(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
3 June 2011 (03.06.2011)

PCT

(10) International Publication Number
WO 2011/064594 A2

(51) International Patent Classification: *G21B 3/00* (2006.01)

(21) International Application Number: PCT/GB2010/051976

(22) International Filing Date: 26 November 2010 (26.11.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data: 0920816.6 27 November 2009 (27.11.2009) GB

(71) Applicant *(for all designated States except US)*: **ISIS INNOVATION LIMITED** [GB/GB]; Ewert House, Ewert Place, Summertown, Oxford, Oxfordshire OX2 7SG (GB).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **VENTIKOS, Yiannis** [GR/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford, Oxfordshire OX1 3PJ (GB). **HAWKER, Nicholas** [GB/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford, Oxfordshire OX1 3PJ (GB).

(74) Agent: **DEHNS**; St Bride's House, 10 Salisbury Square, London EC4Y 8JD (GB).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) Title: ENERGY FOCUSSING

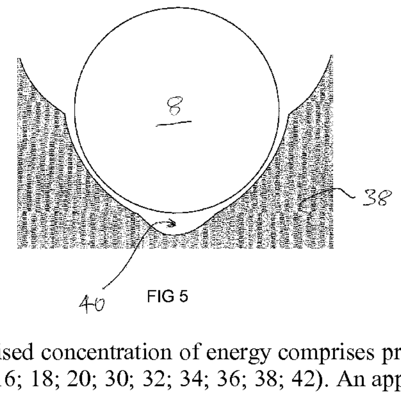

FIG 5

(57) Abstract: A method of producing a localised concentration of energy comprises providing a series of projectiles (8) and firing said projectiles (8) at a target (2; 4; 6; 14; 16; 18; 20; 30; 32; 34; 36; 38; 42). An apparatus for producing localised concentration of energy comprises: means for providing a series of projectiles (8) and means for firing said projectiles (8) at a target (2; 4; 6; 14; 16; 18; 20; 30; 32; 34; 36; 38; 42). The target (2; 4; 6; 14; 16; 18; 20; 30; 32; 34; 36; 38; 42) is configured such that upon striking the target, a projectile (8) traps and compresses a volume of gas (10) between the projectile and the target. The target (2; 4; 6; 14; 16; 18; 20; 30; 32; 34; 36; 38; 42) and the projectile (8) are also configured such that impact of the projectile onto the target gives rise to a converging Shockwave (12) inside the trapped volume of gas (10).

WO 2011/064594 A2

Energy Focussing

This invention relates to methods and apparatus for focussing energy using high velocity liquid droplets or other projectiles striking a target. It relates particularly, although not exclusively, to generating localised energy densities high enough to cause nuclear fusion.

The development of fusion power has been an area of massive investment of time and money for many years. This investment has been largely centred on developing a large scale fusion reactor, at great cost. However, there are other theories that predict much simpler and cheaper mechanisms for creating fusion. Of interest here is the umbrella concept "inertial confinement fusion", which uses mechanical forces (such as shock waves) to concentrate and focus energy into very small areas.

Much of the belief in inertial confinement fusion comes from observations of a phenomenon called sonoluminescence. This occurs when a liquid containing appropriately sized bubbles is driven with a particular frequency of ultrasound. The pressure wave causes the bubble to expand and then collapse very violently; a process usually referred to as inertial cavitation. The rapid collapse of the bubble leads to non-equilibrium compression that causes the contents to heat up to an extent that they emit light [Gaitan, D. F., Crum, L. A., Church, C. C., and Roy, R. A. Journal of the Acoustical Society of America 91(6), 3166–3183 June (1992]. There have been various efforts to intensify this process and one group has claimed to observe fusion [Taleyarkhan, R. P., West, C. D., Cho, J. S., Lahey, R. T., Nigmatulin, R. I., and Block, R. C. *Science* 295(5561), 1868–1873 March (2002)]. However, the observed results have not yet been validated or replicated, in spite substantial effort [Shapira, D. and Saltmarsh, M. *Physical Review Letters* 89(10), 104302 September (2002)].

It has been proposed in US 7445319 to fire spherical drops of water moving at very high speed (~1 km/s) into a rigid target to generate an intense shock wave. This shock wave can be used to collapse bubbles that have been nucleated and subsequently have expanded inside the droplet. It is inside the collapsed bubble that the above-mentioned patent expects fusion to take place. The mechanism of shockwave generation by high-speed droplet impact on a surface has been studied experimentally and numerically before and is well-documented (including work by one of the present patent inventors, [Haller, K. K., Ventikos, Y., Poulikakos, D., and Monkewitz, P. *Journal of Applied Physics* 92(5), 2821–2828 September (2002)].)

The present invention aims to provide an alternative to the aforementioned techniques and may also have other applications. When viewed from a first aspect the invention provides a method of producing a localised concentration of energy comprising: providing a series of projectiles and firing said projectiles at a target, said target being configured such that upon striking said target, a said projectile traps and compresses a volume of gas between the projectile and the target, the target and projectile further being configured such that impact of the projectile onto the target gives rise to a converging shockwave inside the trapped volume of gas.

The invention also extends to apparatus for producing localised concentration of energy comprising: means for providing a series of projectiles, means for firing said projectiles at a target configured such that upon striking said target, said projectiles trap a volume of gas between the projectile and the target, the target and projectile further being configured such that impact of the projectile onto the target gives rise to a converging shockwave inside the trapped volume of gas.

Thus it will be seen by those skilled in the art that in accordance with the invention a volume of gas (or "bubble") is trapped by the projectile which gives rise to an intense concentration of energy within the gas by two mechanisms. The first mechanism is a simple transfer of kinetic energy from the particle into potential energy and subsequently into heat energy as the bubble is compressed while it arrests the motion of the projectile. This includes heating by the bow shock moving in front of the projectile and heating caused by the rebounding of this bow shock and subsequent interactions of further resulting shocks confined within the bubble.

The second mechanism is the transfer of energy from the converging shockwave generated by the impact between the projectile and the surface of the target which propagates from the projectile into the adjacent bubble. As the edge of the shock wave propagates towards the trapped volume, it is focussed, forming a contracting circle. When this shockwave eventually focuses down near to a point, it results in extremely high pressures and temperatures in the compressed bubble. The large reduction in density of the medium in which the shockwave is travelling in going from the projectile to the bubble means that the shockwave generates very high temperatures in the bubble, particularly as it converges to a point.

The invention described herein provides an alternative to the technique described in US 7445319 which may carry its own benefits. The present inventors have recognised that there are significant challenges in the nucleation of a bubble in droplet fired at high speed into a target as suggested in US 7445319. The timing will have to be very precise for the bubble to be at the right moment of its expand-collapse cycle when the shock strikes. By contrast such complexity and associated expense can be avoided in accordance with at least preferred embodiments of the present invention. Moreover the modelling of both techniques carried out by the present inventors suggests that for the same droplet impact velocity, a method in accordance with the invention can give pressure and temperature intensities which are an order of magnitude greater.

The gas is typically trapped from the surroundings in which the target is placed. The term 'gas' as used herein should be understood generically and thus not as limited to pure atomic or molecular gases but also to include vapours, suspensions or micro-suspensions of liquids or solids in a gas or any mixture of these.

It is envisaged in accordance with the invention that the projectiles could be solid or semi-solid e.g. a gel or a polymer, or any material that can be accelerated to suitable speeds, entrap a gaseous volume on a surface and generate the energy density focussing mechanisms described above for pressure and temperature intensification. In a preferred set of embodiments however, the projectiles comprise droplets of liquid. In one particular set of embodiments, the liquid droplets are produced by the apparatus described in US 7380918.

The projectile will typically need to be moving fast enough to generate the shockwave which propagates in the bubble. The desired speed may depend upon the size and material of the projectile, the shape and size of the target, the composition of the gas being trapped etc. In one set of preferred embodiments the projectile has a speed of more than 250 m/s, e.g. more than 500 m/s, e.g. more than 750 m/s. In some embodiments the speed is up to 1000 m/s or more.

There are many shapes and configurations which the target structure might take in order to provide suitable regions for entrapment of a volume of gas when struck by a projectile and which give rise to a converging shockwave into the trapped gas. In one set of embodiments, the target comprises a concave surface shaped so as at least partially to receive the projectile and trap said gas beneath the projectile. The term "beneath" used here should be understood in the frame of reference where the projectile approaches the target from above; no particular spatial orientation relative to any other object or gravity should be inferred. Moreover it should not be inferred that the projectile necessarily approaches the target in a perpendicular manner in the frame of reference of the target.

Such a concave surface as described above may be one which tapers to a cross-sectional area sufficiently small that the projectile cannot fully enter it. The tapered sides could be straight or curved (when viewed in cross-section). Equally the concave surface may have a shape comprising at least a portion having a curvature greater than the curvature of the projectile. In fact if consideration is given to the practical impossibility of producing a perfectly sharp apex in the target, the former condition can be seen merely as a subset of the latter.

Having the projectile at least partly received by the concave target surface gives rise to the desired entrapment of a volume of gas between the target and the projectile. Such arrangements are advantageous as they have been found to give rise to a very strong toroidal shockwave which travels away from the point of impact, into the projectile. As the edge of the shock wave propagates towards the trapped volume, it is focussed, forming a contracting circle. When this shockwave eventually focuses down near to a point, it results in extremely high pressures and temperatures in the compressed bubble.

In another set of embodiments, the target structure comprises a target surface having a discrete depression defined therein which is narrower than the width of the projectile. For example, where the depression has continuous rotational symmetry, as is preferred, its diameter should be less than the maximum width of the projectile. Where the projectile is spherical, as is typically the case, the depression would therefore be of smaller diameter than the diameter of the projectile. A possible advantage associated with a discrete depression of the sort described above is that the volume of gas trapped by the projectile can be closely controlled, whereas in the case of a narrowing concavity into which the projectile is received, the precise volume of gas which is trapped may be dependent to an extent on the precise diameter of the projectile and which may exhibit a statistical variation.

The invention is not limited to a single depression in which gas is trapped by the projectile, and thus in a set of embodiments, the target structure comprises a plurality of depressions. Clearly depending upon the number of such depressions, the size of an individual depression will be significantly smaller than the size of the projectile. Each individual depression may be shaped to encourage the energy focusing by the converging shockwave as described above. An advantage of employing a plurality of depressions is that a greater proportion of the projectile energy may be harnessed. This is especially true for larger projectiles and points towards simplicity of manufacturing for an energy-producing fusion apparatus.

Such pluralities of depressions could be formed in a number of ways. For example, a solid target could be drilled or otherwise machined to produce depressions or pits. In one set of embodiments, however, the depressions are created by the surface texture of the target. For example, the target could be blasted with an abrasive material, etched or otherwise treated to give a desired degree of surface roughness which provides, at the microscopic level, a large number of pits or depressions.

The two sets of embodiments described above: a concave target surface accommodating the projectile; and a target surface having one or more smaller, discrete depressions, are not mutually exclusive. Thus, for example, a target surface might be concave so as at least partially to receive the projectile, whilst also comprising one or more discrete depressions. Such combination could be beneficial in providing the desired behaviour of the shockwave generated inside the projectile, whilst also enjoying the advantages of compressing a plurality of volumes of gas.

In a preferred set of embodiments, the methods described herein are employed to generate nuclear fusion reactions. The fuel for the reaction could be provided by the droplet, the trapped gas bubble, or the fuel could be provided by the target itself. Any of the fuels mentioned in US 7445319 is suitable for use in the present invention. The target itself could be constructed from a solid, as implied in many of the embodiments outlined above, but it could equally well be a liquid. In the case of a solid, any of the proposed materials in US 7445319 could be suitable. In the case of a liquid the required target surface shape could be achieved in a number of ways. For example, the surface of a volume of liquid could be excited with a suitable vibration (e.g. using ultrasound or another method) to generate a wave having the desired shape. Alternatively the desired shape could be achieved through the contact angle between a liquid and a solid surface with appropriately matched wetting properties. Of course, this latter example shows that the surface could comprise a combination of solid and liquid.

The volume of gas which is trapped may be chosen depending on the circumstances but in one set of preferred embodiments is between 5×10^{-11} and 5×10^{-7} litres. As will be apparent from the discussion above, this could be in a single volume or distributed between a plurality of depressions.

The fusion reactions which can be obtained in accordance with certain embodiments of the invention could be used for net energy production (the long term research aim in this field), but the inventors have appreciated that even if the efficiency of the fusion is below that required for net energy production, the reliable fusion which is obtainable in accordance with embodiments of the invention is advantageous for example in the production of tritium which can be used as fuel in other fusion projects and is very expensive to produce using currently existing technologies. The fusion can also be beneficial in giving a fast and safe neutron source which has many possible applications that will be apparent to those skilled in the art.

Moreover, it is not essential in accordance with the invention to produce fusion at all. For example, in some embodiments the techniques and apparatus of the present invention may be advantageously employed as a sonochemistry reactor which can be used to access extreme and unusual conditions.

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

Figs. 1a to 1c are three variants of a target in accordance with the invention;

Figs. 2a to 2c are progressive illustrations of the compression of a bubble generated by a computational fluid dynamics simulation;

Figs. 3a to 3d are variants of targets having discrete depressions in accordance with the invention;

Figs. 4a to 4d are illustrations of various possible embodiments having multiple depressions;

Fig. 5 is an illustration of an embodiment which is both curved and has a discrete depression; and

Fig. 6 is an illustration of an embodiment having both multiple depressions and a curved overall surface shape.

Figs. 1a to 1c show three similar variants of a concave targets 2, 4, 6 which have a tapering cross-section so that when a droplet 8 of appropriate size is fired at the respective target, the taper prevents it reaching the bottom of the concavity and thus a volume of the gas inside the concavity is trapped to form a bubble 10 between the droplet 8 and the target 2, 4, 6. The subsequent process may be seen in greater detail with reference to Figs. 2a to 2c. In each of the three cases shown in Figs. 1a, 1b and 1c, the target 2, 4, 6 has, at some point, a radius of curvature which is less than the radius of the droplet 8. In the case of Figs. 1a and 1c which show apparently point apexes, it will be appreciated that in practice these will have a degree of rounding which inevitably has a smaller radius of curvature than the droplet radius.

Fig. 2a shows the situation shortly after the droplet 8 has hit the target 4. Only one half is shown, but the other half is symmetrically identical. It may be seen that the droplet 8 entraps a bubble of gas 10 between the surface of the droplet 8 and the tapering target surface 4. As the droplet 8 deforms, it compresses the bubble 10 so transferring its kinetic energy into energy in the bubble. Also on impact, a shockwave 12 is generated which begins to propagate into the droplet. As may be appreciated by considering the rotationally symmetric geometry, this shockwave is toroidal in shape. As the edge of the shockwave 12 propagates along the interface between the droplet 8 and the trapped bubble 10, it is focused, forming a contracting circle (Fig. 2b). When the shockwave eventually focuses down to a near point, it results in the generation of extreme pressures and temperatures in the compressed bubble 10 (Fig. 2c). For example, simulations have shown that for a droplet of size 100 microns travelling at a velocity of 500 metres per second striking an inverted conical target of cone angle approximately 45 degrees, pressures approaching 200,000 bar and temperatures exceeding 1,000,000°C are observed. It will be appreciated, however, that there are a large number of parameters that influence the actual results achieved, for example liquid density, ambient pressure and temperature, composition of the gas and of the liquid, impact angle and surface shape.

Figs. 3a to 3d show respective variants of embodiments in which the target surface 14 to 20 has a single discrete depression 22 to 28 formed therein. As may be appreciated from the diagram, these depressions 22 to 28 will typically be significantly smaller than the droplet 8. This means that the volume of gas which is entrapped is essentially independent of small variations in the size of the droplet 8. These embodiments work in the same way as was described above for the embodiments described above by compressing the trapped bubble and intensifying the pressure therein from the shockwave generated by the impact with the target.

Figs. 4a to 4d show variants of embodiments with multiple depressions, in several of which corresponding bubbles can be trapped by a droplet striking the target 30 to 36. The number of bubbles trapped will depend upon the size of the depressions relative to the size of the droplet 8. The surface shapes giving rise to these depressions are merely schematic and illustrative and there are of course many possible variants. They could be created by surface finishing or roughening processes rather than by explicit machining. One of the advantages of this would be that there is a lower requirement for accurate alignment between the droplet 8 and the target 30 to 36. It also means that a single target for receiving multiple streams of droplet simultaneously can be easily prepared. It also opens up the possibility of having a moving, e.g. rotating or sliding target which will carry benefits such as: renewal of target material, harnessing of produced energy, reduction in the need for precision targeting.

Fig. 5 shows another embodiment of the invention in which the target surface 38 is concave and at least partly conforms to and receives the droplet 8, but has at the bottom a discrete depression 40. The curved, more conforming shape can be beneficial in intensifying the shockwave generated when the droplet 8 strikes the target 38 which in turn intensifies the pressures and temperatures inside the bubble trapped in the depression 40.

Finally, Fig. 6 shows an extension of the idea described above in which the surface 42 has a plurality of discrete depressions 44, each of which may trap a bubble of gas. The depressions could be annular - i.e. continuous in the rotational direction of the target - but are preferably discrete in the rotational direction of the target. Moreover, the peaks 46 between the depressions 44 each create a shockwave inside the bubble 8 which, with appropriate optimisation, can be made to converge and reinforce one another in such a way as to further intensify the energy concentrated in the bubbles in each depression 44.

In all of the embodiments described, the apparatus can be used by firing a stream of very high velocity droplets, e.g. of water, by producing a stream of liquid which is then broken up using the apparatus described in US 7380918. In an exemplary implementation the droplets have a diameter of approximately 150 microns, travel at a speed of approximately 1 kilometre a second and are produced at a frequency of approximately 1 Megahertz. In computational modelling, this gave rise to a peak pressure of 4.6×10^9 Pascals which is sufficient to cause temperatures in excess of 1×10^6 degrees C which can be sufficient for a nuclear fusion reaction of the deuterium atoms. The resulting neutrons can either be used in other processes or, in one example, may be absorbed by a neutron absorber for conversion of the kinetic energy of the neutrons to thermal energy and thus conventional thermodynamic energy generation.

However, there are many other ways of producing power. For example Boron-Hydrogen fusion could also be used. Boron-Hydrogen fusion results in Helium nuclei and the methods used to harness the energy from this reaction could be very different - e.g. moving charge could generate electricity directly. Moreover it is not essential for fusion to take place; the enhanced pressures and temperatures caused inside the collapsed bubble by the target shapes in accordance with the invention may be useful in other contexts to study other reactions under exotic conditions.

The invention is applicable in all such contexts as well as many others.

Claims

1. A method of producing a localised concentration of energy comprising: providing a series of projectiles and firing said projectiles at a target, said target being configured such that upon striking said target, a said projectile traps and compresses a volume of gas between the projectile and the target, the target and projectile further being configured such that impact of the projectile onto the target gives rise to a converging shockwave inside the trapped volume of gas.

2. A method as claimed in claim 1, wherein the projectiles comprise droplets of liquid.

3. A method as claimed in claim 1 or 2, wherein the projectile has a speed of more than 250 m/s, e.g. more than 500 m/s, e.g. more than 750 m/s.

4. A method as claimed in claim 1, 2 or 3, wherein the target comprises a concave surface shaped so as at least partially to receive the projectile and trap said gas beneath the projectile.

5. A method as claimed in any preceding claim, wherein the target structure comprises a target surface having a discrete depression defined therein which is narrower than the width of the projectile.

6. A method as claimed in claim 5, wherein the target structure comprises a plurality of depressions.

7. A method as claimed in any preceding claim, employed to generate nuclear fusion reactions.

8. A method as claimed in any preceding claim, wherein the volume of gas which is trapped is between 5×10^{-11} and 5×10^{-7} litres.

9. An apparatus for producing localised concentration of energy comprising: means for providing a series of projectiles, means for firing said projectiles at a target configured such that upon striking said target, said projectiles trap a volume

of gas between the projectile and the target, the target and projectile further being configured such that impact of the projectile onto the target gives rise to a converging shockwave inside the trapped volume of gas.

10. An apparatus as claimed in claim 9, wherein the projectiles comprise droplets of liquid.

11. An apparatus as claimed in claim 9 or 10, wherein the projectile has a speed of more than 250 m/s, e.g. more than 500 m/s, e.g. more than 750 m/s.

12. An apparatus as claimed in claim 9, 10 or 11, wherein the target comprises a concave surface shaped so as at least partially to receive the projectile and trap said gas beneath the projectile.

13. An apparatus as claimed in any of claims 9 to 12, wherein the target structure comprises a target surface having a discrete depression defined therein which is narrower than the width of the projectile.

14. An apparatus as claimed in claim 13, wherein the target structure comprises a plurality of depressions.

15. An apparatus as claimed in any of claims 9 to 14, employed to generate nuclear fusion reactions.

16. An apparatus as claimed in any of claims 9 to 15, wherein the volume of gas which is trapped is between 5×10^{-11} and 5×10^{-7} litres.

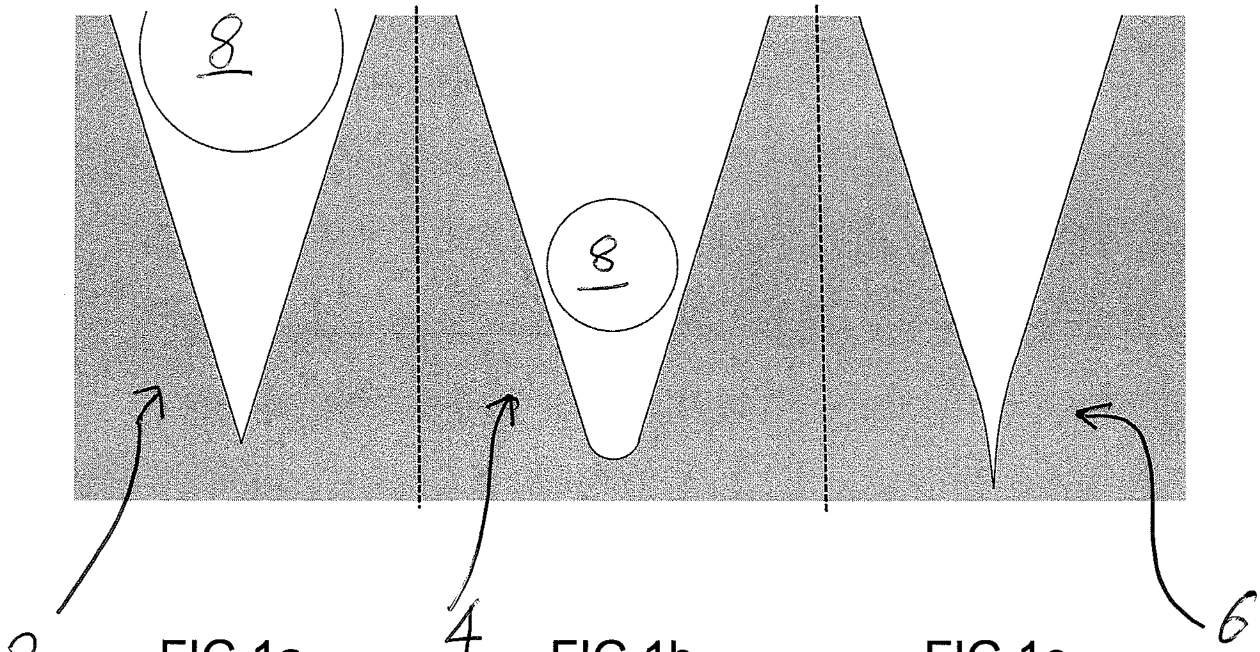

FIG 1a FIG 1b FIG 1c

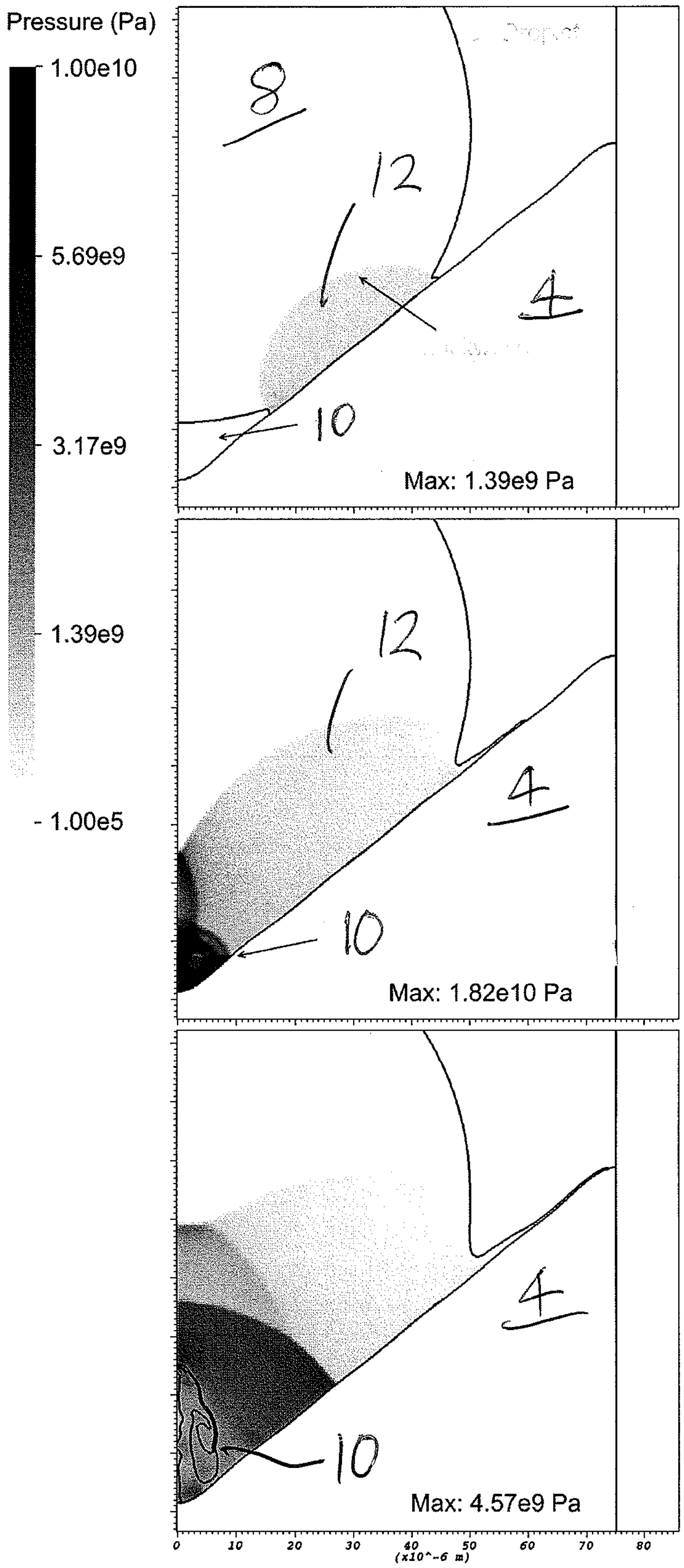

FIG 2a

FIG 2b

FIG 2c

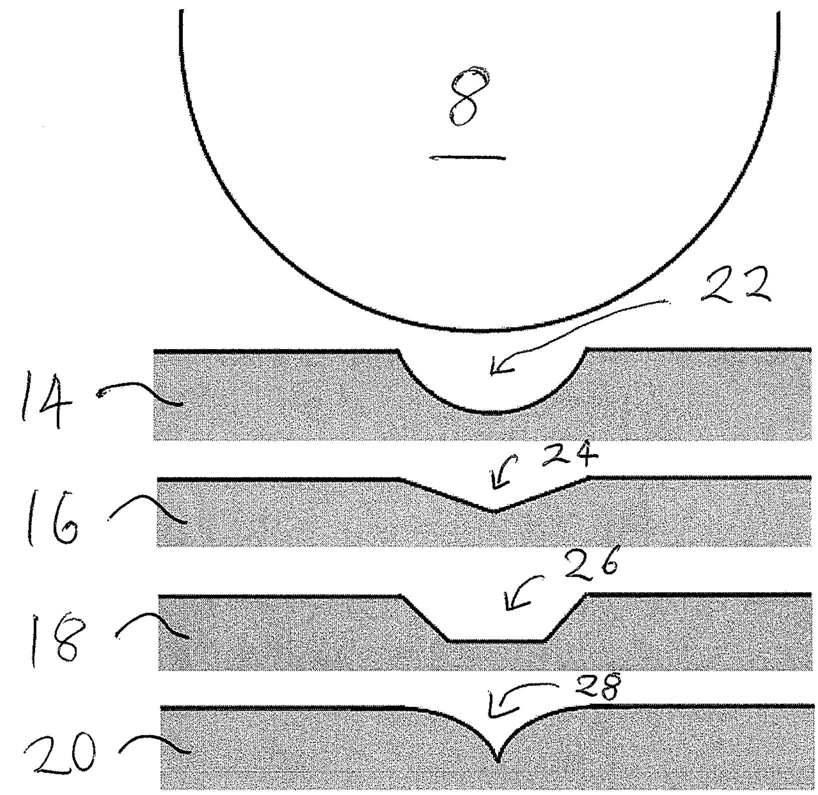

FIG 3a
FIG 3b
FIG 3c
FIG 3d

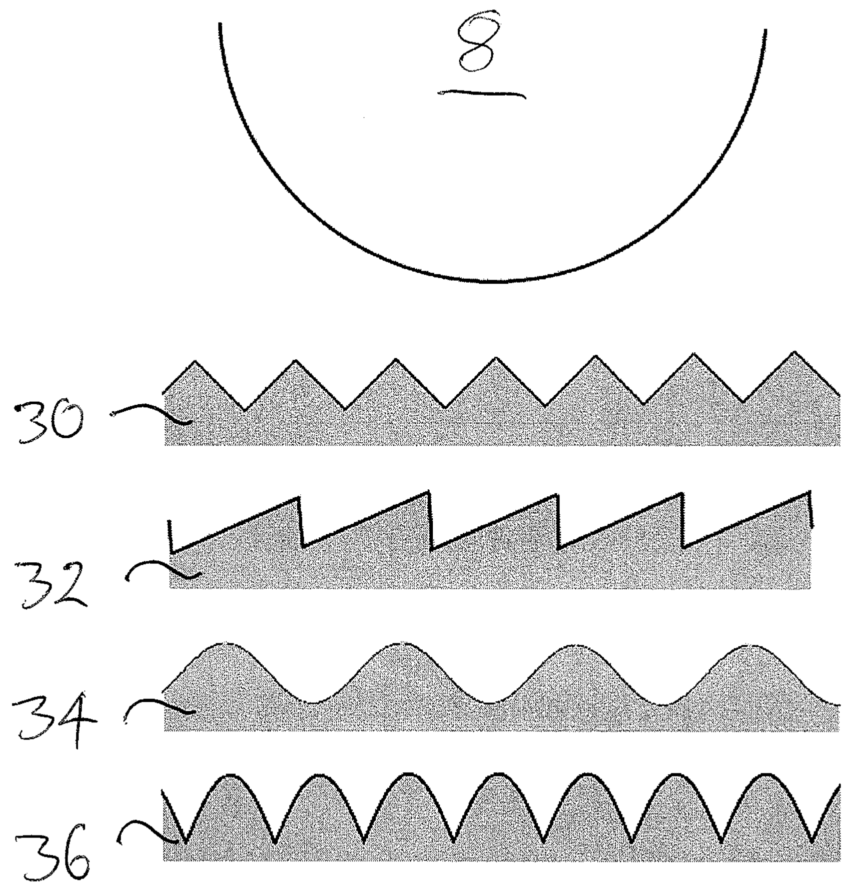

FIG 4a
FIG 4b
FIG 4c
FIG 4d

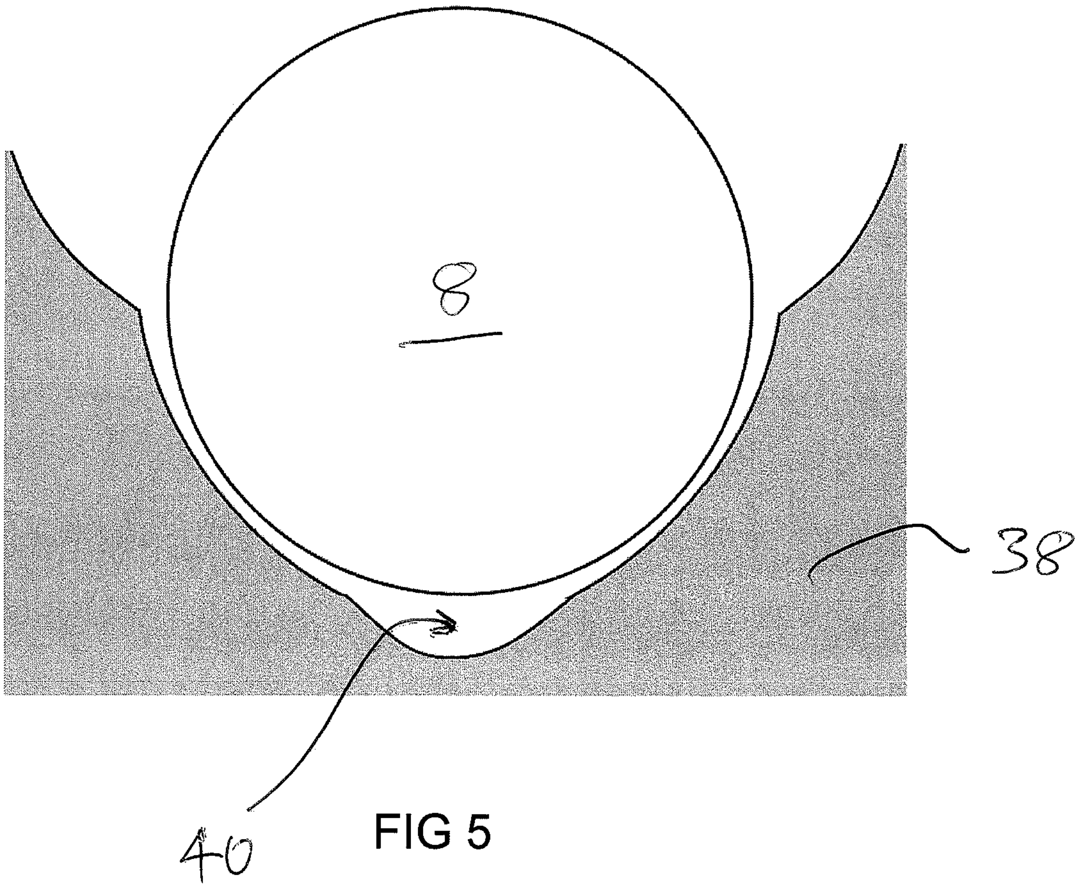

FIG 5

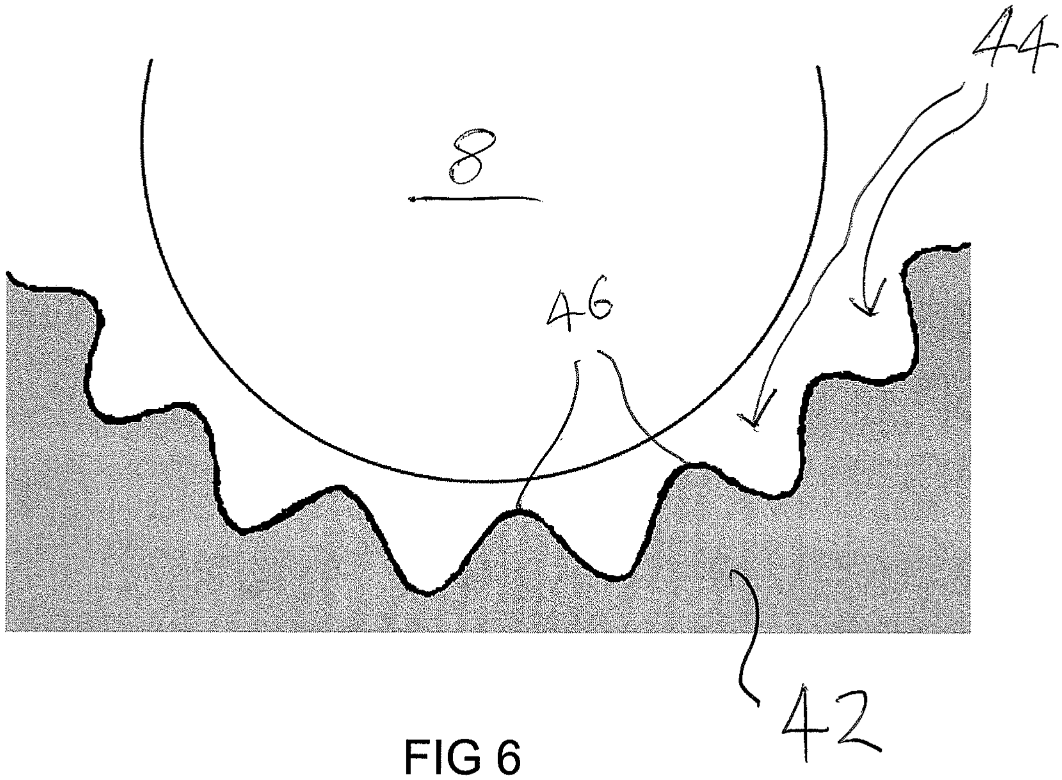

FIG 6