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(54) **Title:** FRICTION STIR WELDING TOOL ASSEMBLY

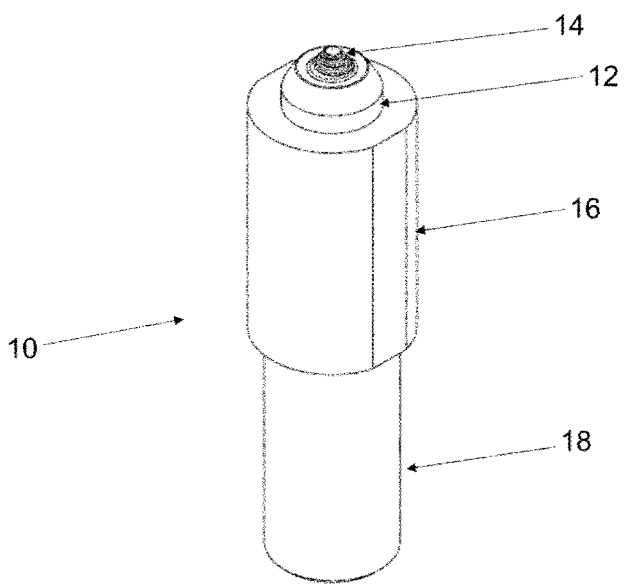

Fig. 1

(57) Abstract: The present disclosure relates to a friction stir welding tool assembly (10) comprising a substrate (12) having a substrate end (12a), the substrate end (12a) comprising a convex portion, and a tip (14) having a tip end (14a), the tip end (14a) comprising a concave portion, the tip further comprising a stirring pin (20), the stirring pin (20) being located at a distal end to the tip end (14a). The tip (14) is formed of a superhard material, and the substrate end (12a) is joined to the tip end (14a) at the corresponding convex and concave portions.

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FRICTION STIR WELDING TOOL ASSEMBLY

FIELD OF THE INVENTION

This disclosure relates to a friction stir welding (FSW) tool assembly. In particular, it relates to a FSW tool assembly for friction stir welding non-ferrous alloys, such as aluminium-silicon alloys.

BACKGROUND

FSW is a technique whereby a rotating tool is brought into forcible contact with two adjacent workpieces to be joined and the rotation of the tool creates frictional and viscous heating of the workpieces. Extensive deformation as mixing occurs along a plastic zone. Upon cooling of the plastic zone, the workpieces are joined along a welding joint. Since the workpiece remains in the solid phase, this process is technically a forging process rather than a welding process, none the less by convention, it is referred to as welding or friction stir welding and that convention is followed here.

In the case of FSW of low temperature metals, such as aluminium, magnesium, titanium and copper and their alloys, polymers, such as thermoplastic polymers, and polymer composites, such as fibre-reinforced polymer composites, the whole tool/tool holder is typically made of a single piece of shaped tool steel, often referred to as a ‘probe’. Aluminium-silicon alloys are a particularly important class of aluminium alloy. FSW of low-silicon content aluminium alloy is commercially performed using high strength steel. However, as the silicon content of the aluminium-silicon alloy is increased, the alloy becomes increasingly abrasive, and because of this the steel tools have insufficient tool life.

There is therefore a need for FSW tools which can withstand more abrasive alloys and provide adequate tool life. Super-hard materials, such as PCBN and PCD, have been proposed for use in FSW tools for this purpose.

However, there are some particular challenges relating to the use of PCD in a FSW tool. For example, it is necessary for the tip to have a thickness which slightly exceeds the weld depth, which for aluminium alloys is typically about 2.5 mm. However, it is difficult to prepare a PCD layer with a thickness of greater than 2.5 mm as such layers are prone to cracking.

It is therefore an aim of the invention to provide a friction stir welding tool assembly that addresses the above-mentioned problem.

SUMMARY OF THE INVENTION

In accordance with the invention, there is provided a friction stir welding tool assembly comprising a substrate having a substrate end, the substrate end comprising a convex portion; and a tip having a tip end, the tip end comprising a concave portion; the tip further comprising a stirring pin, the stirring pin being located at a distal end to the tip end; wherein the tip is formed of a superhard material; the substrate end being joined to the tip end at the corresponding convex and concave portions.

In accordance with the invention, there is further provided a method of forming a friction stir welding assembly as described herein comprising: providing a substrate having a substrate end, the substrate end comprising a convex portion; and a tip having a tip end, the tip end comprising a concave portion; wherein the tip is formed of a superhard material and the substrate end is joined to the tip end at the corresponding convex and concave portions; and forming a stirring pin at a distal end of the tip.

In accordance with the invention, there is further provided a use of the friction stir welding tool assembly as described herein in a friction stir welding process.

Optional and/or preferable features of the invention are provided in claims 2 to 19, 21 and 23-25.

As an option, the substrate end comprises an array of convex portions and the tip end comprises a corresponding array of concave portions.

As an option, the array is discontinuous.

BRIEF DESCIPTION OF THE DRAWINGS

The invention will now be more particularly described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a perspective view of a FSW tool assembly in accordance with the invention;

Figure 2 is a schematic view of an embodiment of the FSW tool assembly in accordance with the invention which shows a means for attaching the substrate to a tool holder;

Figure 3 is a schematic view of an embodiment of the FSW tool assembly in accordance with the invention;

Figure 4 is a schematic view of another embodiment of the FSW tool assembly in accordance with the invention;

Figure 5 is a schematic view of another embodiment of the FSW tool assembly in accordance with the invention;

Figure 6 is a schematic view of another embodiment of the FSW tool assembly in accordance with the invention;

Figure 7A is a schematic view of another embodiment of the FSW tool assembly in accordance with the invention;

Figure 7B shows an enlarged view of the region E in Fig. 7A; and

Figure 8 is a perspective view of an embodiment of a substrate for a FSW tool assembly in accordance with the invention.

The Figures are not drawn to scale.

Throughout the description, similar parts have been assigned the same reference numerals.

<u>DETAILED DESCRIPTION</u>

As shown in Fig. 1, the friction stir welding tool assembly 10 of the present invention comprises a substrate 12 and a tip 14. The substrate 12 may be mounted or mountable onto or into the body 16 of a tool holder. For example, the substrate 12 may be shrink or press fitted into a bore provided in the body 16 of the tool holder, and/or the substrate 12 may be bonded to the body 16 of the tool holder, such as by brazing. Alternatively, the substrate 12 may be attached to the body 16 of the tool holder by means of a screw thread S, as depicted in Fig. 2. This is particularly advantageous as the temperatures reached during FSW of aluminium alloys are greater than 500°C. At these temperatures conventional braze joints can soften and shear under the torque applied to the tool when it is rotated in use. This is avoided by use of a screw thread S to attach the substrate 12 to the body 16 of the tool holder. The screw thread S can be machined into the substrate 12 by electrical discharge machining (EDM) or laser ablation. The tool assembly 10 may further comprise a retention mechanism (not shown) to mechanically lock the substrate 12 and the tool holder together, thereby preventing separation during FSW. The tool holder may further comprise a trunk member 18, which may be solid and cylindrical. The purpose of the trunk member 18 is to facilitate connection of the FSW tool assembly 10 to FSW machinery.

The body 16 and/or the trunk member 18 (if present) of the tool holder may comprise steel, for example stainless steel. In a particular arrangement, the body 16 and/or the trunk member 18 (if present) of the tool holder comprise(s) H13 steel. Alternatively or additionally, the body 16 and/or the trunk member 18 (if present) of the tool holder may comprise a high temperature high strength alloy. For example, the body 16 and/or the trunk member 18 (if present) of the tool holder may comprise any one or more of the following materials: Ni-Cr alloys, such as NIMONIC® 80A, with the general composition of 18.0-21.0 wt.% Cr, 1.8-2.7 wt.% Ti, 1.0-1.8 wt.% Al, 0-0.10 wt.% C, 0-1.0 wt.% Si, 0-0.2 wt.% Cu, 0-3.0 wt.% Fe, 0-0.1 wt.% Mn, 0-2.0 wt.% Co, 0-0.008 wt.% B, 0-0.15 wt.% Zr, 0-0.015 wt.% S, and balance Ni and trace impurities; Inconel alloys (a class of nickel-chromium based super alloys); W-Ni (tungsten-nickel) alloys; TZM (molybdenum-titanium-zirconium) alloys; and high entropy alloys. In general, these alloys are characterised by good strength at elevated temperatures.

The substrate 12 has a substrate end 12a comprising a convex portion, and the tip 14 has a tip end 14a comprising a concave portion. The substrate end 12a is joined to the tip end 14a at the corresponding convex and concave portions. As defined herein, the corresponding concave and convex portions extend along a plane defined by the longitudinal axis L and the diameter d of the substrate. The tip 14 further comprises a stirring pin 20, the stirring pin 20 being located at a distal end to the tip end 14a.

The shape of the stirring pin 20 is not particularly limited, so long as it is suitable for FSW. The stirring pin 20 may have a conical or cylindrical profile. In a particular example, the stirring pin 20 may have a broadly conical profile, tapering outwardly from a rounded apex towards the tip end 14a. The stirring pin 20 may have a cone angle θ_c of from about 15 degrees to about 75 degrees, for example from about 30 degrees to about 45 degrees. As shown in Fig. 3, the cone angle is the included angle between a line a drawn along a vertex of the conical profile of the stirring pin 20 and a line b parallel to the longitudinal axis L. The tip 14 may comprise a shoulder portion proximate the stirring pin 20. This shoulder portion extends circumferentially from the base of the stirring pin 20 to form a broadly planar surface in opposition to the tip end 14a. The shoulder portion is disc-like and has a larger diameter than a circular base of the stirring pin 20. The stirring pin 20 may comprise an inscribed spiral feature running from the apex down towards and onto the shoulder portion. In use, rotation of the tool assembly 10 is such that the spiral drives workpiece material flow from the edge of the shoulder portion to the centre and then down the length of the stirring pin 20. This forces workpiece material to circulate within the stirred zone and to fill the void formed by the stirring pin 20 as the tip 14 traverses in a known manner.

The tip 14 is formed of a superhard material. The superhard material may comprise or consist of diamond. For example, the superhard material may comprise or consist of a diamond-based composite material. Examples of diamond-based composite materials are polycrystalline diamond (PCD) material, silicon carbide-bonded diamond (SCD) material and diamond enhanced carbide (DEC) material, all of which are described in more detail below. The superhard material may comprise or consist of a sintered polycrystalline super-hard material, such as polycrystalline diamond (PCD) material, polycrystalline cubic boron nitride (PCBN) material (as used herein, PCBN material comprises grains of cubic boron nitride (cBN) dispersed within a matrix comprising metal or ceramic material), or silicon carbide-bonded diamond (SCD) material (as used herein, unless otherwise specified, the term “diamond” will include both natural and fabricated diamond). The tip 14 may comprise or consist of diamond enhanced carbide (DEC) material, such as that described in GB2459272A, the entirety of which is incorporated herein by reference. Diamond enhanced carbide refers to any composite material that comprises particulates of diamond or other super-hard phase, such as cubic boron nitride (cBN) and at least one other hard phase (typically including a carbide, such as WC), wherein these particles are held together by means of a binder phase, preferably a metallic binder phase which is typically a transition metal (for example Co). Preferably, the superhard material comprises or consists of PCD material.

As used herein, fabricated diamond, which is also called man-made or synthetic diamond, is diamond material that has been manufactured. As used herein, polycrystalline diamond (PCD) material comprises an aggregation of a plurality of diamond grains, a substantial portion of which are directly inter-bonded with each other and in which the content of diamond is at least about 80 volume per cent of the material. Interstices between the diamond grains may be at least partly filled with a filler material that may comprise catalyst material for synthetic diamond, or they may be substantially empty. As used herein, a catalyst material (which may also be referred to as a solvent / catalyst material) for synthetic diamond is capable of promoting the growth of synthetic diamond grains and or the direct inter-growth of synthetic or natural diamond grains at a temperature and pressure at which synthetic or natural diamond is thermodynamically stable. Examples of catalyst materials for diamond are Fe, Ni, Co and Mn, and certain alloys including these. Bodies comprising PCD material may comprise at least a region from which catalyst material has been removed from the interstices, leaving interstitial voids between the diamond grains. The catalyst material and/or solvent may have been removed by leaching with a strong aqueous acid, for example, by a method as detailed in GB2465175A, GB2499092A or WO2021136833A1, the contents of which are incorporated herein by reference in their entirety.

In an example, the PCD material comprises about 82 weight per cent substantially inter-gown diamond grains and about 18 weight per cent filler material disposed in the interstitial regions between the diamond grains, the filler material comprising cobalt. The diamond grains may have a mean size of from about 1 micron to about 50 microns, for example about 20 microns.

Where the weight or volume per cent content of a constituent of a polycrystalline or composite material is measured, it is understood that the volume of the material within which the content is measured is to be sufficiently large that the measurement is substantially representative of the bulk characteristics of the material. For example, if PCD material comprises inter-grown diamond grains and cobalt filler material disposed in interstices between the diamond grains, the content of the filler material in terms of volume or weight per cent of the PCD material should be measured over a volume of the PCD material that is at least several times the volume of the diamond grains so that the mean ratio of filler material to diamond material is a substantially true representation of that within a bulk sample of the PCD material (of the same grade).

In some example arrangements, the tip 14 may consist of or consist essentially of a single grade of PCD or it may comprise a plurality of PCD grades arranged in various ways, such as in layered or lamination arrangements. The tip 14 may comprise a plurality of strata arranged so that adjacent strata comprise different PCD grades, adjacent strata being directly bonded to each other by inter-growth of diamond grains.

As used herein, a PCD grade is a variant of PCD material characterised in terms of the volume content and or size of diamond grains, the volume content of interstitial regions between the diamond grains and composition of material that may be present within the interstitial regions. Different PCD grades may have different microstructure and different mechanical properties, such as elastic (or Young's) modulus E, modulus of elasticity, transverse rupture strength (TRS), toughness (such as so-called K1C toughness), hardness, density and coefficient of thermal expansion (CTE). Different PCD grades may also perform differently in use. For example, the wear rate and fracture resistance of different PCD grades may be different.

In other example arrangements, the volume of the tip 14 may be at least 70 per cent and at most 150 per cent of the volume of the substrate 12.

In some example arrangements, the substrate 12 may comprise cemented tungsten carbide, for example, cobalt-cemented tungsten carbide, metal, for example, steel, ceramic material, silicon carbide cemented diamond material or superhard material, for example any superhard material detailed above in the context of the tip 14. In some examples, the super-hard material of the tip 14 may be formed joined to the substrate 12, by which is meant that the super-hard material of the tip 14 is produced (for example sintered) in the same general step in which the super-hard tip 14 becomes joined to the substrate 12. In some examples, the substrate 12 may comprise cemented tungsten carbide material including at least about 5 weight per cent and at most about 10 weight per cent or at most about 8 weight per cent binder material, which may comprise cobalt (as measured prior to subjecting the substrate 12 to any high-pressure, high temperature condition at which the super-hard tip 14 may be produced; the actual binder content after such treatment is likely to be somewhat lower). For example, the substrate 12 may comprise cobalt-cemented tungsten carbide material comprising about 92 weight per cent tungsten carbide (WC) grains and about 8 weight per cent cobalt (Co). The tungsten carbide grains may have a mean size of at most about 6 microns, at most about 5 microns or at most about 3 microns. The mean size of the tungsten carbide grains may be at least about 1 micron or at least about 2 microns. The cemented carbide material may have Rockwell hardness “A” of at least about 88 HRa, for example about 88.7 HRa, or at least about 90 HRa; transverse rupture strength of at least about 2,500 megapascals, for example about 2,800 megapascals (MPa); and/or magnetic saturation of at least about 8 $G.cm^3/g$ (Gauss times cubic centimetre per gram) and at most about 16 $G.cm^3/g$ (Gauss times cubic centimetre per gram) or at most about 13 $G.cm^3/g$ (Gauss times cubic centimetre per gram), for example from about 10.5 to about 12.8 $G.cm^3/g$ (Gauss times cubic centimetre per gram) or from about 7 $G.cm^3/g$ (Gauss times cubic centimetre per gram) and at most about 11 $G.cm^3/g$ (Gauss times cubic centimetre per gram), and magnetic coercivity of at least about 6 kA/m (kiloampere per metre) and at most about 14 kA/m (kiloampere per metre), for example from about 7.2 to about 8.8 kiloamperes per metre (kA/m). The fracture toughness may be about 14.6 megapascals (MPa) and the Young’s modulus may be about 600 megapascals (MPa). Cemented carbide having relatively low binder content is likely to provide enhanced stiffness and support for the tip 14 in use, which may help reduce the risk of fracture, and is likely to exhibit good wear resistance.

In some example arrangements, the substrate 12 may comprise an intermediate volume and a core volume comprising cemented carbide material, the intermediate volume being coterminous with the substrate end 12a and with the core volume, the intermediate volume being greater than the volume of the tip 14 and comprising an intermediate material having a mean Young's modulus in the range of about 60 per cent and 90 per cent of the Young's modulus of the super-hard material.

The shape of the substrate end 12a is not particularly limited, so long as it comprises a convex portion. Similarly, the shape of the tip end 14a is not particularly limited, so long as it comprises a concave portion which corresponds to the convex portion of the substrate end 12a. This shape of the tip end 14a means that the stirring pin 20 can be lengthened (e.g. to a suitable length for FSW of non-ferrous metals, including aluminium, magnesium, copper, titanium and alloys thereof, polymers, such as thermoplastic polymers, and polymer composites, such as fibre-reinforced polymer composites) without having to have a correspondingly increased thickness of the PCD layer, as would be required if the tip end 14a was planar, and which would be prone to cracking. The production of a more robust PCD-tipped FSW tool assembly is thereby facilitated.

In an embodiment, the shapes of the tip end 14a and the substrate end 12a are as shown in Fig. 3. Here a generally dome-shaped substrate end 12a is provided with a corresponding tip end 14a. In some example arrangements, the substrate end 12a may include a generally dome-shaped central area having a radius of curvature in the longitudinal plane of at least 1 millimetre, at least 2 millimetres or at least 5 millimetres. In some examples, the radius of curvature of the substrate end 12a may be at most about 20 millimetres.

As noted above, the tip 14 comprises a stirring pin 20 located at a distal end to the tip end 14a. A longitudinal axis L running through the centre of the stirring pin 20 can be defined, as depicted in Fig. 3. The tip 14 can include a sloped surface, e.g. a substantially planar sloped surface, inclined towards the stirring pin 20 and which is disposed at an angle θ to the longitudinal axis L. The angle θ may be in the range 30 degrees to 60 degrees. Alternatively, in place of a substantially planar sloped surface as depicted in Figs. 2-7, the tip 14 can include a curved surface with a radius of from about 15 to about 30 mm, for example from about 20 to about 25 mm. The height P of the stirring pin 20 is measured along longitudinal axis L and may be from about 0.5 mm to about 10 mm, for example from about 1 mm to about 5 mm, for example from about 2 mm to about 3 mm, for example approximately 2.5 mm. The height H1 of the superhard material table, i.e. the distance from the tip end 14a to the distal end of the stirring pin 20, is measured along longitudinal axis L, as is the height H2 of the combined substrate 12 and tip 14 assembly. The height H1 of the superhard material table may be from about 0.5 mm to about 20 mm, for example from about 1 mm to about 10 mm, for example from about 2 mm to about 5 mm, for example approximately 5 mm. The ratio of the height H1 of the superhard material table to the height P of the stirring pin may be from approximately 40:1 to approximately 1:1, for example from approximately 20:1 to approximately 1:1, for example from approximately 10:1 to approximately 1:1, for example from approximately 8:1 to 1:1, for example from approximately 20:3 to approximately 1:1, for example from approximately 4:1 to approximately 1:1, for example from approximately 2:1 to approximately 1:1. The ratio of the height H1 of the superhard material to the height P of the stirring pin may be at most 40:1, or 20:1, or 10:1, or 8:1, or 20:3, or 4:1, or 2:1. The ratio of the height H1 of the superhard material to the height P of the stirring pin may be at least 1:1, or 2:1, or 4:1, or 20:3, or 8:1, or 10:1, or 20:1. The height H2 of the combined substrate and tip assembly may be at least about 8 mm, for example at least about 10 mm, for example at least about 15 mm. Additionally or alternatively, the height H2 of the combined substrate 12 and tip 14 assembly may be at most about 50 mm, for example at most about 45 mm, for example at most about 40 mm, for example at most about 35 mm, for example at most about 30 mm, for example at most about 25 mm. For example, the height H2 of the combined substrate 12 and tip 14 assembly may be in the range of from about 15 mm to about 30 mm, for example from about 20 mm to about 25 mm. The ratio of the height H2 of the combined substrate 12 and tip 14 assembly to the height P of the stirring pin may be from approximately 100:1 to approximately 5:1, for example from approximately 50:1 to approximately 5:1, for example from approximately 25:1 to approximately 5:1, for example from approximately 20:1 to 5:1, for example from approximately 50:3 to approximately 5:1, for example from approximately 10:1 to approximately 5:1. The ratio of the height H2 of the combined substrate 12 and tip 14 assembly to the height P of the stirring pin may be at most 100:1, or 50:1, or 25:1, or 20:1, or 50:3, or 10:1. The ratio of the height H2 of the combined substrate 12 and tip 14 assembly to the height P of the stirring pin may be at least 5:1, or 10:1, or 50:3, or 20:1, or 25:1, or 50:1, or 100:1. The ratio of the height H2 of the combined substrate 12 and tip 14 assembly to the height H1 of the superhard material may be from approximately 100:1 to approximately 2.5:1, for example from approximately 50:1 to approximately 2.5:1, for example from approximately 25:1 to approximately 2.5:1, for example from approximately 10:1 to approximately 2.5:1, for example from approximately 5:1 to approximately 2.5:1. The ratio of the height H2 of the combined substrate 12 and tip 14 assembly to the height H1 of the superhard material may be at most 100:1, or 50:1, or 25:1, or 10:1, or 5:1. The ratio of the height H2 of the combined substrate 12 and tip 14 assembly to the height H1 of the superhard material may be at least 2.5:1, or 5:1, or 10:1, or 25:1, or 50:1, or 100:1. The diameter d of the substrate is measured perpendicular to longitudinal axis L, and can be from about 8 to about 30 mm, for example from about 10 to about 20 mm, for example about 15 mm.

The substrate end 12a may further include a depression and/or a projection and the tip end may comprise a corresponding depression and/or projection. For example, the substrate end 12a shown in Fig. 4 has a projection 22b and the tip end 14a has a corresponding depression 22a. The number of depressions and/or projections is not particularly limited and are applicable to all embodiments shown herein. The projections and/or the depressions may be generally hemispherical. Such depressions and projections can aid in bonding the tip end 14a and the substrate end 12a by providing a greater effective interface boundary area between the tip end 14a and the substrate end 12a.

In some example arrangements, as shown in Fig. 5, the convex portion of the substrate end 12a may have a generally dome-shaped central area at least partly surrounded by a peripheral shelf 24. The domed-shaped area may further include a central depression in the substrate end 12a and a corresponding central projection in the tip end 14a may be provided, or vice versa.

In some example arrangements, as shown in Fig. 6, the convex portion of the substrate end 12a may have a generally flattened dome shape. That is to say, the substrate end 12a has a tapered surface starting from a cylindrical rim of the substrate 12 and ending at an elevated, substantially flat central region formed in the substrate end 12a. The flat central region may have a diameter of about 3.2 mm to about 6 mm. In some example arrangements, the substrate end 12 may have a generally flattened dome-shaped central area at least partly surrounded by a peripheral shelf. The flattened dome-shaped area may include depressions or projections as described above. The tip end 14a has a corresponding shape.

In some example arrangements, as shown in Figs. 7A and 7B, the convex portion of the substrate end 12a may have substantially the same structural features and dimensions as that described above with reference to Fig. 2, except that there is a depression 26 in the substrate end 12a, the bottom of the depression 26 being generally opposite the stirring pin 20 of the tip end 14a and defined by a concavity in the otherwise generally convex substrate end 12a. The substrate end 12a can be described as a hollow-point dome, in which the depression 26 is at least partly surrounded by a ridge 28. The depression 26 may have a longitudinal radius of curvature R_d (i.e. in a plane parallel to L) of at least about 0.5 mm and at most about 10 mm, and a depth D_d from a surrounding ridge 28 of at least about 0.1 mm and at most about 1 mm. In one particular example, the depth R_d is about 0.3 mm.

In some example arrangements, the substrate end 12a includes one or more generally hemispherical projections, and the tip end 14a includes one or more corresponding generally hemispherical depressions, and vice versa.

In the embodiments discussed above, the convex portions of the substrate end have been broadly dome-shaped. However, other types of convex portion structure are also envisaged as part of the invention. For example, the substrate end may comprise an array, for example a discontinuous array, of convex portions and the tip end may comprise a corresponding array of concave portions. An example of a substrate end 12a which comprises a discontinuous array of convex portions is shown in Figure 8. Figure 8 is a perspective view of a substrate 12 which comprises a discontinuous array of convex portions at the substrate end 12a. The tip end 14a (not shown) would have a corresponding discontinuous array of concave portions.

One or more interlayers may be inserted between the substrate end 12a and the tip end 14a. The interlayer may comprise a bonded mass of superhard abrasive particles and refractory particles wherein the size of the superhard abrasive particles is the same as or less than that of the refractory particles. In the interlayer the superhard abrasive particles and the refractory particles will generally be present as discrete entities with little or no or substantially no intergrowth or direct particle-to-particle bonding. A bonding phase may also be present. This bonding phase may comprise or consist of nickel, cobalt, iron or alloys containing one or more of these metals. The interlayer may comprise a composite material formed of non-interbonded grains of super hard material, preferably diamond grains with, for example, any one or more of oxides, nitrides, carbides, silicides, carbonitrides, and/or oxycarbides of any one or more transition metals including titanium, zirconium, vanadium, hafnium, tantalum, niobium, chromium, molybdenum, tungsten, copper, manganese, and/or rhenium or an alloy thereof.

The amount of superhard abrasive particle in the interlayer may generally be in the range of about 10 vol.% to about 90 vol.%.

The superhard abrasive may be diamond or cubic boron nitride. Generally, when the tip comprises PCD, the superhard abrasive will be diamond and when the tip comprises PCBN, the superhard abrasive will be cubic boron nitride. A mixture of superhard abrasive particles may be present in the interlayer.

The refractory particles may be carbide, nitride, or boride. Carbide particles are preferred.

In some example arrangements, the interlayer is formed of a diamond enhanced carbide material as detailed above in the context of the tip 14.

The size of the superhard abrasive particles may be the same as or less than that of the refractory particles. When the size of the superhard abrasive particles is less than that of the refractory particles, they will generally have a size of about 10 microns, preferably about 5 microns or less than that of the refractory particles.

The thickness of the interlayer may be in the range from about 100 to about 2000 microns, typically from about 200 to about 500 microns.

As noted above, the interlayer, if present, is between the tip end 14a and the substrate end 12a. The interlayer will generally have a region in contact with and bonded to the tip end 14a and a region in contact with and bonded to a surface of the substrate end 12a. An additional interlayer or interlayers may also be provided between the superabrasive/carbide interlayer and substrate end 12a and/or between the superabrasive/carbide interlayer and the tip end 14a.

The inclusion of interlayers is advantageous as it reduces peak stresses between the tip end 14a and the substrate end 12a.

A method of forming a friction stir welding assembly 10 as described herein comprises: providing a substrate 12 having a substrate end 12a, the substrate end 12a comprising a convex portion, and a tip 14 having a tip end 14a, the tip end 14a comprising a concave portion, wherein the tip 14 is formed of a superhard material and the substrate end 12a is joined to the tip end 14a at the corresponding convex and concave portions; and forming a stirring pin 20 at a distal end of the tip 14.

The stirring pin 20 may be formed by machining the distal end of the tip 14, for example using laser ablation or electrical discharge machining (EDM).

Prior to machining, the distal end of the tip 14 may be substantially planar, or generally domed, pointed, rounded conical, blunted conical or frusto-conical in profile.

The friction stir welding tool assembly 10 as described herein may be used in a friction stir welding process. In particular, the friction stir welding assembly 10 as described herein may be used for friction stir welding processes involving joining non-ferrous metals, such as aluminium, magnesium, titanium and copper or alloys thereof. The friction stir welding tool assembly as described herein is particularly suitable for use in a friction stir welding process of aluminium-silicon alloys. The increasingly abrasive nature of these alloys as the silicon content is increased results in poor lifetime of conventional steel probes. Typical aluminium-silicon alloys include: Al-50wt.% Si-50wt.%, Al-64wt.% Si-36wt.%, Al-65wt.% Si-35wt.%, Al-75wt.% Si-25wt.%, Al-88wt.% Si-12wt.%, Al-90wt.% Si-10wt.%, and Al-98wt.% Si-2wt.%. The friction stir welding tool assembly 10 as described herein is particularly suitable for use in a friction stir welding process of aluminium-silicon alloys which comprise 9-20 wt.% silicon, with the balance aluminium and inevitable impurities. The friction stir welding tool assembly 10 as described herein may also be used for friction stir welding processes involving polymers, for example thermoplastic polymers. The friction stir welding tool assembly 10 as described herein may also be used for friction stir welding processes involving composite materials, for example polymer composites, such as fibre reinforced polymer composites, or metal matrix composites. The friction stir welding process may involve joining one or more articles comprising one or more non-ferrous metals, polymers or polymer composites as described above. The friction stir welding process may involve joining at least two articles, for example two articles, comprising one or more non-ferrous metals, polymers or polymer composites as described above.

While this invention has been particularly shown and described with reference to embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the scope of the invention as defined by the appended claims.

Certain embodiments of the present invention are as follows:

1. A friction stir welding tool assembly comprising:

a substrate having a substrate end, the substrate end comprising a convex portion; and

a tip having a tip end, the tip end comprising a concave portion;

the tip further comprising a stirring pin, the stirring pin being located at a distal end to the tip end;

wherein the tip is formed of a superhard material;

the substrate end being joined to the tip end at the corresponding convex and concave portions.

2. The friction stir welding tool assembly of embodiment 1, wherein the superhard material comprises or consists of polycrystalline diamond material, polycrystalline cubic boron nitride silicon carbide-bonded diamond material or diamond enhanced carbide material.

3. The friction stir welding tool assembly of embodiment 1 or embodiment 2, wherein the convex portion of the substrate end is substantially dome-shaped.

4. The friction stir welding tool assembly of embodiment 3, wherein the substantially dome-shaped convex portion of the substrate end is at least partly surrounded by a peripheral shelf.

5. The friction stir welding tool assembly of embodiment 1 or embodiment 2, wherein the convex portion of the substrate end is a flattened dome-shaped central area with a flat central region.

6. The friction stir welding tool assembly of embodiment 1 or embodiment 2, wherein the convex portion of the substrate end comprises a depression, the bottom of the depression being opposite the stirring pin of the tip end and defined by a concavity in the otherwise convex portion of the substrate end.

7. The friction stir welding tool assembly of any one of the preceding embodiments, wherein the substrate end includes one or more projections, and the tip end includes one or more corresponding depressions, and/or wherein the tip end includes one or more projections, and the substrate end includes one or more corresponding depressions.

8. The friction stir welding tool assembly of embodiment 7, wherein the projections and depressions are generally hemispherical.

9. The friction stir welding tool assembly of any one of the preceding embodiments, further comprising one or more interlayers between the substrate end and the tip end.

10. The friction stir welding tool assembly of embodiment 9, wherein the one or more interlayers comprise a bonded mass of superhard abrasive particles and refractory particles, wherein the size of the superhard abrasive particles is the same as or less than that of the refractory particles.

11. The friction stir welding tool assembly of embodiment 10, wherein the interlayer further comprises a bonding phase.

12. The friction stir welding tool assembly of embodiment 11, wherein the bonding phase comprises nickel, cobalt, iron, or alloys containing one or more of these metals.

13. The friction stir welding tool assembly of any one of the preceding embodiments, wherein the height H1 of the superhard material table is from about 1 mm to about 10 mm.

14. The friction stir welding tool assembly of any one of the preceding embodiments, further comprising a tool holder, wherein the substrate is attached to the tool holder by means of a screw thread.

15. A method of forming a friction stir welding assembly of any one of the preceding embodiments, comprising:

providing a substrate having a substrate end, the substrate end comprising a convex portion; and a tip having a tip end, the tip end comprising a concave portion;
wherein the tip is formed of a superhard material and the substrate end is joined to the tip end at the corresponding convex and concave portions; and

forming a stirring pin at a distal end of the tip.

16. The method according to embodiment 15, wherein the step of forming a stirring pin comprises using laser ablation and/or electrical discharge machining.

17. Use of the friction stir welding tool assembly of any one of embodiments 1-14 in a friction stir welding process.

18. The use of embodiment 17, wherein the friction stir welding process joins non-ferrous metals.

19. The use of embodiment 18, wherein the non-ferrous metals are aluminium, magnesium, titanium or copper or alloys thereof.

20. The use of embodiment 19, wherein the aluminium alloy is a silicon-aluminium alloy.

CLAIMS

1. A friction stir welding tool assembly comprising:
a substrate having a substrate end, the substrate end comprising a convex portion; and
a tip having a tip end, the tip end comprising a concave portion;
the tip further comprising a stirring pin, the stirring pin being located at a distal end to the tip end;
wherein the tip is formed of a superhard material;
the substrate end being joined to the tip end at the corresponding convex and concave portions.

2. The friction stir welding tool assembly of claim 1, wherein the superhard material comprises diamond.

3. The friction stir welding tool assembly of claim 1, wherein the superhard material is a diamond-based composite material.

4. The friction stir welding tool assembly of claim 1, wherein the superhard material comprises or consists of polycrystalline diamond material.

5. The friction stir welding tool assembly of claim 1, wherein the superhard material comprises or consists of silicon carbide-bonded diamond material.

6. The friction stir welding tool assembly of claim 1, wherein the superhard material comprises or consists of diamond enhanced carbide.

7. The friction stir welding tool assembly of claim 1, wherein the superhard material comprises or consists of polycrystalline cubic boron nitride.

8. The friction stir welding tool assembly of any one of claims 1 to 7, wherein the convex portion of the substrate end is substantially dome-shaped.

9. The friction stir welding tool assembly of claim 8, wherein the substantially dome-shaped convex portion of the substrate end is at least partly surrounded by a peripheral shelf.

10. The friction stir welding tool assembly of any one of claims 1 to 7, wherein the convex portion of the substrate end is a flattened dome-shaped central area with a flat central region.

11. The friction stir welding tool assembly of any one of claims 1 to 7, wherein the convex portion of the substrate end comprises a depression, the bottom of the depression being opposite the stirring pin of the tip end and defined by a concavity in the otherwise convex portion of the substrate end.

12. The friction stir welding tool assembly of any one of the preceding claims, wherein the substrate end includes one or more projections, and the tip end includes one or more corresponding depressions, and/or wherein the tip end includes one or more projections, and the substrate end includes one or more corresponding depressions.

13. The friction stir welding tool assembly of claim 12, wherein the projections and depressions are generally hemispherical.

14. The friction stir welding tool assembly of any one of the preceding claims, further comprising one or more interlayers between the substrate end and the tip end, wherein the one or more interlayers comprise a bonded mass of superhard abrasive particles and refractory particles, wherein the size of the superhard abrasive particles is the same as or less than that of the refractory particles.

15. The friction stir welding tool assembly of claim 14, wherein the interlayer further comprises a bonding phase.

16. The friction stir welding tool assembly of claim 15, wherein the bonding phase comprises nickel, cobalt, iron, or alloys containing one or more of these metals.

17. The friction stir welding tool assembly of any one of the preceding claims, wherein the height H1 of the superhard material table is from about 1 mm to about 10 mm.

18. The friction stir welding tool assembly of any one of the preceding claims, further comprising a tool holder, wherein the substrate is attached to the tool holder by means of a screw thread.

19. The friction stir welding tool assembly of any one of the preceding claims, wherein the substrate end comprises an array of discontinuous convex portions and the tip end comprises a corresponding array of concave portions.

20. A method of forming a friction stir welding assembly of any one of the preceding claims, comprising:

providing a substrate having a substrate end, the substrate end comprising a convex portion; and a tip having a tip end, the tip end comprising a concave portion;

wherein the tip is formed of a superhard material and the substrate end is joined to the tip end at the corresponding convex and concave portions; and

forming a stirring pin at a distal end of the tip.

21. The method according to claim 20, wherein the step of forming a stirring pin comprises using laser ablation and/or electrical discharge machining.

22. Use of the friction stir welding tool assembly of any one of claims 1-19 in a friction stir welding process.

23. The use of claim 22, wherein the friction stir welding process joins non-ferrous metals.

24. The use of claim 23, wherein the non-ferrous metals are aluminium, magnesium, titanium or copper or alloys thereof.

25. The use of claim 24, wherein the aluminium alloy is a silicon-aluminium alloy.

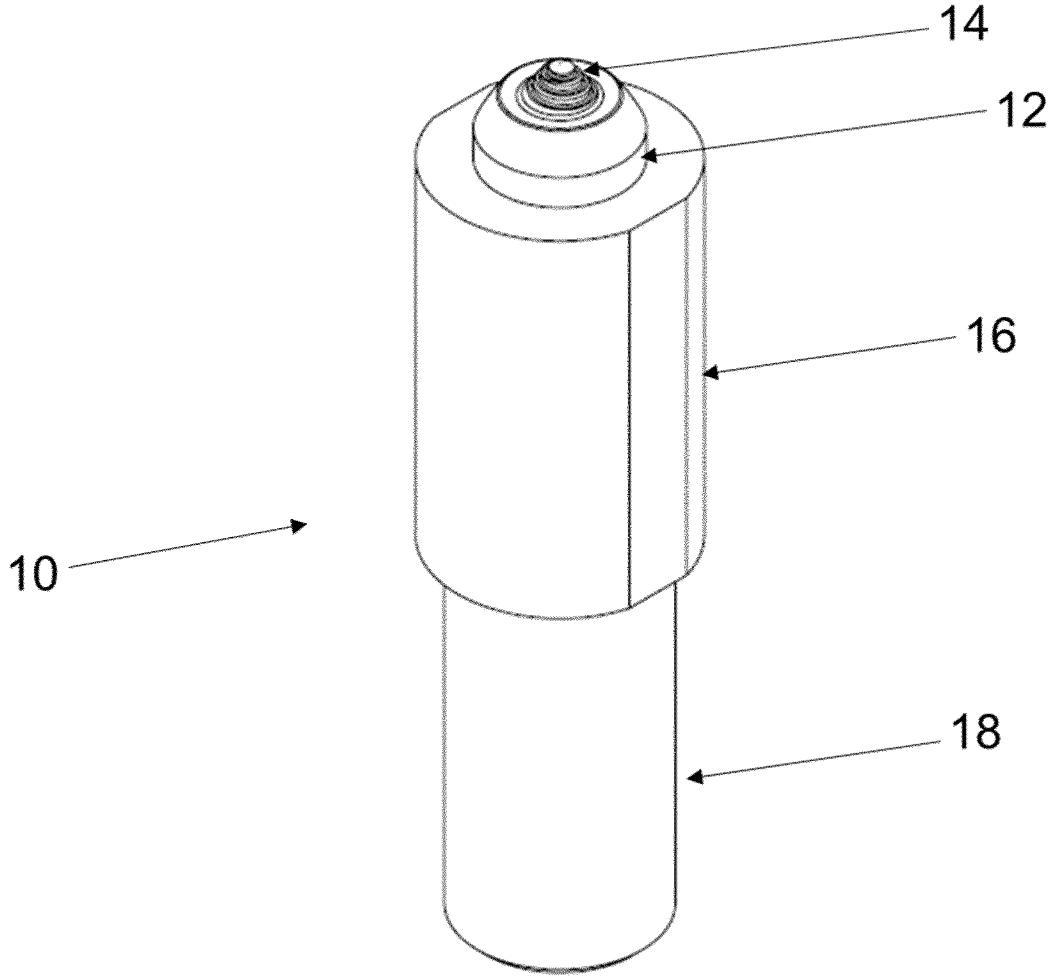

Fig. 1

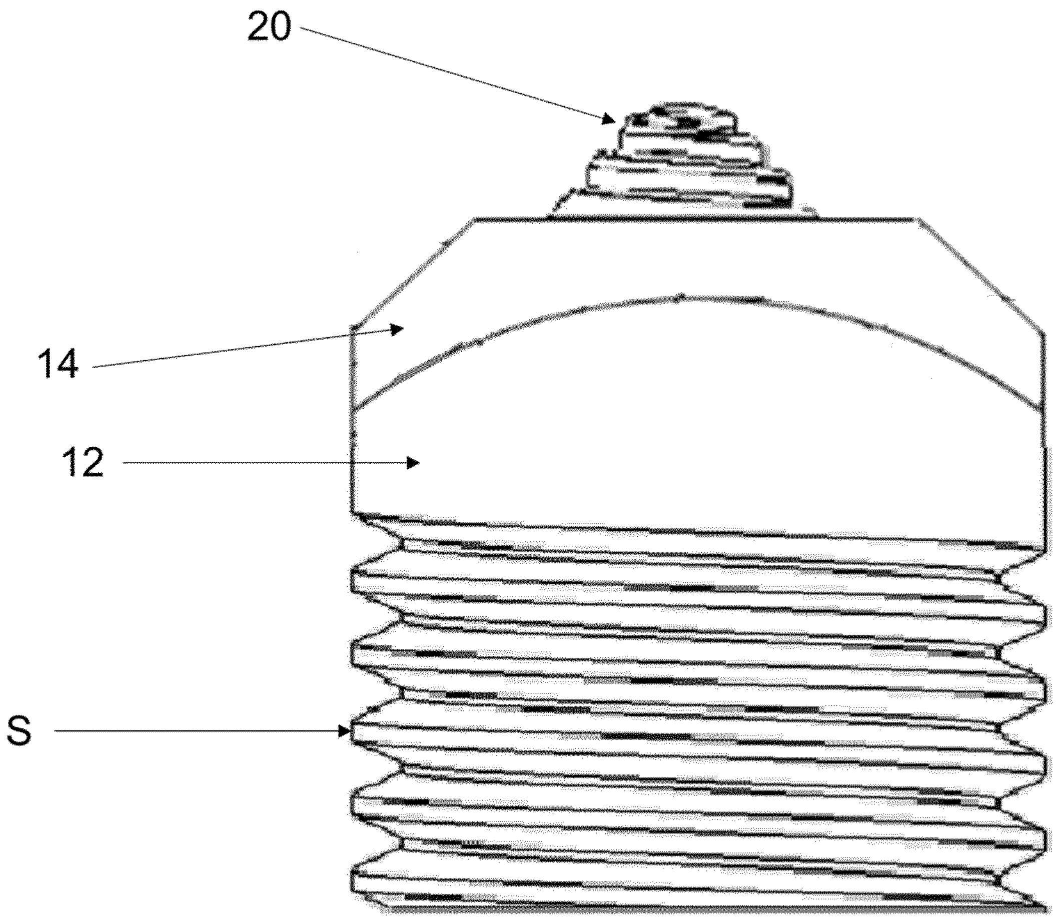

Fig. 2

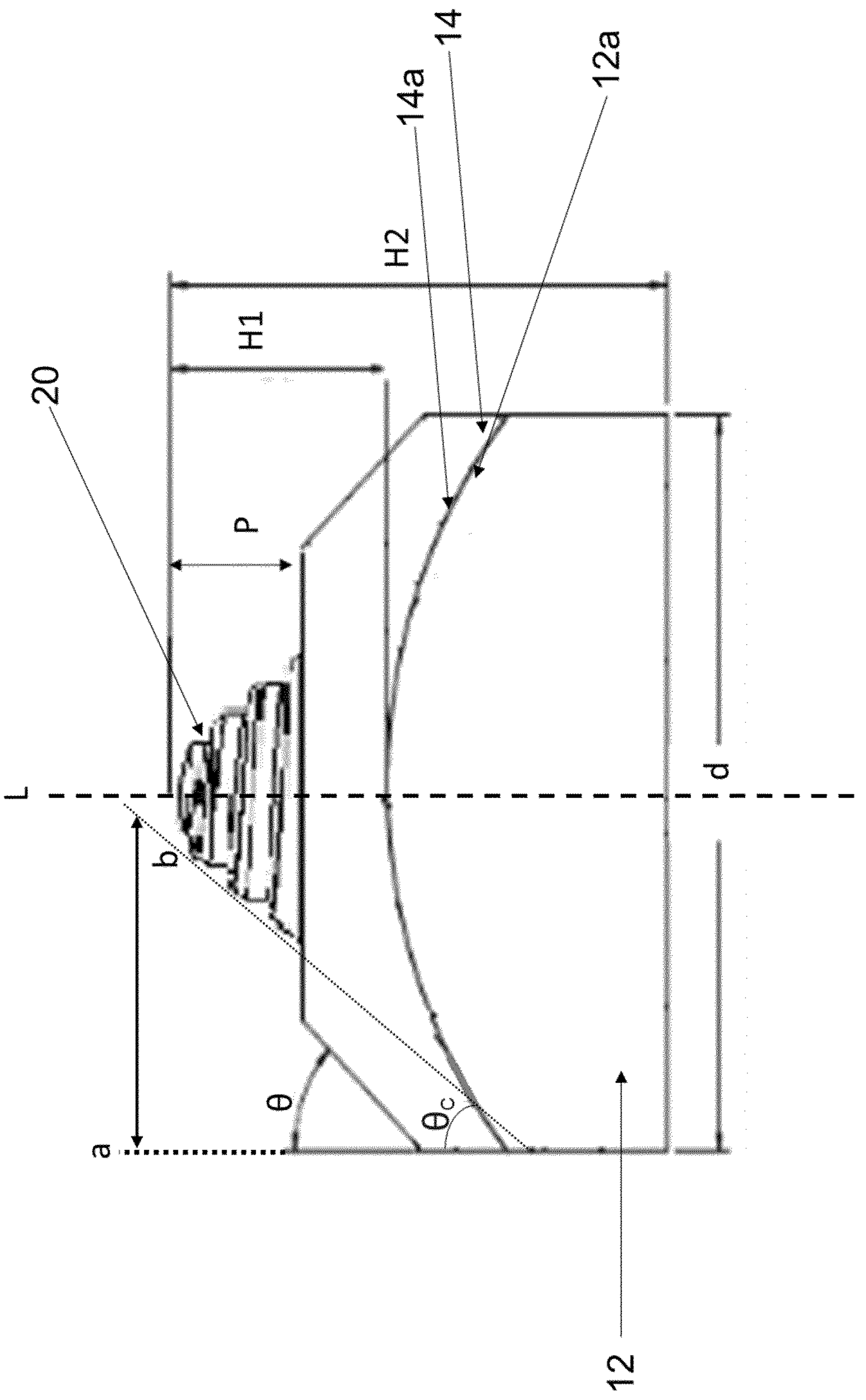

Fig. 3

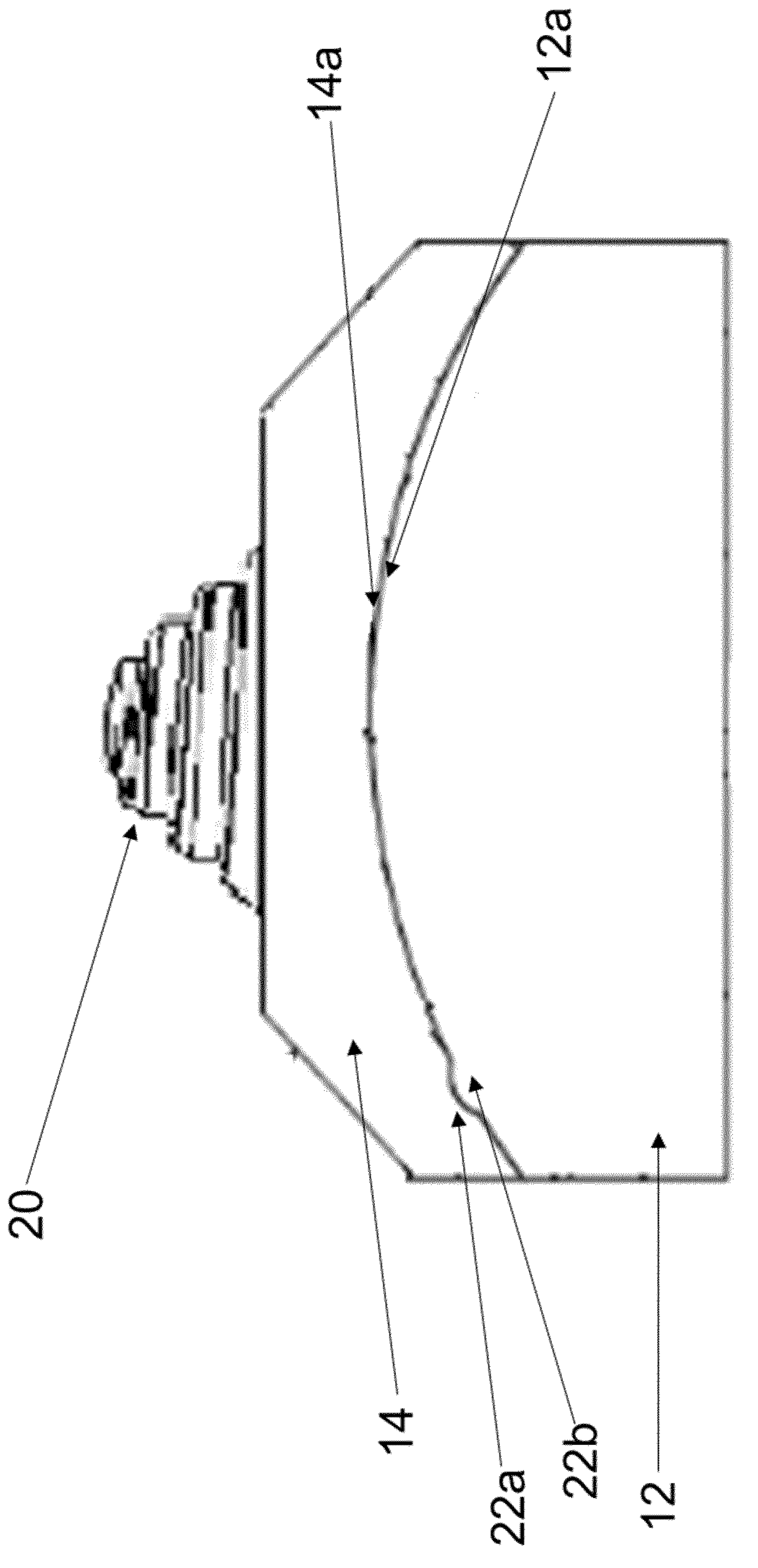

Fig. 4

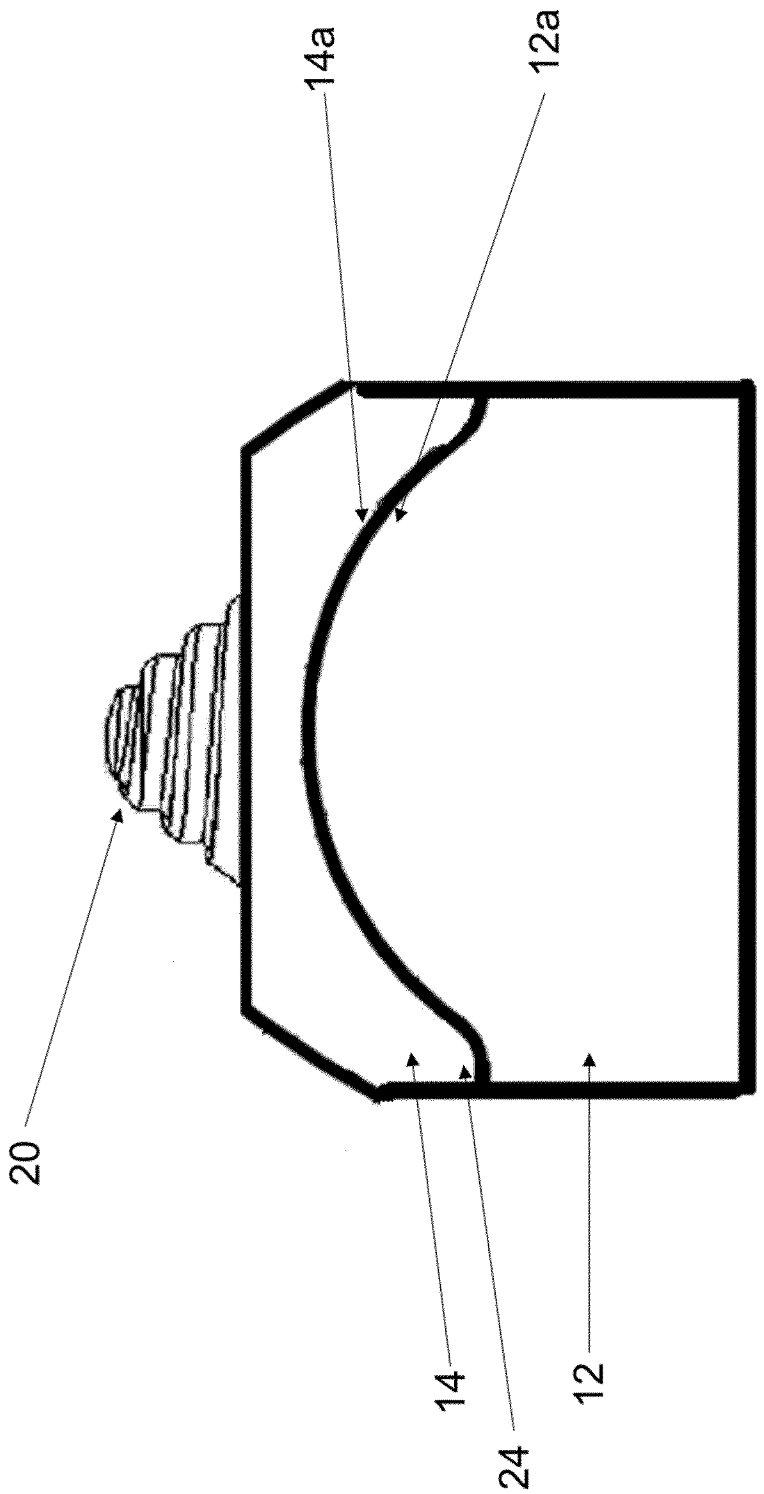

Fig. 5

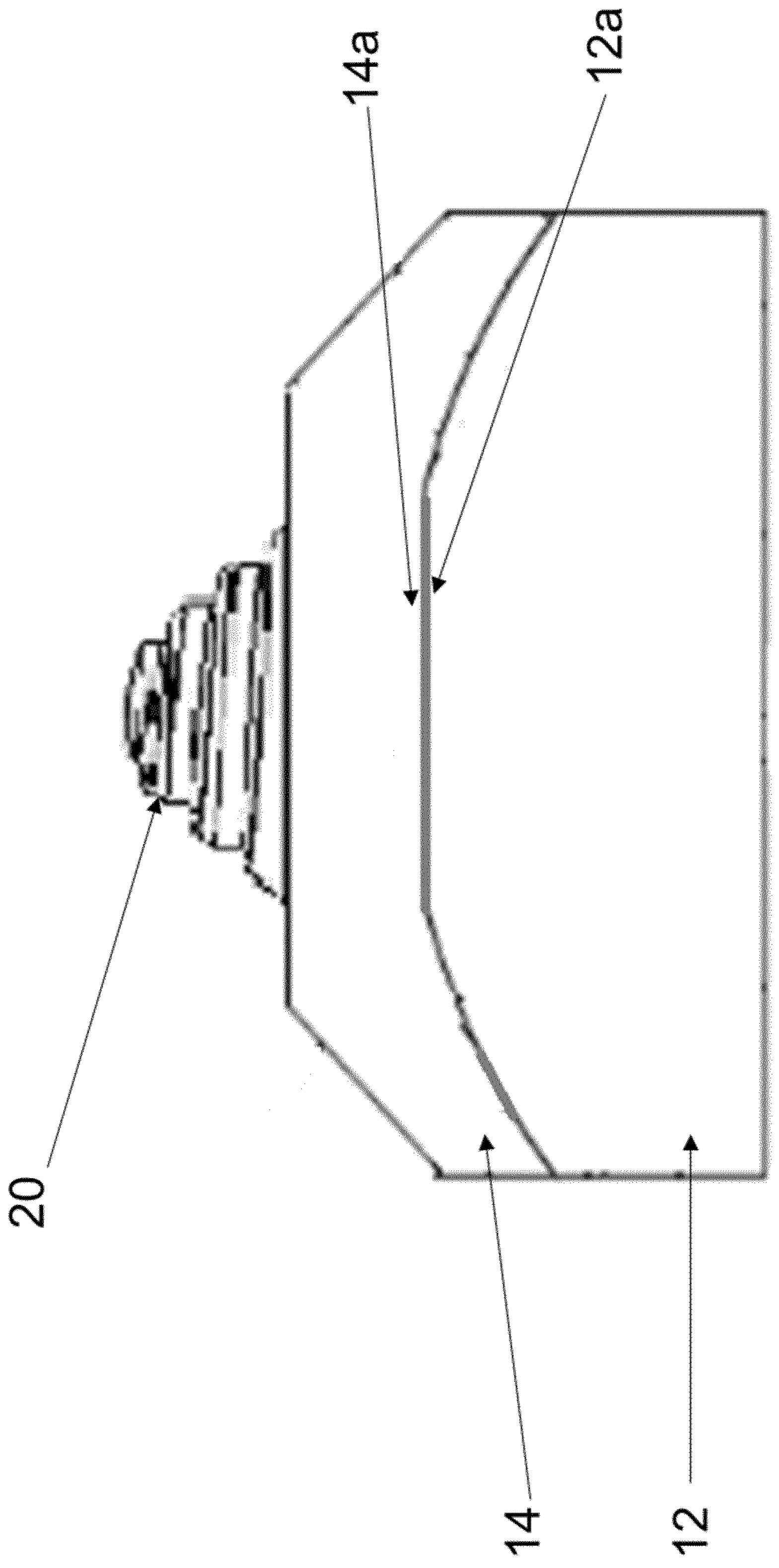

Fig. 6

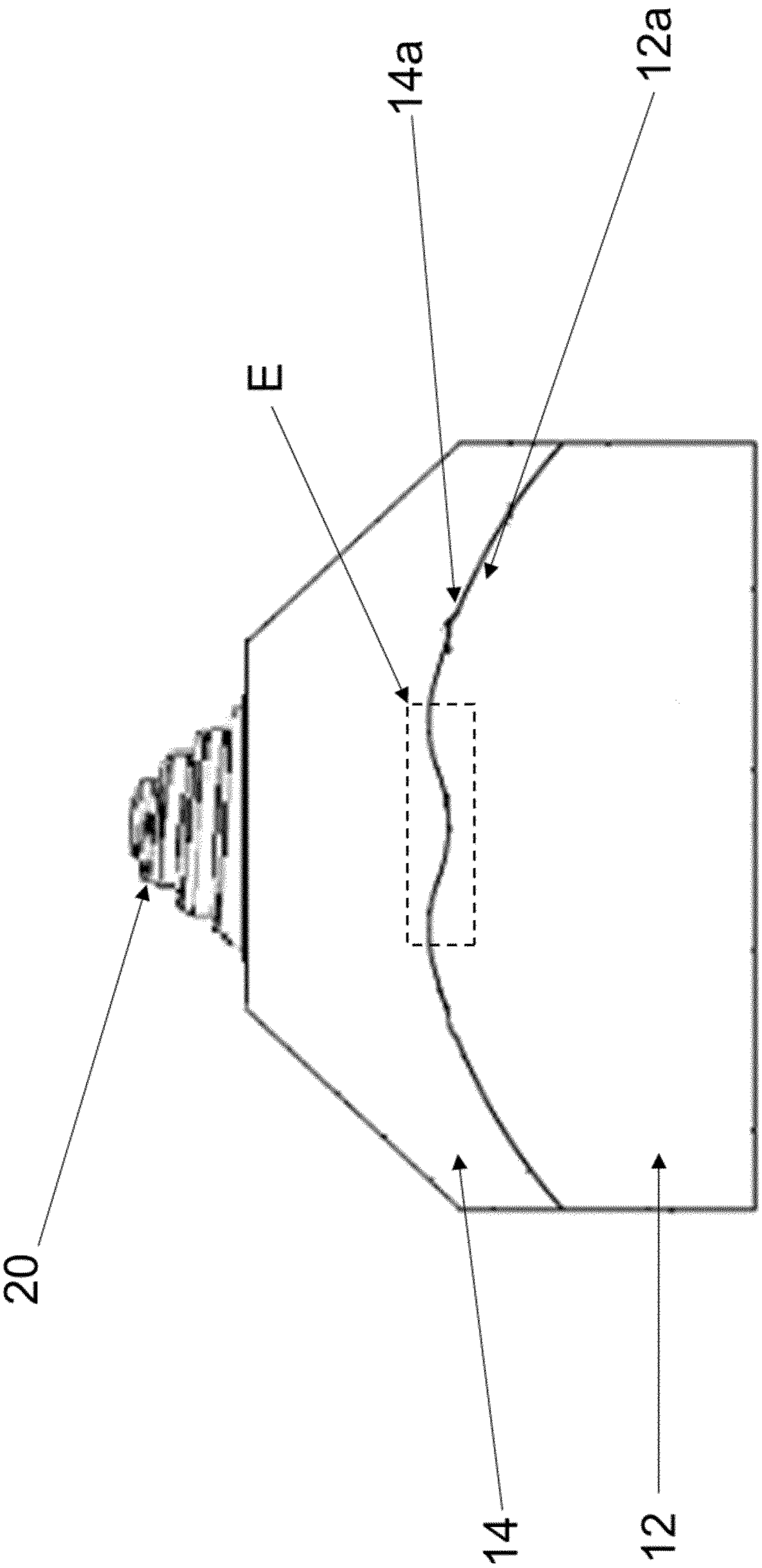

Fig. 7A

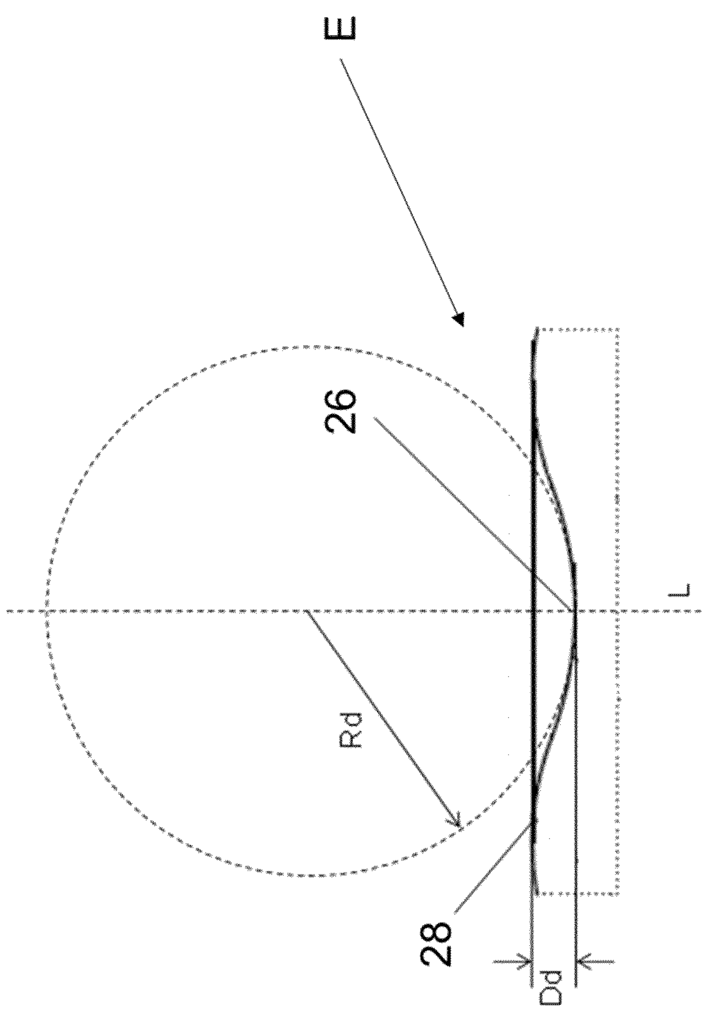

Fig. 7B

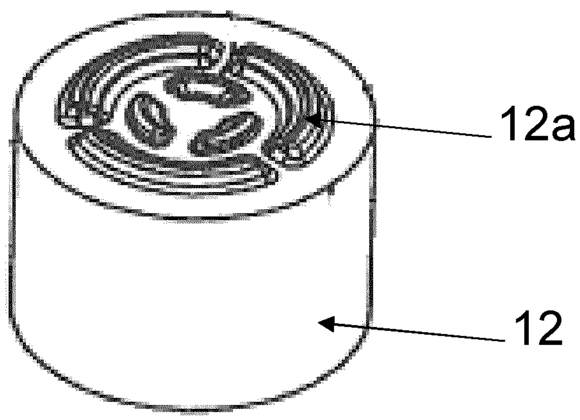

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2023/085822

A. CLASSIFICATION OF SUBJECT MATTER
INV. B23K20/12 B23K20/233 B23K103/10 B23K103/08 B23K103/12
B23K103/14 B23K103/16
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	CN 111 922 507 A (FUNIK ULTRAHARD MAT CO LTD) 13 November 2020 (2020-11-13) claims 1,6; figure 3 paragraphs [0002], [0008], [0010] -----	1-7, 20-24 14-17
X Y	JP 2005 199281 A (DIJET IND CO LTD) 28 July 2005 (2005-07-28) paragraphs [0001], [0026], [0028]; claim 1; figure 4 -----	1,8,10, 20,22-24 9
X	US 8 834 595 B2 (CHRISTOPHERSON JR DENIS [US]; FEDERAL MOGUL CORP [US]) 16 September 2014 (2014-09-16) column 4, line 58 - column 5, line 13; figure 6 paragraph [0001] -----	1,20,22

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 March 2024	28/03/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Péridis, Marc

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	EP 1 341 637 B1 (UNIV BRIGHAM YOUNG [US]; PACKER SCOTT [US]; FELTER PAUL ALLEN [US]) 9 July 2008 (2008-07-09) figures 2A, 7A, 7B, 7C paragraphs [0011], [0015], [0016], [0045], [0047], [0059], [0075] -----	1-4,7, 11,12, 18-25 9,13
X Y	GB 2 607 671 A (ELEMENT SIX UK LTD [GB]) 14 December 2022 (2022-12-14) page 5, line 25 - page 6, line 5 page 4, line 30 - line 32 page 5, line 4 - line 5 page 7, line 4 - line 12 -----	1,20,22 17
X Y	WO 2007/089890 A2 (SII MEGADIAMOND INC [US]; STEEL RUSSELL J [US]; EYRE RONALD K [US]) 9 August 2007 (2007-08-09) page 4, line 9 - line 25; claim 11; figures 1, 2 -----	1,20,22 14-16
X	EP 3 450 082 B1 (MAZAK CORP [US]) 16 December 2020 (2020-12-16) paragraphs [0019], [0020]; claims 1,6,8; figure 4 -----	1,20,22
Y	US 9 234 423 B2 (ELEMENT SIX ABRASIVES SA [LU]; ELEMENT SIX GMBH [DE]) 12 January 2016 (2016-01-12) column 5, line 42 - line 54; figures 4A, 5 -----	13

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2023/085822

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 111922507 A	13-11-2020	NONE	
JP 2005199281 A	28-07-2005	JP 4375665 B2	02-12-2009
		JP 2005199281 A	28-07-2005
US 8834595 B2	16-09-2014	CA 2760894 A1	11-11-2010
		US 2009212089 A1	27-08-2009
		US 2012228361 A1	13-09-2012
		US 2014377118 A1	25-12-2014
		WO 2010129206 A2	11-11-2010
EP 1341637 B1	09-07-2008	AT E400391 T1	15-07-2008
		AT E400392 T1	15-07-2008
		AU 6136501 A	20-11-2001
		AU 6458001 A	20-11-2001
		CA 2409485 A1	15-11-2001
		CA 2409489 A1	15-11-2001
		CN 1436110 A	13-08-2003
		CN 1436111 A	13-08-2003
		CN 1631601 A	29-06-2005
		CN 1654154 A	17-08-2005
		EP 1341637 A1	10-09-2003
		EP 1345729 A1	24-09-2003
		JP 4545368 B2	15-09-2010
		JP 4827359 B2	30-11-2011
		JP 2003532542 A	05-11-2003
		JP 2003532543 A	05-11-2003
		KR 20030022117 A	15-03-2003
		KR 20030022118 A	15-03-2003
		MX PA02010935 A	06-09-2004
		MX PA02010936 A	06-09-2004
		US 2002011509 A1	31-01-2002
		US 2002014516 A1	07-02-2002
		US 2004134972 A1	15-07-2004
		US 2004155093 A1	12-08-2004
		US 2007102492 A1	10-05-2007
		US 2010146866 A1	17-06-2010
		US 2011297733 A1	08-12-2011
		US 2013062395 A1	14-03-2013
		US 2014034710 A1	06-02-2014
		WO 0185384 A1	15-11-2001
		WO 0185385 A1	15-11-2001
		ZA 200208785 B	16-02-2004
		ZA 200208786 B	16-02-2004
GB 2607671 A	14-12-2022	GB 2607671 A	14-12-2022
		WO 2022200585 A1	29-09-2022
WO 2007089890 A2	09-08-2007	CA 2640730 A1	09-08-2007
		CN 101394963 A	25-03-2009
		EP 1979121 A2	15-10-2008
		JP 2009525181 A	09-07-2009
		US 2007187465 A1	16-08-2007
		WO 2007089890 A2	09-08-2007
EP 3450082 B1	16-12-2020	EP 3450082 A1	06-03-2019
		JP 7412075 B2	12-01-2024
		JP 2019081197 A	30-05-2019

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2023/085822

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
		US 2019061046 A1	28-02-2019
		US 2023107348 A1	06-04-2023
US 9234423 B2	12-01-2016	CN 104093933 A	08-10-2014
		EP 2795062 A2	29-10-2014
		GB 2498844 A	31-07-2013
		US 2014361601 A1	11-12-2014
		WO 2013092346 A2	27-06-2013

Form PCT/ISA/210 (patent family annex) (April 2005)