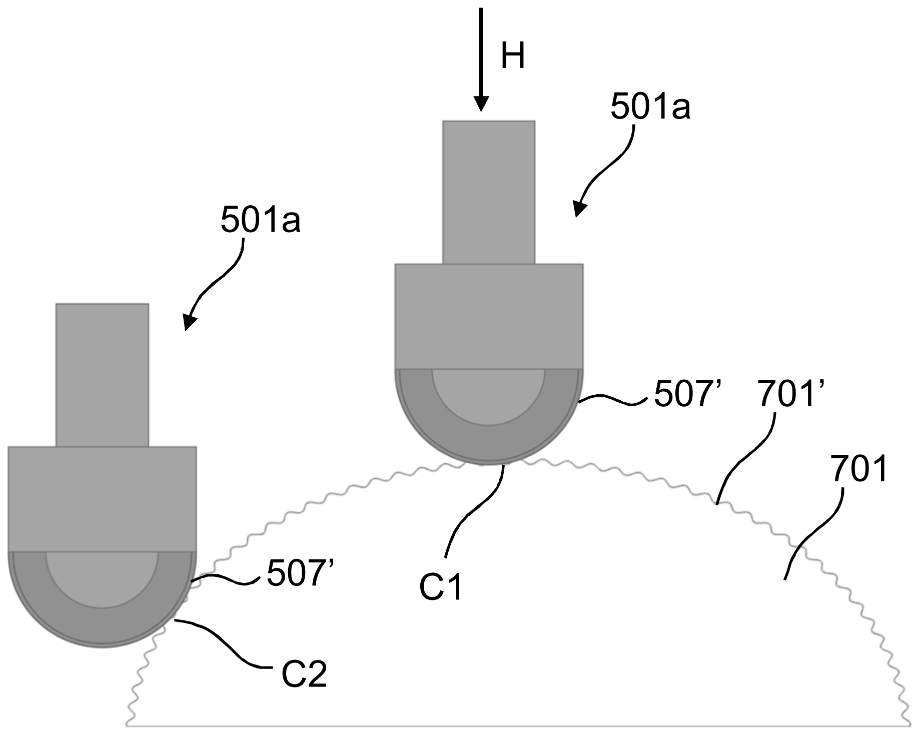
H
501a
501a
507'
701'
701
507'
C1
C2

Fig. 7(a)

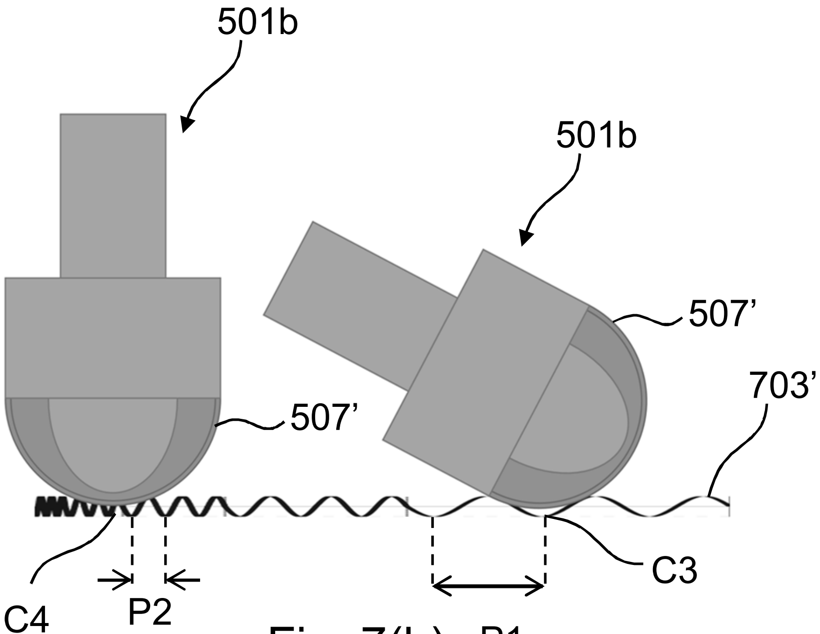
501b
501b
507'
703'
507'
C3
C4
P2
P1

Fig. 7(b)

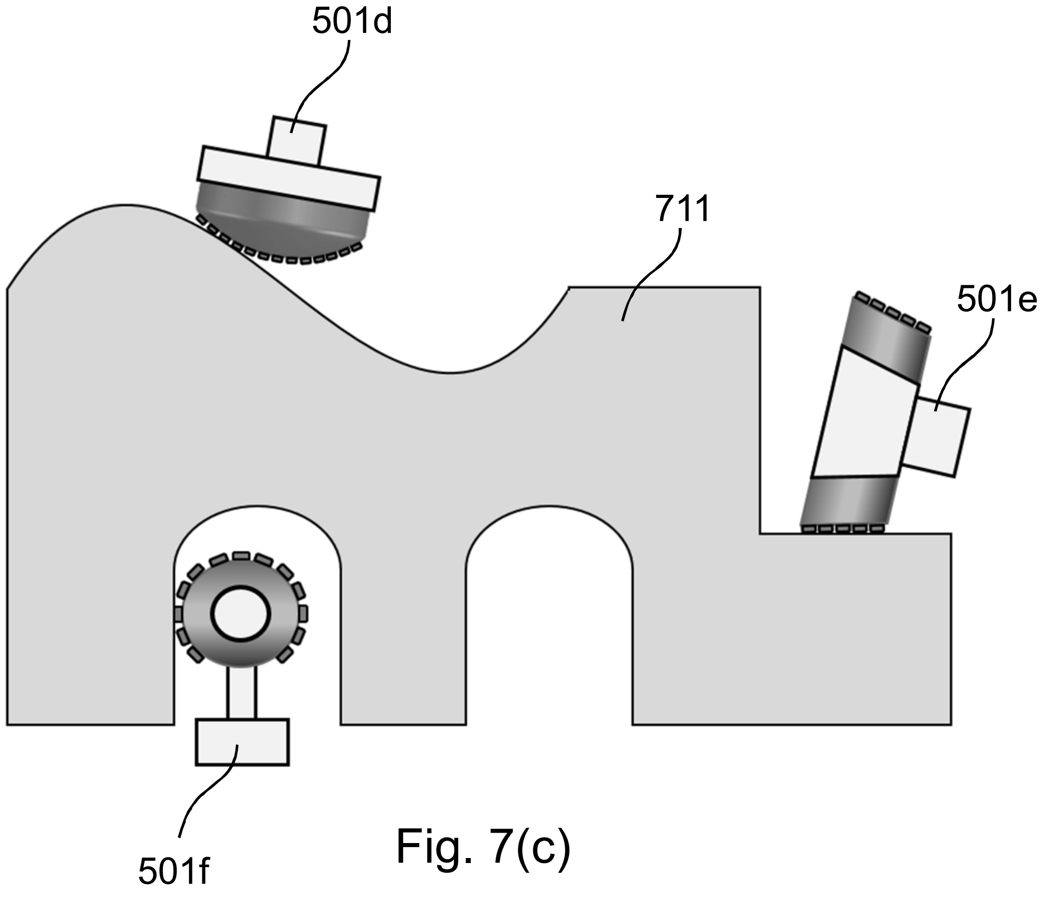

Fig. 7(c)

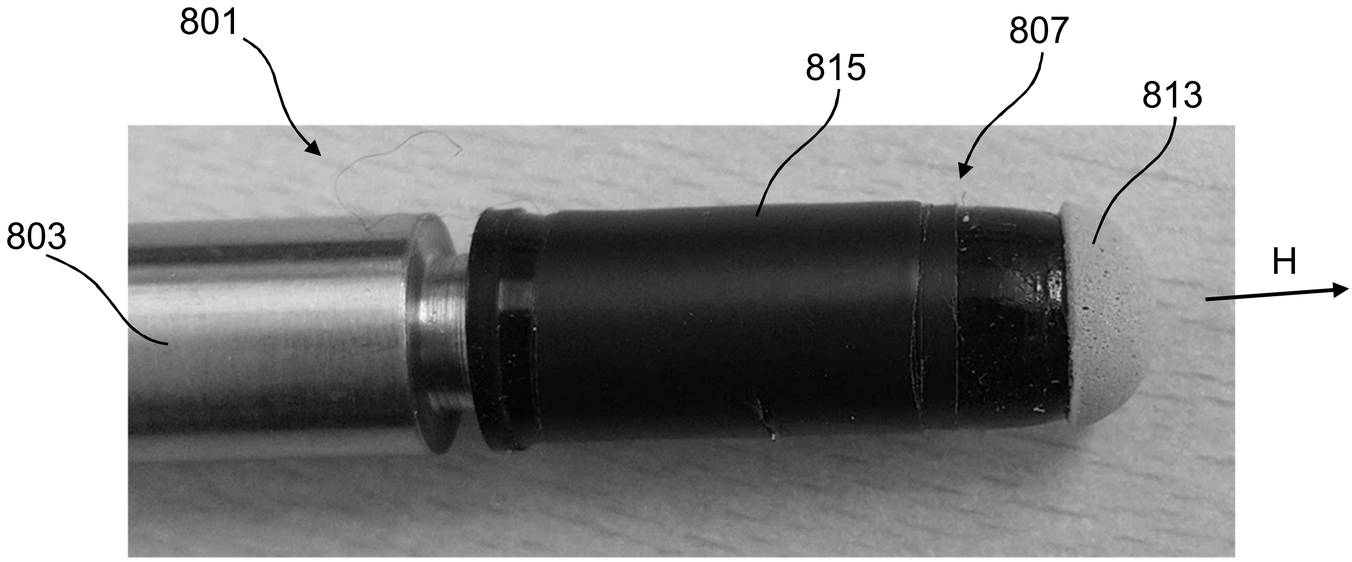

Fig. 8(a)

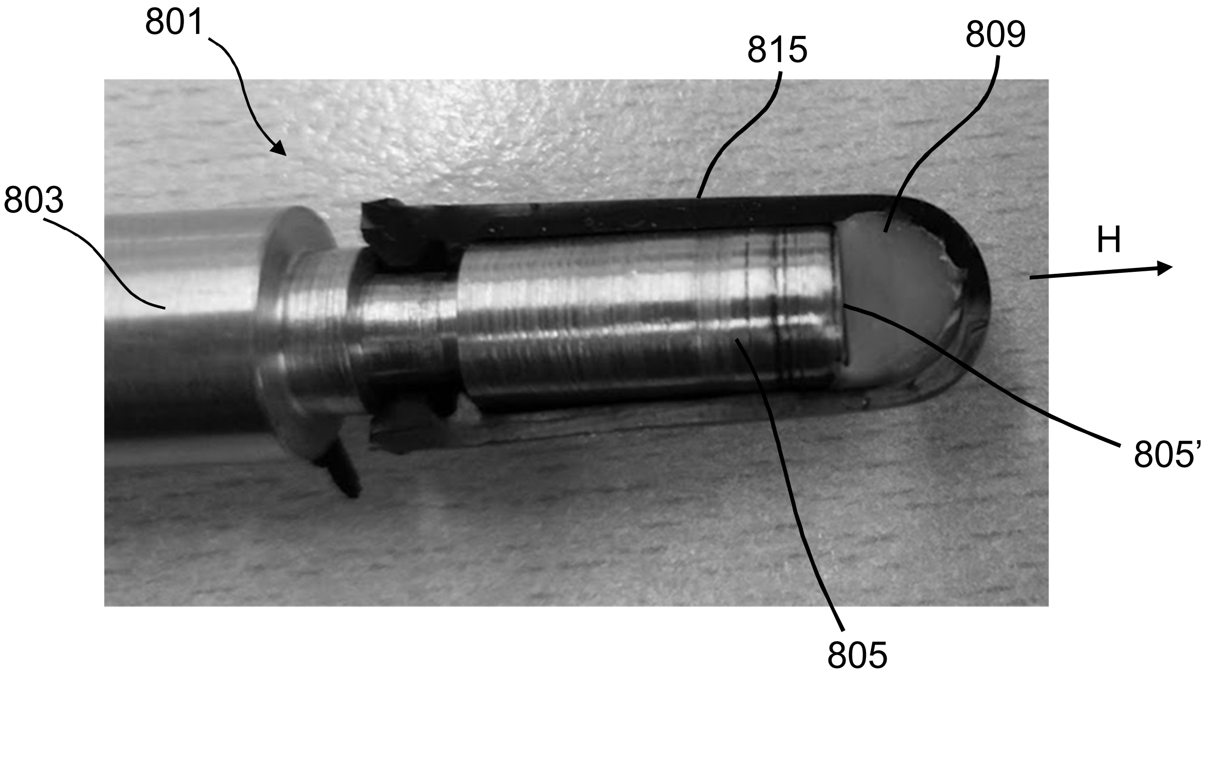

Fig. 8(b)

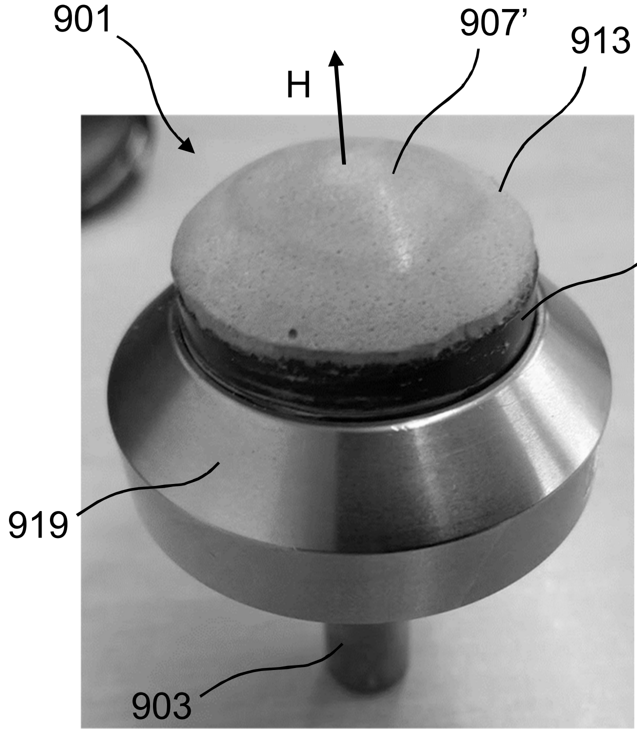

Fig. 9(a)

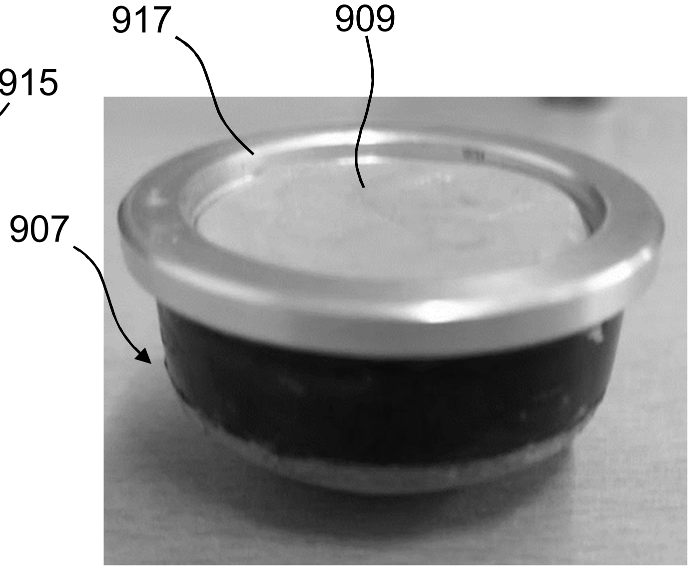

Fig. 9(b)

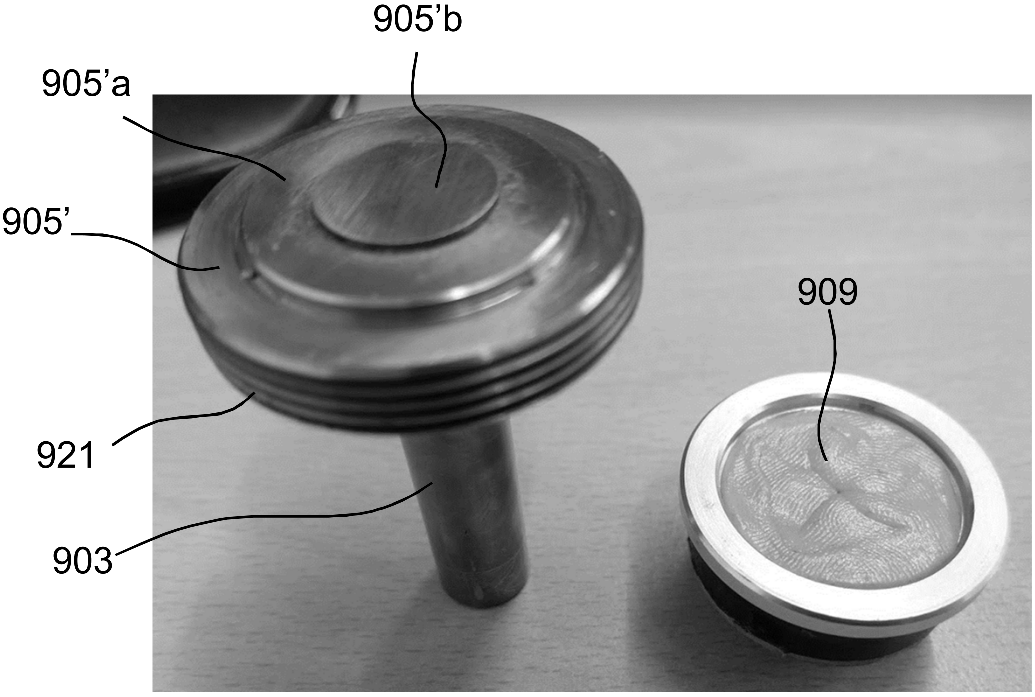

Fig. 9(c)

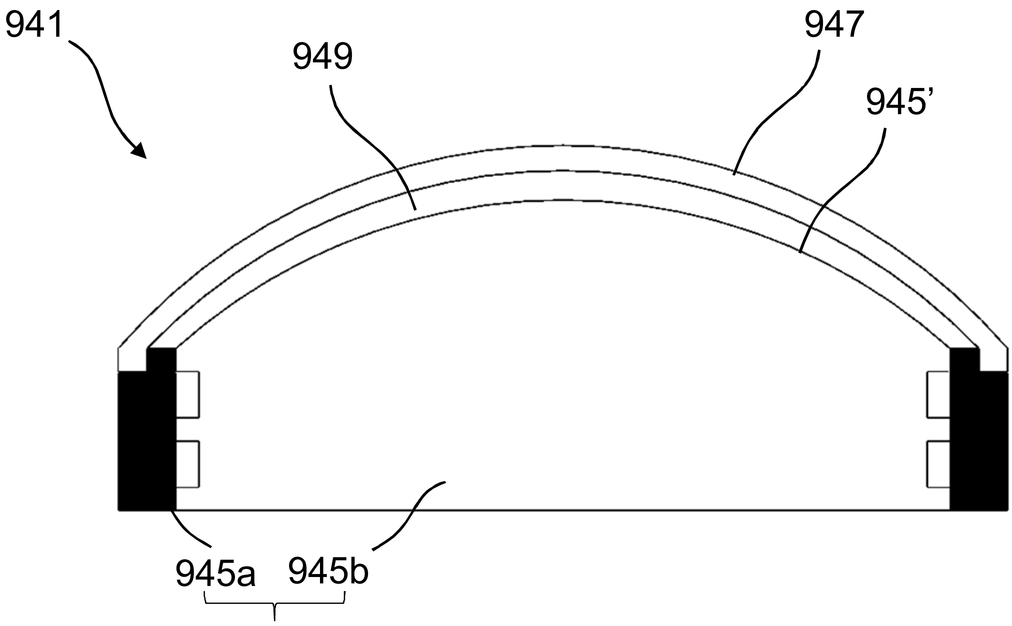

Fig. 10(a)

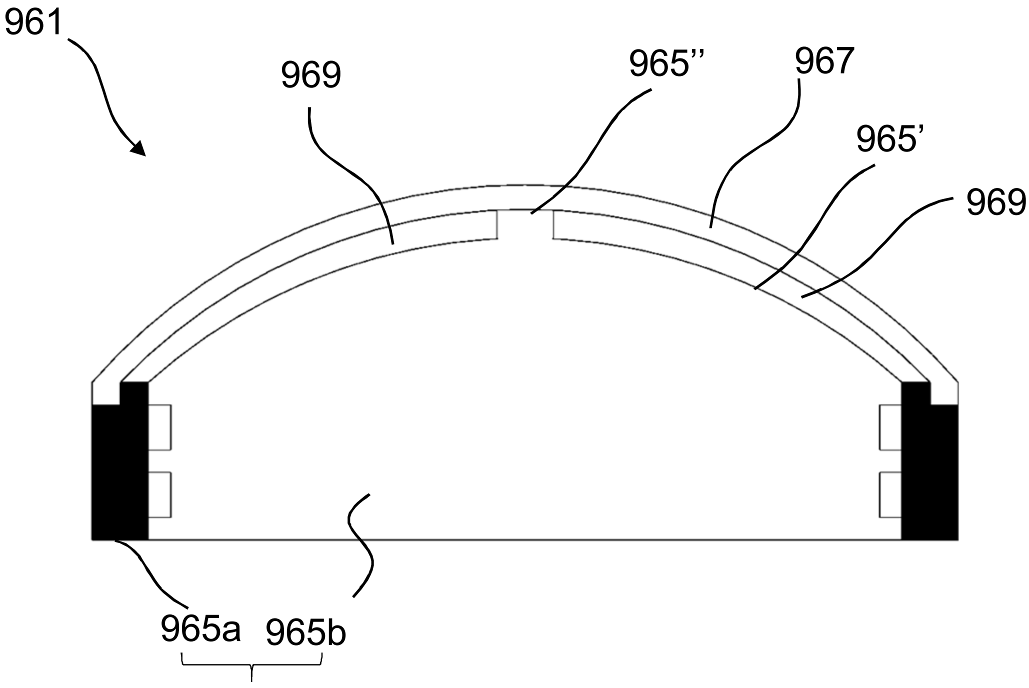

Fig. 10(b)

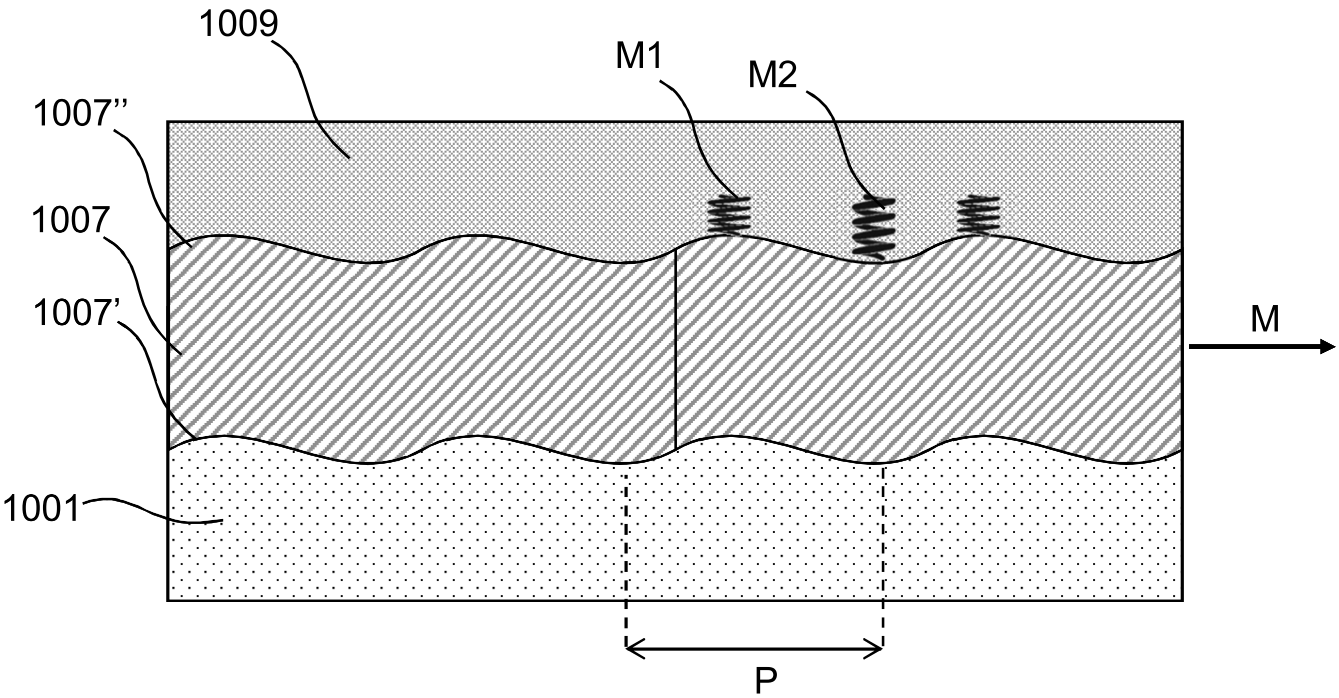

Fig. 11(a)

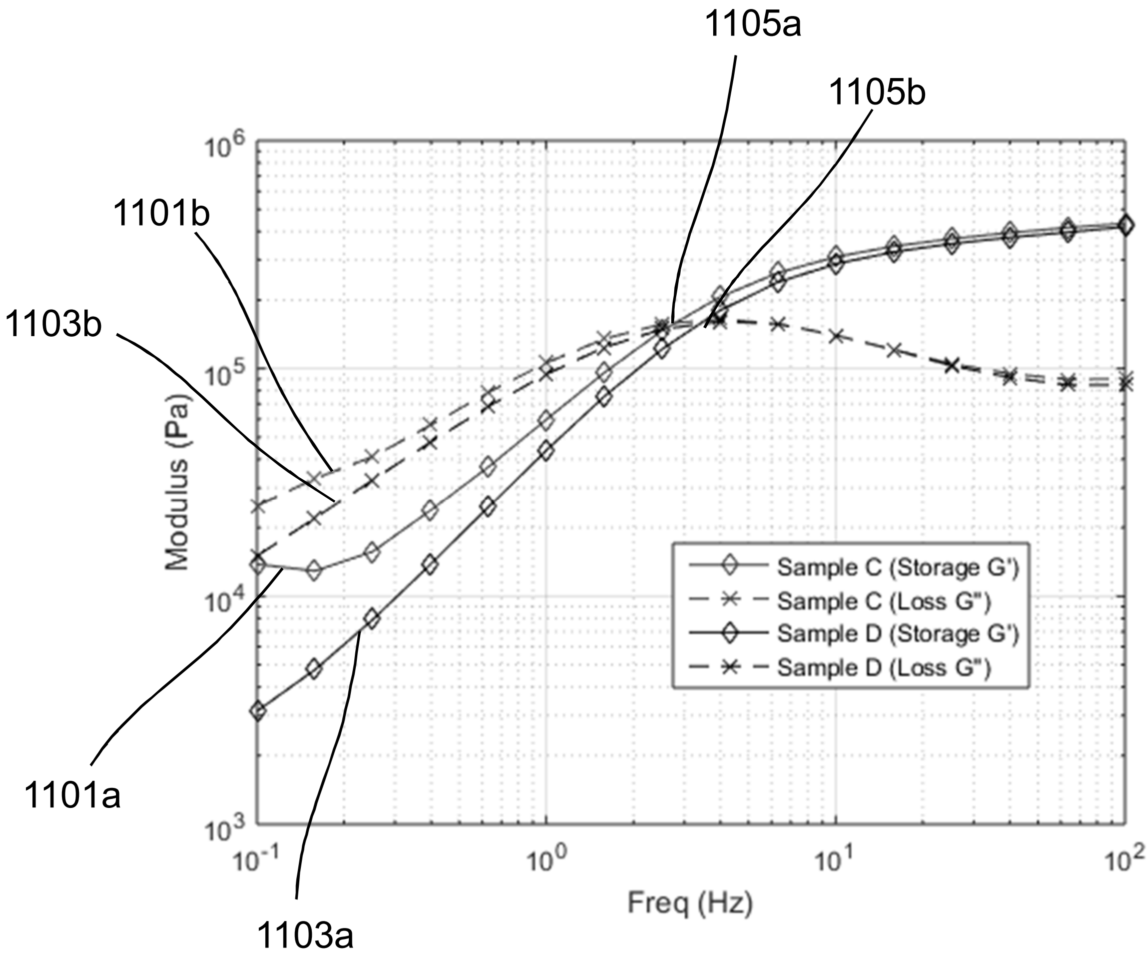

Fig. 11(b)

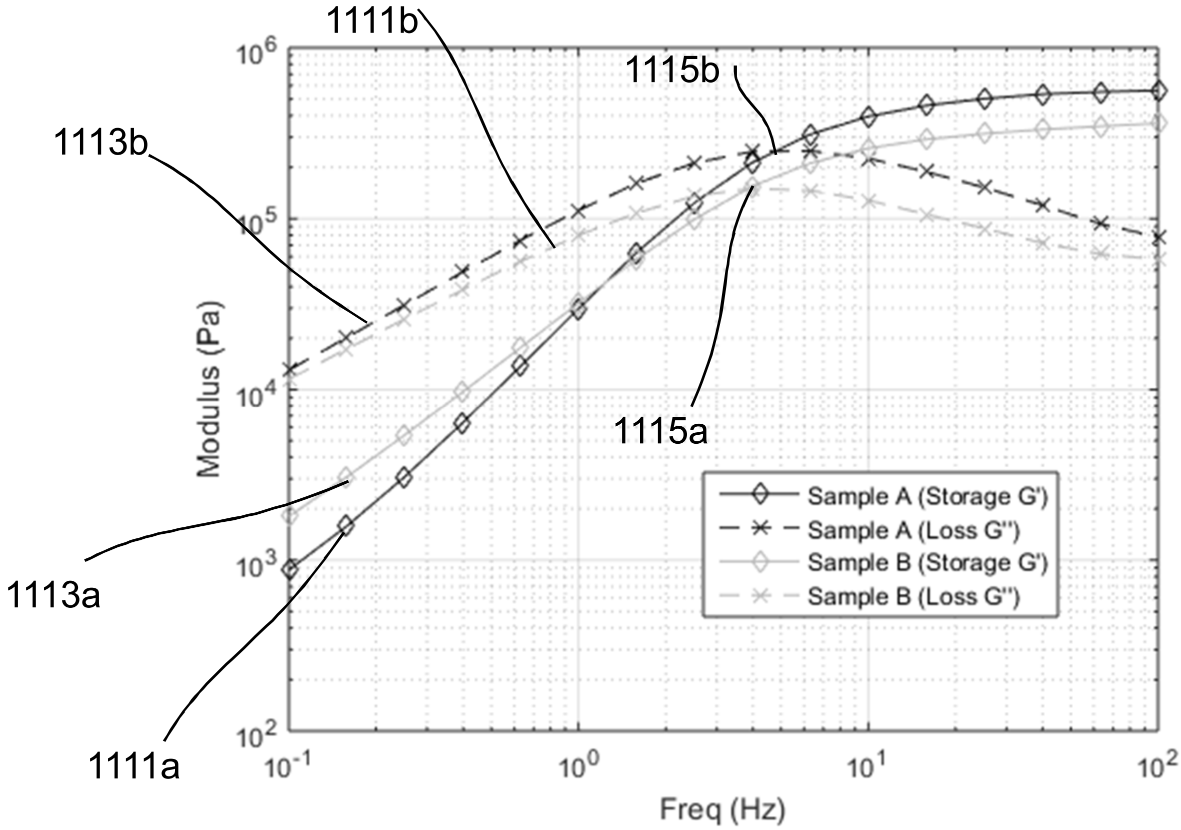
1111b
1115b
1113b
1115a
1113a
1111a
10^6
10^5
10^4
10^3
10^2
Modulus (Pa)
10^{-1}
10^0
10^1
10^2
Freq (Hz)
Sample A (Storage G')
Sample A (Loss G'')
Sample B (Storage G')
Sample B (Loss G'')

Fig. 11(c)

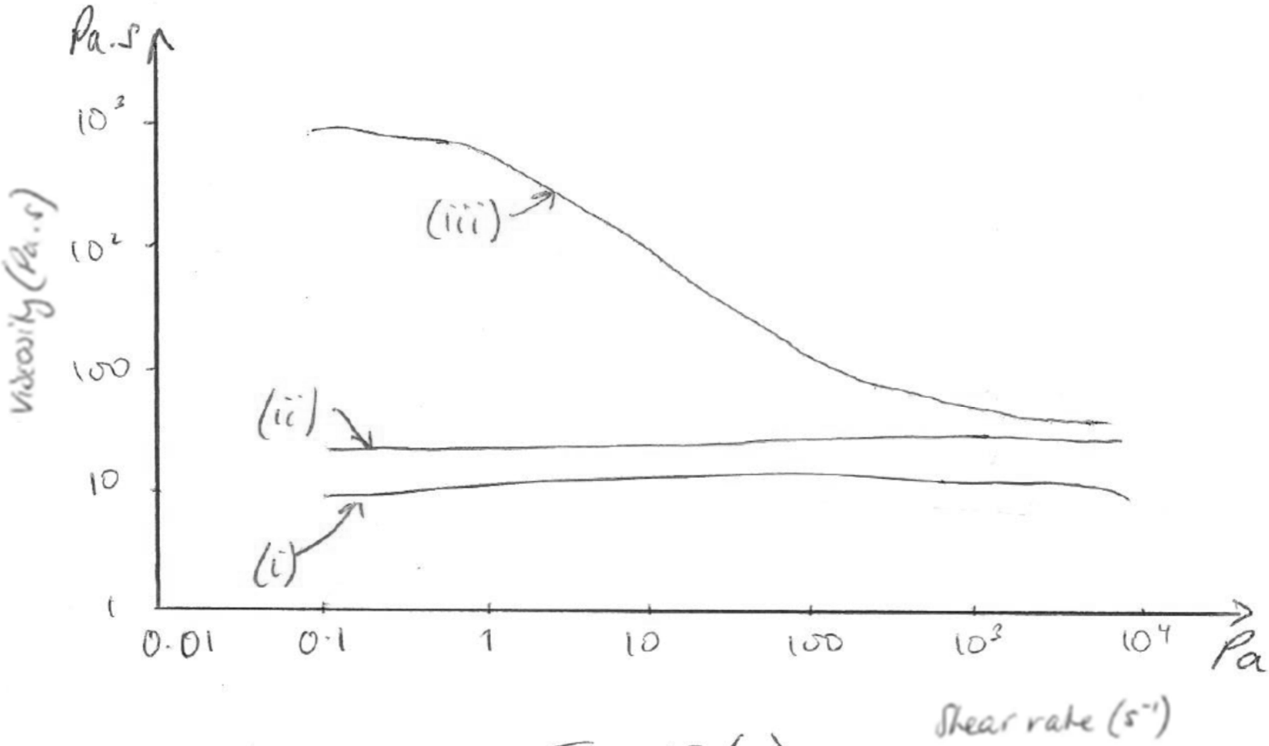

Fig. 12(a)

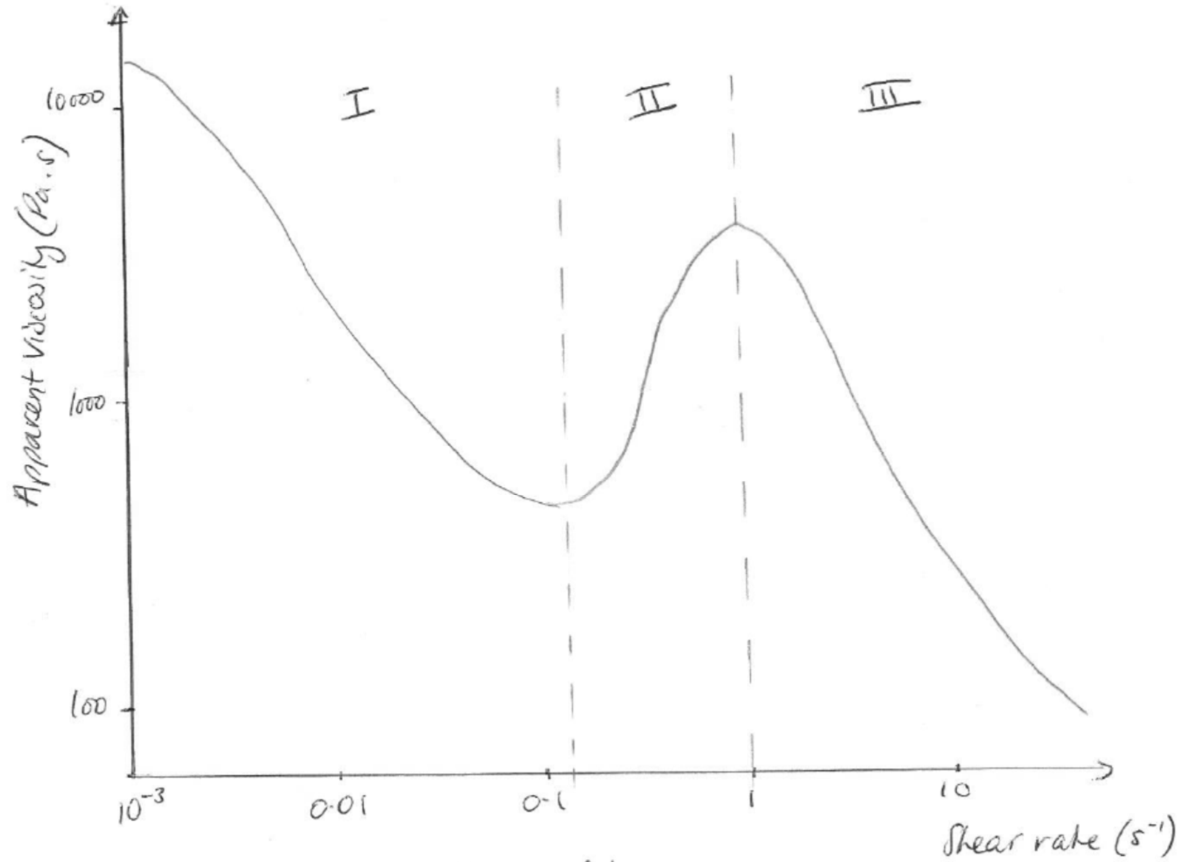

Fig 12(b)

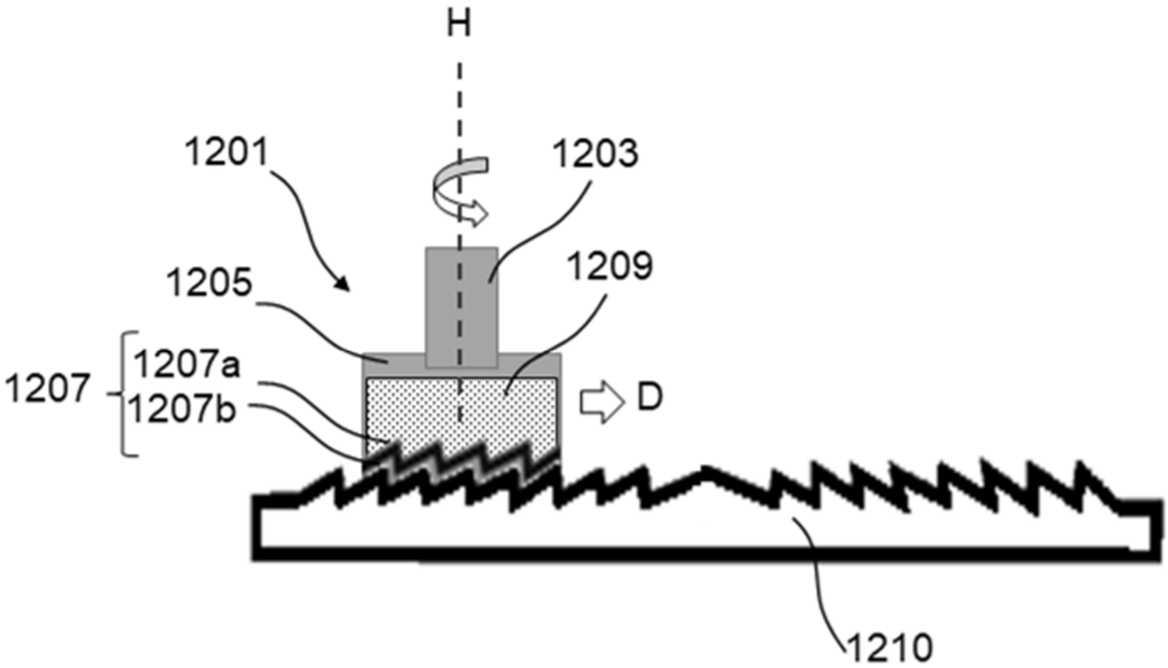

Fig. 13(a)

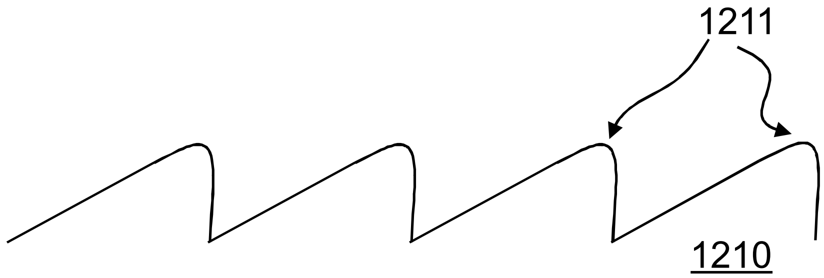

Fig. 13(b)

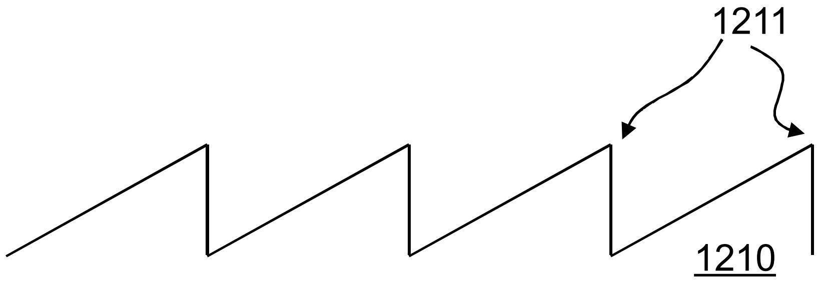

Fig. 13(c)

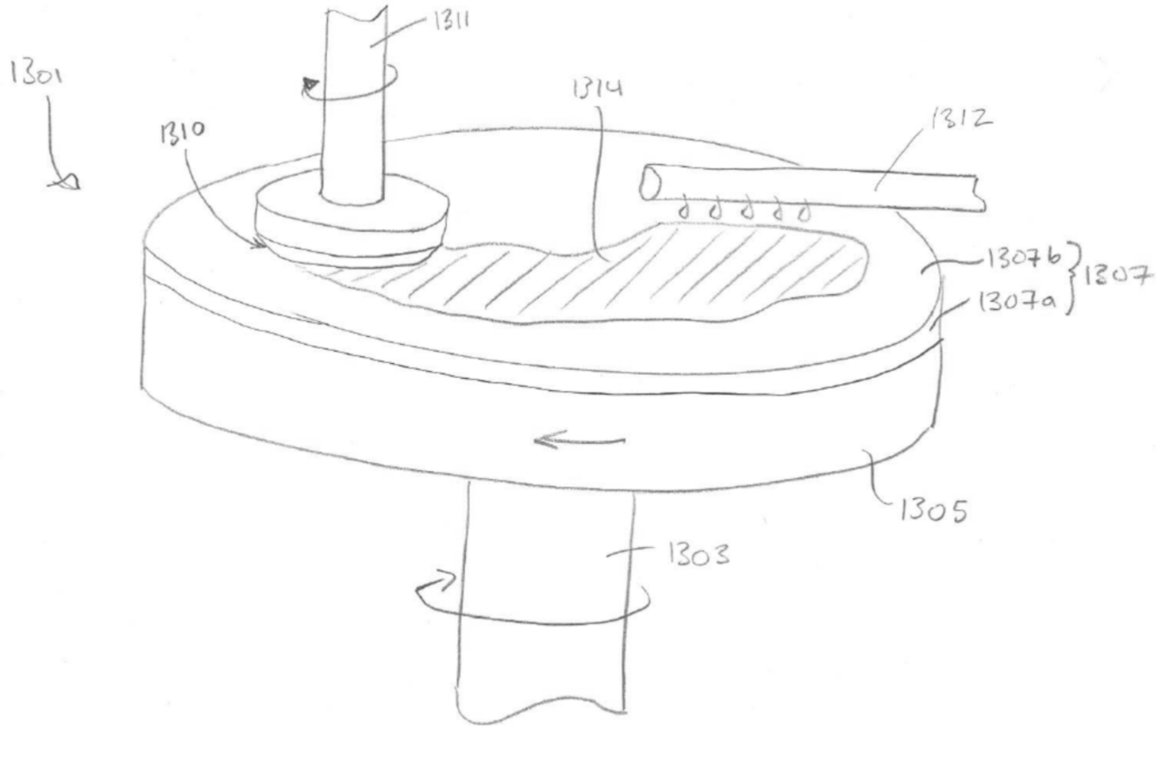

Fig. 14(a)

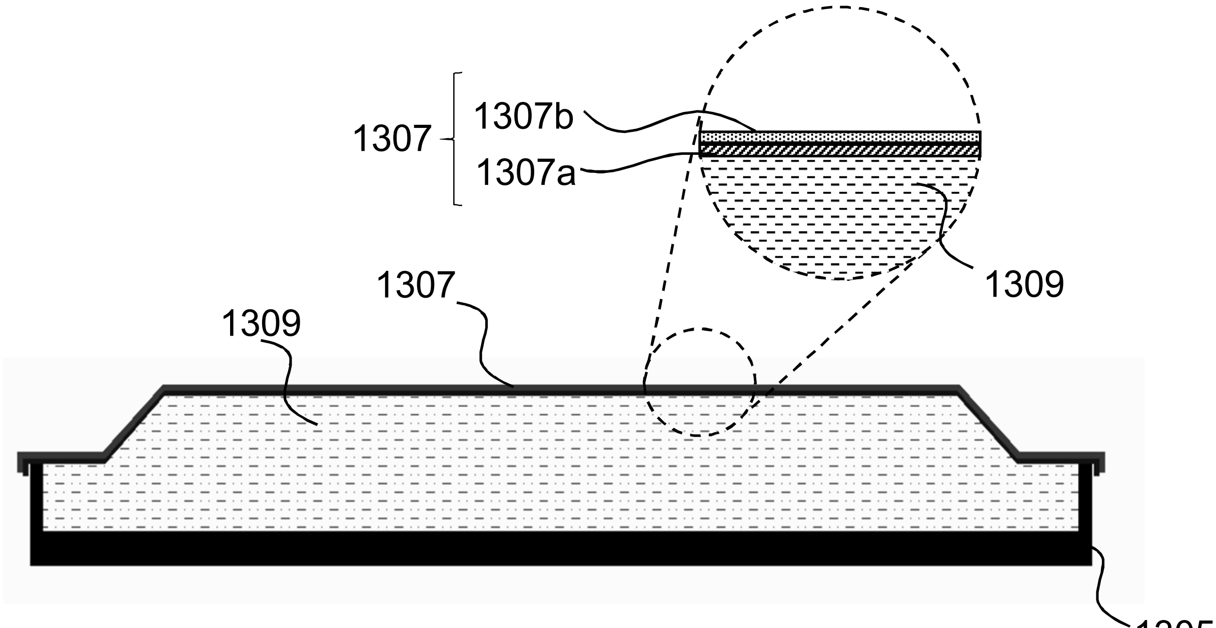

Fig. 14(b)

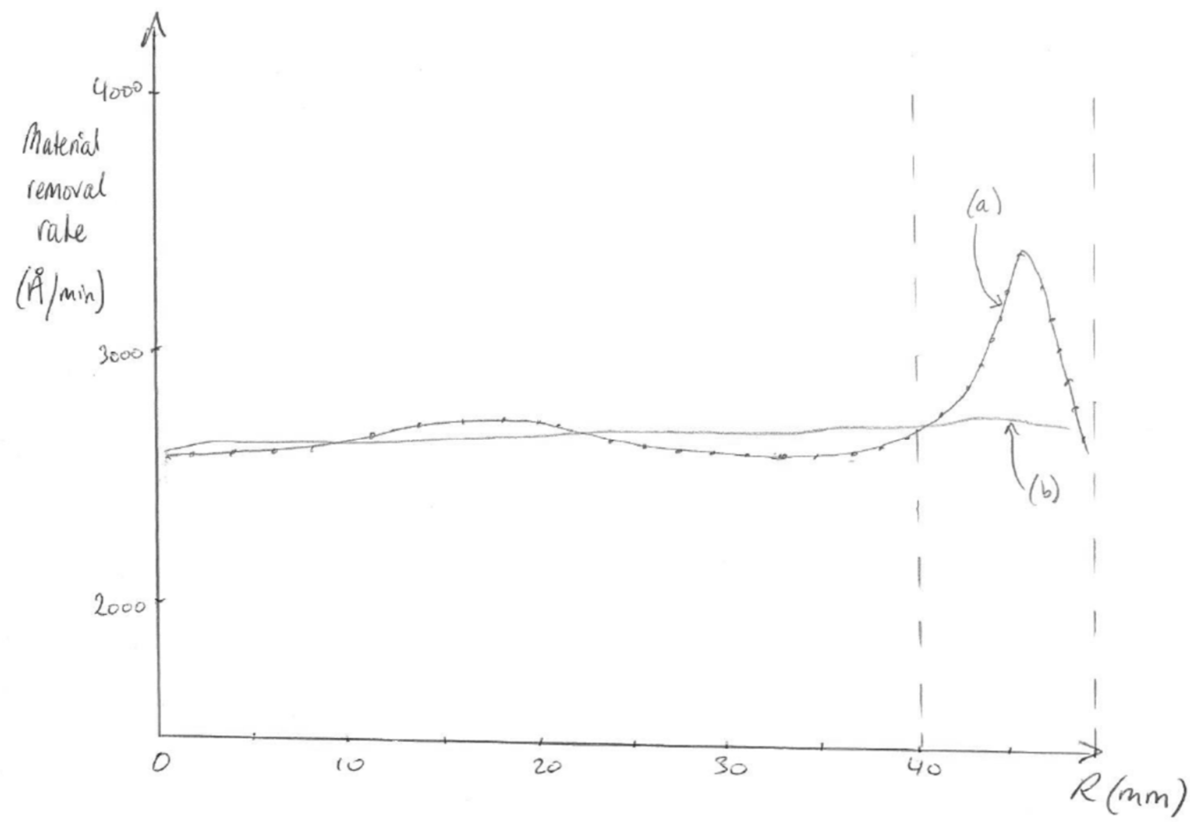

Fig. 15