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(54) **METHOD OF HIGH POWER LASER-MECHANICAL DRILLING**

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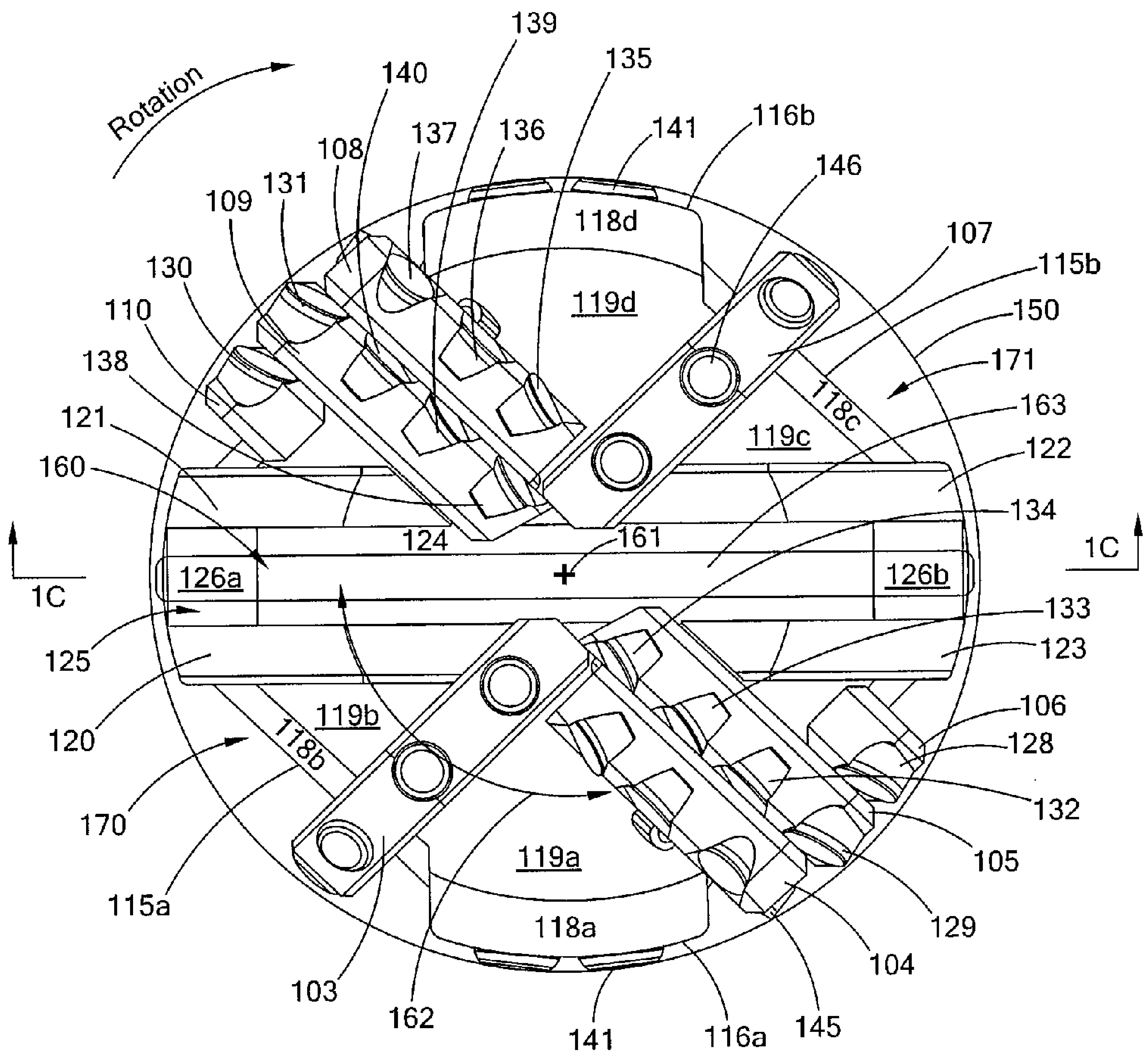
(57) **ABSTRACT**

There is provided a laser-mechanical method for drilling boreholes that utilizes specific combinations of high power directed energy, such as laser energy, in combination with mechanical energy to provide a synergistic enhancement of the drilling process.



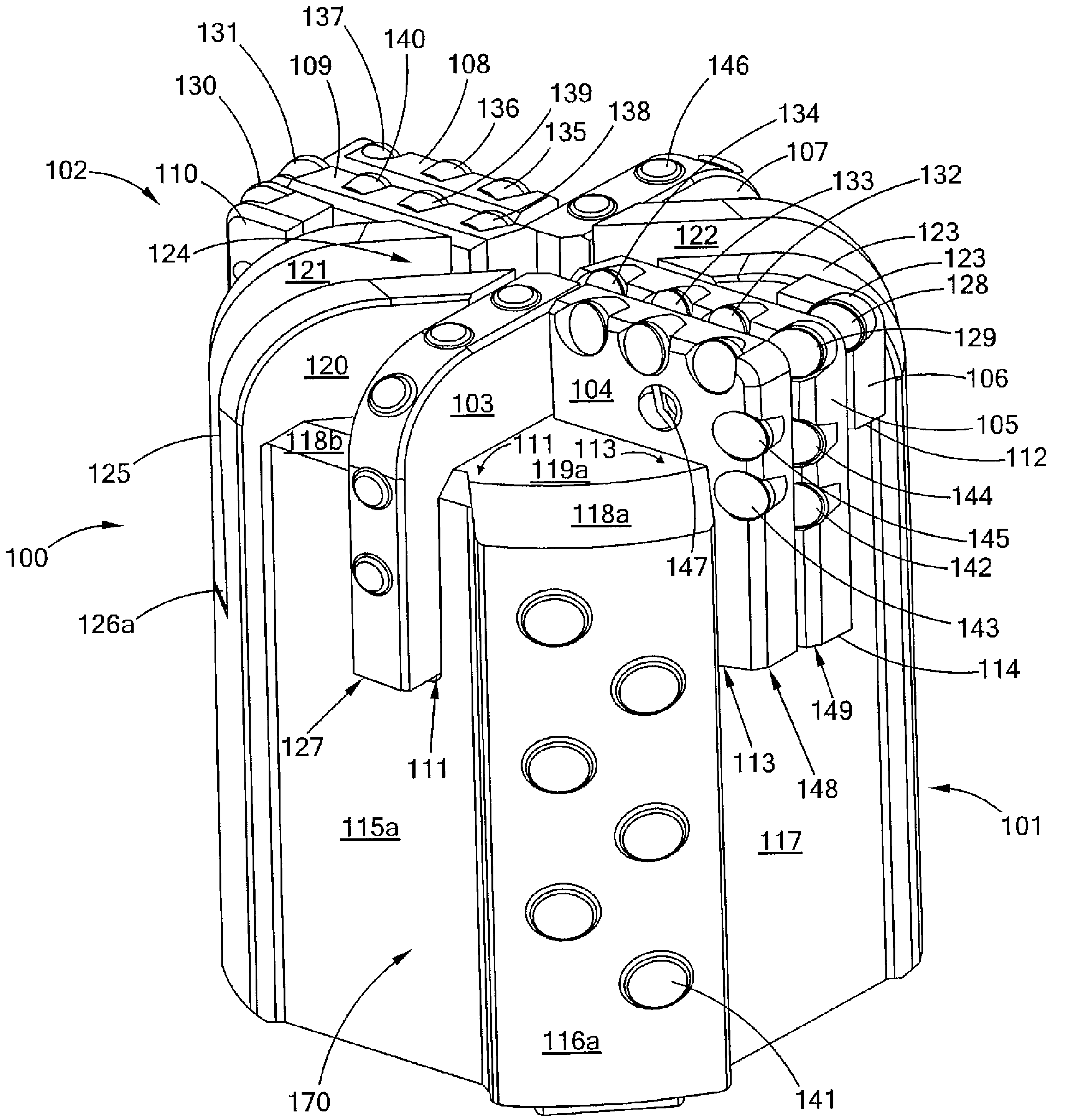


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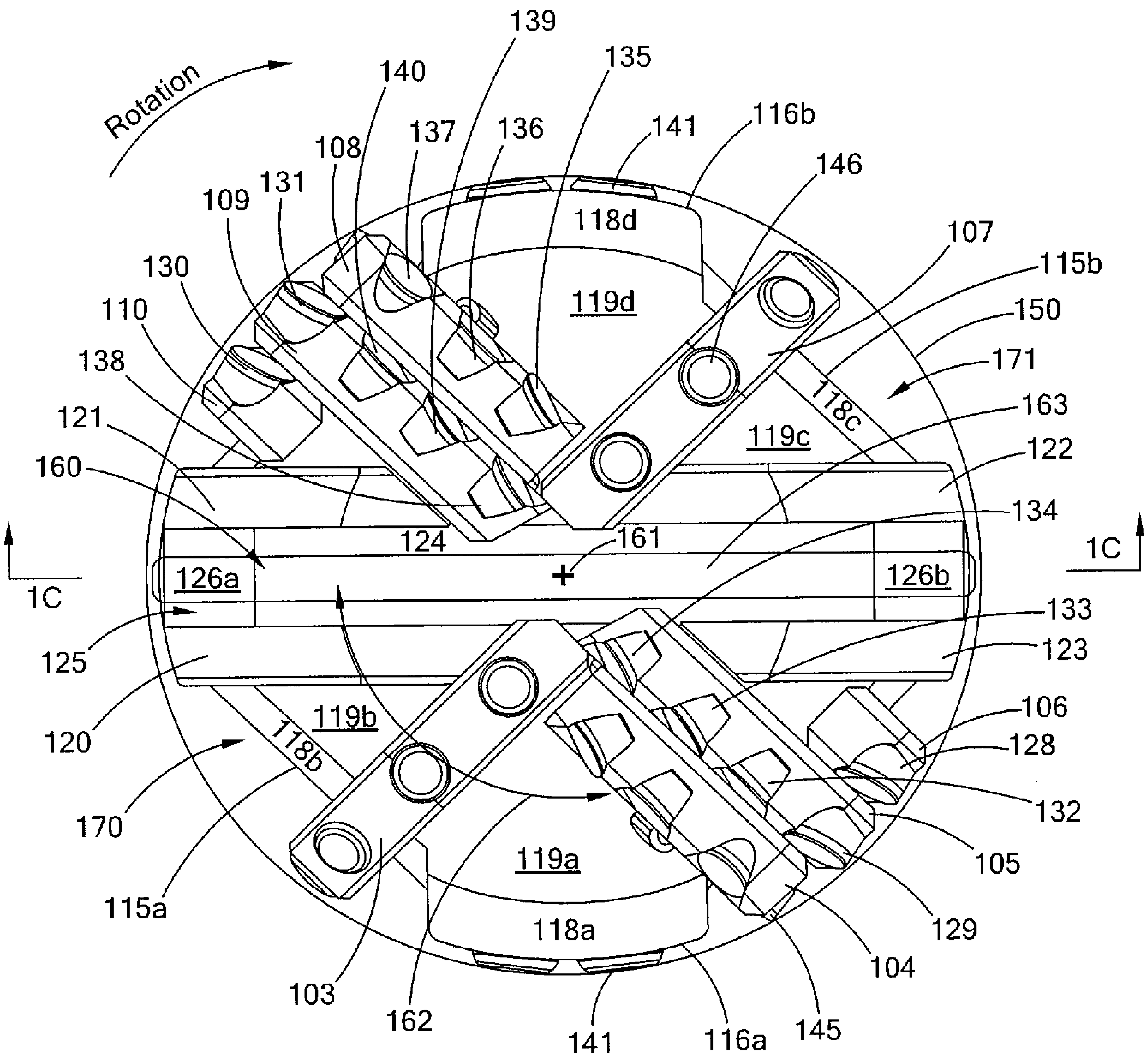
Fig. 1A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1C
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Fig. 1B

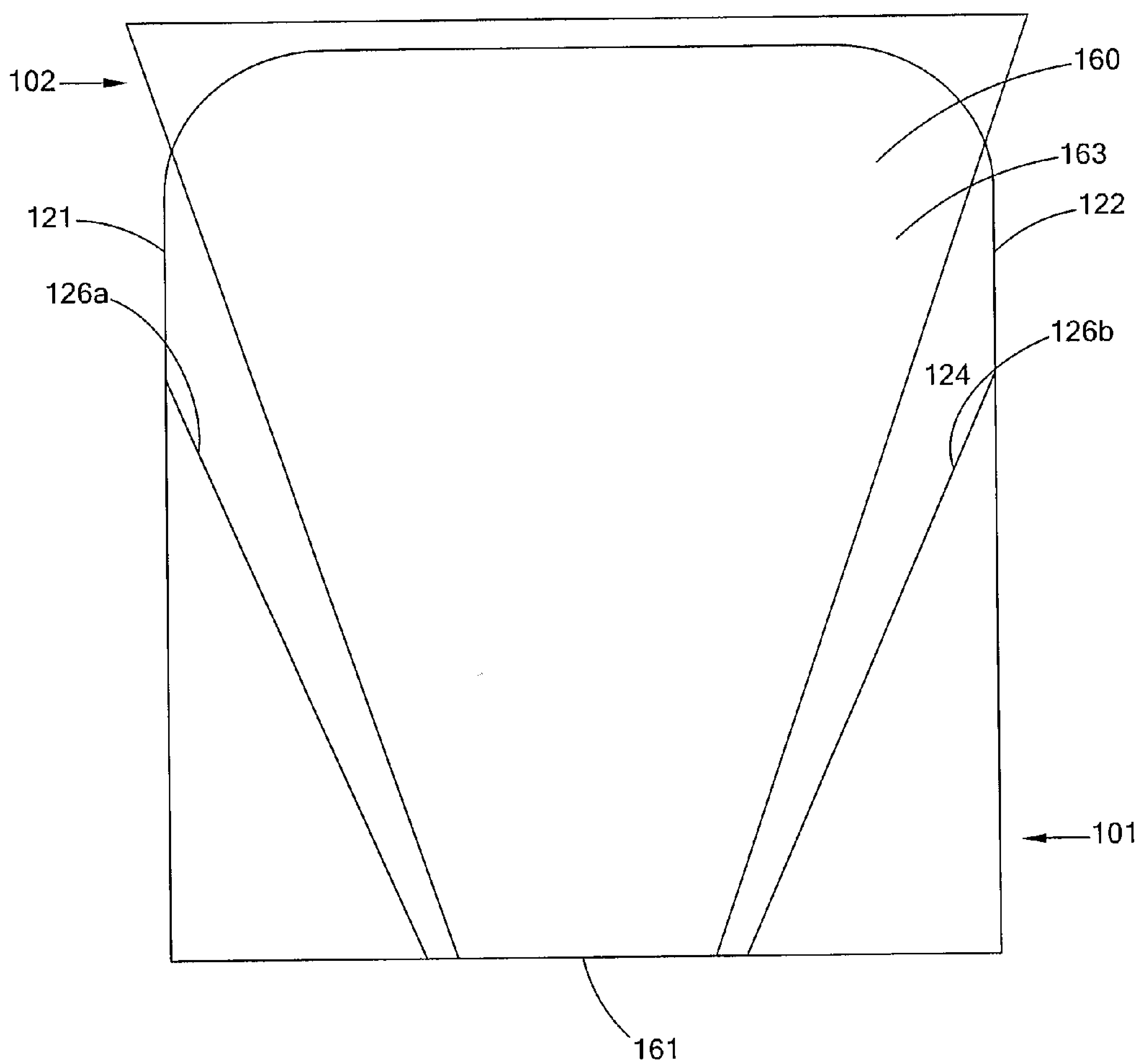

Fig. 1C

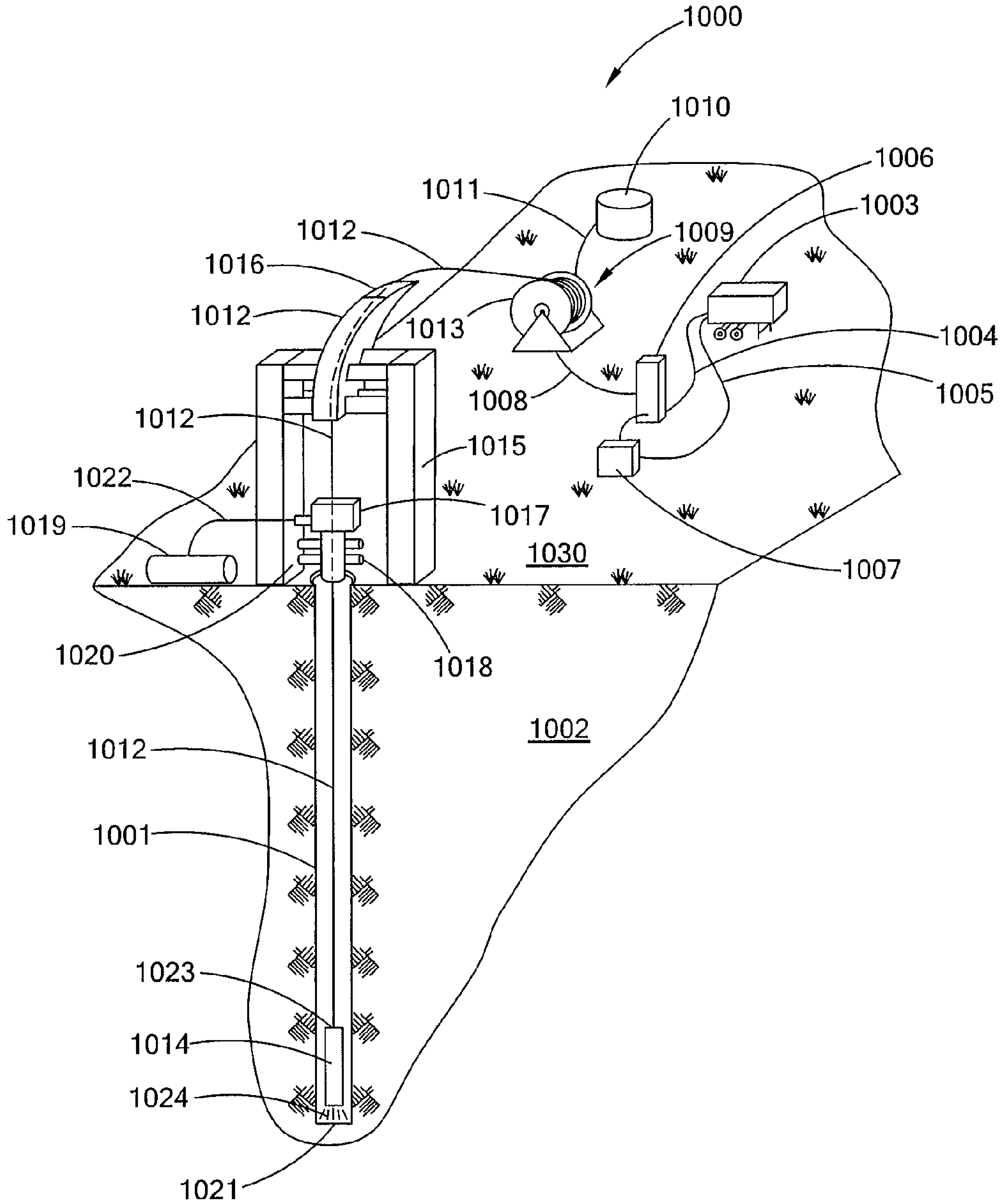
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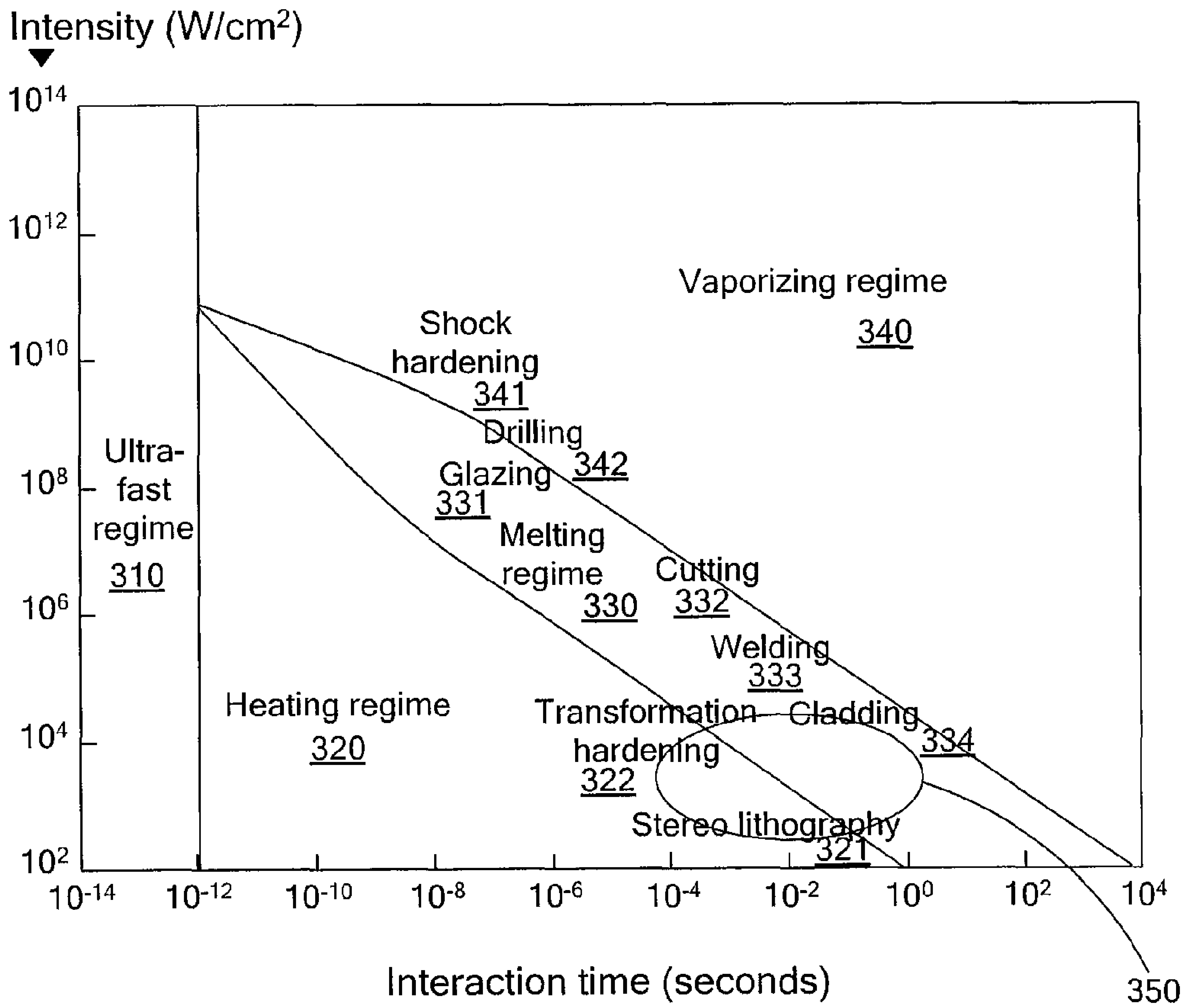
Fig. 2



Intensity (W/cm2)
10^14
10^12
10^10
10^8
10^6
10^4
10^2
Ultra-fast regime
310
Heating regime
320
Vaporizing regime
340
Shock hardening
341
Drilling
342
Glazing
331
Melting regime
330
Cutting
332
Welding
333
Transformation hardening
322
Cladding
334
Stereo lithography
321
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
10^0
10^2
10^4
Interaction time (seconds)
350

Fig. 3

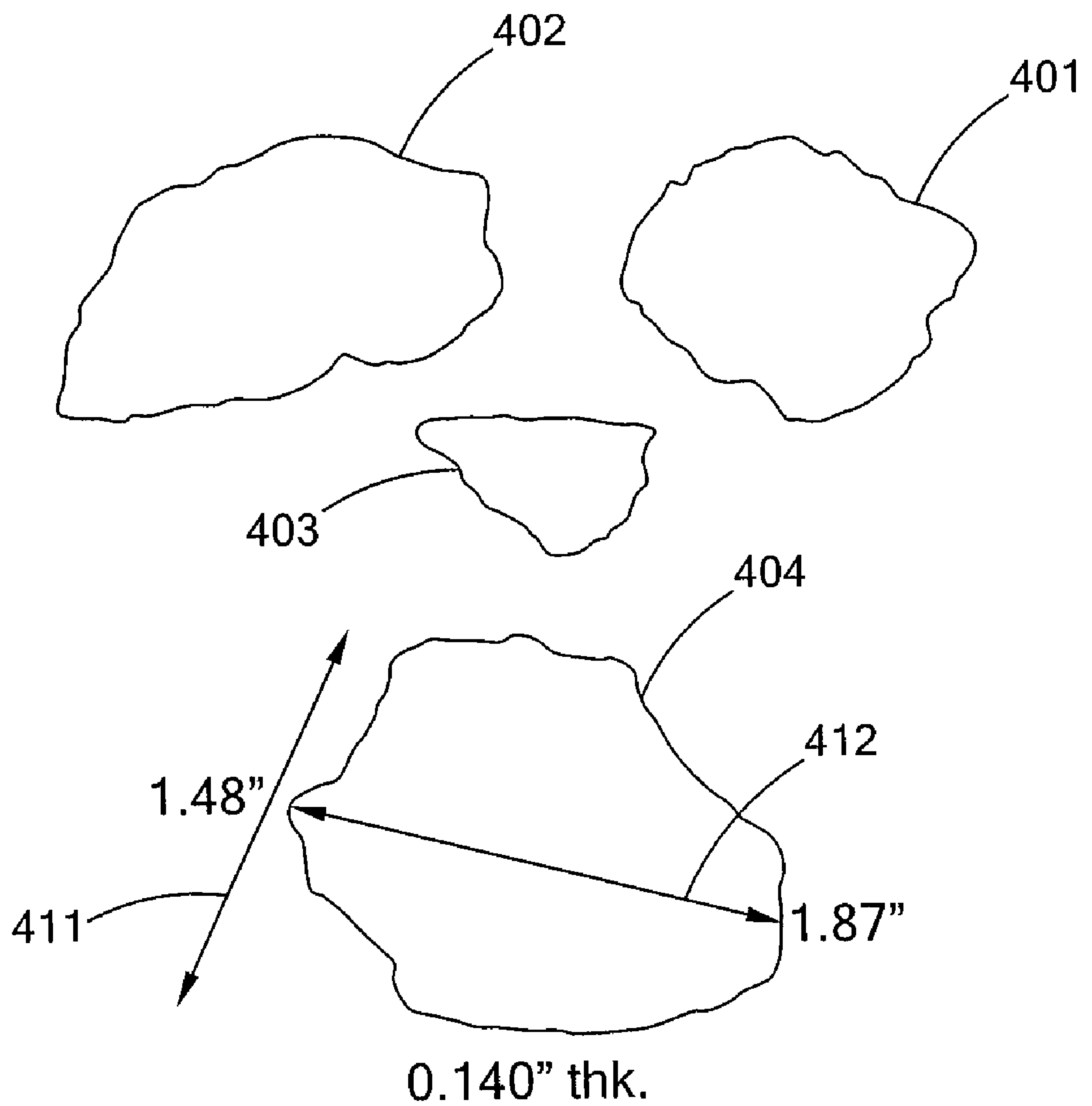
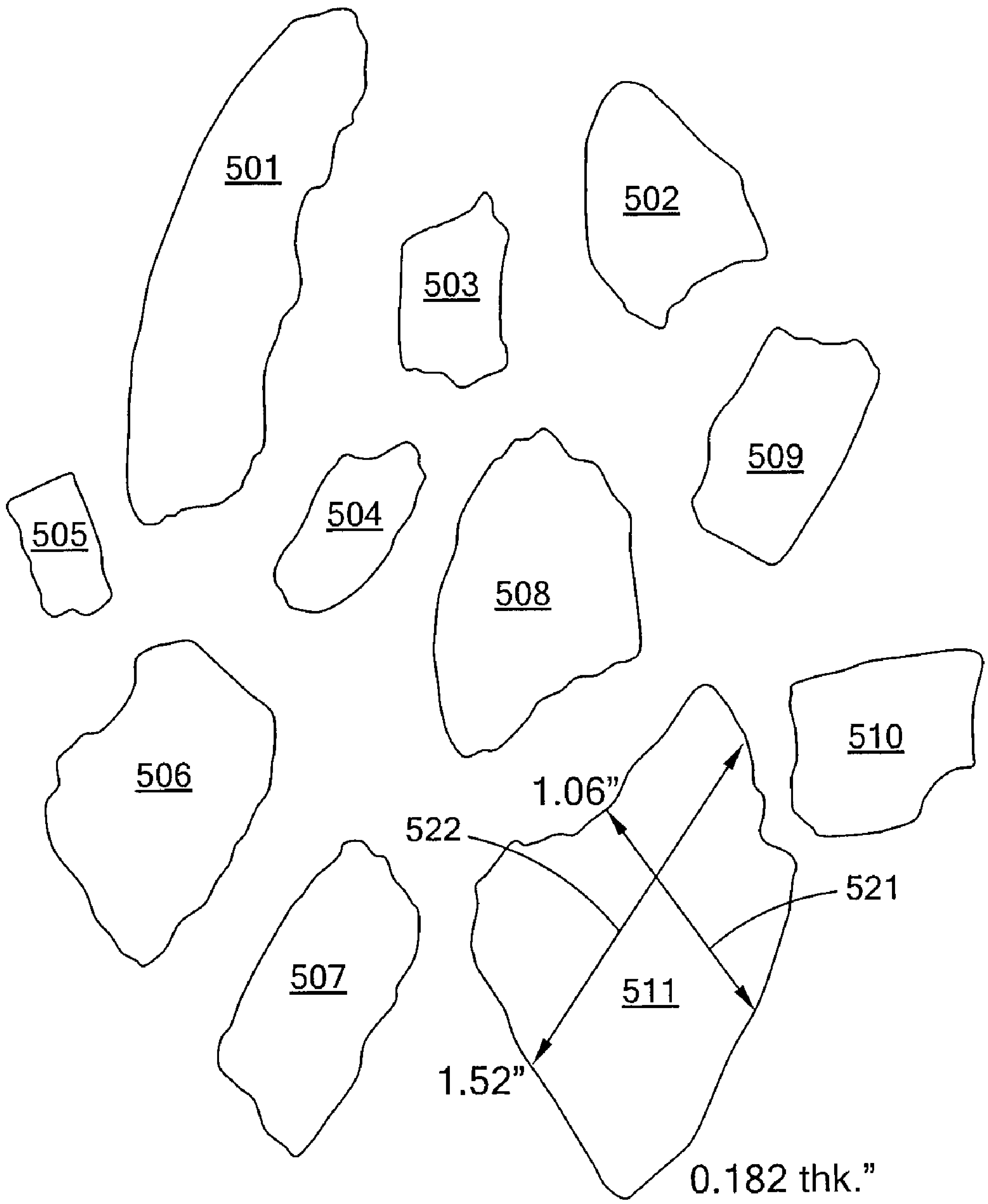


Fig. 4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502
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1.06"
522
521
1.52"
0.182 thk."

Fig. 5

METHOD OF HIGH POWER LASER-MECHANICAL DRILLING

[0001] This application: (i) claims, under 35 U.S.C. §119 (e)(1), the benefit of the filing date of Feb. 24, 2011 of U.S. provisional application Ser. No. 61/446,041; (ii) claims, under 35 U.S.C. §119(e)(1), the benefit of the filing date of Feb. 24, 2011 of U.S. provisional application Ser. No. 61/446,312; (iii) claims, under 35 U.S.C. §119(e)(1), the benefit of the filing date of Feb. 24, 2011 of U.S. provisional application Ser. No. 61/446,040; (iv) claims, under 35 U.S.C. §119(e)(1), the benefit of the filing date of Feb. 24, 2011 of U.S. provisional application Ser. No. 61/446,043; (v) claims, under 35 U.S.C. §119(e)(1), the benefit of the filing date of Feb. 24, 2011 of U.S. provisional application Ser. No. 61/446,042; (vi) is a continuation-in-part of U.S. patent application Ser. No. 12/544,038 filed Aug. 19, 2009, which claims under 35 U.S.C. §119(e)(1) the benefit of the filing date of Feb. 17, 2009 of U.S. provisional application Ser. No. 61/153,271, the benefit of the filing date of Oct. 17, 2008 of U.S. provisional application Ser. No. 61/106,472, the benefit of the filing date of Oct. 3, 2008 of U.S. provisional application Ser. No. 61/102,730, and the benefit of the filing date of Aug. 20, 2008 of U.S. provisional application Ser. No. 61/090,384; (vii) is a continuation-in-part of U.S. patent application Ser. No. 12/543,968 filed Aug. 19, 2009; and (viii) is a continuation-in-part of U.S. patent application Ser. No. 12/543,986 filed Aug. 19, 2009, which claims under 35 U.S.C. §119(e)(1) the benefit of the filing date of Feb. 17, 2009 of U.S. provisional application Ser. No. 61/153,271, the benefit of the filing date of Oct. 17, 2008 of U.S. provisional application Ser. No. 61/106,472, the benefit of the filing date of Oct. 3, 2008 of U.S. provisional application Ser. No. 61/102,730, and the benefit of the filing date of Aug. 20, 2008 of U.S. provisional application Ser. No. 61/090,384, the entire disclosures of each of which are incorporated herein by reference.

[0002] This invention was made with Government support under Award DE-AR0000044 awarded by the Office of ARPA-E U.S. Department of Energy. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

Field of the Invention

[0003] The present inventions relate to high power laser energy tools and systems and methods.

[0004] As used herein, unless specified otherwise, "high power laser energy" means a laser beam having at least about 1 kW (kilowatt) of power. As used herein, unless specified otherwise "great distances" means at least about 500 m (meter). As used herein the term "substantial loss of power," "substantial power loss" and similar such phrases, mean a loss of power of more than about 3.0 dB/km (decibel/kilometer) for a selected wavelength. As used herein the term "substantial power transmission" means at least about 50% transmittance.

[0005] As used herein, unless specified otherwise, the term "earth" should be given its broadest possible meaning, and includes, the ground, all natural materials, such as rocks, and artificial materials, such as concrete, that are or may be found in the ground, including without limitation rock layer formations, such as, granite, basalt, sandstone, dolomite, sand, salt, limestone, rhyolite, quartzite and shale rock.

[0006] As used herein, unless specified otherwise, the term "borehole" should be given it broadest possible meaning and includes any opening that is created in a material, a work piece, a surface, the earth, a structure (e.g., building, protected military installation, nuclear plant, offshore platform, or ship), or in a structure in the ground, (e.g., foundation, roadway, airstrip, cave or subterranean structure) that is substantially longer than it is wide, such as a well, a well bore, a well hole, a micro hole, slimhole, a perforation and other terms commonly used or known in the arts to define these types of narrow long passages. Wells would further include exploratory, production, abandoned, reentered, reworked, and injection wells. Although boreholes are generally oriented substantially vertically, they may also be oriented on an angle from vertical, to and including horizontal. Thus, using a vertical line, based upon a level as a reference point, a borehole can have orientations ranging from 0° i.e., vertical, to 90°,i.e., horizontal and greater than 90° e.g., such as a heel and toe and combinations of these such as for example "U" and "Y" shapes. Boreholes may further have segments or sections that have different orientations, they may have straight sections and arcuate sections and combinations thereof; and for example may be of the shapes commonly found when directional drilling is employed. Thus, as used herein unless expressly provided otherwise, the "bottom" of a borehole, the "bottom surface" of the borehole and similar terms refer to the end of the borehole, i.e., that portion of the borehole furthest along the path of the borehole from the borehole's opening, the surface of the earth, or the borehole's beginning. As used herein unless specified otherwise, the terms "side" and "wall" of a borehole should to be given their broadest possible meaning and include the longitudinal surfaces of the borehole, whether or not casing or a liner is present, as such, these terms would include the sides of an open borehole or the sides of the casing that has been positioned within a borehole. Boreholes may be made up of a single passage, multiple passages, connected passages and combinations thereof, in a situation where multiple boreholes are connected or interconnected each borehole would have a borehole bottom. Boreholes may be formed in the sea floor, under bodies of water, on land, in ice formations, or in other locations and settings.

[0007] Boreholes are generally formed and advanced by using mechanical drilling equipment having a rotating drilling tool, e.g., a bit. For example and in general, when creating a borehole in the earth, a drilling bit is extending to and into the earth and rotated to create a hole in the earth. In general, to perform the drilling operation the bit must be forced against the material to be removed with a sufficient force to exceed the shear strength, compressive strength or combinations thereof, of that material. Thus, in conventional drilling activity mechanical forces exceeding these strengths of the rock or earth must be applied. The material that is cut from the earth is generally known as cuttings, e.g., waste, which may be chips of rock, dust, rock fibers and other types of materials and structures that may be created by the bit's interactions with the earth. These cuttings are typically removed from the borehole by the use of fluids, which fluids can be liquids, foams or gases, or other materials know to the art.

[0008] As used herein, unless specified otherwise, the term "advancing" a borehole should be given its broadest possible meaning and includes increasing the length of the borehole. Thus, by advancing a borehole, provided the orientation is not horizontal, e.g., less than 90° the depth of the borehole may also be increased. The true vertical depth ("TVD") of a borehole is the distance from the top or surface of the borehole to the depth at which the bottom of the borehole is located, measured along a straight vertical line. The measured depth ("MD") of a borehole is the distance as measured along the actual path of the borehole from the top or surface to the bottom. As used herein unless specified otherwise the term depth of a borehole will refer to MD. In general, a point of reference may be used for the top of the borehole, such as the rotary table, drill floor, well head or initial opening or surface of the structure in which the borehole is placed.

[0009] As used herein, unless specified otherwise, the terms "ream", "reaming", a borehole, or similar such terms, should be given their broadest possible meaning and includes any activity performed on the sides of a borehole, such as, e.g., smoothing, increasing the diameter of the borehole, removing materials from the sides of the borehole, such as e.g., waxes or filter cakes, and under-reaming.

[0010] As used herein, unless specified otherwise, the terms "drill bit", "bit", "drilling bit" or similar such terms, should be given their broadest possible meaning and include all tools designed or intended to create a borehole in an object, a material, a work piece, a surface, the earth or a structure including structures within the earth, and would include bits used in the oil, gas and geothermal arts, such as fixed cutter and roller cone bits, as well as, other types of bits, such as, rotary shoe, drag-type, fishtail, adamantine, single and multi-toothed, cone, reaming cone, reaming, self-cleaning, disc, three cone, rolling cutter, crossroller, jet, core, impreg and hammer bits, and combinations and variations of the these.

[0011] Mechanical bits cut rock with shear stresses created by rotating a cutting surface against the rock and placing a large amount of weight-on-bit ("WOB"). Mechanical bits cut rock by applying crushing (compressive) and/or shear stresses created by rotating a cutting surface against the rock and placing a large amount of WOB. In the case of a bit made of the material polycrystalline diamond compact ("PDC"), e.g., a PDC bit, this action is primarily by shear stresses and in the case of roller cone bits this action is primarily by crushing (compression) and shearing stresses. For example, the WOB applied to an 8¾" PDC bit may be up to 15,000 lbs, and the WOB applied to an 8¾" roller cone bit may be up to 60,000 lbs. When mechanical bits are used for drilling hard and ultra-hard rock excessive WOB, rapid bit wear, and long tripping times result in an effective drilling rate that is essentially economically unviable. The effective drilling rate is based upon the total time necessary to complete the borehole and, for example, would include time spent tripping in and out of the borehole, as well as, the time for repairing or replacing damaged and worn bits.

[0012] As used herein, unless specified otherwise, the term "drill pipe" should be given its broadest possible meaning and includes all forms of pipe used for drilling activities; and refers to a single section or piece of pipe. As used herein the terms "stand of drill pipe," "drill pipe stand," "stand of pipe," "stand" and similar type terms are to be given their broadest possible meaning and include two, three or four sections of drill pipe that have been connected, e.g., joined together, typically by joints having threaded connections. As used herein the terms "drill string," "string," "string of drill pipe," string of pipe" and similar type terms are to be given their broadest definition and would include a stand or stands joined together for the purpose of being employed in a borehole. Thus, a drill string could include many stands and many hundreds of sections of drill pipe.

[0013] As used herein, unless specified otherwise, the term "tubular" should be given its broadest possible meaning and includes drill pipe, casing, riser, coiled tube, composite tube, vacuum insulated tubing ("VIT), production tubing and any similar structures having at least one channel therein that are, or could be used, in the drilling industry. As used herein the term "joint" is to be given its broadest possible meaning and includes all types of devices, systems, methods, structures and components used to connect tubulars together, such as for example, threaded pipe joints and bolted flanges. For drill pipe joints, the joint section typically has a thicker wall than the rest of the drill pipe. As used herein the thickness of the wall of tubular is the thickness of the material between the internal diameter of the tubular and the external diameter of the tubular.

SUMMARY

[0014] There has been a long-standing need for rapidly and efficiently drilling boreholes into hard and very hard materials, and to do so with minimal damage to the drilling bit. The present inventions, among other things, solve these and other needs by providing the articles of manufacture, devices and processes taught herein.

[0015] Thus, there is provided herein a method of directed energy mechanical drilling having the steps of: providing directed energy to a surface of a material; providing mechanical energy to that surface; so that the ratio of directed energy to mechanical energy is greater than about 5; and, in this manner a borehole is advance through the surface of the material.

[0016] Further, there is provided a method directed energy mechanical drilling having steps including: providing directed energy to a surface of a material; providing mechanical energy to the surface; so that the ratio of directed energy to mechanical energy is greater than about 10; and, in this manner a borehole is advance through the surface of the material.

[0017] Moreover, there is provided a method of directed energy mechanical drilling including the following: providing directed energy to a surface of a material; providing mechanical energy to the surface; so that the ratio of directed energy to mechanical energy is greater than about 20; and, in this manner a borehole is advance through the surface of the material.

[0018] Still further, there is provided a method of providing directed energy to a surface of a material and providing mechanical energy to the surface; in a manner where the ratio of directed energy to mechanical energy is greater than about 40; and, in this manner a borehole is advance through the surface of the material.

[0019] Further still, there is provided directed energy mechanical drilling by directing directed energy to a surface of a material and directing mechanical energy to the surface in a ratio of directed energy to mechanical energy that is greater than about 2 and this manner a borehole is advance through the surface of the material.

[0020] Additionally, there is provided a method of directed energy mechanical drilling having the steps of: providing high power laser directed energy to a surface of a material; providing mechanical energy to the surface; and, so that the ratio of high power laser directed energy to mechanical energy is greater than about 5; and, in this manner a borehole is advance through the surface of the material.

[0021] Yet still additionally, there is provided a directed energy mechanical drilling method of providing high power laser directed energy to a surface of a material; providing mechanical energy to the surface; in the ratio of high power laser directed energy to mechanical energy that is greater than about 10; and, thus advancing a borehole through the surface of the material.

[0022] Additionally, there is provided a method of directed energy mechanical drilling by providing high power laser directed energy to a surface of a material, providing mechanical energy to the surface, so that the ratio of high power laser directed energy to mechanical energy is greater than about 20; and, in this manner a borehole is advance through the surface of the material.

[0023] Still further, there is provided a method of directed energy mechanical drilling having steps including: providing high power laser directed energy to a surface of a material; providing mechanical energy to the surface; and, so that the ratio of high power laser directed energy to mechanical energy is greater than about 40; and, in this manner a borehole is advance through the surface of the material.

[0024] Yet additionally, there is provided a directed energy mechanical drilling method by providing high power laser directed energy to a surface; providing mechanical energy to the surface; in a ratio of directed energy to mechanical energy that is greater than about 2 and, thus advancing a borehole through the surface of the material are utilized.

[0025] Still further, the methods may also include steps, conditions and parameters in which: the directed energy is high power laser energy and in which the high power laser directed energy has a power of at least about 40 kW; the surface is not substantially melted by the laser energy; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds; the mechanical energy is provided by a bit having a weight-on-bit less than about 1000 pounds; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration of at least about 10 feet per hour; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration of at least about 10 feet per hour; the high power laser directed energy has a power of at least about 20 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration of at least about 20 feet per hour; the high power laser directed energy has a power of at least about 20 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration of at least about 20 feet per hour; the high power laser directed energy has a power of at least about 20 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration of at least about 20 feet per hour; the high power laser directed energy has a power of at least about 50 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration of at least about 20 feet per hour; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds so that the borehole is advanced at a rate of penetration the rate of penetration of at least about 20 feet per hour through material having an average hardness of about 20 ksi (kilopound per square inch) or greater; the borehole is advanced for greater than about 500 feet; and the borehole is advanced for greater than about 5,000 feet.

[0026] Moreover, there is provided a method of advancing borehole in the earth using high power laser mechanical drilling techniques, the method involving: directing laser energy, in a moving pattern, to a bottom surface of a borehole in the earth; heating the earth with the directed laser energy to a point below the melting point; providing mechanical energy to the heated earth; so that the ratio of laser energy to mechanical energy is greater than about 2; and, in this manner the borehole is advanced

[0027] Furthermore, the methods may also include steps, conditions and parameters in which: the laser energy has a power of about 20 kW or greater; the power/area of the laser energy on the surface of the bottom of the borehole is about 50 W/cm^2 or greater; the power/area of the laser energy on the surface of the bottom of the borehole is about 75 W/cm^2 or greater; the power/area of the laser energy on the surface of the bottom of the borehole is about 100 W/cm^2 or greater; the laser energy on the surface of the bottom of the borehole is about 200 W/cm^2 or greater; the power/area of the laser energy on the surface of the bottom of the borehole is about 300 W/cm^2 or greater; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds; the mechanical energy is provided by a bit having a weight-on-bit less than about 1000 pounds; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and so that the borehole is advanced at a rate of penetration of at least about 10 feet per hour; the mechanical energy is provided by a bit having a weight-on-bit, so that the weight-on-bit is less than about 2000 pounds and so that the borehole is advanced at a rate of penetration of at least about 20 feet per hour; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and so that borehole is advances at a rate of penetration of at least about 10 feet per hour through material having an average hardness of about 20 ksi or greater; the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and so that the borehole is advanced at a rate of penetration of at least about 20 feet per hour through material having an average hardness of about 20 ksi or greater; and the borehole is advanced for greater than about 1,000 feet, greater than about 2,000 feet, and greater than then about 5,000 feet and greater than about 10,000 feet.

[0028] Moreover, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of material having a hardness greater than about 30 ksi by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole while propagating a laser beam against the borehole surface; with an RPM of from about 240 to about 720, a WOB of less than about 2,000 lbs, a DE Power/Area of about 90 W/cm^2 to about 560 W/cm^2, and an ME Power/Area of about 4 W/cm^2 to about 250 W/cm^2; and in this manner the borehole is advanced at an ROP of at least about 10 ft/hr.

[0029] Further, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of material having a hardness greater than about 30 ksi by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole while propagating a laser beam against the borehole surface; with an RPM of from about 600 to about 800, a WOB of less than about 5,000 lbs, a DE

Power/Area of about 40 W/cm^2 to about 250 W/cm^2, and an ME Power/Area of about 200 W/cm^2 to about 3000 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 15 ft/hr.

[0030] Additionally, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of material having a hardness greater than about 20 ksi by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole while propagating a laser beam against the borehole surface; with an RPM of from about 600 to about 1250, a WOB of from about 500 to about 5,000 lbs, a DE Power/Area of about 90 W/cm^2 to about 570 W/cm^2, and an ME Power/Area of about 40 W/cm^2 to about 270 W/cm^2; and in this manner the borehole is advanced at an ROP of at least about 10.

[0031] Yet additionally, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole with an RPM of about 250, a WOB of from about 1,000 lbs, a DE Power/Area of about 370 W/cm^2, and an ME Power/Area of about 40 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 20 ft/hr.

[0032] Yet still further, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method having the steps of: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 190 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 50 ft/hr.

[0033] Further still, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 370 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 50 ft/hr.

[0034] Still further, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 5,000 lbs, a DE Power/Area of about 290 W/cm^2, and an ME Power/Area of about 240 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 20 ft/hr.

[0035] Moreover, there is provided a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, this method includes: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 1,200, a WOB of from about 500 lbs, a DE Power/Area of about 470 W/cm^2, and an ME Power/Area of about 100 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 30 ft/hr.

[0036] Still further, a method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 470 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and, in this manner the borehole is advanced at an ROP of at least about 30 ft/hr.

[0037] Furthermore, there is also provided a method of laser-mechanical drilling a borehole in a formation by: providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source; applying from the high power laser beam source a high power laser beam to a surface of the borehole, so that the high power laser beam generates an intensity ranging from about 150 to about 250 W/cm^2 on a surface of the borehole for an elapsed time sufficient to cause a surface temperature rise in the range from about 400 degrees C. to about 1,000 degrees C. and thus forming a laser applied surface; and applying a mechanical force to the laser applied surface, so that the mechanical force generates an intensity ranging from about 30 to about 250 W/cm^2 to remove the laser applied surface of the borehole.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038] FIG. **1**A is a perspective view of an embodiment of a fixed cutter laser-mechanical bit in accordance with the present invention.

[0039] FIG. **1**B is a bottom view of the bit of FIG. **1**A.

[0040] FIG. **1**C is a cross section view of the bit of FIGS. **1**A and **1**B taken along line **1**C-**1**C.

[0041] FIG. **2** is a schematic of an embodiment of a high power laser drilling, workover and completion unit in accordance with the present invention.

[0042] FIG. **3** is a chart showing various directed energy regimes.

[0043] FIG. **4** is schematic of chips of basalt.

[0044] FIG. **5** is a schematic of chips of dolomite.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0045] The present inventions relate to directed energy mechanical drilling methods that utilize high power directed energy in conjunction with mechanical forces. These methods may find uses in many different types of materials and structures, such as metal, stone, composites, concrete, the earth, and structures in the earth. In particular, these methods may find preferable uses in situations and environments where advancing a borehole with conventional, e.g., non-directed energy technology, was difficult or impossible, because, for example, the remoteness of the area where the borehole was to be advanced, difficult environmental conditions or other factors that placed great, and at times insurmountable burdens on conventional drilling or boring technologies. These methods also find preferable uses in situations where reduced noise and vibrations, compared to conventional technologies, are desirable or a requisite.

[0046] In general, the present methods involve the application of directed energy and mechanical forces to a surface, e.g., the bottom of a borehole, to remove material and advance the borehole. The directed energy and mechanical forces are preferably applied in a rotating or revolving manner, so that they are so moved about or on the surface to be drilled (i.e., the drilling surface), e.g., the bottom of a borehole. "Directed energy" would include, for example, optical laser energy, non-optical laser energy, microwaves, sound waves, plasma, electric arcs, flame, flame jets, steam and combinations of the foregoing, as well as, water jets (although a water jet may be viewed as having a mechanical interaction with the drilling surface, for the purpose of this specification it will be characterized amongst the group of directed energies, based upon the following specific definition of mechanical energy), and other forms of energy that are not "mechanical energy" as defined in these specifications. "Mechanical energy," as used herein, is limited to energy that is transferred to the drilling surface by the interaction or contact of a solid object, e.g., a drill bit cutter, roller cone, or a saw blade, with the drilling surface.

[0047] These methods provide for the application of unique combinations of directed energy and mechanical force to obtain a synergism. This synergism enables these methods to advance boreholes through very hard materials, such as hard rocks and ultra hard rocks, with very low WOB, e.g., less than about 5,000 lbs, less than about 2000 lbs and preferably about 1000 lbs or less. This reduction in WOB has the potential benefit of providing for substantially longer drilling bit life, longer drilling times where the bit can remain in the borehole, and reduced tripping, which in turn has the potential to greatly reduce the cost of drilling a borehole. In addition to reducing WOB, in other processes, such as in a cutting application, the associated mechanical forces that are needed may similarly be greatly reduced.

[0048] In general, and using drilling a borehole in the earth as an illustrative example, as the bit is rotated in the bottom of the borehole, the directed energy is propagated at the bottom surface (and potentially side and gauge surfaces). The directed energy weakens (and may also partially remove, and remove) the material so contacted, i.e., directed energy affected material. The mechanical devices, e.g., cutters, then rotate in the borehole, contacting and removing the directed energy affected material (and potentially some additional material). However, it is preferable, as shown by the examples below, that the mechanical cutter, and the mechanical energy that it delivers, is only sufficient to remove the directed energy affected material. In this way the life of the cutters is preserved, damage is minimized, and the amount of heat built up from friction is controlled and preferably in some embodiments kept to a minimum.

[0049] Preferably, in these methods the source of directed energy is a high power laser beam. Thus, and more preferably the laser beam, or beams, may have 10 kW, 20 kW, 40 kW, 80 kW or more power; and have a wavelength in the range of from about 445 nm (nanometers) to about 2100 nm, preferably in the range of from about 800 to 1900 nm, and more preferably in the ranges of from about 1530 nm to 1600 nm, from about 1060 nm to 1080 nm, and from about 1800 nm to 1900 nm. Further, the types of laser beams and sources for providing a high power laser beam may be the devices, systems, optical fibers and beam shaping and delivery optics that are disclosed and taught in the following US patent applications and US Patent Application Publications: Publication No. US 2010/0044106, Publication No. US 2010/0044105, Publication No. US 2010/0044103, Publication No. US 2010/0044102, Publication No. US 2010/0215326, Publication No. 2012/0020631, Ser. No. 13/210,581, and Ser. No. 61/493,174, the entire disclosures of each of which are incorporated herein by reference. The source for providing rotational movement may be a string of drill pipe rotated by a top drive or rotary table, a down hole mud motor, a down hole turbine, a down hole electric motor, and, in particular, may be the systems and devices disclosed in the following US patent applications and US Patent Application Publications: Publication No. US 2010/0044106, Publication No. US 2010/0044104, Publication No. US 2010/0044103, Ser. No. 12/896,021, Ser. No. 61/446,042 and Ser. No. 13/211,729, the entire disclosures of each of which are incorporated herein by reference. The high power lasers for example may be fiber lasers or semiconductor lasers having 10 kW, 20 kW, 50 kW or more power and, which emit laser beams with wavelengths preferably in about the 1064 nm range, about the 1070 nm range, about the 1360 nm range, about the 1455 nm range, about the 1550 nm range, about the 1070 nm range, about the 1083 nm range, or about the 1900 nm range (wavelengths in the range of 1900 nm may be provided by Thulium lasers). Thus, by way of example, there is contemplated the use of four, five, or six, 20 kW lasers to provide a laser beam in a bit having a power greater than about 60 kW, greater than about 70 kW, greater than about 80 kW, greater than about 90 kW and greater than about 100 kW. One laser may also be envisioned to provide these higher laser powers.

[0050] Preferably, the source of mechanical energy is a fixed cutter drill bit or roller cone used as part of a laser-mechanical bit. In general, the components of a laser mechanical bit may be made from materials that are known to those of skill in the art for such applications or components, or that are later developed for such applications. For example, the bit body may be made from steel, preferably a high-strength, weldable steel, such as SAE **9310**, or cemented carbide matrix material. The blades may be made from similar types of material. The blades and the bit body may be made, for example by milling, from a single piece of metal, or they may be separately made and affixed together. The cutters may be made from for example, materials such as polycrystalline diamond compact ("PDC"), grit hotpressed inserts ("GHI"), and other materials known to the art or later developed by the art. Cutters are commercially available from for example US Synthetic, MegaDiamond, and Element **6**. The roller cone arms may be made from steel, such as SAE **9310**. Like the blades, the arms and the bit body may be made from a single piece of metal, or they may be made from separate pieces of metal and affixed together. Roller cone inserts, for example, may be made from sintered tungsten carbide insert ("TCI") or the roller cones may be made with milled teeth ("MTs"). Roller cones, roller cone inserts, and roller cones and leg assemblies, may be obtained commercially from Varel International, while TCI may be obtained from for example Kennametal or ATI Firth Sterling. It is preferred that the inner surface of the beam path be made of material that does not absorb the laser energy, and thus, it is preferable that such surfaces be reflective or polished surfaces. It is also preferred that any surfaces of the bit that may be exposed to reflected laser energy, reflections, also be non-absorptive, minimally absorptive, and preferably be polished or made reflective of the laser beam.

[0051] An example of such a bit and system to provide the high power laser energy and mechanical energy are set forth in FIGS. **1**A to C, and in FIG. **2**.

[0052] In FIGS. **1**A, **1**B and **1**C there is shown views of an embodiment of a fixed cutter type laser-mechanical bit. Thus, there is provided a laser-mechanical bit **100** having a body section **101** and a bottom section **102**. The bottom section **102** has mechanical blades **103**, **104**, **105**, **106**, **107**, **108**, **109**, and **110**.

[0053] The bit body **101** may have a receiving slot for each mechanical blade. For example, in FIG. **1**A receiving slots, **111**, **112**, **113**, are **114** are identified. Note that with respect to blades, of the type shown as blades **108**, **109** and **110**, the receiving slots may be joined or partially joined, into a unitary opening. The bit body **101** has side surfaces or areas, e.g., **115***a*, **115***b*, **117** in which the blade receiving slots are formed. The bit body **101** has surfaces or areas, e.g., **116***a*, **116***b* for supporting gauge pads, e.g., **141**. The bit body **101** further has surfaces **119***a*, **119***b*, **119***c*, **119***d*, that in this embodiment are substantially normal to the surfaces **115***a*, **115***b*, **116***a*, **116***b*, which surfaces **115***a*, **115***b*, have part of the blade receiving slots formed therein. The surface **119** *a*, **119***b*, **119***c*, **119***d* are connected to surfaces **115***a*, **115***b*, **116***a*, **116***b* by angled surfaces or areas **118***a*, **118***b*, **118***c*, **118***d*.

[0054] The bit is further provided with beam blades, **120**, **121**, **122**, **123**. In this embodiment the beam blades are positioned along essentially the entirely of the width of the bit **100** and merge at the end **126** of beam path slot **125** into a unitary structure. The inner surfaces or sides of the beam blades form, in part, slot **125**. The outer surfaces or sides of the beam blades also form a sidewall for the junk slots, e.g., **170**. Thus, the beam blades are positioned in both the bit body section **101** and the bottom section **102**. Other positions and configurations of the beam blades are contemplated. In the embodiment of FIGS. **1**A and **1**B the bottom of the beam blades is located at about the same level as the depth of cut limiters, e.g., **146**, that are located on blades **103**, **107**, i.e. depth of cut blades, and slightly below the bottom of the cutters, e.g., **134**. As used herein "bottom" refers to the section of the bit that is intended to engage or be closest to the bottom of a borehole, and top of the bit refers to the section furthers away from the bottom. The distance between the top and the bottom of the bit would be the bit length, or longitudinal dimension; and the width would be the dimension transverse to the length, e.g., the outside diameter of the bit, as used herein unless specified otherwise.

[0055] The longitudinal position of the bottom of the beam blades with respect to the cutters and any depth of cut limiters, e.g., the beam blades relative proximity to the bottom of the borehole, may be varied in each bit design and configuration and will depend upon factors such as the power of the laser beam, the type of rock or earth being drilled, the flow of and type of fluid used to keep the beam path clear of cuttings and debris. In general it is preferable that the longitudinal positioning of the bottoms of the beam blades, any depth of cut limiter blades and the cutter blades all be relatively close, as shown in FIG. **1**A, although other positions and configurations are envisioned.

[0056] A beam path **124** is formed in the bit, and is bordered, in part, by the inner surfaces or sides of the beam blades **120**, **121**, **122**, **123** and the inner ends of blades **103**, **105**, **107** and **109**. In this embodiment the beam path extends through the center axis **161** of the bit and divides the bit into two separate sections, as more clearly seen in FIG. **1**B. Thus, it is preferable that the structures and their configuration on one side of the beam path **124**, be similar, and more preferably the same, as the structures on the other side of the beam path **124**, which is the case for this embodiment. This positioning and configuration is preferred, although other positions and configurations are contemplated. The beam path **124** should be close to, but preferably not touch the beam blades or the beam blade inner surfaces. When using high power laser energy, and in particular laser energy greater than 5 kW, 10 kW, 20 kW, 40 kW, 80 kW and greater, if the beam path, and, in particular, the laser beam **160**, which is propagated along the beam path, contacts a blade it will melt or otherwise remove that section of the blade in the beam path, and potentially damage the remaining section of the blade, bit, or other bit structure or component that is struck.

[0057] The beam path in this embodiment also serves as a fluid path for a fluid, such as air, nitrogen, or a transmissive, or substantially transmissive liquid to the laser beam. This fluid is used to keep the laser beam path clear and also to remove or help remove cuttings from the borehole. Configurations, systems and methods for providing and removing such fluids in laser drilling, and for keeping the beam path clear, as well as, the removal of cuttings from the borehole, during laser drilling are provided in the following US patent applications and US Patent Application Publications: Publication No. US 2010/0044102, Publication No. US 2010/0044103, Publication No. US 2010/0044104, Ser. No. 12/896,021, Ser. No. 13/211,729, Ser. No. 13/210,581 and Ser. No. 13/222,931, the entire disclosures of each of which are incorporated herein by reference.

[0058] The beam blades **120**, **121**, **122** and **123** form a beam path slot **125**, which slot has ends, e.g., **126***a*, **126***b*. In this embodiment, although other configurations and positions are contemplated, the beam path slot **125** extends from the bottom section **102** partially into the bit body section **101**. The beam path slot **125** may also have end sections **126***a*, **126***b*, these end sections **126***a*, **126***b*, are angled, such that they do not extend into the beam path. The beam pattern, e.g., the shape of the area of illumination by the laser upon the bottom of the borehole, or at any cross section of the beam as it is traveling toward the area to be cut, e.g., a borehole surface, when the bit is not in rotation, in this embodiment is preferably a narrow ellipse or rectangular type of pattern, and more preferably may be such a generally elliptical rectangular pattern where less energy or on laser energy is provided to center of pattern. (In FIG. **1**B the laser beam **160** is shown as having a beam pattern that is substantially rectangular.) The beam path for this pattern expands from the optics, not shown, until it strikes the bottom of the borehole (see and compare, FIG. **1**C showing a cross section of the laser beam **160** and the beam path **161**, with FIG. **1**B showing the bottom view of the laser beam pattern, and thus, the shape of the area of illumination of the bottom surface of the borehole by the laser beam when the beam is not rotating). It should additionally be noted that in this embodiment the beam path is such that the area of illumination of the bottom of the borehole surface is wider, i.e., a larger diameter, than the diameter of the bit, put about the same as the outer diameter of the gauge cutters. It is contemplated that the area of illumination may be equal to the bit diameter (excluding or including gauge cutters and/or gauge reamers as forming the outer diameter of the bit), substantially the same as the bit diameter (excluding or including gauge cutters and/or gauge reamers as forming the outer diameter of the bit), greater than the bit diameter (excluding or including gauge cutters and/or gauge reamers as forming the outer diameter of the bit). The bottom of the end section **126** also defines the end of the slot **125** with respect to the outer surface of the bit body. In this embodiment the end of the slot **125** is at about the same longitudinal position as the end of the blades, e.g., **127**.

[0059] The slot, beam slot or beam path slot refers to the opening or openings, e.g., a slot, in the sides, or side walls, of the bit that permit the beam path and the laser beam to extend out of, or from the side of the bit, as illustrated, by way of example, in FIG. **1**C.

[0060] In the embodiment of FIGS. **1**A-C there are provided gauge cutters, **128**, **129**, **130**, **131**. The gauge cutters are located on blades **105**, **106**, **109** and **110**. Blades **106** and **110** only support gauge cutters **128**, **130**. Blades **105**, **109** support gauge cutters **131**, **129**, as well as, bottom cutters **132**, **133**, **134**, **138**, **139**, **140**, which cutters remove material from the bottom of the borehole, after it has been softened, or otherwise weakened, e.g., laser-affected material, by the laser beam **160**. Depending upon the configuration and shape of the laser beam, the gauge cutters may also be removing laser-affected rock or material. Gauge pads, e.g., **141** are positioned in surfaces of the bit body, e.g., **116***a*. In this embodiment gauge reamers **142**, **143**, **144**, **145** are positioned in blades **104**, **105** (and also similarly positioned in blades **108**, **109** although not seen in FIG. **1**A). Blades **103** and **107** have depth of cut limiters, e.g., **146**. The blades, and in particular the blades having cutters, may have internal passages for cooling, e.g., vents or ports, such as, e.g., **147**, **148**, **149** (it being noted that the actual openings for vents **148**, **149**, are not seen in the view of FIG. **1**A).

[0061] As best illustrated in FIG. **1**B, the cutters are positioned with respect to each other, such that they each take a slightly different path along the bottom of the borehole, in this way each cutter is assisting in the removal of laser-affected rock, and preferably does not encounter any rock that has not first been affected by the laser. In this embodiment the distance of travel by a cutter before it contacts laser-affected rock is shown by arc **162**. Arc **162** defines an angle between the laser beam path, and in this embodiment the laser beam, and the plane of the blade supporting the cutters. This angle, which may be referred to as the "beam path angle," can be from about 90 degrees to about 140 degrees, about 100 degrees to about 130 degrees, and about 110 degrees to about 120 degrees. Beam path angles of less than 90 degrees may be employed, but are not preferred, as they tend to not give enough time for the heat deposited by the laser to affect the rock before the cutter reaches the area of laser affected rock. (Greater angles than 140 degrees may be employed, however, at greater angles space and strength of component issues can become significant, as the blades have very little space in which to be positioned.) Additionally, when multiple blades are used, each blade could have the same, substantially the same, or a different angle (although care should be taken when using different angles to make certain that the cutters and overall engagement with the borehole surface is properly balanced.) In the embodiment of FIG. **1**B this angle, defined by arc **162**, is 135 degrees.

[0062] This angle between the laser beam (and the beam path, since generally in a properly functioning bit they are coincident) and the cutter position has a relationship to, and can be varied and selected to, address and maximize, efficiency based upon several factors, including for example, the laser power that is delivered to the rock, the reflectivity and absorptivity of the rock to the laser beam, the rate and depth to which the laser beam's energy is transmitted into the rock, the thermal properties of the rock, the porosity of the rock, and the speed, i.e., RPM at which the bit is rotated. Thus, as the laser is fired, e.g., a laser beam is propagated, along its beam path from optics to the surface of the borehole, a certain amount of time will pass from when the laser first contacts a particular area of the surface of the borehole until the cutter revolves around and reaches that point. This time can be referred to as soak time. Depending upon the above factors, the soak time can be adjusted, and optimized to a certain extent by the selection of the cutter-laser beam angle.

[0063] The bit **100** has channels, e.g., junk slots, **170**, **171** that provide a space between the bit **100** and the wall or side surface **150** of the borehole, for the passage of cuttings up the borehole. The relationship of the gauge cutters **129**, **128**, **131**, **130** as well as other components of the bit **100** to the wall of the borehole **150** can been seen in FIG. **1**B.

[0064] The blades that support the cutters, **104**, **105**, **106**, **108**, **109**, **110**, i.e., the cutter blades, in the embodiment of FIGS. **1**A-C, are essentially right angle shaped. Thus, the bottom section of the blades, i.e., the lower end holding the cutters that engage the bottom and/or gauge of the borehole, and also the associated bottom of the cutters positioned in that end (e.g., cutters **134**,**133**, **132**,**129**), are along an essentially straight line that forms a right angle with the side section of the blades, i.e., the side end holding the cutters that engage the side and/or gauge of the borehole, and also the associated side of the cutters positioned in that end (e.g., cutters **142**, **144**, **129**) form a right angle. This right angle configuration of all of the cutter blades, as shown in the embodiment of FIG. **1**, is referred to as a flat bottom configuration, or a flat bottom laser-mechanical bit. Thus, the lower ends of the blades, as well as their associated cutters, are essentially co-planar and thus provided the flat bottom of the bottom section **102** of the bit **100**. Accordingly, in laser mechanical-bits, having fixed cutters, it is preferable that the bottom of the bit, as primarily defined by the end of the cutter blades, and the position of the cutters in those ends, is essentially flat and more preferably flat, and as such will engage the borehole in an essentially even manner, and more preferably an even manner, and will in general provide a borehole with an essentially flat bottom and more preferably a flat bottom.

[0065] In the bit of FIG. **1** the cutters, e.g., **134**, **133**, **132**, gauge cutters, e.g., **129**, and gauge reamers, e.g., **144**, **142**, may be PDC; and the gauge pads, e.g., **141**, may be carbide inserts, which provides for impact resistance, enhanced wear, as well as bit stability.

[0066] Further examples of laser-mechanical bits, beam paths, beam patterns including split beam patterns, hybrid-laser-mechanical bits, beam path angles and related processes and systems are disclosed and taught in the following U.S. patent applications Ser. No. 61/446,043 and co-filed patent application having attorney docket no. 13938/79 (Foro s13a), the entire disclosures of each of which are incorporated herein by reference.

[0067] Thus, in general, and by way of example, there is provided in FIG. **2** a high efficiency laser drilling system **1000** for creating a borehole **1001** in the earth **1002**. FIG. **2** provides a cut away perspective view showing the surface of the earth **1030** and a cut away of the earth **1002** below the surface **1030**. In general and by way of example, there is provided a source of electrical power **1003**, which provides electrical power by cables **1004** and **1005** to a laser **1006** and a chiller **1007** for the laser **1006**. The laser provides a laser beam, i.e., laser energy, that can be conveyed by a laser beam transmission means **1008** to a spool of tubing **1009**. A source of fluid **1010** is provided. The fluid is conveyed by fluid conveyance means **1011** to the spool of tubing **1009**.

[0068] The spool of tubing **1009**, e.g., coiled tubing, composite tubing or other conveyance device, is rotated to advance and retract the tubing **1012**. Preferred examples of such conveyance means are disclosed and taught in the following US patent applications and US Patent Application Publications: Publication No. US 2010/0044106, Publication No. US 2010/0044104, Publication No. US 2010/0044105, Publication No. US 2010/0044103, Publication No. US 2010/0215326, Publication No. 2012/0020631, Ser. No. 13/210,581, Ser. No. 13/366,882 and Ser. No. 13/211,729, the entire disclosures of each of which are incorporated herein by reference. Thus, the laser beam transmission means **1008** and the fluid conveyance means **1011** are attached to the spool of tubing **1009** by means of rotating coupling means **1013**. The tubing **1012** contains a means to transmit the laser beam along the entire length of the tubing, i.e., "long distance high power laser beam transmission means," to the bottom hole assembly, **1014**. The tubing **1012** also contains a means to convey the fluid along the entire length of the tubing **1012** to the bottom hole assembly **1014**.

[0069] Additionally, there is provided a support structure **1015**, which holds an injector **1016**, to facilitate movement of the tubing **1012** in the borehole **1001**. Further other support structures may be employed, for example, such structures could be derrick, crane, mast, tripod, or other similar type of structure or hybrid and combinations of these. As the borehole is advance to greater depths from the surface **1030**, the use of a diverter **1017**, a blow out preventer (BOP) **1018**, and a fluid and/or cutting handling system **1019** may become necessary. The tubing **1012** is passed from the injector **1016** through the diverter **1017**, the BOP **1018**, a wellhead **1020** and into the borehole **1001**.

[0070] The fluid is conveyed to the bottom **1021** of the borehole **1001**. At that point the fluid exits at or near the bottom hole assembly **1014** and is used, among other things, to carry the cuttings, which are created from advancing a borehole, back up and out of the borehole. Thus, the diverter **1017** directs the fluid as it returns carrying the cuttings to the fluid and/or cuttings handling system **1019** through connector **1022**. This handling system **1019** is intended to prevent waste products from escaping into the environment and separates and cleans waste products and either vents the cleaned fluid to the air, if permissible environmentally and economically, as would be the case if the fluid was nitrogen, or returns the cleaned fluid to the source of fluid **1010**, or otherwise contains the used fluid for later treatment and/or disposal.

[0071] The BOP **1018** serves to provide multiple levels of emergency shut off and/or containment of the borehole should a high-pressure event occur in the borehole, such as a potential blow-out of the well. The BOP is affixed to the wellhead **1020**. The wellhead in turn may be attached to casing. For the purposes of simplification the structural components of a borehole such as casing, hangers, and cement are not shown. It is understood that these components may be used and will vary based upon the depth, type, and geology of the borehole, as well as, other factors.

[0072] The downhole end **1023** of the tubing **1012** is connected to the bottom hole assembly **1014**. The bottom hole assembly **1014** contains optics for delivering the laser beam **1024** to its intended target, in the case of FIG. **1**, the bottom **1021** of the borehole **1001**. The bottom hole assembly **1014**, for example, also contains means for delivering the fluid.

[0073] Thus, in general this system operates to create and/or advance a borehole by having the laser create laser energy in the form of a laser beam. The laser beam is then transmitted from the laser through the spool and into the tubing. At which point, the laser beam is then transmitted to the bottom hole assembly where it is directed toward the surfaces of the earth and/or borehole.

[0074] Without being bound by the following theory providing an explanation for the synergistic effects the present method obtains, and without being bound by the following theory of energy-rock interaction, physics and thermodynamics, the following theory is offered by way of illustration and to assist in the understanding of, and explanation for, the surprising and never before obtained results of these methods.

[0075] Thus, this process can be viewed as a hybrid thermal/mechanical process in which thermally-induced compressive stresses are generated in a thin skin of rock at the drilling surface. These thermally induced stresses create fractures parallel to the surface of the rock and give rise to rock removal from the borehole via chips of material. Mechanical cutter action is present primarily to ensure continuous removal of the fractured material, which in the presence of laser energy only might not be completely expelled from the surface. The physics of the process and experimental and theoretical results indicate that higher rates of penetration can be achieved by increases in laser power delivered to the drilling surface.

[0076] When laser power is absorbed by a rock, the response depends on both the intensity of the impinging laser power, as well as, the illumination time. As shown in the chart of FIG. **3**, the material response can generally include several regimes, which may be generally classified as: an ultrafast regime **310**, a heating regime **320**, a melting regime **330**, and a vaporization regime **340**. Various processes may occur along these regimes, such as shock hardening **341**, drilling **342**, glazing **331**, cutting **332**, welding **333**, cladding **334**, stereo lithography **321**, and transformation hardening **322**. At laser intensities and times below the melting of rock, regime **340**, lies the regime in which spallation or rock fragmentation occur, as shown in regime area **350**. The spallation regime **350** is the preferred area in which it is presently believed that the greatest synergistic benefit for the tailored directed energy mechanical energy process may occur.

[0077] When laser power is absorbed by the rock, a thin layer of rock near the surface of the sample is rapidly heated. The thickness of the layer is determined both by the quantity of absorbed laser power, and the thermal properties of the rock. Rock is a naturally insulating material, which means that the propagation of heat into the rock is slow, and the heated region may by necessity be very near the surface. In an unconstrained rock sample, laser absorption would cause the heated region to expand in volume. However, in a drilling environment, the heated rock is constrained on all sides by the surrounding rock mass, and the result is a thermally induced stress state in the heated section that is compressive in nature.

[0078] When the magnitude of the thermally induced stress reaches a level comparable to the compressive strength of the rock, it induces fracture in the direction of the maximum compressive stress (i.e., parallel to the heated surface). Under sufficiently large stress, these fractures can extend to very long distances until they intersect with the surface, resulting in the formation of chips, in a process known as "spallation". Turning to FIG. **4**, these chips **401**, **402**, **403**, **404** are characterized by a high aspect ratio, e.g., the lateral dimensions 1.48" arrow **411**, and 1.87" arrow **412** are much greater than the thickness 0.140" of chip **404**. These chips, e.g., **401** of FIG. **4** are basalt. Similar characteristics of dolomite chips are shown in FIG. **5**. Thus, chips **501**, **502**, **503**, **504**, **505**, **506**, **507**, **508**, **509**, **510**, and **511** are characterized by a high aspect ratio, e.g., the lateral dimensions 1.06" arrow **521**, and 1.52" arrow **522**, are much greater than the thickness 0.182" of chip **511**.

[0079] However, spallation without a mechanical removal mechanism may be and at time has been shown to be an unreliable drilling solution. Not every rock type spalls (e.g., a spallable limestone is believed to have never been identified, for example), and macroscopic fractures in the rock mass can inhibit the spallation process. Although the generation of thermal stress and stress-induced fracture is likely a universal rock response, the explosive release of spalled chips is presently believed to be material specific.

[0080] The introduction of mechanical action to a primarily thermal process, then, can increase robustness in a synergistic manner by removing the thermally fractured and damaged material without relying on explosive spallation for rock removal. For a combined thermal/mechanical process, a laser represents an ideal directed energy source, as a high flux of energy can be delivered to the rock over a precisely controlled area designed to minimize heat loads on the mechanical cutters. In the preferred method of operation the role of the mechanical cutters is to provide a minimum amount of pressure sufficient to remove the damaged material; and so that they do not otherwise contribute substantially to the rate of material removal.

[0081] The surface temperature of the rock during the process may generally be around 250-650° C., which is the temperature rise sufficient to generate compressive stresses comparable to the strength of the rock; broader ranges are provide in the table of examples and may prove advantageous for various tailored drilling conditions and parameters, Under intense laser power, the surface temperature rise may be sufficient to melt rock directly under the laser beam. This melting would reduce or eliminate the thermal stresses responsible for laser processing, and is therefore preferably a condition to be avoided for this method of processing. Processes whereby the rock surface is melted allowed to cool and then scraped off are contemplated. Such processes do not rely upon a spallation regime and thus may have a broader application to different materials and in particular materials that do not exhibit spallation. Thus, this directed energy mechanical energy process is not material specific.

[0082] The methods provided herein can further be understood by the exemplary conditions and parameters set forth in the examples of Table 1. As used in the Table 1, the headings have the following meanings:

[0083] WOB: Weight on bit. Force applied by the bit. Units of pounds.

[0084] ROP: Rate of penetration. This is the speed of advancement of the drilling surface. Units of feet per hour.

[0085] RPM: Rotation speed of the bit in revolutions per minute.

[0086] Torque: the degree of twist applied by the bit. Units of foot-pounds.

[0087] Mechanical power: The power transmitted to the rock by the bit, given by the equation torque*RPM. Units of kilowatts.

[0088] Ratio of DE/ME: The ratio of directed energy or directed laser energy to mechanical energy is the delivered directed laser energy (DE) divided by the delivered mechanical energy (ME). Dimensionless number.

[0089] DE Power/Area: The directed energy laser power per unit of drilling surface area. Units are Watts per square centimeter.

[0090] ME Power/Area: The delivered mechanical energy power per unit of drilling surface area. Units are Watts per square centimeter.

TABLE 1

Example #	Rock Type	Compressive Strength (ksi)	Sonic Velocity (m/s)	Porosity (%)	Laser Power (kW)	RPM	Hole Diameter (inches)	WOB
1	Sandstone	35	4800	3.8%	5	120	3.25	200
2	Sandstone	35	4800	3.8%	5	240	3.25	1000
3	Sandstone	35	4800	3.8%	5	360	3.25	200
4	Sandstone	35	4800	3.8%	5	720	3.25	2000
5	Sandstone	35	4800	3.8%	10	120	3.25	200
6	Sandstone	35	4800	3.8%	10	240	3.25	1000
7	Sandstone	35	4800	3.8%	10	360	3.25	200
8	Sandstone	35	4800	3.8%	10	720	3.25	2000
9	Sandstone	35	4800	3.8%	10	1200	3.25	500
10	Sandstone	35	4800	3.8%	15	120	3.25	200
11	Sandstone	35	4800	3.8%	15	240	3.25	1000
12	Sandstone	35	4800	3.8%	15	360	3.25	200
13	Sandstone	35	4800	3.8%	15	720	3.25	2000
14	Sandstone	35	4800	3.8%	15	1200	3.25	500
15	Sandstone	35	4800	3.8%	20	120	3.25	200
16	Sandstone	35	4800	3.8%	20	240	3.25	1000
17	Sandstone	35	4800	3.8%	20	360	3.25	200
18	Sandstone	35	4800	3.8%	20	720	3.25	2000
19	Sandstone	35	4800	3.8%	20	1200	3.25	500
20	Sandstone	35	4800	3.8%	25	240	3.25	1000
21	Sandstone	35	4800	3.8%	25	360	3.25	200

TABLE 1-continued

22	Sandstone	35	4800	3.8%	25	720	3.25	2000
23	Sandstone	35	4800	3.8%	25	1200	3.25	500
24	Sandstone	35	4800	3.8%	30	240	3.25	1000
25	Sandstone	35	4800	3.8%	30	360	3.25	200
26	Sandstone	35	4800	3.8%	30	720	3.25	2000
27	Sandstone	35	4800	3.8%	30	1200	3.25	500
28	Sandstone	35	4800	3.8%	10	240	6	1500
29	Sandstone	35	4800	3.8%	10	360	6	3000
30	Sandstone	35	4800	3.8%	10	720	6	2000
31	Sandstone	35	4800	3.8%	10	1200	6	500
32	Sandstone	35	4800	3.8%	20	120	6	500
33	Sandstone	35	4800	3.8%	20	240	6	1500
34	Sandstone	35	4800	3.8%	20	360	6	3000
35	Sandstone	35	4800	3.8%	20	720	6	2000
36	Sandstone	35	4800	3.8%	20	1200	6	500
37	Sandstone	35	4800	3.8%	30	120	6	500
38	Sandstone	35	4800	3.8%	30	240	6	1500
39	Sandstone	35	4800	3.8%	30	360	6	3000
40	Sandstone	35	4800	3.8%	30	720	6	2000
41	Sandstone	35	4800	3.8%	30	1200	6	500
42	Sandstone	35	4800	3.8%	40	120	6	500
43	Sandstone	35	4800	3.8%	40	240	6	1500
44	Sandstone	35	4800	3.8%	40	360	6	3000
45	Sandstone	35	4800	3.8%	40	720	6	2000
46	Sandstone	35	4800	3.8%	40	1200	6	500
47	Sandstone	35	4800	3.8%	50	120	6	500
48	Sandstone	35	4800	3.8%	50	240	6	1500
49	Sandstone	35	4800	3.8%	50	360	6	3000
50	Sandstone	35	4800	3.8%	50	720	6	2000
51	Sandstone	35	4800	3.8%	50	1200	6	500
52	Sandstone	35	4800	3.8%	60	240	6	1500
53	Sandstone	35	4800	3.8%	60	360	6	3000
54	Sandstone	35	4800	3.8%	60	720	6	2000
55	Sandstone	35	4800	3.8%	60	1200	6	500
56	Sandstone	35	4800	3.8%	70	240	6	1500
57	Sandstone	35	4800	3.8%	70	360	6	3000
58	Sandstone	35	4800	3.8%	70	720	6	2000
59	Sandstone	35	4800	3.8%	70	1200	6	500
60	Sandstone	35	4800	3.8%	80	360	6	3000
61	Sandstone	35	4800	3.8%	80	720	6	2000
62	Sandstone	35	4800	3.8%	80	1200	6	500
63	Sandstone	35	4800	3.8%	15	240	8.5	2000
64	Sandstone	35	4800	3.8%	15	360	8.5	3500
65	Sandstone	35	4800	3.8%	15	720	8.5	5000
66	Sandstone	35	4800	3.8%	15	1200	8.5	1000
67	Sandstone	35	4800	3.8%	30	120	8.5	1000
68	Sandstone	35	4800	3.8%	30	240	8.5	2000
69	Sandstone	35	4800	3.8%	30	360	8.5	3500
70	Sandstone	35	4800	3.8%	30	720	8.5	5000
71	Sandstone	35	4800	3.8%	45	120	8.5	1000
72	Sandstone	35	4800	3.8%	45	240	8.5	2000
73	Sandstone	35	4800	3.8%	45	360	8.5	3500
74	Sandstone	35	4800	3.8%	45	720	8.5	5000
75	Sandstone	35	4800	3.8%	45	1200	8.5	1000
76	Sandstone	35	4800	3.8%	60	120	8.5	1000
77	Sandstone	35	4800	3.8%	60	240	8.5	2000
78	Sandstone	35	4800	3.8%	60	360	8.5	3500
79	Sandstone	35	4800	3.8%	60	720	8.5	5000
80	Sandstone	35	4800	3.8%	60	1200	8.5	1000
81	Sandstone	35	4800	3.8%	75	120	8.5	1000
82	Sandstone	35	4800	3.8%	75	240	8.5	2000
83	Sandstone	35	4800	3.8%	75	360	8.5	3500
84	Sandstone	35	4800	3.8%	75	720	8.5	5000
85	Sandstone	35	4800	3.8%	75	1200	8.5	1000
86	Sandstone	35	4800	3.8%	90	120	8.5	1000
87	Sandstone	35	4800	3.8%	90	240	8.5	2000
88	Sandstone	35	4800	3.8%	90	360	8.5	3500
89	Sandstone	35	4800	3.8%	90	720	8.5	5000
90	Sandstone	35	4800	3.8%	90	1200	8.5	1000
91	Sandstone	35	4800	3.8%	105	120	8.5	1000
92	Sandstone	35	4800	3.8%	105	240	8.5	2000
93	Sandstone	35	4800	3.8%	105	360	8.5	3500
94	Sandstone	35	4800	3.8%	105	720	8.5	5000
95	Sandstone	35	4800	3.8%	105	1200	8.5	1000
96	Sandstone	35	4800	3.8%	120	240	8.5	2000
97	Sandstone	35	4800	3.8%	120	360	8.5	3500

TABLE 1-continued

98	Sandstone	35	4800	3.8%	120	720	8.5	5000
99	Sandstone	35	4800	3.8%	120	1200	8.5	1000
100	Dolomite	30	5400	3.2%	5	240	3.25	1000
101	Dolomite	30	5400	3.2%	5	360	3.25	200
102	Dolomite	30	5400	3.2%	5	720	3.25	2000
103	Dolomite	30	5400	3.2%	10	120	3.25	200
104	Dolomite	30	5400	3.2%	10	240	3.25	1000
105	Dolomite	30	5400	3.2%	10	360	3.25	200
106	Dolomite	30	5400	3.2%	10	720	3.25	2000
107	Dolomite	30	5400	3.2%	10	1200	3.25	500
108	Dolomite	30	5400	3.2%	15	120	3.25	200
109	Dolomite	30	5400	3.2%	15	240	3.25	1000
110	Dolomite	30	5400	3.2%	15	360	3.25	200
111	Dolomite	30	5400	3.2%	15	720	3.25	2000
112	Dolomite	30	5400	3.2%	15	1200	3.25	500
113	Dolomite	30	5400	3.2%	20	120	3.25	200
114	Dolomite	30	5400	3.2%	20	240	3.25	1000
115	Dolomite	30	5400	3.2%	20	360	3.25	200
116	Dolomite	30	5400	3.2%	20	720	3.25	2000
117	Dolomite	30	5400	3.2%	20	1200	3.25	500
118	Dolomite	30	5400	3.2%	25	120	3.25	200
119	Dolomite	30	5400	3.2%	25	240	3.25	1000
120	Dolomite	30	5400	3.2%	25	360	3.25	200
121	Dolomite	30	5400	3.2%	25	720	3.25	2000
122	Dolomite	30	5400	3.2%	25	1200	3.25	500
123	Dolomite	30	5400	3.2%	30	120	3.25	200
124	Dolomite	30	5400	3.2%	30	240	3.25	1000
125	Dolomite	30	5400	3.2%	30	360	3.25	200
126	Dolomite	30	5400	3.2%	30	720	3.25	2000
127	Dolomite	30	5400	3.2%	30	1200	3.25	500
128	Dolomite	30	5400	3.2%	10	240	6	1500
129	Dolomite	30	5400	3.2%	10	360	6	3000
130	Dolomite	30	5400	3.2%	10	720	6	2000
131	Dolomite	30	5400	3.2%	10	1200	6	500
132	Dolomite	30	5400	3.2%	20	120	6	500
133	Dolomite	30	5400	3.2%	20	240	6	1500
134	Dolomite	30	5400	3.2%	20	360	6	3000
135	Dolomite	30	5400	3.2%	20	720	6	2000
136	Dolomite	30	5400	3.2%	20	1200	6	500
137	Dolomite	30	5400	3.2%	30	120	6	500
138	Dolomite	30	5400	3.2%	30	240	6	1500
139	Dolomite	30	5400	3.2%	30	360	6	3000
140	Dolomite	30	5400	3.2%	30	720	6	2000
141	Dolomite	30	5400	3.2%	30	1200	6	500
142	Dolomite	30	5400	3.2%	40	120	6	500
143	Dolomite	30	5400	3.2%	40	240	6	1500
144	Dolomite	30	5400	3.2%	40	360	6	3000
145	Dolomite	30	5400	3.2%	40	720	6	2000
146	Dolomite	30	5400	3.2%	40	1200	6	500
147	Dolomite	30	5400	3.2%	50	120	6	500
148	Dolomite	30	5400	3.2%	50	240	6	1500
149	Dolomite	30	5400	3.2%	50	360	6	3000
150	Dolomite	30	5400	3.2%	50	720	6	2000
151	Dolomite	30	5400	3.2%	50	1200	6	500
152	Dolomite	30	5400	3.2%	60	120	6	500
153	Dolomite	30	5400	3.2%	60	240	6	1500
154	Dolomite	30	5400	3.2%	60	360	6	3000
155	Dolomite	30	5400	3.2%	60	720	6	2000
156	Dolomite	30	5400	3.2%	60	1200	6	500
157	Dolomite	30	5400	3.2%	70	120	6	500
158	Dolomite	30	5400	3.2%	70	240	6	1500
159	Dolomite	30	5400	3.2%	70	360	6	3000
160	Dolomite	30	5400	3.2%	70	720	6	2000
161	Dolomite	30	5400	3.2%	70	1200	6	500
162	Dolomite	30	5400	3.2%	80	120	6	500
163	Dolomite	30	5400	3.2%	80	240	6	1500
164	Dolomite	30	5400	3.2%	80	360	6	3000
165	Dolomite	30	5400	3.2%	80	720	6	2000
166	Dolomite	30	5400	3.2%	80	1200	6	500
167	Dolomite	30	5400	3.2%	15	120	8.5	1000
168	Dolomite	30	5400	3.2%	15	240	8.5	2000
169	Dolomite	30	5400	3.2%	15	360	8.5	3500
170	Dolomite	30	5400	3.2%	15	720	8.5	5000
171	Dolomite	30	5400	3.2%	15	1200	8.5	1000
172	Dolomite	30	5400	3.2%	30	120	8.5	1000
173	Dolomite	30	5400	3.2%	30	240	8.5	2000

TABLE 1-continued

174	Dolomite	30	5400	3.2%	30	360	8.5	3500
175	Dolomite	30	5400	3.2%	30	720	8.5	5000
176	Dolomite	30	5400	3.2%	45	120	8.5	1000
177	Dolomite	30	5400	3.2%	45	240	8.5	2000
178	Dolomite	30	5400	3.2%	45	360	8.5	3500
179	Dolomite	30	5400	3.2%	45	720	8.5	5000
180	Dolomite	30	5400	3.2%	60	120	8.5	1000
181	Dolomite	30	5400	3.2%	60	240	8.5	2000
182	Dolomite	30	5400	3.2%	60	360	8.5	3500
183	Dolomite	30	5400	3.2%	60	720	8.5	5000
184	Dolomite	30	5400	3.2%	75	120	8.5	1000
185	Dolomite	30	5400	3.2%	75	240	8.5	2000
186	Dolomite	30	5400	3.2%	75	360	8.5	3500
187	Dolomite	30	5400	3.2%	75	720	8.5	5000
188	Dolomite	30	5400	3.2%	75	1200	8.5	1000
189	Dolomite	30	5400	3.2%	90	120	8.5	1000
190	Dolomite	30	5400	3.2%	90	240	8.5	2000
191	Dolomite	30	5400	3.2%	90	360	8.5	3500
192	Dolomite	30	5400	3.2%	90	720	8.5	5000
193	Dolomite	30	5400	3.2%	90	1200	8.5	1000
194	Dolomite	30	5400	3.2%	105	120	8.5	1000
195	Dolomite	30	5400	3.2%	105	240	8.5	2000
196	Dolomite	30	5400	3.2%	105	360	8.5	3500
197	Dolomite	30	5400	3.2%	105	720	8.5	5000
198	Dolomite	30	5400	3.2%	105	1200	8.5	1000
199	Dolomite	30	5400	3.2%	120	120	8.5	1000
200	Dolomite	30	5400	3.2%	120	240	8.5	2000
201	Dolomite	30	5400	3.2%	120	360	8.5	3500
202	Dolomite	30	5400	3.2%	120	720	8.5	5000
203	Dolomite	30	5400	3.2%	120	1200	8.5	1000
204	Granite	20	4700	1.5%	5	240	3.25	1000
205	Granite	20	4700	1.5%	5	360	3.25	200
206	Granite	20	4700	1.5%	5	720	3.25	2000
207	Granite	20	4700	1.5%	5	1200	3.25	500
208	Granite	20	4700	1.5%	10	120	3.25	200
209	Granite	20	4700	1.5%	10	240	3.25	1000
210	Granite	20	4700	1.5%	10	360	3.25	200
211	Granite	20	4700	1.5%	10	720	3.25	2000
212	Granite	20	4700	1.5%	15	240	3.25	1000
213	Granite	20	4700	1.5%	15	360	3.25	200
214	Granite	20	4700	1.5%	15	720	3.25	2000
215	Granite	20	4700	1.5%	20	720	3.25	2000
216	Granite	20	4700	1.5%	25	720	3.25	2000
217	Granite	20	4700	1.5%	25	1200	3.25	500
218	Granite	20	4700	1.5%	30	720	3.25	2000
219	Granite	20	4700	1.5%	30	1200	3.25	500
220	Granite	20	4700	1.5%	10	120	6	500
221	Granite	20	4700	1.5%	10	240	6	1500
222	Granite	20	4700	1.5%	10	360	6	3000
223	Granite	20	4700	1.5%	10	720	6	2000
224	Granite	20	4700	1.5%	20	120	6	500
225	Granite	20	4700	1.5%	20	240	6	1500
226	Granite	20	4700	1.5%	20	360	6	3000
227	Granite	20	4700	1.5%	20	720	6	2000
228	Granite	20	4700	1.5%	20	1200	6	500
229	Granite	20	4700	1.5%	30	240	6	1500
230	Granite	20	4700	1.5%	30	360	6	3000
231	Granite	20	4700	1.5%	30	720	6	2000
232	Granite	20	4700	1.5%	30	1200	6	500
233	Granite	20	4700	1.5%	40	240	6	1500
234	Granite	20	4700	1.5%	40	360	6	3000
235	Granite	20	4700	1.5%	40	720	6	2000
236	Granite	20	4700	1.5%	40	1200	6	500
237	Granite	20	4700	1.5%	50	360	6	3000
238	Granite	20	4700	1.5%	50	720	6	2000
239	Granite	20	4700	1.5%	50	1200	6	500
240	Granite	20	4700	1.5%	60	720	6	2000
241	Granite	20	4700	1.5%	60	1200	6	500
242	Granite	20	4700	1.5%	70	720	6	2000
243	Granite	20	4700	1.5%	70	1200	6	500
244	Granite	20	4700	1.5%	80	1200	6	500
245	Granite	20	4700	1.5%	15	120	8.5	1000
246	Granite	20	4700	1.5%	15	240	8.5	2000
247	Granite	20	4700	1.5%	15	360	8.5	3500
248	Granite	20	4700	1.5%	15	720	8.5	5000
249	Granite	20	4700	1.5%	30	120	8.5	1000

TABLE 1-continued

250	Granite	20	4700	1.5%	30	240	8.5	2000
251	Granite	20	4700	1.5%	30	360	8.5	3500
252	Granite	20	4700	1.5%	30	720	8.5	5000
253	Granite	20	4700	1.5%	30	1200	8.5	1000
254	Granite	20	4700	1.5%	45	120	8.5	1000
255	Granite	20	4700	1.5%	45	240	8.5	2000
256	Granite	20	4700	1.5%	45	360	8.5	3500
257	Granite	20	4700	1.5%	45	720	8.5	5000
258	Granite	20	4700	1.5%	45	1200	8.5	1000
259	Granite	20	4700	1.5%	60	240	8.5	2000
260	Granite	20	4700	1.5%	60	360	8.5	3500
261	Granite	20	4700	1.5%	60	720	8.5	5000
262	Granite	20	4700	1.5%	75	240	8.5	2000
263	Granite	20	4700	1.5%	75	360	8.5	3500
264	Granite	20	4700	1.5%	75	720	8.5	5000
265	Granite	20	4700	1.5%	90	360	8.5	3500
266	Granite	20	4700	1.5%	90	720	8.5	5000
267	Granite	20	4700	1.5%	105	720	8.5	5000
268	Granite	20	4700	1.5%	120	720	8.5	5000
269	Basalt	40	5100	2.1%	5	120	3.25	200
270	Basalt	40	5100	2.1%	5	240	3.25	1000
271	Basalt	40	5100	2.1%	5	360	3.25	200
272	Basalt	40	5100	2.1%	5	720	3.25	2000
273	Basalt	40	5100	2.1%	10	240	3.25	1000
274	Basalt	40	5100	2.1%	10	360	3.25	200
275	Basalt	40	5100	2.1%	10	720	3.25	2000
276	Basalt	40	5100	2.1%	10	1200	3.25	500
277	Basalt	40	5100	2.1%	15	720	3.25	2000
278	Basalt	40	5100	2.1%	15	1200	3.25	500
279	Basalt	40	5100	2.1%	20	720	3.25	2000
280	Basalt	40	5100	2.1%	20	1200	3.25	500
281	Basalt	40	5100	2.1%	10	240	6	1500
282	Basalt	40	5100	2.1%	10	360	6	3000
283	Basalt	40	5100	2.1%	10	720	6	2000
284	Basalt	40	5100	2.1%	10	1200	6	500
285	Basalt	40	5100	2.1%	20	240	6	1500
286	Basalt	40	5100	2.1%	20	360	6	3000
287	Basalt	40	5100	2.1%	20	720	6	2000
288	Basalt	40	5100	2.1%	20	1200	6	500
289	Basalt	40	5100	2.1%	30	360	6	3000
290	Basalt	40	5100	2.1%	30	720	6	2000
291	Basalt	40	5100	2.1%	30	1200	6	500
292	Basalt	40	5100	2.1%	40	720	6	2000
293	Basalt	40	5100	2.1%	40	1200	6	500
294	Basalt	40	5100	2.1%	50	1200	6	500
295	Basalt	40	5100	2.1%	15	120	8.5	1000
296	Basalt	40	5100	2.1%	15	240	8.5	2000
297	Basalt	40	5100	2.1%	15	360	8.5	3500
298	Basalt	40	5100	2.1%	15	720	8.5	5000
299	Basalt	40	5100	2.1%	15	1200	8.5	1000
300	Basalt	40	5100	2.1%	30	120	8.5	1000
301	Basalt	40	5100	2.1%	30	240	8.5	2000
302	Basalt	40	5100	2.1%	30	360	8.5	3500
303	Basalt	40	5100	2.1%	30	720	8.5	5000
304	Basalt	40	5100	2.1%	45	240	8.5	2000
305	Basalt	40	5100	2.1%	45	360	8.5	3500
306	Basalt	40	5100	2.1%	45	720	8.5	5000
307	Basalt	40	5100	2.1%	45	1200	8.5	1000
308	Basalt	40	5100	2.1%	60	360	8.5	3500
309	Basalt	40	5100	2.1%	60	720	8.5	5000
310	Basalt	40	5100	2.1%	60	1200	8.5	1000
311	Basalt	40	5100	2.1%	75	720	8.5	5000
312	Basalt	40	5100	2.1%	75	1200	8.5	1000
313	Basalt	40	5100	2.1%	90	720	8.5	5000
314	Basalt	40	5100	2.1%	90	1200	8.5	1000
315	Basalt	40	5100	2.1%	105	1200	8.5	1000

Example #	ROP (ft/hr)	Surface Temp. Rise (DegC.)	Torque (ft-lbs)	Mechanical Power (kW)	Ratio of DE/ME	DE Power/Area (W/cm^2)	ME Power/Area (W/cm^2)
1	5.5	434	13.1	0.22	22.3	93.4	4.2
2	6.6	341	65.7	2.24	2.2	93.4	41.8
3	5.7	341	13.1	0.67	7.4	93.4	12.6
4	15.9	170	131.4	13.44	0.4	93.4	251.0
5	10.6	651	13.1	0.22	44.7	186.8	4.2

TABLE 1-continued

6	12.4	504	65.7	2.24	4.5	186.8	41.8
7	11.7	467	13.1	0.67	14.9	186.8	12.6
8	19.4	308	131.4	13.44	0.7	186.8	251.0
9	13.1	338	32.9	5.60	1.8	186.8	104.6
10	14.5	866	13.1	0.22	67.0	280.3	4.2
11	17.1	660	65.7	2.24	6.7	280.3	41.8
12	16.8	592	13.1	0.67	22.3	280.3	12.6
13	24.4	416	131.4	13.44	1.1	280.3	251.0
14	19.2	410	32.9	5.60	2.7	280.3	104.6
15	17.5	1081	13.1	0.22	89.3	373.7	4.2
16	20.9	814	65.7	2.24	8.9	373.7	41.8
17	21.2	717	13.1	0.67	29.8	373.7	12.6
18	29.1	514	131.4	13.44	1.5	373.7	251.0
19	24.9	481	32.9	5.60	3.6	373.7	104.6
20	24.0	968	65.7	2.24	11.2	467.1	41.8
21	24.9	841	13.1	0.67	37.2	467.1	12.6
22	33.4	608	131.4	13.44	1.9	467.1	251.0
23	30.0	550	32.9	5.60	4.5	467.1	104.6
24	26.6	1121	65.7	2.24	13.4	560.5	41.8
25	28.1	965	13.1	0.67	44.7	560.5	12.6
26	37.2	700	131.4	13.44	2.2	560.5	251.0
27	34.8	619	32.9	5.60	5.4	560.5	104.6
28	3.7	311	182.0	6.20	1.6	54.8	34.0
29	6.5	217	364.0	18.60	0.5	54.8	102.0
30	5.6	204	242.6	24.80	0.4	54.8	136.0
31	3.4	257	60.7	10.34	1.0	54.8	56.7
32	6.6	575	60.7	1.03	19.4	109.6	5.7
33	7.4	451	182.0	6.20	3.2	109.6	34.0
34	9.7	362	364.0	18.60	1.1	109.6	102.0
35	9.2	312	242.6	24.80	0.8	109.6	136.0
36	7.2	322	60.7	10.34	1.9	109.6	56.7
37	9.6	754	60.7	1.03	29.0	164.5	5.7
38	10.8	582	182.0	6.20	4.8	164.5	34.0
39	13.1	480	364.0	18.60	1.6	164.5	102.0
40	12.9	398	242.6	24.80	1.2	164.5	136.0
41	11.0	381	60.7	10.34	2.9	164.5	56.7
42	12.2	933	60.7	1.03	38.7	219.3	5.7
43	13.8	711	182.0	6.20	6.5	219.3	34.0
44	16.3	591	364.0	18.60	2.2	219.3	102.0
45	16.4	478	242.6	24.80	1.6	219.3	136.0
46	14.6	439	60.7	10.34	3.9	219.3	56.7
47	14.3	1112	60.7	1.03	48.4	274.1	5.7
48	16.5	839	182.0	6.20	8.1	274.1	34.0
49	19.2	699	364.0	18.60	2.7	274.1	102.0
50	19.8	555	242.6	24.80	2.0	274.1	136.0
51	18.1	497	60.7	10.34	4.8	274.1	56.7
52	18.9	966	182.0	6.20	9.7	328.9	34.0
53	21.8	805	364.0	18.60	3.2	328.9	102.0
54	22.9	630	242.6	24.80	2.4	328.9	136.0
55	21.5	554	60.7	10.34	5.8	328.9	56.7
56	21.0	1093	182.0	6.20	11.3	383.7	34.0
57	24.2	910	364.0	18.60	3.8	383.7	102.0
58	25.8	705	242.6	24.80	2.8	383.7	136.0
59	24.7	611	60.7	10.34	6.8	383.7	56.7
60	26.3	1015	364.0	18.60	4.3	438.6	102.0
61	28.5	780	242.6	24.80	3.2	438.6	136.0
62	27.8	668	60.7	10.34	7.7	438.6	56.7
63	2.7	274	343.8	11.71	1.3	41.0	32.0
64	4.5	195	601.6	30.75	0.5	41.0	84.0
65	14.6	94	859.4	87.85	0.2	41.0	240.0
66	2.6	224	171.9	29.28	0.5	41.0	80.0
67	4.9	481	171.9	2.93	10.2	81.9	8.0
68	5.5	385	343.8	11.71	2.6	81.9	32.0
69	7.0	313	601.6	30.75	1.0	81.9	84.0
70	14.5	188	859.4	87.85	0.3	81.9	240.0
71	7.4	616	171.9	2.93	15.4	122.9	8.0
72	8.2	485	343.8	11.71	3.8	122.9	32.0
73	9.7	405	601.6	30.75	1.5	122.9	84.0
74	15.5	274	859.4	87.85	0.5	122.9	240.0
75	8.4	330	171.9	29.28	1.5	122.9	80.0
76	9.6	750	171.9	2.93	20.5	163.9	8.0
77	10.7	582	343.8	11.71	5.1	163.9	32.0
78	12.3	490	601.6	30.75	2.0	163.9	84.0
79	17.4	349	859.4	87.85	0.7	163.9	240.0
80	11.2	375	171.9	29.28	2.0	163.9	80.0
81	11.6	884	171.9	2.93	25.6	204.9	8.0

TABLE 1-continued

82	13.0	678	343.8	11.71	6.4	204.9	32.0
83	14.7	572	601.6	30.75	2.4	204.9	84.0
84	19.6	416	859.4	87.85	0.9	204.9	240.0
85	14.0	419	171.9	29.28	2.6	204.9	80.0
86	13.3	1018	171.9	2.93	30.7	245.8	8.0
87	15.1	774	343.8	11.71	7.7	245.8	32.0
88	17.0	652	601.6	30.75	2.9	245.8	84.0
89	21.9	479	859.4	87.85	1.0	245.8	240.0
90	16.7	463	171.9	29.28	3.1	245.8	80.0
91	14.9	1152	171.9	2.93	35.9	286.8	8.0
92	17.0	869	343.8	11.71	9.0	286.8	32.0
93	19.1	731	601.6	30.75	3.4	286.8	84.0
94	24.2	539	859.4	87.85	1.2	286.8	240.0
95	19.3	506	171.9	29.28	3.6	286.8	80.0
96	18.8	964	343.8	11.71	10.2	327.8	32.0
97	21.1	810	601.6	30.75	3.9	327.8	84.0
98	26.3	598	859.4	87.85	1.4	327.8	240.0
99	21.8	549	171.9	29.28	4.1	327.8	80.0
100	5.1	207	65.7	2.24	2.2	93.4	41.8
101	4.1	218	13.1	0.67	7.4	93.4	12.6
102	21.7	79	131.4	13.44	0.4	93.4	251.0
103	7.7	406	13.1	0.22	44.7	186.8	4.2
104	9.2	310	65.7	2.24	4.5	186.8	41.8
105	8.3	295	13.1	0.67	14.9	186.8	12.6
106	21.6	159	131.4	13.44	0.7	186.8	251.0
107	9.7	211	32.9	5.60	1.8	186.8	104.6
108	10.6	536	13.1	0.22	67.0	280.3	4.2
109	12.7	406	65.7	2.24	6.7	280.3	41.8
110	12.1	371	13.1	0.67	22.3	280.3	12.6
111	22.9	232	131.4	13.44	1.1	280.3	251.0
112	14.1	256	32.9	5.60	2.7	280.3	104.6
113	12.9	666	13.1	0.22	89.3	373.7	4.2
114	15.6	500	65.7	2.24	8.9	373.7	41.8
115	15.4	446	13.1	0.67	29.8	373.7	12.6
116	25.4	298	131.4	13.44	1.5	373.7	251.0
117	18.3	300	32.9	5.60	3.6	373.7	104.6
118	14.7	796	13.1	0.22	111.6	467.1	4.2
119	18.0	593	65.7	2.24	11.2	467.1	41.8
120	18.2	521	13.1	0.67	37.2	467.1	12.6
121	28.0	358	131.4	13.44	1.9	467.1	251.0
122	22.1	342	32.9	5.60	4.5	467.1	104.6
123	16.2	926	13.1	0.22	134.0	560.5	4.2
124	20.0	686	65.7	2.24	13.4	560.5	41.8
125	20.7	596	13.1	0.67	44.7	560.5	12.6
126	30.5	416	131.4	13.44	2.2	560.5	251.0
127	25.6	384	32.9	5.60	5.4	560.5	104.6
128	2.9	187	182.0	6.20	1.6	54.8	34.0
129	8.2	106	364.0	18.60	0.5	54.8	102.0
130	6.4	100	242.6	24.80	0.4	54.8	136.0
131	2.5	161	60.7	10.34	1.0	54.8	56.7
132	4.7	359	60.7	1.03	19.4	109.6	5.7
133	5.5	278	182.0	6.20	3.2	109.6	34.0
134	9.0	203	364.0	18.60	1.1	109.6	102.0
135	8.0	179	242.6	24.80	0.8	109.6	136.0
136	5.2	203	60.7	10.34	1.9	109.6	56.7
137	6.9	468	60.7	1.03	29.0	164.5	5.7
138	8.0	359	182.0	6.20	4.8	164.5	34.0
139	11.0	282	364.0	18.60	1.6	164.5	102.0
140	10.4	237	242.6	24.80	1.2	164.5	136.0
141	7.9	240	60.7	10.34	2.9	164.5	56.7
142	8.8	577	60.7	1.03	38.7	219.3	5.7
143	10.2	438	182.0	6.20	6.5	219.3	34.0
144	13.1	353	364.0	18.60	2.2	219.3	102.0
145	12.9	288	242.6	24.80	1.6	219.3	136.0
146	10.5	276	60.7	10.34	3.9	219.3	56.7
147	10.5	685	60.7	1.03	48.4	274.1	5.7
148	12.2	516	182.0	6.20	8.1	274.1	34.0
149	15.2	420	364.0	18.60	2.7	274.1	102.0
150	15.3	337	242.6	24.80	2.0	274.1	136.0
151	13.1	311	60.7	10.34	4.8	274.1	56.7
152	11.9	792	60.7	1.03	58.1	328.9	5.7
153	14.0	593	182.0	6.20	9.7	328.9	34.0
154	17.0	486	364.0	18.60	3.2	328.9	102.0
155	17.5	384	242.6	24.80	2.4	328.9	136.0
156	15.5	346	60.7	10.34	5.8	328.9	56.7
157	13.1	900	60.7	1.03	67.7	383.7	5.7

TABLE 1-continued

158	15.6	670	182.0	6.20	11.3	383.7	34.0
159	18.8	551	364.0	18.60	3.8	383.7	102.0
160	19.6	430	242.6	24.80	2.8	383.7	136.0
161	17.9	381	60.7	10.34	6.8	383.7	56.7
162	14.2	1008	60.7	1.03	77.4	438.6	5.7
163	17.1	747	182.0	6.20	12.9	438.6	34.0
164	20.3	615	364.0	18.60	4.3	438.6	102.0
165	21.6	476	242.6	24.80	3.2	438.6	136.0
166	20.1	415	60.7	10.34	7.7	438.6	56.7
167	1.5	215	171.9	2.93	5.1	41.0	8.0
168	2.2	162	343.8	11.71	1.3	41.0	32.0
169	5.5	94	601.6	30.75	0.5	41.0	84.0
170	19.7	46	859.4	87.85	0.2	41.0	240.0
171	2.1	133	171.9	29.28	0.5	41.0	80.0
172	3.5	301	171.9	2.93	10.2	81.9	8.0
173	4.1	236	343.8	11.71	2.6	81.9	32.0
174	6.3	176	601.6	30.75	1.0	81.9	84.0
175	19.8	92	859.4	87.85	0.3	81.9	240.0
176	5.3	384	171.9	2.93	15.4	122.9	8.0
177	6.1	299	343.8	11.71	3.8	122.9	32.0
178	8.0	239	601.6	30.75	1.5	122.9	84.0
179	19.7	138	859.4	87.85	0.5	122.9	240.0
180	7.0	465	171.9	2.93	20.5	163.9	8.0
181	7.9	359	343.8	11.71	5.1	163.9	32.0
182	9.8	294	601.6	30.75	2.0	163.9	84.0
183	19.7	183	859.4	87.85	0.7	163.9	240.0
184	8.4	546	171.9	2.93	25.6	204.9	8.0
185	9.6	418	343.8	11.71	6.4	204.9	32.0
186	11.5	345	601.6	30.75	2.4	204.9	84.0
187	20.1	228	859.4	87.85	0.9	204.9	240.0
188	10.2	262	171.9	29.28	2.6	204.9	80.0
189	9.7	627	171.9	2.93	30.7	245.8	8.0
190	11.2	476	343.8	11.71	7.7	245.8	32.0
191	13.2	395	601.6	30.75	2.9	245.8	84.0
192	20.9	270	859.4	87.85	1.0	245.8	240.0
193	12.1	289	171.9	29.28	3.1	245.8	80.0
194	10.9	708	171.9	2.93	35.9	286.8	8.0
195	12.6	534	343.8	11.71	9.0	286.8	32.0
196	14.7	444	601.6	30.75	3.4	286.8	84.0
197	21.9	310	859.4	87.85	1.2	286.8	240.0
198	14.0	316	171.9	29.28	3.6	286.8	80.0
199	11.9	789	171.9	2.93	41.0	327.8	8.0
200	13.9	592	343.8	11.71	10.2	327.8	32.0
201	16.1	493	601.6	30.75	3.9	327.8	84.0
202	23.1	348	859.4	87.85	1.4	327.8	240.0
203	15.8	342	171.9	29.28	4.1	327.8	80.0
204	7.3	481	65.7	2.24	2.2	93.4	41.8
205	5.2	507	13.1	0.67	7.4	93.4	12.6
206	47.9	177	131.4	13.44	0.4	93.4	251.0
207	7.4	331	32.9	5.60	0.9	93.4	104.6
208	8.7	1097	13.1	0.22	44.7	186.8	4.2
209	11.5	800	65.7	2.24	4.5	186.8	41.8
210	10.2	748	13.1	0.67	14.9	186.8	12.6
211	48.4	354	131.4	13.44	0.7	186.8	251.0
212	14.7	1099	65.7	2.24	6.7	280.3	41.8
213	14.0	985	13.1	0.67	22.3	280.3	12.6
214	48.7	530	131.4	13.44	1.1	280.3	251.0
215	48.8	706	131.4	13.44	1.5	373.7	251.0
216	48.8	883	131.4	13.44	1.9	467.1	251.0
217	26.2	898	32.9	5.60	4.5	467.1	104.6
218	48.7	1060	131.4	13.44	2.2	560.5	251.0
219	29.5	1030	32.9	5.60	5.4	560.5	104.6
220	2.8	606	60.7	1.03	9.7	54.8	5.7
221	4.4	423	182.0	6.20	1.6	54.8	34.0
222	18.5	232	364.0	18.60	0.5	54.8	102.0
223	14.3	197	242.6	24.80	0.4	54.8	136.0
224	5.7	951	60.7	1.03	19.4	109.6	5.7
225	7.4	701	182.0	6.20	3.2	109.6	34.0
226	18.4	464	364.0	18.60	1.1	109.6	102.0
227	14.4	393	242.6	24.80	0.8	109.6	136.0
228	7.0	465	60.7	10.34	1.9	109.6	56.7
229	10.0	953	182.0	6.20	4.8	164.5	34.0
230	18.5	695	364.0	18.60	1.6	164.5	102.0
231	15.9	570	242.6	24.80	1.2	164.5	136.0
232	10.3	580	60.7	10.34	2.9	164.5	56.7
233	12.2	1199	182.0	6.20	6.5	219.3	34.0

TABLE 1-continued

234	19.2	917	364.0	18.60	2.2	219.3	102.0
235	18.1	730	242.6	24.80	1.6	219.3	136.0
236	13.4	692	60.7	10.34	3.9	219.3	56.7
237	20.4	1130	364.0	18.60	2.7	274.1	102.0
238	20.3	882	242.6	24.80	2.0	274.1	136.0
239	16.3	801	60.7	10.34	4.8	274.1	56.7
240	22.3	1029	242.6	24.80	2.4	328.9	136.0
241	19.0	910	60.7	10.34	5.8	328.9	56.7
242	24.2	1173	242.6	24.80	2.8	383.7	136.0
243	21.5	1019	60.7	10.34	6.8	383.7	56.7
244	23.8	1127	60.7	10.34	7.7	438.6	56.7
245	2.1	503	171.9	2.93	5.1	41.0	8.0
246	3.5	347	343.8	11.71	1.3	41.0	32.0
247	12.6	193	601.6	30.75	0.5	41.0	84.0
248	43.5	110	859.4	87.85	0.2	41.0	240.0
249	4.5	770	171.9	2.93	10.2	81.9	8.0
250	5.7	573	343.8	11.71	2.6	81.9	32.0
251	12.5	387	601.6	30.75	1.0	81.9	84.0
252	43.9	219	859.4	87.85	0.3	81.9	240.0
253	5.8	381	171.9	29.28	1.0	81.9	80.0
254	6.5	1028	171.9	2.93	15.4	122.9	8.0
255	7.9	767	343.8	11.71	3.8	122.9	32.0
256	13.0	573	601.6	30.75	1.5	122.9	84.0
257	44.1	328	859.4	87.85	0.5	122.9	240.0
258	8.4	477	171.9	29.28	1.5	122.9	80.0
259	9.9	955	343.8	11.71	5.1	163.9	32.0
260	14.2	744	601.6	30.75	2.0	163.9	84.0
261	44.3	437	859.4	87.85	0.7	163.9	240.0
262	11.6	1138	343.8	11.71	6.4	204.9	32.0
263	15.6	906	601.6	30.75	2.4	204.9	84.0
264	44.5	546	859.4	87.85	0.9	204.9	240.0
265	17.0	1062	601.6	30.75	2.9	245.8	84.0
266	44.6	655	859.4	87.85	1.0	245.8	240.0
267	44.6	764	859.4	87.85	1.2	286.8	240.0
268	44.6	874	859.4	87.85	1.4	327.8	240.0
269	4.0	1122	13.1	0.22	22.3	93.4	4.2
270	4.8	868	65.7	2.24	2.2	93.4	41.8
271	4.2	849	13.1	0.67	7.4	93.4	12.6
272	12.1	432	131.4	13.44	0.4	93.4	251.0
273	8.8	1339	65.7	2.24	4.5	186.8	41.8
274	8.4	1219	13.1	0.67	14.9	186.8	12.6
275	14.3	803	131.4	13.44	0.7	186.8	251.0
276	9.7	851	32.9	5.60	1.8	186.8	104.6
277	17.6	1107	131.4	13.44	1.1	280.3	251.0
278	14.1	1061	32.9	5.60	2.7	280.3	104.6
279	20.6	1388	131.4	13.44	1.5	373.7	251.0
280	17.9	1265	32.9	5.60	3.6	373.7	104.6
281	2.7	782	182.0	6.20	1.6	54.8	34.0
282	4.9	549	364.0	18.60	0.5	54.8	102.0
283	4.2	501	242.6	24.80	0.4	54.8	136.0
284	2.4	613	60.7	10.34	1.0	54.8	56.7
285	5.4	1185	182.0	6.20	3.2	109.6	34.0
286	7.1	949	364.0	18.60	1.1	109.6	102.0
287	6.8	798	242.6	24.80	0.8	109.6	136.0
288	5.3	798	60.7	10.34	1.9	109.6	56.7
289	9.5	1286	364.0	18.60	1.6	164.5	102.0
290	9.5	1041	242.6	24.80	1.2	164.5	136.0
291	8.1	971	60.7	10.34	2.9	164.5	56.7
292	12.0	1270	242.6	24.80	1.6	219.3	136.0
293	10.8	1141	60.7	10.34	3.9	219.3	56.7
294	13.3	1309	60.7	10.34	4.8	274.1	56.7
295	1.5	856	171.9	2.93	5.1	41.0	8.0
296	1.9	674	343.8	11.71	1.3	41.0	32.0
297	3.4	482	601.6	30.75	0.5	41.0	84.0
298	11.1	244	859.4	87.85	0.2	41.0	240.0
299	1.9	527	171.9	29.28	0.5	41.0	80.0
300	3.5	1262	171.9	2.93	10.2	81.9	8.0
301	4.0	991	343.8	11.71	2.6	81.9	32.0
302	5.1	805	601.6	30.75	1.0	81.9	84.0
303	11.1	488	859.4	87.85	0.3	81.9	240.0
304	5.9	1282	343.8	11.71	3.8	122.9	32.0
305	7.1	1065	601.6	30.75	1.5	122.9	84.0
306	11.7	719	859.4	87.85	0.5	122.9	240.0
307	6.2	826	171.9	29.28	1.5	122.9	80.0
308	8.9	1309	601.6	30.75	2.0	163.9	84.0
309	12.9	924	859.4	87.85	0.7	163.9	240.0

TABLE 1-continued

310	8.3	957	171.9	29.28	2.0	163.9	80.0
311	14.4	1112	859.4	87.85	0.9	204.9	240.0
312	10.3	1086	171.9	29.28	2.6	204.9	80.0
313	15.9	1292	859.4	87.85	1.0	245.8	240.0
314	12.2	1213	171.9	29.28	3.1	245.8	80.0
315	14.1	1339	171.9	29.28	3.6	286.8	80.0

[0091] In these examples of drilling conditions and parameters, the laser power is to be delivered to the rock surface. The examples are for use with air as the fluid for drilling, and may be utilized with, by way of example, the bits and systems that are described in FIGS. **1**A-C and **2** of this specification and with the bits and systems disclosed and taught in U.S. patent applications Ser. No. 61/446,043 and co-filed patent application having attorney docket no. 13938/79 (Foro s13a).

[0092] Thus, from the forgoing examples, which provide various illustrative laser-mechanical drilling conditions and parameters, there is contemplated generally, and by way of further example, a method of laser-mechanical drilling a borehole in a formation having at least 500 feet, at least about 1,000 ft, at least about 5,000 and at least about 10,000 feet of material having a hardness greater than about 15 ksi, greater than about 20 ksi, greater than about 30 ksi, and greater than about 40 ksi and at drilling rates, e.g., ROP, of at least about 10 ft/hr, at least about 20 ft/hr, at least about 30 ft/hr and at least about 40 ft/hr. Such methods in generally would include, by way of example, drilling under the following conditions and parameters: (i) an RPM of from about 240 to about 720, a WOB of less than about 2,000 lbs, a DE Power/Area of about 90 W/cm^2 to about 560 W/cm^2, and an ME Power/Area of about 4 W/cm^2 to about 250 W/cm^2; (ii) an RPM of from about 600 to about 800, a WOB of less than about 5,000 lbs, a DE Power/Area of about 40 W/cm^2 to about 250 W/cm^2, and an ME Power/Area of about 200 W/cm^2 to about 3000 W/cm^2; (iii) an RPM of from about 600 to about 1250, a WOB of from about 500 to about 5,000 lbs, a DE Power/Area of about 90 W/cm^2 to about 570 W/cm^2, and an ME Power/Area of about 40 W/cm^2 to about 270 W/cm^2; (iv) an RPM of about 250, a WOB of from about 1,000 lbs, a DE Power/Area of about 370 W/cm^2, and an ME Power/Area of about 40 W/cm^2; (v) an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 190 W/cm^2, and an ME Power/Area of about 250 W/cm^2; (vi) an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 370 W/cm^2, and an ME Power/Area of about 250 W/cm^2; (vii) an RPM of from about 720, a WOB of from about 5,000 lbs, a DE Power/Area of about 290 W/cm^2, and an ME Power/Area of about 240 W/cm^2; (viii) an RPM of from about 1,200, a WOB of from about 500 lbs, a DE Power/Area of about 470 W/cm^2, and an ME Power/Area of about 100 W/cm^2; (ix) an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 470 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and, combinations and variations of these.

[0093] Many other uses for the present inventions may be developed or realized and thus, the scope of the present inventions is not limited to the foregoing examples, uses conditions, and applications. For example, in addition to the foregoing examples and embodiments, the implementation of these directed/mechanical energy processes may find applications in down hole tools, and may also be utilized in holes openers, perforators, reamers, whipstocks, and other types of boring tools.

[0094] The present inventions may be embodied in other forms than those specifically disclosed herein without departing from their spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive.

What is claimed:

1. A method of directed energy mechanical drilling comprising:
a. providing directed energy to a surface of a material;
b. providing mechanical energy to the surface; and,
c. wherein the ratio of directed energy to mechanical energy is greater than about 5; and,
d. whereby a borehole is advance through the surface of the material.

2. A method directed energy mechanical drilling comprising:
a. providing directed energy to a surface of a material;
b. providing mechanical energy to the surface; and,
c. wherein the ratio of directed energy to mechanical energy is greater than about 10; and,
d. whereby a borehole is advance through the surface of the material.

3. A method of directed energy mechanical drilling comprising:
a. providing directed energy to a surface of a material;
b. providing mechanical energy to the surface; and,
c. wherein the ratio of directed energy to mechanical energy is greater than about 20; and,
d. whereby a borehole is advance through the surface of the material.

4. A method of directed energy mechanical drilling comprising:
a. providing directed energy to a surface of a material;
b. providing mechanical energy to the surface; and,
c. wherein the ratio of directed energy to mechanical energy is greater than about 40; and,
d. whereby a borehole is advance through the surface of the material.

5. A directed energy mechanical drilling comprising:
a. providing directed energy to a surface;
b. providing mechanical energy to the surface; and,
c. wherein the ratio of directed energy to mechanical energy is greater than about 2; and,
d. whereby a borehole is advance through the surface of the material.

6. A method of directed energy mechanical drilling comprising:
a. providing high power laser directed energy to a surface of a material;
b. providing mechanical energy to the surface; and,

c. wherein the ratio of high power laser directed energy to mechanical energy is greater than about 5; and,

d. whereby a borehole is advance through the surface of the material.

7. A method directed energy mechanical drilling comprising:

a. providing high power laser directed energy to a surface of a material;

b. providing mechanical energy to the surface; and,

c. wherein the ratio of high power laser directed energy to mechanical energy is greater than about 10; and,

d. whereby a borehole is advance through the surface of the material.

8. A method of directed energy mechanical drilling comprising:

a. providing high power laser directed energy to a surface of a material;

b. providing mechanical energy to the surface; and,

c. wherein the ratio of high power laser directed energy to mechanical energy is greater than about 20; and,

d. whereby a borehole is advance through the surface of the material.

9. A method of directed energy mechanical drilling comprising:

a. providing high power laser directed energy to a surface of a material;

b. providing mechanical energy to the surface; and,

c. wherein the ratio of high power laser directed energy to mechanical energy is greater than about 40; and,

d. whereby a borehole is advance through the surface of the material.

10. A directed energy mechanical drilling comprising:

a. providing high power laser directed energy to a surface;

b. providing mechanical energy to the surface; and,

c. wherein the ratio of directed energy to mechanical energy is greater than about 2; and,

d. whereby a borehole is advance through the surface of the material.

11. The method of claim 6, wherein the high power laser directed energy has a power of at least about 40 kW.

12. The method of claim 8, wherein the surface is not substantially melted by the laser energy.

13. The method of claim 8, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds.

14. The method of claim 9, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 1000 pounds.

15. The method of claim 11, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 1000 pounds.

16. The methods of claim 9, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 10 feet per hour.

17. The methods of claim 11, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 10 feet per hour.

18. The methods of claim 6, wherein the high power laser directed energy has a power of at least about 20 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 20 feet per hour.

19. The methods of claim 8, wherein the high power laser directed energy has a power of at least about 20 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 20 feet per hour.

20. The methods of claim 10, wherein the high power laser directed energy has a power of at least about 20 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 20 feet per hour.

21. The methods of claim 8, wherein the high power laser directed energy has a power of at least about 50 kW and the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 20 feet per hour.

22. The methods of claim 6, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration the rate of penetration of at least about 20 feet per hour through material having an average hardness of about 20 ksi or greater.

23. The method of claim 6, wherein the borehole is advanced for greater than about 500 feet.

24. The methods of claim 9, wherein the borehole is advanced for greater than about 5,000 feet.

25. A method of advancing a borehole in the earth using high power laser mechanical drilling techniques, the method comprising:

a. directing laser energy, in a moving pattern, to a bottom surface of a borehole in the earth;

b. heating the earth with the directed laser energy to a point below the melting point;

c. providing mechanical energy to the heated earth;

d. wherein the ratio of laser energy to mechanical energy is greater than about 2; and,

e. whereby the borehole is advanced

26. The method of claim 25, wherein the laser energy has a power of about 20 kW or greater.

27. The method of claim 25, wherein the power/area of the laser energy on the surface of the bottom of the borehole is about 50 W/cm^2 or greater.

28. The method of claim 25, wherein the power/area of the laser energy on the surface of the bottom of the borehole is about 75 W/cm^2 or greater.

29. The method of claim 25, wherein the power/area of the laser energy on the surface of the bottom of the borehole is about 100 W/cm^2 or greater.

30. The method of claim 25, wherein the power/area of the laser energy on the surface of the bottom of the borehole is about 200 W/cm^2 or greater.

31. The method of claim 25, wherein the power/area of the laser energy on the surface of the bottom of the borehole is about 300 W/cm^2 or greater.

32. The method of claim 29, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds.

33. The method of claim **30**, wherein mechanical energy is provided by a bit having a weight-on-bit less than about 1000 pounds.

34. The method of claim **28**, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 10 feet per hour.

35. The method of claim **28**, wherein the mechanical energy is provided by a bit having a weight-on-bit, wherein the weight-on-bit is less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 20 feet per hour.

36. The method of claim **30**, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein borehole is advances at a rate of penetration of at least about 10 feet per hour through material having an average hardness of about 20 ksi or greater.

37. The method of claim **30**, wherein the mechanical energy is provided by a bit having a weight-on-bit less than about 2000 pounds and wherein the borehole is advanced at a rate of penetration of at least about 20 feet per hour through material having an average hardness of about 20 ksi or greater.

38. The method of claim **36**, wherein the borehole is advanced for greater than about 1,000 feet.

39. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of material having a hardness greater than about 30 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole while propagating a laser beam against the borehole surface; with an RPM of from about 240 to about 720, a WOB of less than about 2,000 lbs, a DE Power/Area of about 90 W/cm^2 to about 560 W/cm^2, and an ME Power/Area of about 4 W/cm^2 to about 250 W/cm^2;

c. whereby the borehole is advanced at an ROP of at least about 10 ft/hr.

40. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of material having a hardness greater than about 30 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole while propagating a laser beam against the borehole surface; with an RPM of from about 600 to about 800, a WOB of less than about 5,000 lbs, a DE Power/Area of about 40 W/cm^2 to about 250 W/cm^2, and an ME Power/Area of about 200 W/cm^2 to about 3000 W/cm^2;

c. whereby the borehole is advanced at an ROP of at least about 15 ft/hr.

41. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of material having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole while propagating a laser beam against the borehole surface; with an RPM of from about 600 to about 1250, a WOB of from about 500 to about 5,000 lbs, a DE Power/Area of about 90 W/cm^2 to about 570 W/cm^2, and an ME Power/Area of about 40 W/cm^2 to about 270 W/cm^2;

c. whereby the borehole is advanced at an ROP of at least about 10.

42. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole with an RPM of about 250, a WOB of from about 1,000 lbs, a DE Power/Area of about 370 W/cm^2, and an ME Power/Area of about 40 W/cm^2; and,

c. whereby the borehole is advanced at an ROP of at least about 20 ft/hr.

43. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 190 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and,

c. whereby the borehole is advanced at an ROP of at least about 50 ft/hr.

44. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 370 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and,

c. whereby the borehole is advanced at an ROP of at least about 50 ft/hr.

45. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 5,000 lbs, a DE Power/Area of about 290 W/cm^2, and an ME Power/Area of about 240 W/cm^2; and,

c. whereby the borehole is advanced at an ROP of at least about 20 ft/hr.

46. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 1,200, a WOB of from about 500 lbs, a DE Power/Area of about 470 W/cm^2, and an ME Power/Area of about 100 W/cm^2; and,

c. whereby the borehole is advanced at an ROP of at least about 30 ft/hr.

47. A method of laser-mechanical drilling a borehole in a formation having at least 500 feet of hard rock material, having a hardness greater than about 20 ksi, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. rotating the laser-mechanical bit against a surface of the borehole with an RPM of from about 720, a WOB of from about 2,000 lbs, a DE Power/Area of about 470 W/cm^2, and an ME Power/Area of about 250 W/cm^2; and,

c. whereby the borehole is advanced at an ROP of at least about 30 ft/hr.

48. A method of laser-mechanical drilling a borehole in a formation, the method comprising:

a. providing a laser-mechanical bit into a borehole, the laser-mechanical bit in optical communication with a high power laser beam source;

b. applying from the high power laser beam source a high power laser beam to a surface of the borehole, wherein the high power laser beam generates an intensity ranging from about 150 to about 250 W/cm^2 on a surface of the borehole for an elapsed time sufficient to cause a surface temperature rise in the range from about 400 degrees C. to about 1,000 degrees C., whereby a laser applied surface is formed;

c. applying a mechanical force to the laser applied surface, wherein the mechanical force generates an intensity ranging from about 30 to about 250 W/cm^2 to remove the laser applied surface of the borehole.

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