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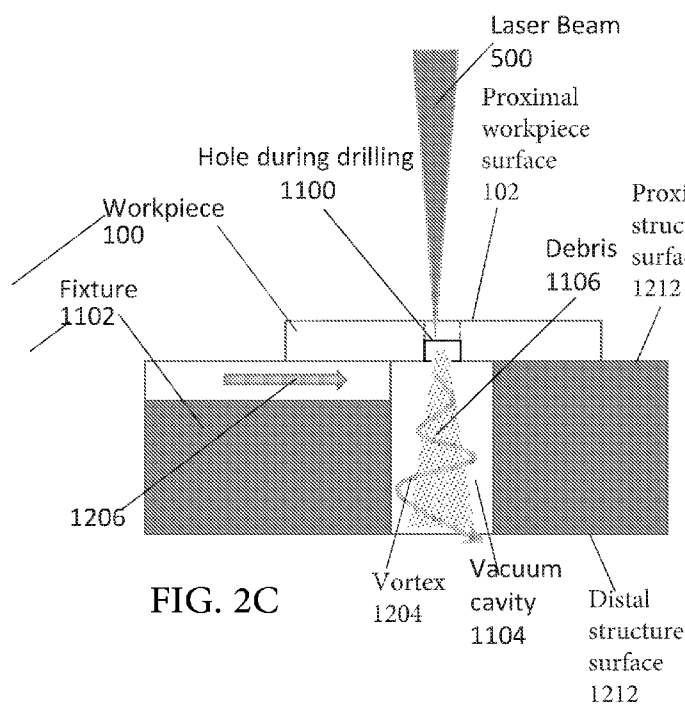


FIG. 2C

(57) Abstract: A laser target on a transparent workpiece (100) can be positioned over a vacuum cavity (1104). The vacuum cavity may be supplied with a debris collection fluid, such as air, through an entrance conduit (1208) to establish a vortex (1204) beneath a feature (1100) intended to be machined. The vortex facilitates removal of laser-generated debris (1106) during pass-through bottom-to-top machining of the feature.

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REMOVAL OF DEBRIS ASSOCIATED WITH LASER DRILLING OF TRANSPARENT MATERIALS

TECHNICAL FIELD

[0001] This application relates to systems and methods for debris removal during laser-micromachining and, in particular, to systems and methods for debris removal during laser pass-through micromachining.

BACKGROUND

[0002] Laser machining can create debris that diminishes the quality of features made by the laser. The debris may also disrupt the effectiveness of subsequent pulses in the laser machining process. The debris may also cause extra time or different techniques or parameters to be used to accomplish its removal. Moreover, the method of debris removal can differently affect the outcome of different laser-machining operations.

SUMMARY

[0003] This summary is provided to introduce a selection of concepts in a simplified form that are further described in greater detail below. This summary is not intended to identify key or essential inventive concepts of the claimed subject matter, nor is it intended for determining the scope of the claimed subject matter.

[0004] In some embodiments, a method for micromachining a workpiece, comprises: supporting a target location of the workpiece over a cavity; establishing vacuum pressure to the cavity; generating a laser beam having beam parameters including a major spot dimension at a focal point and a wavelength that is transparent to the workpiece; propagating the laser beam along a beam path that directs the laser beam in propagation direction along a beam axis to the target location on the workpiece, wherein the workpiece has bulk material between a proximal surface of the workpiece and a distal surface of the workpiece with respect to the propagation direction of the laser beam such that the beam axis intersects the proximal surface before intersecting the distal surface, wherein the beam parameters are adapted for propagating the laser beam through the workpiece to form a depthwise feature in the workpiece, wherein the depthwise feature includes a sidewall, wherein the laser parameters are adapted so that the depthwise feature is formed predominantly from the distal surface toward the proximal surface, wherein formation of the depthwise feature creates debris, and wherein introduction of the debris

collection fluid facilitates removal of debris from the depthwise feature during its formation; and removing the debris during formation of the feature, wherein removing the debris includes providing a debris collection fluid to the cavity.

[0005] In some additional, cumulative, or alternative embodiments, a laser system for micromachining a workpiece, comprises: a laser adapted for generating a laser beam having beam parameters including a major spot dimension at a focal point and a wavelength that is transparent to the workpiece; a workpiece support structure adapted for supporting the workpiece, wherein the workpiece support structure includes a cavity for receiving a debris collection fluid, the cavity adapted for connection to a vacuum source, and the cavity having a cross-sectional dimension adapted to be larger than the major spot dimension, and wherein the workpiece support structure includes an entrance conduit extending from the cavity through the workpiece support structure, the entrance conduit adapted for providing the debris collection fluid into the cavity; and a beam-positioning system adapted for propagating the laser beam along a beam path that directs the laser beam in propagation direction along a beam axis to a target location on the workpiece over the cavity, the workpiece having bulk material between a proximal surface and a distal surface with respect to the propagation direction of the laser beam such that the beam axis is adapted to intersect the proximal surface before intersecting the distal surface, the beam parameters adapted for propagating the laser beam through the workpiece to form a depthwise feature in the workpiece, wherein the laser parameters are adapted so that the depthwise feature is formed predominantly from the distal surface toward the proximal surface.

[0006] In some additional, cumulative, or alternative embodiments, the debris collection fluid is provided through an entrance conduit formed in a workpiece support structure. In some additional, cumulative or alternative embodiments, the debris collection fluid is provided to the cavity through a nozzle.

[0007] In some additional, cumulative, or alternative embodiments, the entrance conduit comprises a groove in a structure surface of the workpiece support structure.

[0008] In some additional, cumulative, or alternative embodiments, the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the entrance conduit connects to the cavity closer to the proximal port than the distal port.

[0009] In some additional, cumulative, or alternative embodiments, the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the entrance conduit connects to the cavity at the proximal port.

[0010] In some additional, cumulative, or alternative embodiments, the proximal surface faces up and the distal surface faces down.

[0011] In some additional, cumulative, or alternative embodiments, a portion of the entrance conduit slants toward the proximal port from an elevation below the proximal port.

[0012] In some additional, cumulative, or alternative embodiments, a portion of the entrance conduit has a slant angle toward with respect to a proximal plane of the proximal port of the cavity, and wherein slant angle is smaller than 75 degrees, smaller than 60 degrees, smaller than 45 degrees, smaller than 25 degrees, smaller than 10 degrees, or is smaller than 5 degrees. In some additional, cumulative, or alternative embodiments, the slant angle is greater than 5 degrees, greater than 15 degrees, greater than 30 degrees, or greater than 45 degrees.

[0013] In some additional, cumulative, or alternative embodiments, the entrance conduit provides positively pressurized debris collection fluid.

[0014] In some additional, cumulative, or alternative embodiments, the pressurized debris collection fluid is directed into the feature during its formation.

[0015] In some additional, cumulative, or alternative embodiments, an air nozzle is positioned with the cavity.

[0016] In some additional, cumulative, or alternative embodiments, a portion of the entrance conduit has a circular cross-section, or a rectangular cross-section.

[0017] In some additional, cumulative, or alternative embodiments, the cavity has a circumference, and wherein the entrance conduit intersects the circumference of the cavity at an intersection angle that is within 25 degrees, 15 degrees, or 5 degrees of a line tangent to the circumference. In some additional, cumulative, or alternative embodiments, the entrance conduit intersects the circumference of the cavity at an intersection angle that is tangent to the circumference. In some additional, cumulative, or alternative embodiments, the entrance conduit intersects the circumference of the cavity at an intersection angle that provides the debris collection fluid with a vortex flow that descends from the proximal port toward the distal port of the cavity.

[0018] In some additional, cumulative, or alternative embodiments, the debris collection fluid is provided through multiple entrance conduits formed in a workpiece support structure.

[0019] In some additional, cumulative, or alternative embodiments, and wherein at least some of the multiple entrance conduits have entrance ports to the cavity that are equally or unequally spaced apart. In some additional, cumulative, or alternative embodiments, at least some of the multiple entrance ports lie in the same plane or lie in different planes.

[0020] In some additional, cumulative, or alternative embodiments, the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the proximal port has a circumference, wherein the cavity have a depthwise central axis that is centrally located with respect to the proximal port, wherein the feature formed in the distal surface of the workpiece has a cavity dimension, and wherein the target location is positioned at distance from the depthwise central axis of the cavity that is within 10 times the feature major dimension, within 5 times the feature major dimension, or within 2 times the feature major dimension. In some additional, cumulative, or alternative embodiments, the feature formed in the distal surface of the workpiece has a feature major dimension, and wherein the target location is positioned centrally at the depthwise central axis of the cavity.

[0021] In some additional, cumulative, or alternative embodiments, multiple features are formed in the workpiece while it is stationary over the cavity of the workpiece support structure.

[0022] In some additional, cumulative, or alternative embodiments, the workpiece support structure includes multiple cavities, wherein at least one feature is formed over more than two cavities.

[0023] In some additional, cumulative, or alternative embodiments, the entrance conduit has a conduit cross-sectional major dimension that is smaller than a cavity cross-sectional major dimension of the cavity. In some additional, cumulative, or alternative embodiments, the entrance conduit has a conduit cross-sectional major dimension that is at least 25 times, at least 10 times, or at least 5 times smaller than a cavity cross-sectional major dimension of the cavity.

[0024] In some additional, cumulative, or alternative embodiments, the entrance conduit provides positively pressurized debris collection fluid at a flow rate of 25 cc/sec to 1500 cc/sec.

[0025] In some additional, cumulative, or alternative embodiments, the vacuum pressure is greater than 10 kPa, greater than or equal to 45 kPa, or greater than or equal to 55 kPa.

[0026] In some additional, cumulative, or alternative embodiments, the entrance conduit provides positively pressurized debris collection fluid at a positive pressure, and wherein the vacuum pressure is at least 1.5 times stronger than the positive pressure.

[0027] In some additional, cumulative, or alternative embodiments, the workpiece comprises a glass.

[0028] In some additional, cumulative, or alternative embodiments, the feature comprises a through hole via or an elongated trench in the distal surface of the workpiece.

[0029] In some additional, cumulative, or alternative embodiments, the debris collection fluid comprises air.

[0030] In some additional, cumulative, or alternative embodiments, the feature has a major dimension that is smaller than 1 mm, 500 microns, 50 microns, 25 microns, 10 microns or 5 microns.

[0031] In some additional, cumulative, or alternative embodiments, the feature is formed by a trepanning process.

[0032] In some additional, cumulative, or alternative embodiments, the debris collection fluid exhibits a vortex flow that descends from the proximal port toward the distal port of the cavity in a vortex direction, wherein the feature is formed by a trepanning process in a scanning direction that is opposite the vortex direction or that is the same as the vortex direction.

[0033] In some additional, cumulative, or alternative embodiments, the debris collection fluid is provided to the cavity before the laser beam is propagated to the target location on the workpiece.

[0034] In some additional, cumulative, or alternative embodiments, the major spot dimension is smaller than a cross-sectional dimension the cavity.

[0035] Additional aspects and advantages will be apparent from the following detailed description of exemplary embodiments, which proceeds with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0036] FIG. 1A is a plan view showing a workpiece with an intended feature to be created, wherein the workpiece is supported by a workpiece support structure.

[0037] FIG. 1B is a cross-sectional side view showing a vacuum cavity within the workpiece support structure, wherein the vacuum cavity is positioned beneath the intended feature to be created.

[0038] FIG. 1C is a cross-sectional side view showing pass-through bottom-to-top creation of the intended feature positioned over the vacuum cavity.

[0039] FIG. 2A is a plan view showing an entrance conduit extending from the vacuum cavity through the workpiece support structure, wherein the entrance conduit is adapted for providing the debris collection fluid into the cavity.

[0040] FIG. 2B is a cross-sectional side view showing cooperation of the entrance conduit and the vacuum cavity to create a vortex of debris collection fluid.

[0041] FIG. 2C is a cross-sectional side view showing pass-through bottom-to-top creation of the intended feature positioned over the vortex in the vacuum cavity.

[0042] FIG. 3 is an enlarged photograph showing a prototype of the workpiece support structure of FIG 12A supporting a workpiece with a created feature.

[0043] FIG. 4A, 4B, and 4C are respective electron micrographs showing features created over the vacuum cavity, under conditions of: no vacuum, vacuum without flow of debris collection fluid, and vacuum with flow of debris collection fluid.

[0044] FIGS. 5A, 5B, and 5C are plan views showing alternative embodiments having different intercept angles for the entrance conduit to the perimeter of the vacuum cavity.

[0045] FIG. 5D is a plan view showing a curved entrance conduit intercepting the perimeter of the vacuum cavity.

[0046] FIG. 6A is a plan view showing an alternative embodiment having two entrance conduits extending from the vacuum cavity through the workpiece support structure.

[0047] FIG. 6B is a plan view showing an alternative embodiment having six entrance conduits extending from the vacuum cavity through the workpiece support structure.

[0048] FIG. 7A is a plan view showing a pressurized supply channel nozzle for providing the debris collection fluid under pressure into the cavity.

[0049] FIG. 7B is a cross-sectional side view showing cooperation of the entrance conduit, the vacuum cavity, and the pressurized supply channel to create a vortex of debris collection fluid.

[0050] FIG. 7C is a cross-sectional side view showing pass-through bottom-to-top creation of the intended feature positioned over the vortex in the vacuum cavity.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0051] Example embodiments are described below with reference to the accompanying drawings. Many different forms and embodiments are possible without deviating from the spirit and teachings of this disclosure and so this disclosure should not be construed as limited to the example embodiments set forth herein. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will convey the scope of the disclosure to those skilled in the art. In the drawings, the sizes and relative sizes of components may be may be disproportionate and/or exaggerated for clarity. The terminology used herein is for the purpose of describing particular example embodiments only and is not intended to be limiting. As used herein, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Unless otherwise specified, a range of values, when recited, includes both the upper and lower limits of the range, as well as any sub-ranges therebetween.

[0052] Referring to FIGS. 1A and 1B, a workpiece 100 includes an exterior surface having a first major surface region 102, a second major surface region 104 opposite the first major surface region 102, and one or more side surface regions extending from the first major surface region 102 to the second major surface region 104. In the illustrated embodiment, the first major surface region 102 and the second major surface region 104 are both substantially flat and parallel to one another. Accordingly, the distance from the first major surface region 102 and the second major surface region 104 can define the thickness, t , of the workpiece 100. In one embodiment, the thickness of the workpiece 100 is in a range from 200 μm to 10 mm. In another embodiment, however, the thickness of the workpiece 100 can be less than 200 μm or greater than 10 mm. In yet another embodiment, the first major surface region 102 and the second major surface region 104 may not be substantially flat, may not be parallel to one another, or a combination thereof.

[0053] Generally, the workpiece 100 is formed of a hard optical material such as corundum, a ceramic, a semiconductor, a metal or metal alloy, a glass, a glass-ceramic, or the like or a combination thereof. Exemplary ceramic materials from which the workpiece 100 can be formed include alumina, beryllia, zirconia, or the like or a combination thereof. Exemplary semiconductor materials from which the workpiece 100 can be formed include Group IV elemental or compound semiconductors (e.g., silicon, germanium, silicon-germanium, silicon carbide, or the like or a combination thereof), III-V compound semiconductors, II-VI compound semiconductors, II-V compound semiconductors, I-VII compound semiconductors, IV-VI compound semiconductors, semiconductor oxides, or the like, or a combination thereof.

[0054] Exemplary metals and metal alloys from which the workpiece 100 can be formed include aluminum, titanium, stainless steel, or the like, or alloys or other combinations thereof. Exemplary glasses from which the workpiece 100 can be formed include soda-lime glass, borosilicate glass, aluminosilicate glass, aluminoborosilicate glass, sodium-aluminosilicate glass, calcium-aluminosilicate glass, phosphate glass, fluoride glass, chalcogenide glass, bulk metallic glass, or the like, or a combination thereof.

[0055] In one embodiment, the workpiece 100 is provided as a plate, sheet, substrate, etc., of glass (e.g., soda-lime glass, borosilicate glass, aluminosilicate glass, aluminoborosilicate glass, sodium-aluminosilicate glass, calcium-aluminosilicate glass, etc.) which may be unstrengthened, thermally strengthened, chemically strengthened, or the like. When the glass workpiece is strengthened, each of the first major surface region 102 and the second major surface region 104 can be compressively stressed while a region in the interior of the sheet of glass is in a state of tension to compensate for the surface compression at the first major surface region 102 and the second major surface region 104. Thus, the sheet of strengthened glass can be characterized as including a pair of compression regions (i.e., regions where the glass is in a state of compression), such as regions compression regions 108a and 108b, extending from the first major surface region 102 and the second major surface region 104 and separated by a central tension region (i.e., a region where the glass is in a state of tension) such as tension region 108c. The thickness of a compression region 108a or 108b is known as the “depth of layer” (DOL).

[0056] Generally, the surface compression at each of the first major surface region 102 and the second major surface region 104 can be in a range from 69 MPa to 1GPa. In other embodiments, however, the surface compression at any of the first major surface region 102 or

second major surface region 104 can be less than 69 MPa or greater than 1GPa. Generally, the DOL can be in a range from 20 μm to 100 μm . In other embodiments, however, the DOL can be less than 20 μm or greater than 100 μm . The maximum tensile stress of the sheet within the tension region can be determined by the following formula:

$$CT = \frac{CS \times DOL}{t - 2 \times DOL}$$

[0057] where CS is the aforementioned surface compression at the first major surface region 102 and second major surface region 104, t is the thickness of the sheet of glass (expressed in millimeters, mm), DOL is the depth of layer of the compression region(s) (expressed in mm), and CT is the maximum central tension within the sheet of glass (expressed in MPa).

[0058] Having exemplarily described a workpiece 100 capable of being machined according to embodiments of the present invention, exemplary embodiments of machining the workpiece 100 will now be described. Generally, the workpiece 100 is laser- machined using laser light having a wavelength to which the workpiece 100 is at least substantially transparent. Thus, interactions between the laser light and material of the workpiece 100 during the laser-machining process can typically be characterized as those involving non- linear absorption of laser energy by the workpiece material.

[0059] The laser machining processes may create debris can create debris that can diminish the quality of the workpiece 100 or the quality of features made by the laser. The debris may also disrupt the effectiveness of subsequent pulses in the laser machining process. For example, subsequent pulses may address the debris that lands within the feature (upstream of laser processing), but the debris may cause extra time or different techniques or parameters to be used to accomplish its removal. However, some redeposited debris may be difficult or impossible to remove without compromising the workpiece 100 as a whole.

[0060] In conventional top-to-bottom laser-micromachining techniques, vacuum pressure (outflow pull) and/or forced fluid pressure (inflow push) have been used above the workpiece 100 to move debris away from the features and away from laser optical components during feature formation. However, fluid flow techniques above the workpiece 100 are generally not as useful during pass-through (bottom-to-top) laser micromachining operations. Although, such techniques could remove some debris after a through hole is created, providing an (upward) escape route for the debris.

[0061] FIG. 1A is a plan view showing a workpiece 100 with an intended feature 1100 to be created, wherein the workpiece 100 is supported by a workpiece support structure 1102, such as a chuck and/or support frame. FIG. 1B is a cross-sectional side view showing a vacuum cavity 1104 within the workpiece support structure 1102, wherein the vacuum cavity 1104 is positioned beneath the intended feature 1100 to be created. FIG. 1C is a cross-sectional side view showing pass-through bottom-to-top creation of the intended feature 100 positioned over the vacuum cavity 1104. With reference to FIGS. 1A, 1B, and 1C (collectively FIG. 1), the applicant has created features 1100 in the workpiece 100 wherein the workpiece 100 was positioned relative to the workpiece support structure 1102 such that the features 1100 were positioned adjacent to, or in communication with, the vacuum cavity 1104 while under vacuum pressure during the formation of the features 1100. Under a pass-through bottom-to-top micromachining process in this configuration, the vacuum cavity 1104 is covered completely by the workpiece 100 (initially by the distal surface of the workpiece 100, also referred to herein as a “distal workpiece surface,” which faces toward the fixture 1102) in such a way that there is no moving debris collection fluid to assist ablated glass particles or other debris to be removed away from the feature 100 during its formation. Despite the vacuum pressure much of the debris stays in the feature 1100 until the feature 1100 is completely drilled from the distal workpiece surface to a surface of the workpiece 100 that is opposite the distal workpiece surface (also referred to herein as a “proximal workpiece surface”) to permit debris collection fluid, such as air, to flow from above the proximal workpiece surface through the feature 1100 to the vacuum cavity 1104.

[0062] Because the feature formation is predominantly initiated from the distal workpiece surface, when the generated debris 1106 is not removed efficiently from the features 1100, the ongoing debris 1106 may accumulate on top of previously generated debris 1106 (downstream of laser processing) and affect the quality of the feature 1100. The through-hole nature of the feature 1100 may be partly blocked. The feature 1100 may exhibit poor shape such as poor roundness. The major cross-sectional dimension 1108 of the feature 1100 may exhibit undesirable variation between the distal workpiece surface and the proximal workpiece surface, or multiple features 1100 may exhibit undesirable variation in the major cross-sectional dimension 1108. The features 1100 may also exhibit other undesirable thermal defects. Additionally, excessive heat over accumulated debris 1106 can melt the debris 1106 and

eventually recast it to block completely the desired through-hole nature of the feature 1100.

Trapped debris 1106 can also cause additional defects, such as cracking or chipping.

[0063] To address these issues, the applicant provided the workpiece support structure 1102 with an entrance conduit 1200 through which debris collection fluid 1202 can flow to the vacuum cavity 1104 during creation of the feature 1100. FIG. 2A is a plan view showing the entrance conduit 1200 extending from the vacuum cavity 1104 through the workpiece support structure 1102. FIG. 2B is a cross-sectional side view showing cooperation of the entrance conduit 1200 and the vacuum cavity 1104 to create a fluid flow, such as a vortex 1204, within the debris collection fluid 1202. FIG. 2C is a cross-sectional side view showing pass-through bottom-to-top creation of the intended feature 1100 positioned over the vortex 1204 in the vacuum cavity 1104. With reference to FIGS. 2A, 2B, and 2C (collectively FIG. 2), the addition of the entrance conduit 1200 permits the debris collection fluid 1202 to have a fluid flow along a flow direction 1206 along a fluid flow path into the vacuum cavity 1104 to facilitate removal of debris 1106 during the feature formation process before a through hole is created in the feature 1100.

[0064] The debris collection fluid 1202 can be a liquid or a gas. Exemplary liquids may include one or more of water, a debris (or workpiece material) etchant or solvent, or an oxidizing agent, with or without an additive. Debris etchants or solvents may include one or more of, nitric acid (HNO_3), acetic acid (CH_3COOH), or hydrofluoric acid (HF). The debris collection fluid 1202 may also include at least one additive such as water, an alcohol (e.g., ethanol, methanol, isopropyl alcohol, etc.), an organic solvent (e.g., acetone, etc.), or the like or a combination thereof. These liquids may be heated, cooled, or super cooled. Exemplary gases may include one or more of air, oxygen, nitrogen, or an inert gas.

[0065] The vacuum cavity 1104 has a cavity proximal port 1112 and a cavity distal port 1114 such that the workpiece 100 is closer to the cavity proximal port 1112 than the cavity distal port 1114. Similarly, the laser beam axis intersects the cavity proximal port 1112 before intersecting the cavity distal port 1114. The cavity proximal port 1112 and the cavity distal port 1114 may have the same shape and the same cross-sectional area, or the cavity proximal port 1112 and the cavity distal port 1114 may have different shapes and different same cross-sectional areas. In some embodiments, the cavity proximal port 1112 and the cavity distal port 1114 have circular profiles, but they may be rectangular or have other curvatures or shapes. In some embodiments,

the cavity proximal port 1112 has a larger area than the cavity distal port 1114. In some embodiments, the cavity distal port 1114 has a larger area than the cavity proximal port 1112.

[0066] The cavity proximal port 1112 and the cavity distal port 1114 may have a cavity cross-sectional major dimension 1108 that is smaller than 50 mm. In some embodiments, the cavity cross-sectional major dimension 1108 is smaller than 25 mm. In some embodiments, the cavity cross-sectional major dimension 1108 is smaller than 10 mm. In some embodiments, the cavity cross-sectional major dimension 1108 is smaller than 5 mm.

[0067] The cavity proximal port 1112 and the cavity distal port 1114 may be parallel, and they may be axially aligned, or the vacuum cavity 1104 may have a slant. Alternatively, the cavity proximal port 1112 and the cavity distal port 1114 may be transversely aligned. The cavity proximal port 1112 and the cavity distal port 1114 typically have a cavity cross-sectional major dimension 1108 that is larger than the feature major dimension 1110.

[0068] Although the entrance conduit 1100 can have a conduit cross-sectional major dimension 1208 that is larger than the cavity cross-sectional major dimension 1108, the entrance conduit 1100 typically has a conduit cross-sectional major dimension 1208 that is smaller than the cavity cross-sectional major dimension 1108 of the cavity. In some embodiments, the conduit cross-sectional major dimension 1208 is at least 25 times smaller than the cavity cross-sectional major dimension 1108. In some embodiments, the conduit cross-sectional major dimension 1208 is at least 10 times smaller than the cavity cross-sectional major dimension 1108. In some embodiments, the conduit cross-sectional major dimension 1208 is at least 5 times smaller than the cavity cross-sectional major dimension 1108. The entrance conduit 1100 can have a cross-section of any shape. In some embodiments, the conduit cross-sectional shape is circular. In some embodiments, the conduit cross-sectional shape is rectangular.

[0069] In some embodiments, the entrance conduit 1200 comprises a groove in the proximal structure surface 1212 of the workpiece support structure 1102. In some embodiments, the entrance conduit 1200 is formed within in the workpiece support structure 1102. In some embodiments, the entrance conduit 1200 connects to the vacuum cavity 1104 closer to the cavity proximal port 1112 than the cavity distal port 1114. In some embodiments, the entrance conduit 1200 connects to the vacuum cavity 1104 at the cavity proximal port 1112.

[0070] The entrance conduit 1200 can connect to the vacuum cavity 1104 at slant toward the cavity proximal port 1112 from an elevation below the cavity proximal port 1112. In some

embodiments, the entrance conduit 1200 has a slant angle with respect to a proximal plane of the cavity proximal port that is smaller than 75 degrees. In some embodiments, the slant angle is smaller than 60 degrees. In some embodiments, the slant angle is smaller than 45 degrees. In some embodiments, the slant angle is smaller than 25 degrees. In some embodiments, the slant angle is smaller than 10 degrees. In some embodiments, the slant angle is smaller than 5 degrees. In some embodiments, the slant angle is greater than 5 degrees. In some embodiments, the slant angle is greater than 15 degrees. In some embodiments, the slant angle is greater than 30 degrees. In some embodiments, the slant angle is greater than 45 degrees.

[0071] The entrance conduit 1200 can alternatively or additionally connect to the vacuum cavity 1104 at an intersection angle α (FIG. 5A) with respect to an edge of the perimeter or a line tangent to the circumference of the cavity proximal port 1112. FIGS. 5A, 5B, and 5C are plan views showing alternative embodiments having different intercept angles α for the entrance conduit to the perimeter of the vacuum cavity 1104. In some embodiments, the intersection angle α provides the debris collection fluid with a flow, such as a vortex 1204, that descends from the cavity proximal port 1112 toward the cavity distal port 1114. In some embodiments, the intersection angle α is smaller than 25 degrees. In some embodiments, the intersection angle α is smaller than 15 degrees. In some embodiments, the intersection angle is smaller than 5 degrees. In some embodiments, the intersection angle α is zero degrees, i.e. the entrance conduit is collinear with the edge of the perimeter or tangent to the circumference of the cavity proximal port 1112. FIG. 5D is a plan view showing a curved entrance conduit 1200 intercepting the perimeter of the vacuum cavity 1104. The curved entrance conduit 1200 can also be adapted to have a favorable intercept angles α for the entrance conduit to the perimeter of the vacuum cavity 1104.

[0072] Multiple features 1100 can be formed in the workpiece 100 while it is stationary over the vacuum cavity 1104 of the workpiece support structure 1102. For example, if multiple features 1100 are to be formed in the same workpiece 100, the workpiece support structure 1102 may have multiple vacuum cavities 1104, and the workpiece 100 can be positioned so that multiple intended features 1100 are simultaneously aligned over the respective multiple vacuum cavities 1104. In some embodiments, however, the target locations of the multiple intended

features 1100 can simultaneously be positioned over a single vacuum cavity 1104, i.e., the area of the cavity proximal port 1112 can be large enough to be beneath the locations of multiple intended features 1100.

[0073] The vacuum cavity 1104 can have a depthwise central axis that is centrally located with respect to the cavity proximal port 1112. Generally, the workpiece 100 is positioned with respect to the workpiece support structure 1102 so that feature 1100 is formed within 5 mm of the depthwise central axis. In some embodiments, the target location for the beam axis is positioned at distance from the depthwise central axis of the vacuum cavity that is within 10 times the feature major dimension. In some embodiments, the target location is positioned at distance from the depthwise central axis of the vacuum cavity that is within 5 times the feature major dimension. In some embodiments, the target location is positioned at distance from the depthwise central axis of the vacuum cavity that is within 2 times the feature major dimension. In some embodiments, the target location is positioned centrally at the depthwise central axis of the vacuum cavity. Ideally for many embodiments, the laser beam axis is collinear with the depthwise central axis of the vacuum cavity 1104.

The vortex 1204 can be laminar or turbulent or even a nonvortex-like fluid flow that is partly or wholly rotating, turbulent, or whirling to help removal of the debris 1106 generated by laser ablation process. The vacuum pressure can be rough, high, or ultrahigh. In many embodiments, rough vacuum is adequate to prevent debris accumulation. In some embodiments, the vacuum pressure greater than or equal to 10 kPa. However, depending on the size of the major feature dimension 1110, the nature of the workpiece material and debris 1106, and various laser parameters, higher vacuum pressure may be desirable. The various characteristics of the vacuum cavity 1104 and the entrance conduit 1200 can be optimized to collect debris 1106 from the micromachining process and prevent the debris from re-depositing within the feature 1100. For example, in micromachining applications that involve trepanning or spiral processing, the scan direction of the trepanning or spiral processing can be adjusted with respect to the vortex direction of the vortex flow that descends from the cavity proximal port 1112 toward the cavity distal port 1114. In some embodiments, the scanning direction is opposite the vortex direction. In some embodiments, the scanning direction is the same as the vortex direction.

[0074] FIG. 3 is an enlarged photograph showing a prototype of the workpiece support structure 1102 of FIG 2A supporting a workpiece with a created feature. FIG. 4A, 4B, and 4C

are respective electron micrographs showing features created over the vacuum cavity, under conditions of: no vacuum, vacuum without flow of debris collection fluid, and vacuum with flow of debris collection fluid. With reference to FIGS. 3, 4A, 4B, and 4C, the micromachining without vacuum appears to have resulted in partial occlusion of the feature 1100 and debris accumulation on the entire interior surface of the vacuum cavity 1104. The micromachining with vacuum appears to have resulted in substantially less occlusion of the feature 1100 but still exhibited debris accumulation on the distal surface of the feature 1100 and on the entire interior surface of the vacuum cavity 1104. The micromachining with vacuum in cooperation with flow of debris collection fluid appears to have resulted in a substantially pristine feature 1100. The micromachining with vacuum in cooperation with flow of debris collection fluid also significantly reduced cycle time by reducing, and in some cases eliminating, the cleaning process from the laser parameter recipe. Moreover, the micromachining with vacuum in cooperation with flow of debris collection fluid showed substantial improvement in the feature quality, especially with respect to residual debris and hole size variation.

[0075] More than one entrance conduit 1200 can extend through the workpiece support structure 1102 to each vacuum cavity 1104. FIG. 6A is a plan view showing an alternative embodiment having two entrance conduits 1200 extending from the vacuum cavity 1104 through the workpiece support structure 1102. FIG. 6B is a plan view showing an alternative embodiment having six entrance conduits 1200 extending from the vacuum cavity 1104 through the workpiece support structure 1102. With reference to FIGS. 6A and 6B, the entrance conduits 1200 can be symmetrically or evenly spaced around the perimeter of (the cavity proximal port 1112) the vacuum cavity 1104. In some embodiments, however, the entrance conduits 1200 can be asymmetrically or unevenly spaced around the perimeter of (the cavity proximal port 1112) the vacuum cavity 1104.

[0076] The debris collection fluid flowing through the entrance conduits 1200 can be pressurized or unpressurized. Moreover, the entrance conduit 1200 need not be formed in the workpiece support structure 1102. Instead in some embodiments, the entrance conduit 1200 may take the form of a supply channel 1700 (FIG. 7A) that terminates at or within the vacuum cavity 1104. In some embodiments, the entrance conduit 1200 provides positively pressurized debris collection fluid at a flow rate of 25 cc/sec to 1500 cc/sec. In some embodiments, the entrance

conduit 1200 provides vacuum pressure that is at least 1.5 times stronger than the positive pressure.

[0077] In some additional, cumulative, or alternative embodiments, the debris collection fluid can be delivered by one or more micro-jets or nozzles into the feature 1100 as it is being formed to further improve the efficiency of the debris removal. FIG. 7A is a plan view showing a pressurized supply channel 1700, which may include the microjet(s) or nozzle(s) for providing the debris collection fluid under pressure into the vacuum cavity 1104. FIG. 7B is a cross-sectional side view showing cooperation of the entrance conduit 1200, the vacuum cavity 1104, and the pressurized supply channel 1700 to create a vortex 1204 of debris collection fluid. FIG. 7C is a cross-sectional side view showing pass-through bottom-to-top creation of the intended feature 1100 positioned over the vortex 1204 in the vacuum cavity 1104. With reference to FIGS. 7A, 7B, and 7C, the pressurized debris collection fluid can be directed into the feature 1100 during its formation. The pressurized supply channel 1700 and/or its terminal micro-jet or nozzle can be positioned within the vacuum cavity 1104 and can be directed at or into the feature 1100. Moreover, the pressurized supply channel 1700 may take the place of entrance conduit 1200, or supplement it.

[0078] The foregoing is illustrative of embodiments of the invention and is not to be construed as limiting thereof. Although a few specific example embodiments have been described, those skilled in the art will readily appreciate that many modifications to the disclosed exemplary embodiments, as well as other embodiments, are possible without materially departing from the novel teachings and advantages of the invention.

[0079] Accordingly, all such modifications are intended to be included within the scope of the invention as defined in the claims. For example, skilled persons will appreciate that the subject matter of any sentence or paragraph can be combined with subject matter of some or all of the other sentences or paragraphs, except where such combinations are mutually exclusive.

[0080] It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiments without departing from the underlying principles of the invention. The scope of the present invention should, therefore, be determined by the following claims, with equivalents of the claims to be included therein.

WHAT IS CLAIMED IS:

1. A method for micromachining a workpiece, comprising:
supporting a target location of the workpiece over a cavity;
establishing vacuum pressure to the cavity;
generating a laser beam having beam parameters including a major spot dimension at a focal point and a wavelength that is transparent to the workpiece;
propagating the laser beam along a beam path that directs the laser beam in propagation direction along a beam axis to the target location on the workpiece, wherein the workpiece has bulk material between a proximal surface of the workpiece and a distal surface of the workpiece with respect to the propagation direction of the laser beam such that the beam axis intersects the proximal surface before intersecting the distal surface, wherein the beam parameters are adapted for propagating the laser beam through the workpiece to form a depthwise feature in the workpiece, wherein the depthwise feature includes a sidewall, wherein the laser parameters are adapted so that the depthwise feature is formed predominantly from the distal surface toward the proximal surface, wherein formation of the depthwise feature creates debris, and wherein introduction of the debris collection fluid facilitates removal of debris from the depthwise feature during its formation; and
removing the debris during formation of the feature, wherein removing the debris includes providing a debris collection fluid to the cavity.
2. The method of claim 1, wherein the debris collection fluid is provided through an entrance conduit formed in a workpiece support structure.
3. The method claim 2, wherein the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the entrance conduit connects to the cavity closer to the proximal port than the distal port.
4. The method claim 2, wherein the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the entrance conduit connects to the cavity at the proximal port.
5. The method of claim 2, wherein a portion of the entrance conduit slants toward the proximal port from an elevation below the proximal port.

6. The method of claim 1, wherein the entrance conduit provides positively pressurized debris collection fluid.

7. The method of claim 6, wherein the pressurized debris collection fluid is directed into the feature during its formation.

8. The method of claim 1, wherein the cavity has a circumference, and wherein the entrance conduit intersects the circumference of the cavity at an intersection angle that is within 25 degrees of a line tangent to the circumference.

9. The method of claim 1, wherein the cavity has a circumference, and wherein the entrance conduit intersects the circumference of the cavity at an intersection angle that is tangent to the circumference.

10. The method claim 1, wherein the cavity has a circumference, and wherein the entrance conduit intersects the circumference of the cavity at an intersection angle that provides the debris collection fluid with a vortex flow that descends from the proximal port toward the distal port of the cavity.

11. The method of claim 1, wherein the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the proximal port has a circumference, wherein the cavity have a depthwise central axis that is centrally located with respect to the proximal port, wherein the feature formed in the distal surface of the workpiece has a feature major dimension, and wherein the target location is positioned at distance from the depthwise central axis of the cavity that is within 10 times the feature major dimension.

12. The method of claim 1, wherein the cavity has a proximal port and a distal port, wherein the proximal port is closer to the workpiece than the distal port, wherein the proximal port has a circumference, wherein the cavity have a depthwise central axis that is centrally located with respect to the proximal port, wherein the feature formed in the distal surface of the workpiece has a feature major dimension, and wherein the target location is positioned centrally at the depthwise central axis of the cavity.

13. The method of claim 1, wherein multiple features are formed in the workpiece while it is stationary over the cavity of the workpiece support structure.

14. The method of claim 1, wherein the workpiece support structure includes multiple cavities, wherein at least one feature is formed over more than two cavities.

15. The method of claim 1, wherein the entrance conduit has a conduit cross-sectional major dimension that is smaller than a cavity cross-sectional major dimension of the cavity.

16. The method of claim 1, wherein the vortex has a turbulent flow.

17. The method of claim 2, wherein the entrance conduit has a conduit cross-sectional major dimension that is at least 5 times smaller than a cavity cross-sectional major dimension of the cavity.

18. The method of claim 2, wherein the entrance conduit provides positively pressurized debris collection fluid at a flow rate in a range from 25 cc/sec to 1500 cc/sec.

19. The method of claim 1, wherein the vacuum pressure is greater than 10 kPa.

20. The method of claim 1, wherein the entrance conduit provides positively pressurized debris collection fluid at a positive pressure, and wherein the vacuum pressure is at least 1.5 times stronger than the positive pressure.

21. The method of claim 1, wherein the debris collection fluid comprises air.

22. A laser system for micromachining a workpiece, comprising:

a laser adapted for generating a laser beam having beam parameters including a major spot dimension at a focal point and a wavelength that is transparent to the workpiece;

a workpiece support structure adapted for supporting the workpiece, wherein the workpiece support structure includes a cavity for receiving a debris collection fluid, the cavity adapted for connection to a vacuum source, and the cavity having a cross-sectional dimension adapted to be larger than the major spot dimension, and wherein the workpiece support structure includes an entrance conduit extending from the cavity through the workpiece support structure, the entrance conduit adapted for providing the debris collection fluid into the cavity; and

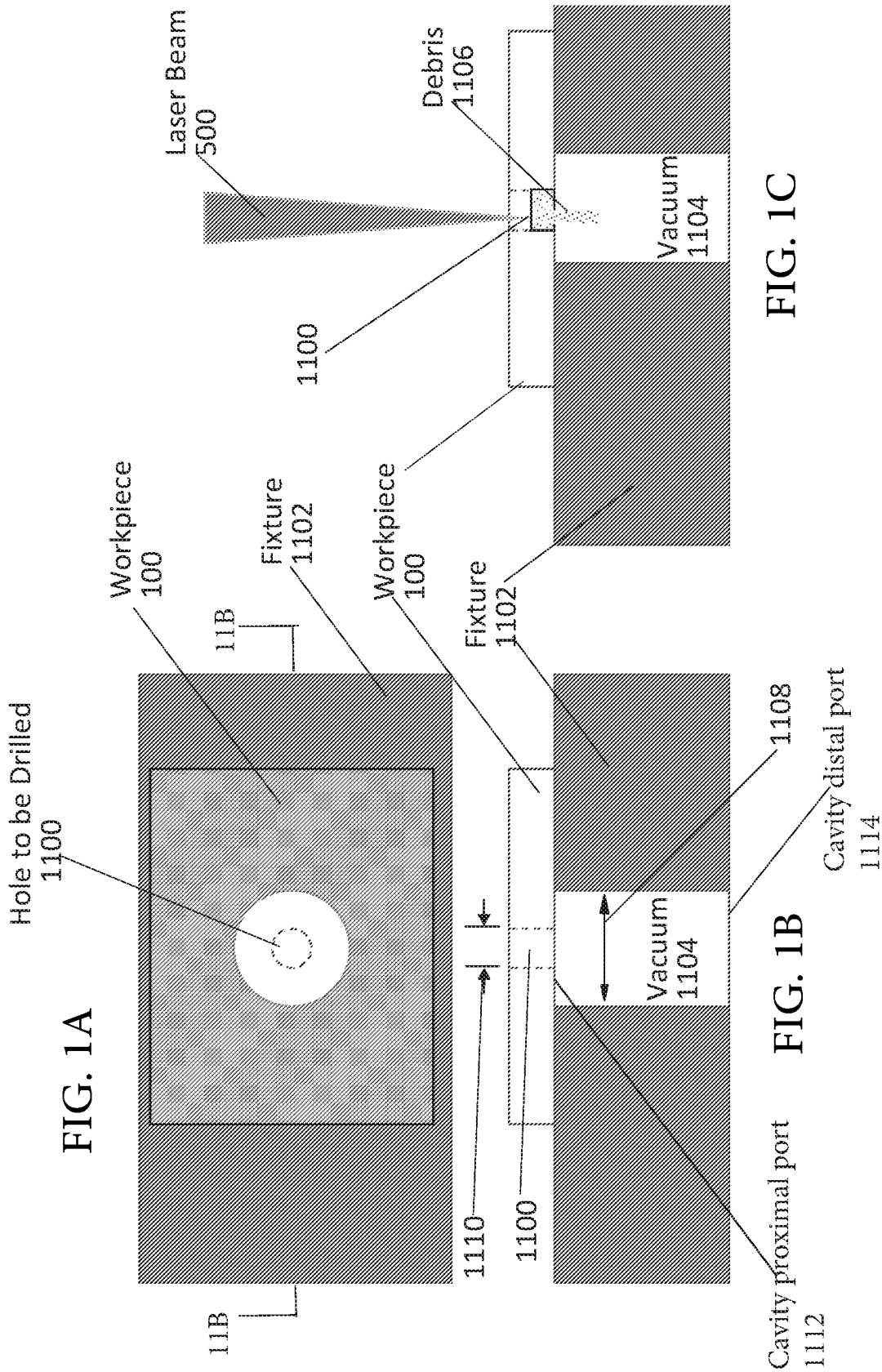
a beam-positioning system adapted for propagating the laser beam along a beam path that directs the laser beam in propagation direction along a beam axis to a target location on the workpiece over the cavity, the workpiece having bulk material between a proximal surface and a distal surface with respect to the propagation direction of the laser beam such that the beam axis is adapted to intersect the proximal surface before intersecting the distal surface, the beam parameters adapted for propagating the laser beam through the workpiece to form a depthwise feature in the workpiece, wherein the laser parameters are adapted so that the depthwise feature is formed predominantly from the distal surface toward the proximal surface.

23. A laser system for micromachining a workpiece, comprising:

a laser adapted for generating a laser beam having beam parameters including a major spot dimension at a focal point and a wavelength that is transparent to the workpiece;

a workpiece support structure adapted for supporting the workpiece, wherein the workpiece support structure includes a cavity for receiving a debris collection fluid, the cavity adapted for connection to a vacuum source, and the cavity having a cross-sectional dimension adapted to be larger than the major spot dimension, wherein an entrance conduit is adapted for providing the debris collection fluid into the cavity, wherein the entrance conduit comprises a nozzle; and

a beam-positioning system adapted for propagating the laser beam along a beam path that directs the laser beam in propagation direction along a beam axis to a target location on the workpiece over the cavity, the workpiece having bulk material between a proximal surface and a distal surface with respect to the propagation direction of the laser beam such that the beam axis is adapted to intersect the proximal surface before intersecting the distal surface, the beam parameters adapted for propagating the laser beam through the workpiece to form a depthwise feature in the workpiece, wherein the laser parameters are adapted so that the depthwise feature is formed predominantly from the distal surface toward the proximal surface.



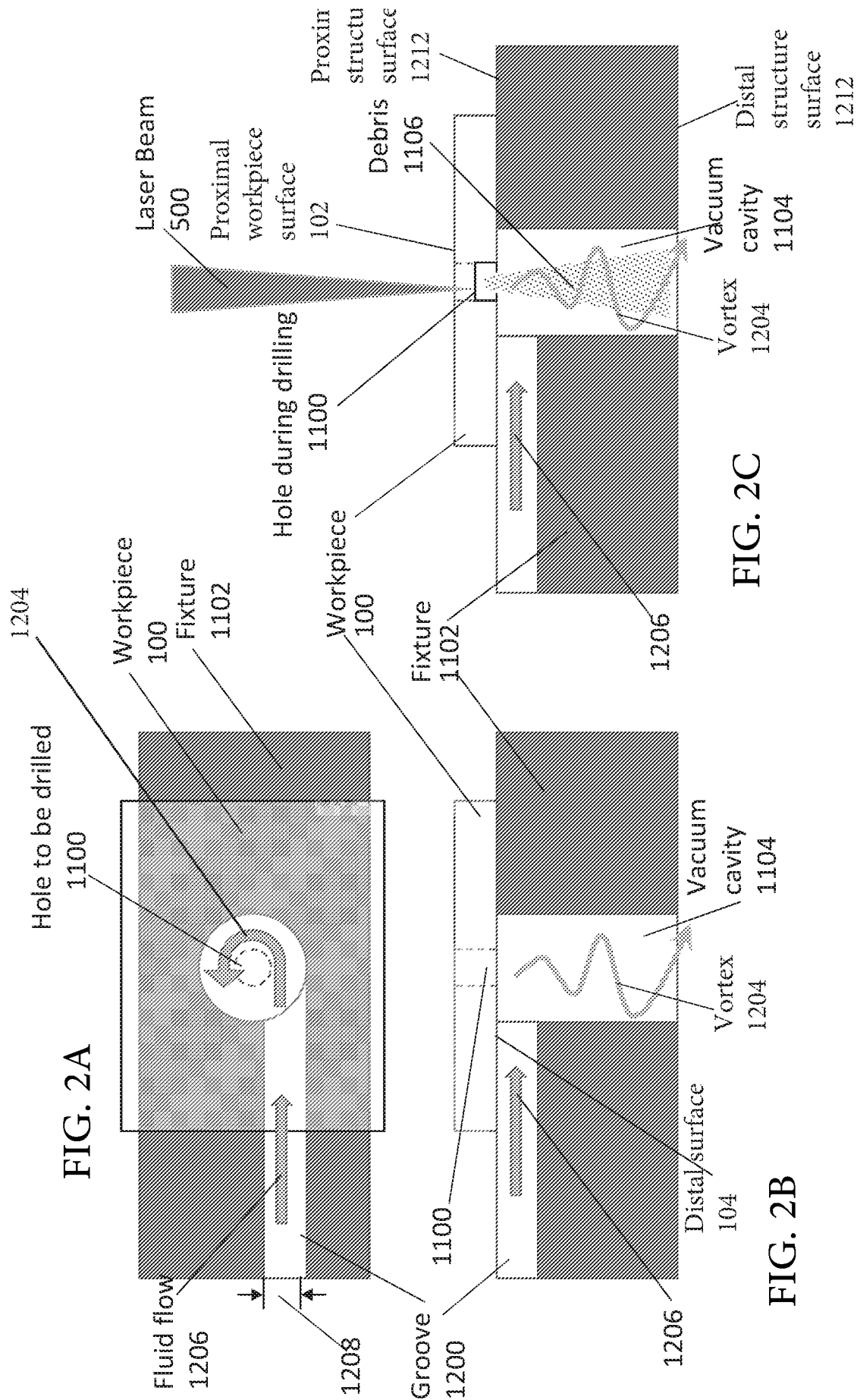
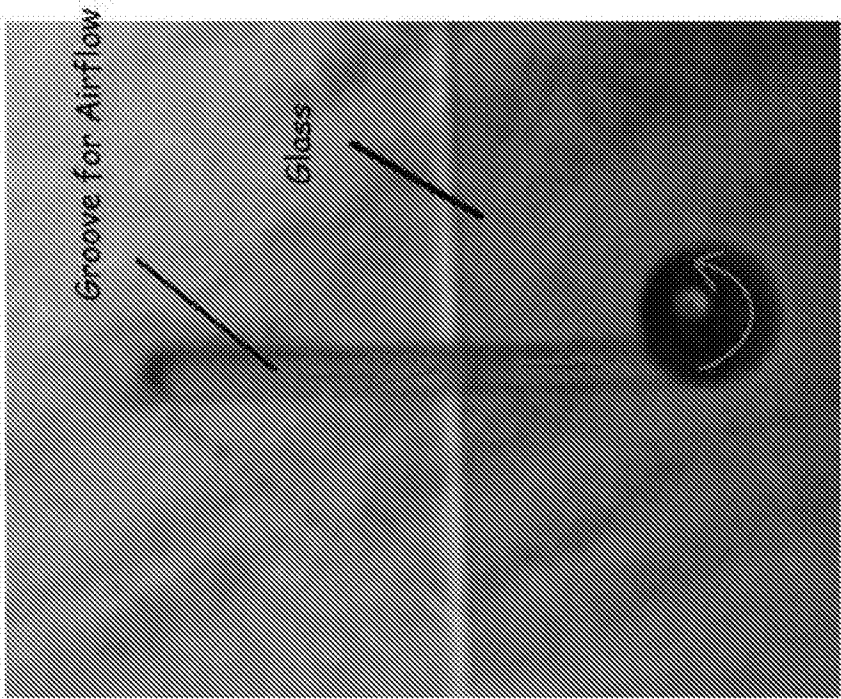


FIG. 3



Comparison of the Results

FIG. 4A : No Vacuum

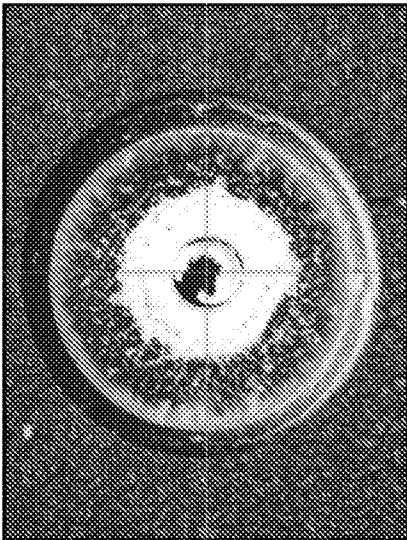


FIG. 4B : Vacuum without Airflow

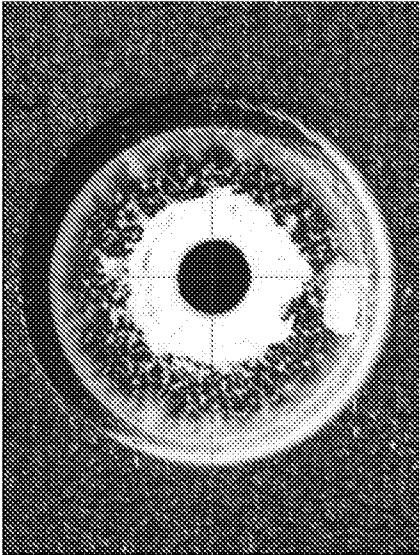
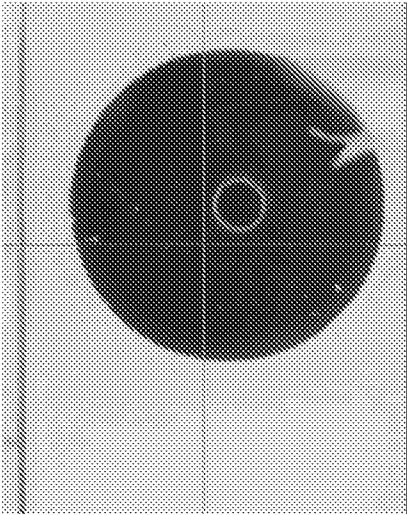


FIG. 4C: Vacuum with Airflow



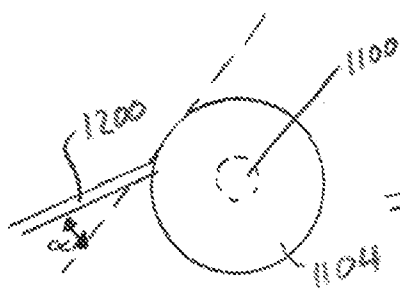


FIG. 5A

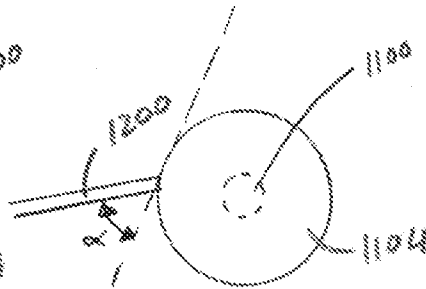


FIG. 5B

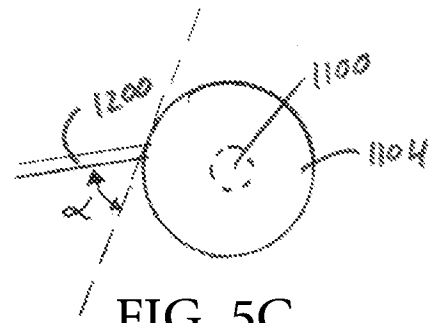


FIG. 5C

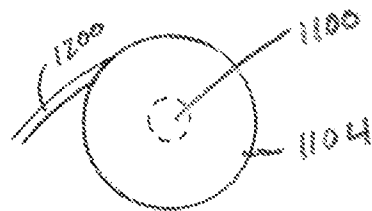


FIG. 5D

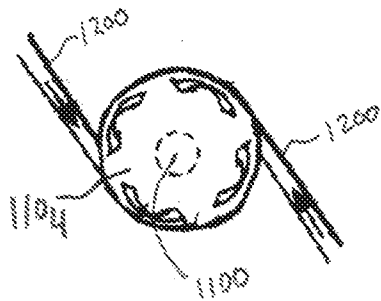


FIG. 6A

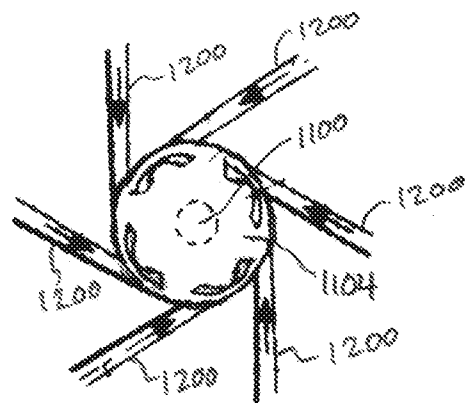


FIG. 6B

FIG. 7A

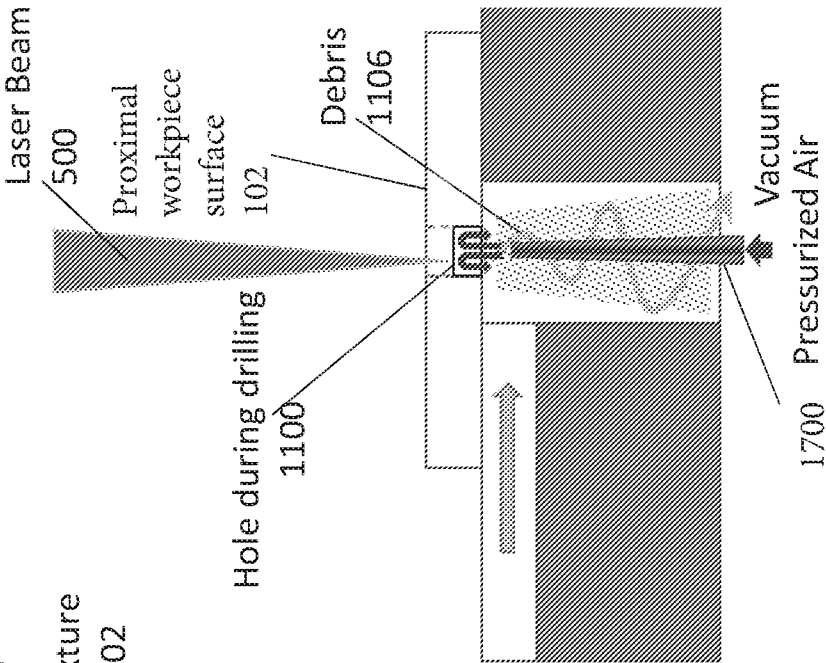
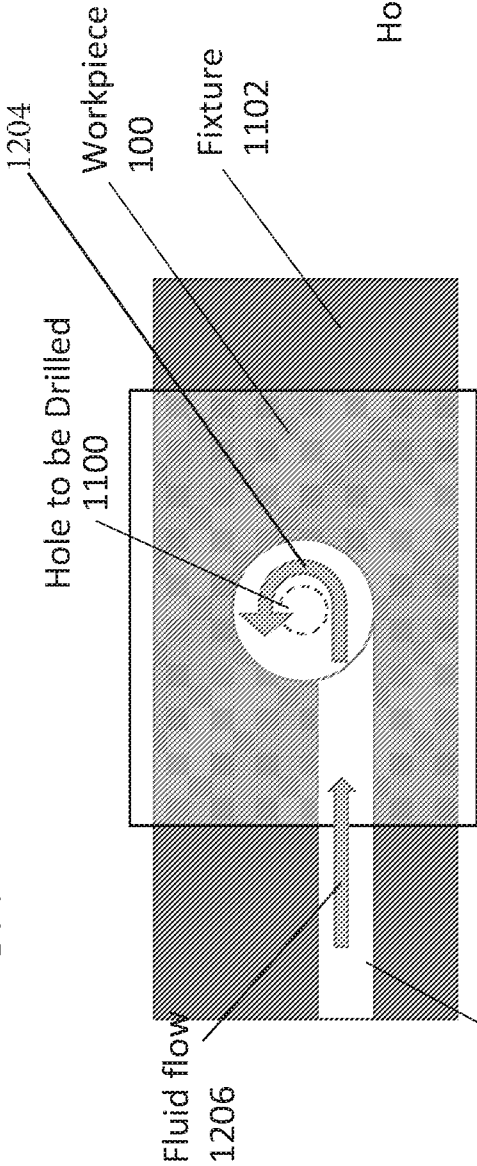


FIG. 7B

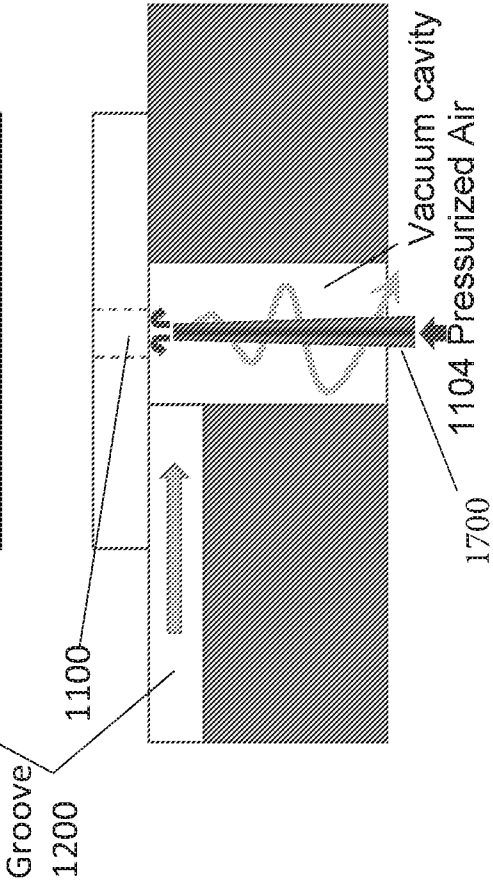


FIG. 7C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/048041**A. CLASSIFICATION OF SUBJECT MATTER****B23K 26/16(2006.01)i, B23K 26/38(2006.01)i, B23K 103/00(2006.01)n**

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 26/16; B23K 26/14; B23K 26/38; B23K 26/00; B23K 26/082; G03B 27/32; G03F 7/20; B23K 26/382; B23K 103/00

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: remove, debris, laser, micromachining, workpiece, depthwise, feature, wavelength, collect, fluid

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2016-122821 A2 (IMRA AMERICA, INC.) 04 August 2016 See paragraphs [0037]-[0044], [0056]-[0057], [0069]-[0080], [0104], [0121], [0150]; claims 1, 24; and figures 1-2, 3A-3C, 4A-4C.	1-9, 11-15, 17-22
Y		10, 16, 23
Y	US 2009-0068598 A1 (MURASE et al.) 12 March 2009 See paragraphs [0013], [0065]-[0066]; and figure 5.	10, 16, 23
A	US 2009-0314753 A1 (KOSMOWSKI, MARK T.) 24 December 2009 See paragraphs [0014]-[0017], [0024]; and figures 1, 3.	1-23
A	US 2016-0221121 A1 (ROHR, INC.) 04 August 2016 See paragraphs [0033]-[0041], [0052]-[0060]; and figures 1-4, 8.	1-23
A	US 2008-0210675 A1 (SASAKI et al.) 04 September 2008 See paragraphs [0039], [0050]-[0051], [0079]; and figures 2-3, 9.	1-23

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

13 December 2017 (13.12.2017)

Date of mailing of the international search report

13 December 2017 (13.12.2017)

Name and mailing address of the ISA/KR

International Application Division

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2017/048041

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US 2009-0314753 A1	24/12/2009	CN 102112267 A JP 2011-524811 A KR 10-2011-0038627 A TW 201002461 A US 8207472 B2 WO 2009-155202 A2 WO 2009-155202 A3	29/06/2011 08/09/2011 14/04/2011 16/01/2010 26/06/2012 23/12/2009 06/05/2010
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