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- (71) Applicant: **THE MANUFACTURING TECHNOLOGY CENTRE LIMITED** [GB/GB]; Pilot Way, Ansty Business Park, Coventry Warwickshire CV7 9JU (GB).
- (72) Inventors: **WIMPENNY, Professor David**; 18 Peckleton Lane, Desford Leicestershire LE9 9JU (GB). **TREPLETON, Dr Ross**; 2 Elms Road, Sutton Coldfield, Birmingham West Midlands B72 1JF (GB). **ATTIA, Dr Usama**; 19 Milholme Green, Solihull West Midlands B92 9NP (GB).
- (74) Agent: **BARKER BRETTELL LLP**; 100 Hagley Road, Edgbaston, Birmingham West Midlands B16 8QQ (GB).
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(54) Title: A METHOD FOR FORMING A THREE DIMENSIONAL OBJECT

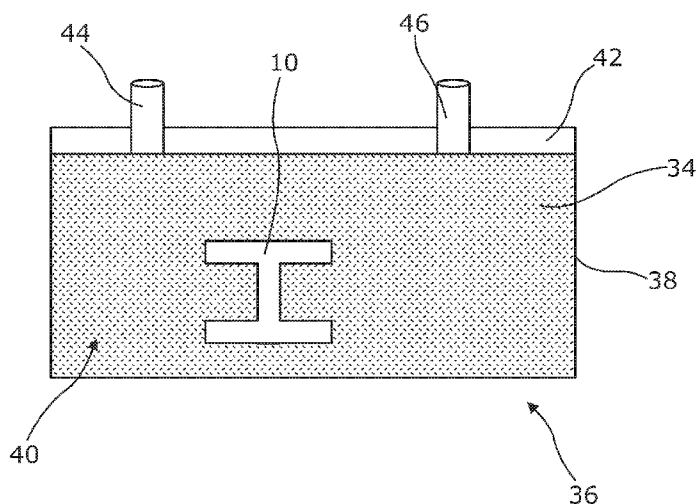


Fig. 5

(57) Abstract: A method for forming a three dimensional object including the steps of: depositing successive layers of powder onto a surface; selectively bonding the powder to form a three dimensional object; surrounding the three dimensional object with a particulate material; and urging the particulate matter towards the object to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the object such that the object is densified.



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A METHOD FOR FORMING A THREE DIMENSIONAL OBJECT

This invention relates to a method for forming a three-dimensional object. In particular, the invention is related to a method for forming a three-dimensional object
5 from a powder.

Methods and apparatus for producing a three-dimensional object from a powder are known.

10 One such method is known as additive layer manufacture (ALM). ALM employs an apparatus which is typically configured to deposit successive layers of powder onto a surface. For each layer the apparatus selectively bonds the powder so that the bonded powder forms an area that corresponds to the required cross-sectional area of the layer of the desired three-dimensional object. The three-dimensional object is thus formed
15 by a layer by layer process. ALM is advantageous as it permits the manufacture of three-dimensional objects having relatively complicated geometry, structure and / or other functional properties that cannot be so easily made using other methods, if at all.

There are a number of ways of bonding the powder together as part of ALM. Some
20 apparatus have a high energy beam which is directed to energise the powder and thereby fuse or melt the powder so it is bonded together. The high energy beam may be an electron beam or an electromagnetic radiation beam, e.g. laser radiation.

Another method of bonding the powder together as part of ALM involves selectively
25 applying a binder which can chemically bind the powder particles together. In such a method, the binder is selectively applied to portions of a first layer of powder and then a second layer of powder is deposited thereon. The binder will bind the powder from corresponding portions of the first and second layers through contact therebetween. Binders may be used that can bind the powder without requiring the application of any
30 heat or other types of binders may be used that require the binder to be heated to a certain temperature to bind the powder as part of the ALM process.

For certain applications, the three-dimensional object has to be of a relatively high strength and it is necessary for the density of the object to be correspondingly high. In
35 other words, its porosity must be relatively low. In order to achieve this, ALM

methods that employ an energy beam to bond the powder together require energising the powder of a given layer repeated times. A first stage, may involve, for example, heating the powder so as to sinter the powder together. A second stage may involve applying further heat to the powder in order to bring them closer to the melting /
5 liquefaction temperature of the powder and further sinter the powder together. Then a third, final, stage may involve energising the powder further so as to raise its temperature to the melting / liquefaction temperature of the powder causing the powder to fully melt and become densified.

10 There are drawbacks with this approach. The use of a high energy beam being applied in this three-stage process per layer of powder requires a relatively long period of time and requires a large amount of energy, particularly if the powder is a metal and thus has a high melting temperature. Furthermore, due to the high energy beam energising the powder in three stages for each successive layer, there is the corresponding
15 multiplication of any bonding defects / errors that could have arisen at each of those stages for each layer. Thus the final object may suffer from a number of bond defects and would likely have inhomogeneous properties. In addition to the above, the three-dimensional object, even when processed as described, may still not have a sufficiently low porosity to be suitable for the intended use. For example, the three-
20 dimensional object may still be permeable to gas.

Other methods for forming a three-dimensional object from a powder include Hot-Isostatic-Pressing (HIP) and Cold-Isostatic-Pressing (CIP). HIP involves providing a high-pressure containment vessel and placing the powder therein before sealing the
25 vessel and exposing the vessel to high temperatures and applying high pressure isotropically to the exterior surface of the vessel. This causes the vessel to be compressed and thereby presses the powder together at high pressure, the powder then undergoes bonding through a combination of plastic deformation, creep and diffusion rather than melting of the powder particles. The powder is formed into a three-
30 dimensional object through this process. The vessel is then removed from the three-dimensional object, by for example, etching or machining the vessel away. CIP is similar to HIP with the exception that no heat is applied to the vessel when it is pressed. A drawback of HIP and CIP is the requirement to create a complex shaped vessel in which to load the powder. This means that HIP/CIP cannot easily (if at all)
35 offer the complex objects that are achievable, by ALM, for example.

It is known to combine ALM with HIP in order to form a fully dense three-dimensional object. In such a method, the three-dimensional object is formed by ALM. The three-dimensional object is then placed in a high-pressure vessel which is
5 exposed to high temperature and high pressure as described above in relation to HIP. The HIP process, when used in this way, can densify internal porosity within the three-dimensional object so that it has a very high density / very low porosity. However, surface breaking porosity cannot be closed using this approach.

10 The present invention is devised to address one or more of the disadvantages highlighted above.

According to a first aspect of the invention we provide a method for forming a three dimensional object including the steps of:

15 depositing successive layers of powder onto a surface;
 selectively bonding the powder to form a three dimensional object;
 surrounding the three dimensional object with a particulate material; and
 urging the particulate matter towards the object to exert a pressure directly or
 indirectly thereon and applying heat directly or indirectly to the object such that the
20 object is densified.

Optionally the step of selectively bonding the powder includes forming the three dimensional object to be porous.

25 Preferably the step of selectively bonding the powder includes forming the three dimensional object to have a density magnitude that is higher than the tap density magnitude of the powder.

The step of selectively bonding the powder may include forming the three dimensional
30 object to have a density magnitude that is 5 to 25%, preferably 10 to 15%, higher than the tap density magnitude of the powder.

The step of selectively bonding the powder may include forming the three dimensional object to have a density magnitude of between 70 and 90%, preferably 70 to 85%, and
35 more preferably 70% or substantially 70%.

The three dimensional object may be porous and gas permeable. The porous three dimensional object may have an open porosity.

- 5 According to a second aspect of the present invention, we provide a method for forming a three dimensional object including the steps of:

depositing successive layers of powder onto a surface;

- selectively bonding the powder to form a gas permeable exterior skin having a first density magnitude, wherein the exterior skin defines an interior volume of powder having a second density magnitude, and wherein the first density magnitude is
10 higher than the second density magnitude.

The method may include the step of selectively bonding the powder which forms the interior volume.

15

Optionally the step of selectively bonding the powder which forms the interior volume is performed synchronously or substantially synchronously with the selective bonding of the powder which forms the exterior skin.

- 20 The method may include energising one or more portions of the layers which form the exterior skin a greater amount than another portion or portions of the layers which form the exterior skin.

The exterior skin may vary in thickness or may be substantially uniform in thickness.

25

The first density magnitude may be between 70 to 90%, preferably between 70 and 80%. More preferably the first density magnitude is at least 70%, preferably it is 70% or substantially 70%.

- 30 Optionally the second density and / or the first density magnitude(s) is / are higher than the tap density of the powder. Preferably the second density magnitude is between 65 and 75%. More preferably the second density magnitude is between 65 and 70%. Most preferably, the second density magnitude is 65% or substantially 65%.

The step of selectively bonding may include energising the powder. Preferably, the step of energising the powder includes directing an energy beam thereat. The energy beam may include electromagnetic radiation and / or an electron beam.

- 5 The method(s) of the first and / or second aspects of the invention may include selectively depositing a binder material onto one or more of the layers of powder.

Optionally, the method(s) include the step of energizing one or more portions of the layer(s) which form the object a greater amount than another portion or portions of the
10 said layer(s). The methods may include, for one or more of the layers of powder, the step of selectively depositing more powder in a first area of the layer(s) than at a second area of said layer(s). Optionally, for one or more of the layers of powder, the method(s) include the step of selectively depositing at least two different powders to form the layer(s).

15

The powder may include one or more of: a metal powder, a ceramic powder or a composite material powder.

According to a third aspect of the invention, we provide a method according to the
20 second aspect of the invention including the further steps of:

surrounding the exterior skin of the three dimensional object with a pressure transfer medium; and

urging the pressure transfer medium towards the exterior skin of the object to exert a pressure directly or indirectly thereon and applying heat directly or indirectly
25 to the object such that the exterior skin and interior volume are densified.

According to a fourth aspect of the invention, we provide a method for forming a plurality of three dimensional objects including the steps of:

forming or providing a plurality of three dimensional objects each formed in
30 accordance with the method of the second aspect of the invention;

surrounding the respective exterior skins of the plurality of the objects with a pressure transfer medium; and

urging the pressure transfer medium material towards the respective exterior skins of the objects to exert a pressure directly or indirectly thereon and applying heat

directly or indirectly to the objects such that the exterior skin and interior volume are densified.

According to a fifth aspect of the invention, we provide a method for forming a

5 plurality of three dimensional objects including the steps of:

forming or providing a plurality of three dimensional objects each formed by:

depositing successive layers of powder onto a surface;

and

selectively bonding the powder to form a three dimensional object;

10 surrounding the plurality of objects with a particulate material;

and

urging the particulate material towards the objects to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the objects such that the objects are densified.

15

The method may include the step of providing a housing which defines a chamber and placing the three dimensional object(s) in the chamber prior to or after the pressure transfer medium / particulate material has been deposited in the chamber.

20 The method may include the step of applying pressure directly or indirectly on the housing in order to urge the pressure transfer medium / particulate material towards the respective exterior skin(s) / exterior surfaces of the three dimensional object(s).

The method may include the step of applying heat directly or indirectly to the housing
25 in order to heat the three dimensional object(s).

The method may include the step of applying a vacuum to the chamber once the three dimensional object(s) have been placed therein and the pressure transfer medium / particulate material deposited therein.

30

The method may include applying pressure to the housing after the chamber has been sealed.

Optionally, the pressure and heat is applied synchronously or substantially
35 synchronously.

The pressure transfer medium may include a fluid, preferably a gas, and / or a particulate material.

- 5 The particulate material may be non-tessellating. Preferably, the particulate material includes one or more of: silica, alumina.

According to a sixth aspect of the invention, we provide a method for forming a component including the steps of:

- 10 providing a first three dimensional object having an exterior surface;
providing a second three dimensional object having an exterior surface;
bringing respective portions of the exterior surfaces of the first and second three dimensional objects close to one another or into engagement;
urging the respective portions towards each other in order to exert a pressure
15 directly or indirectly thereon and applying heat directly or indirectly to the objects such that the respective portions are directly bonded to each other.

The method may include the steps of:

- surrounding the exterior surfaces of the first and second three dimensional
20 objects with a pressure transfer medium, preferably a particulate material; and
urging the pressure transfer medium towards one or both of the exterior surfaces of the first and second three dimensional objects in order to urge the respective portions towards each other.

- 25 One or both of the first and second three dimensional objects have been obtained from the method according to any one of the previous aspects of the inventions.

- Preferably one or both of the first and second three dimensional objects have: a gas permeable exterior skin having a first density magnitude; and an interior volume
30 defined by the exterior powder and having a second density magnitude, wherein the first density magnitude is greater than the second density magnitude.

Further features of the above mentioned aspects of the invention are set out in the dependent claims thereto which are appended hereto.

Examples of the invention will now be described by way of example only with reference to the accompanying drawings, of which:-

Figure 1 is a perspective view of a three-dimensional object which may be formed according to an embodiment of the present invention;

Figure 2 is a schematic diagram of an apparatus for use in forming the three dimensional object of figure 1 in accordance with an embodiment of the present invention;

10

Figure 3 is a plan cross-sectional view of the object of figure 1 having been formed using a method according to an embodiment of the present invention;

Figure 4 shows successive layers formed using the apparatus of figure 2 and which correspond to cross-sectional layers of the object shown in figure 3;

15

Figure 5 is a schematic diagram of an apparatus for use in densifying the object shown in figure 3;

Figures 6a and 6b are micrographs showing edge and centre portions of an object formed in accordance with an embodiment of the present invention;

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Figure 7 is a schematic diagram of two objects and a component formed from the two objects in accordance with an embodiment of the present invention;

25

Figure 8a is a schematic diagram of the objects of figure 7 placed in an apparatus for forming the component;

Figures 8b to 8h are micrographs showing various portions of the objects / apparatus shown in figure 8a that have been taken at stages of a method performed to densify / bond the objects together in accordance with an embodiment of the present invention;

30

Figure 9 is a plan view of a component that may be formed in accordance with an embodiment of the present invention; and

35

Figure 10 is a perspective view of an object for use in forming the component shown in figure 9.

Referring to the figures, a method for forming a three dimensional object according to an embodiment of one or more aspects of the invention will be described.

The method will be described with reference to forming a three-dimensional object 10 as shown in Fig. 1. The object 10 has two identical end portions which are 'H'-shaped and has an intermediate portion extending therebetween which is rectangular in shape.

10 An example of an apparatus for use with the method will now be described for the purpose of describing the method.

Fig. 2 shows an ALM apparatus 11 for forming a three-dimensional object layer by layer from a powder. The apparatus 11 includes a powder storage device 12 for storing powder, a surface 14 for receiving powder and a powder deposit device 16 for depositing powder to the surface 14. The powder storage device 12 is connectable with the powder deposit device 16 so as to transfer powder from the powder storage device 12 to the powder deposit device 16. The powder deposit device 16 is positioned above the work surface 14 and can be moved to effect movement of the powder deposit device 16 back and forth across the surface 14 to deposit powder across the surface 14 and form a layer of powder thereon. The apparatus 11 includes a transformation device 20 for producing a high energy beam for bonding one or more portions of a layer of powder on the surface 14. After a layer of powder has been bonded as required, the surface 14 is lowered and the process is successively repeated until the object is formed. In this embodiment, the transformation device 20 provides a high energy electron beam. In variant embodiments, the transformation device 20 is a laser for producing electromagnetic radiation suitable for bonding and/or heating the powder. The apparatus 11 includes a guiding mechanism (not shown) for guiding the high energy beam to the required portions of a layer of powder on the surface 14. In variant embodiments, the apparatus 11 may include a device for selectively depositing binder onto the layer of powder for use in conjunction with the transformation device 20 or without requiring the transformation device 20 at all.

Apparatus 11 is connected to and operable by a control system 22 to which a user provides a representation of the three-dimensional object to be produced and which operates the apparatus 11 so as to form the three-dimensional object. Operation of the

apparatus 11 in order to bond the powder together so as to form a three-dimensional object is well known and so will not be described in any more detail hereinafter.

The use of apparatus 11 for forming the three dimensional object 10 according to an
5 embodiment of a first aspect of the invention will now be described.

The apparatus 11 is provided with titanium powder (but the process is applicable to any metallic or ceramic powder) and prepared for operation in a known manner. The user provides a 3D representation of the object 10 to the control system 22 of
10 apparatus 11. The control system 22 translates the 3D representation into a series of cross-sectional layers. These steps are known in the art.

With reference to fig. 3, according to the method, the control system 22 is configured to operate the various components of the apparatus 11 to deposit successive layers of
15 powder onto the surface 14 and to selectively bond the powder to form the object 10 such that it has a porous exterior skin 24 having a first density magnitude ρ_1 and an interior volume of powder 26 defined by the exterior skin 24 having a density magnitude ρ_2 . The exterior skin 24 can be gas permeable. When referring to the interior volume of powder 26, the term powder is used to denote the powder being in a
20 range of states, e.g. the powder may be in a loose state, i.e. not bonded at all, or it may be in a bonded state, i.e. sintered, melted or otherwise bonded.

The method involves bonding the powder such that the first density magnitude ρ_1 is greater than the second density magnitude ρ_2 . In other words, the powder particles
25 which form the exterior skin 24 are more densely packed together than the powder particles which form the interior volume 26.

In more detail and with reference to fig. 4, the control system operates the operative components of apparatus 11 to deposit a first layer of powder onto the surface 14. The
30 first layer is spread over an area that is generally square shaped and is larger than the area of the cross-sectional layer of the object 10 to be formed. Once the first layer of powder has been deposited on the surface 14, the control system 22 operates the transformation device 20 to generate a high energy electron beam and the guiding mechanism guides the beam to selectively bond the powder to form an area of bonded
35 powder that corresponds in shape (i.e. 'H' shaped) and size to the cross-sectional area

of the first cross-sectional layer 27 of the object. The bonded powder is porous and has the first density magnitude ρ_1 . The bonded powder has open porosity such that it is gas permeable. The bonding of the powder is achieved by the transformation device 20 energising the powder to an elevated temperature so as to sinter the powder together. The powder is not fully melted or liquefied in this process. A second layer of powder is then deposited and selectively bonded in the same manner to form a second cross-sectional layer 28 which is bonded to the first cross-sectional layer 27 of object 10. The next layer of powder is then deposited. However, the powder is selectively bonded only at a peripheral area 30 of the layer of powder and the peripheral area 30 corresponds in shape to the peripheral area of the required cross-sectional layer of the object 10. The peripheral area 30 is porous and also has the first density magnitude ρ_1 . In this embodiment, powder in an area 32 defined interiorly of the peripheral area 30 of bonded powder is not energised by the transformation device 20 and so is not bonded together. The powder contained in this interior area 32 has the second density magnitude ρ_2 .

The process then continues to similarly form a series of layers for which only a peripheral area of powder is bonded and the interior area of which is formed of loose powder until the final few cross-sectional layers of the object 10 are to be formed. For these final cross-sectional layers, the entire area of the cross-sectional layers is bonded in a similar manner to that described for the first layer. The object 10 thus formed has a porous exterior skin 24 having the first density magnitude ρ_1 which defines an interior volume 26 of powder having the second density magnitude ρ_2 . The object 10 is gas permeable. Gas can flow through the object from a portion of the exterior skin into the interior volume of the object. Using this approach the interior volume 26 consists of either loose, or semi sintered powder whilst the exterior skin 24 is formed of semi sintered or sintered powder. The object 10 has been formed relatively quickly as each layer of powder has only been subjected to a relatively low energisation by the transformation device 20, prior to the next layer of powder being deposited thereon. In other embodiments, the control system 22 operates the transformation device 20 and the guiding mechanism to bond, e.g. sinter, the powder that forms the internal volume 26. The powder may be bonded, e.g. sintered, to have a lower density magnitude than that of the powder that forms the exterior skin. In embodiments, the bonding of the powder to form the areas of the exterior skin and the

internal volume are performed synchronously for each layer. In embodiments, they may not be performed synchronously, e.g. as separate steps.

5 The porous exterior skin 24 is substantially uniform in thickness t . In embodiments, the porous exterior skin may vary in thickness.

10 In the example described, the exterior skin 24 surrounds the whole of the interior volume 26 of the object 10, i.e. it separates the whole of the interior volume 26 from atmosphere. In embodiments, the one or more portions of the interior volume 26 may be exposed to atmosphere.

15 An advantageous method will now be described that has been unexpectedly successful for densifying object 10 formed by the method discussed above. The method includes surrounding the exterior skin 24 of the object 10 with a pressure transfer medium 34 and urging the pressure transfer medium 34 towards the exterior skin 24 of the object 10 to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the object 10 such that the exterior skin 24 and the interior volume 26 are densified.

20 Fig. 5 shows an apparatus 36 for use in one such method. The apparatus 36 includes a housing 38 which defines a chamber 40. The housing 38 has an open end which can be closed by a chamber lid 42 so as to close the chamber 40 in a fluid-tight manner. The chamber lid 42 includes two conduits 44, 46 which fluidly communicate with the chamber 40. The conduits 44, 46 are connectable to a vacuum source (not shown) in order to apply a vacuum to the chamber 40. The conduits 44, 46 include valves (not shown) that can be opened or closed. The conduits 44, 46 include filters (not shown) that inhibit the pressure transfer medium 34 from passing therethrough. When closed, the valves provide a fluid tight seal between the chamber 40 and the outside environment.

30

Apparatus 36 includes a heat source for applying heat to the housing and a means to exert pressure on the housing isotropically. These are not shown and will not be described in any detail because they are well known in the art.

In embodiments, the heat source and / or means for exerting pressure may be provided separately or externally of the apparatus 36.

A method of densifying object 10 using apparatus 36 will now be described. The chamber lid 42 is moved to an open position to allow access to the chamber 40 and the object 10 is placed therein. A pressure transfer medium 34 is deposited in the chamber 40 so as to surround the exterior skin 24 of the object 10. In this embodiment, the pressure transfer medium 34 is a particulate material such as non-tessellating silica. In embodiments, other 10 particulate materials may be used such as alumina. The most appropriate type of particulate material used may be selected based on the powder being used to form the object and / or other properties of the object prior to densification, e.g. the size / shape of the cell structure of the object. For example, the size of the particulate material particles may be chosen to have a size which is larger than any open cells that exist on the exterior surface of the object being densified.

15

The chamber lid 42 is moved to a closed position and welded so as to seal the chamber 40 in a fluid tight manner with the exception of the conduits 44, 46 whose valves are in an open position. The conduits 44, 46 are connected to a vacuum source (not shown) and a vacuum is applied to the chamber 40 so as to evacuate any gas present therein. Once a sufficient vacuum has been reached within the chamber 40, the conduits are sealed so as to seal the chamber in a fluid tight manner.

20

The apparatus 36 is operated so as to apply heat to the housing 38 and exert an isotropic pressure thereon. Housing 36 is made from a thermally conductive material, in this case, steel, and thus transmits the applied heat through to the pressure transfer medium 34. The pressure transfer medium 34 is also thermally conductive and so transmits heat to the object 10 through engagement with the exterior skin 24 thereof, thereby causing the temperature of the object 10 to increase. Synchronously with the application of heat, pressure is exerted on the housing 38 causing it to transmit a pressure in a direction towards the chamber 40 and thereby exert a pressure on the pressure transfer medium 34. The pressure transfer medium 34 is then urged by the housing 38 towards the exterior skin 24 and exerts a pressure thereon.

30

The increase in temperature of the object 10 makes it possible for the powder of the exterior skin 24 and interior volume 26 to be bonded more closely together on the

35

application of pressure thereon. Thus, the pressure exerted by the pressure transfer medium 34 causes the exterior skin 24 and interior volume 26 to densify, increasing the first and second density magnitudes ρ_1 , ρ_2 .

5 The object 10 therefore shrinks in volume, although its shape and geometry is substantially preserved. The application of heat and pressure to the housing 38 continues over a period of time until the exterior skin 24 and interior volume 26 of the object 10 are at a required density magnitude, e.g. fully dense, i.e. non-porous. The application of heat and pressure is then stopped, and the object 10 cools down to
10 ambient temperature, before or after it has been removed from the chamber 40. The object 10 is now fully dense and is ready for use in the desired end application.

In embodiments, one or more portions of the exterior skin 24 may be formed to have a higher strength relative to another portion or portions of the exterior skin 24 so as to
15 maintain the desired geometry of the object during densification. In other words, portions of the exterior skin which may be more susceptible to deformation or breakage may be reinforced. This may be achieved by increasing the thickness of the exterior skin and/or increasing the density of said portions. It may include energising one or more portions of the layers which form the exterior skin a greater amount than
20 another portion or portions of the layers which form the exterior skin.

It has been found that various parameters associated with the methods described can be optimised to enhance the efficacy of the said methods.

25 Tap density is a term of the art and refers to the density of a powder as measured after a predefined amount of the powder has been placed in a container and vibrated according to a pre-determined method. Standards have been formulated for this purpose. For example, there is an ASTM standard — ASTM B527-14 — for determining the tap density of metal powders and compounds.

30

Advantageously, the bonding of the powder need only be done to a small amount higher than the tap density such that the first density magnitude and / or the second density magnitude(s) is / are higher than the tap density of the powder so as to allow adequate handling of the object. For example the first and second density magnitudes

may be 5 to 25%, advantageously 10 to 15% higher than the tap density magnitude of the powder.

It has been found that forming the object to have the first density magnitude ρ_1 between 70 and 90% is efficacious. It is also efficacious to have the first density magnitude ρ_1 between 70 and 80% and particularly efficacious for the first density magnitude ρ_1 to be at least 70%, preferably 70% or substantially 70%.

The inventors have found advantages in having the object formed so that the second density magnitude ρ_2 is between 65 and 75%. Further advantages are found in having the second density magnitude ρ_2 between 65 and 70%, and in particular to be 70% or substantially 70%.

According to a further aspect of the invention, the inventors have found that any object formed by depositing successive layers of powder onto a surface and selectively bonding the powder may be advantageously densified by surrounding the object with a pressure transfer medium of particulate material and urging the pressure transfer medium towards the object to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the object such that the object is densified. Such a method is beneficial as it offers great time and resource savings in comparison to an object formed solely by additive layer manufacture (ALM) and which may have been densified using other methods.

The inventors have found that such an object may be porous and/or gas permeable prior to densification. The object may have one or more portions of open porosity that are connected so as to permit gas to flow from an exterior portion of the object to an interior portion thereof. The object may have a mix of open porosity and closed porosity portions.

The inventors have unexpectedly discovered that an object formed by ALM can be densified using the pressure transfer medium for a range of density magnitudes of the object. The bonded powder need only have sufficiently strong bonding to permit safe handling of the object as part of the method. For example, the density magnitude of the bonded powder need only be a relatively small amount higher than the tap density of the powder.

It has been found that the object, prior to densification through the use of particulate material, may have a density magnitude that is 5 to 25%, advantageously 10 to 15% higher than the tap density magnitude of the powder. Lower densities are
5 advantageous because it generally requires less energy and time to bond powder to such density magnitudes. Prior to densification, the three dimensional object may beneficially have a density magnitude of between 70 and 90%, preferably 70 to 85%, and more preferably 70% or substantially 70%.

10 Although the method for densifying object 10 utilises apparatus 36, other apparatus or configurations thereof may be used. For example, in embodiments, the apparatus may include other means for heating the object such as directly heating the object rather than indirectly heating it through the housing. Such a means may include induction heating, for example. In embodiments, the pressure transfer medium may indirectly
15 apply pressure on the exterior skin through an intermediate wall. For example, the object may be placed in a deformable metal tool that seals the object in a fluid tight manner and is then placed in the chamber. The pressure transfer medium then exerts a pressure on the metal tool which transmits said pressure on the exterior skin / surface of the object. Such a pressure transfer medium may be a liquid, e.g. hydraulic oil, a
20 gas, e.g. Argon, or a complex fluid. In embodiments, the pressure transfer medium may be urged towards the exterior skin by other means, e.g. electromagnetic fields.

For an object which may have been formed to have one or more portions of its interior volume exposed to atmosphere prior to the object being densified, the method includes
25 the step of using a further object, e.g. a metal tool, to seal said portion(s) from the pressure transfer medium. The pressure transfer medium would be urged against the metal tool which would transmit said pressure onto the portions so as to densify them.

The methods described for forming and densifying an object have a number of
30 advantages over the prior art. The object can be formed in a layer by layer manner from the powder in a relatively short amount of time using the ALM apparatus because each layer of powder may only require a single energisation stage. Furthermore, a relatively low amount of energy is consumed because the powder is only energised to the extent necessary, e.g. sintered, to bond the powder together to
35 form a porous / gas permeable exterior skin, rather than completely melting /

liquefying the powder to make the object non-porous / gas impermeable. The interior volume of powder is not energised at all and the energy that would otherwise have been expended to do so has been saved in comparison to prior art methods. In embodiments for which the interior volume of powder is energised, the powder is again only energised to the extent necessary to bond the powder together and is not completely melted / liquefied.

In addition to the advantages associated with the short time and lower energy required to form the object using the ALM apparatus, the object is also less likely to have any bonding defects because a given layer of powder may only be energised once rather than a repeated number of times. In other words, the object has a very homogeneous structure and properties throughout.

It has been unexpectedly found by the inventors that even though the exterior skin of object is porous and the interior volume of powder has an even higher porosity magnitude, i.e. lower density magnitude, the methods described to densify the object works with great success, forming a fully dense object. Fig. 6a, 6b are micrographs showing edge (Fig. 6a) and centre portions (Fig. 6b) of an object formed from titanium Ti 6-4 powder and using sand as a pressure transfer medium according to the methods described. In this case, the object was formed using additive layer manufacture to have a low density before it was densified. The object was raised to a temperature of 1180°C and a pressure of 140 MPa was exerted thereon for a period of four hours in order to densify it.

It will be seen that the object is fully dense at both its edge and centre portions. This is highly advantageous, as it means that fully dense objects having relatively complex geometry / physical characteristics and properties can be made in an energy efficient manner and with great time savings over prior art methods.

For example, the physical properties of the object can be tailored to suit a particular end application. Consider an object that is required to have a predetermined thermal conductivity profile such that the thermal conductivity is higher at certain portions of the object than at others. In order to form such an object in accordance with a method according to a first aspect of the present invention, for one or more of the layers of powder, the ALM apparatus may be configured to selectively deposit more powder in

a first area of the layer(s) than at a second area of said layer(s). In other words, there would be more powder particles deposited in the first area in comparison to the second area, i.e. the material density of the object at the first area will be greater than the second area. The material density is linked to the thermal conductivity, and hence, the thermal conductivity varies a predetermined amount between these areas. Examples of other physical properties of an object that can be varied in this way include its ferromagnetism, electrical conductivity, Young's modulus. Advantageously, the method described allows for such relatively complicated objects to be formed in a time and energy efficient manner. Prior art ALM methods, for example, would take considerably longer to achieve the same results because they require melting the powder in multiple stages, and also, would be less reliable because of the higher likelihood of bonding defects.

Further benefits can be realized by densifying a plurality of objects made according to embodiments of aspects of the invention simultaneously. For example, by placing said objects in a single chamber.

The method has been described with reference to forming an object from a metallic powder consisting of a single material. In embodiments, the object may be formed from a number of different powders and for one or more of the layers of powder, the method includes the step of selectively depositing at least two different powders to form the layer(s). The use of the term 'different' powders is used to denote any number of powder properties, e.g. the chemical substance from which the powder is made, the sizes of the powder particles that make up the powder, the grade of powder or any pre-conditioned states of the powder (e.g. heated, pre-stressed etc.).

Although the embodiments described are with reference to forming an object from titanium powder other powders may be used. These include powders from metals, e.g. lead, bronze, aluminium, nickel, steel and / or any metal alloys. Other powders include ceramic powders and composite material powders, e.g. metal and ceramic matrixes.

Parameters of the methods may be adjusted or dependent on the powder material and/or desired properties, e.g. geometry of the object to be formed.

A method for forming a component according to an embodiment of one or more further aspects of the present invention will now be described. Objects 52, 54 are shown schematically in fig. 7 separately and when bonded together to form component 50.

5

The method will be described with reference to a study conducted by the inventors to form a fully dense component 50 from a first three dimensional object 52 that is porous and a second three dimensional object 54 that is fully dense. Object 52 is cylindrical in shape and defines a central passage 53 for receiving object 54. Object 10 52 has been formed by a CIP process from titanium powder Ti 6-4 and so is porous, i.e. not fully dense. It has a density magnitude of 80%, i.e. it has a porosity magnitude of 20%.

Object 54 is a cylindrical rod machined from titanium powder Ti 6-4 and is fully 15 dense. In embodiments, the object 54 may have been formed by other methods, e.g. from powder using pressing. The object 54 is of such a volume that it occupies substantially all of the central passage 53 when positioned therein.

The method includes using an apparatus 60 similar to apparatus 36 with the exception 20 that it has a cylindrical chamber 62 and alumina is used as the pressure transfer medium 64. Object 52 is placed in the chamber 62 and the object 54 positioned in the passage 53. The configuration is shown schematically in fig. 8a and fig. 8b is a micrograph showing a portion of the pressure transfer medium 64 which is adjacent the housing of the apparatus 60. Apparatus 60 is then operated in a similar manner to 25 that described previously with reference to densifying object 10.

The method causes the pressure transfer medium 64 to densify object 52 and directly bond object 54 to object 52 about respective portions of the exterior surfaces of object 52 and object 54, so as to form a fully dense component 50. The objects 52, 54 are 30 chemically bonded together and form a single integral component. In other words, the objects 52, 54 have been formed together into a single component and are no longer distinguishable from one another.

The efficacy of the method is illustrated by fig. 8c to 8h which are a series of 35 micrographs of the objects 52, 54 prior to and after application of the method.

Fig. 8c shows object 52 prior to it being densified. Object 52 is porous and not fully dense. Fig. 8d shows a portion of the object 52 adjacent the pressure transfer medium 64, whilst fig. 8e to 8g. show various portions of object 52 adjacent object 54. It can be seen that object 52 is fully dense whilst object 54 is not. Fig. 8h shows a portion of object 52 adjacent object 54 after the pressure and heat has been applied for a period of time. It can be seen that object 52 has been densified in comparison to before the method was employed. Furthermore, the interface between object 54 and object 52 is fully dense, i.e. there is no difference in the structure at regions adjacent the interface. The objects 52, 54 are thus directly bonded together.

This method is advantageous as it permits densification of object 52 and bonding of object 54 thereto to form a substantially integral component as part of a single process. In embodiments, the objects that form the component may be made of different materials, e.g. one of the objects may be formed from a ceramic material and one of the objects may be formed from a metal.

Advantageously, the method permits bonding and / or densification of such objects that are made from different materials. In embodiments both objects may be porous prior to them being bonded and densified as part of the same method.

In accordance with an aspect of the invention, the inventors have found that it is possible to form a component by bonding together two objects regardless of how the objects have been formed themselves. The method involves placing respective portions of exterior surfaces of the objects close into engagement and then urging the respective portions towards each other in order to exert a pressure thereon and applying heat to the objects such that the respective portions are directly bonded to each other. The pressure and / or heat may be exerted indirectly. The objects may be urged towards one another by surrounding the exterior surfaces of the objects with a pressure transfer medium such as fluid or particulate matter in a similar manner to that described previously. The method permits formation of relatively large components that have a complex geometry from a plurality of objects having a relatively less complex geometry.

The method will be described with reference to forming component 70 shown in fig. 9. The component 70 is of a hexagonal shape and defines a hexagonal opening extending centrally therethrough. Component cannot be easily manufactured using known methods. Consider ALM, for example. ALM can be used to make objects having
5 complex geometry but available apparatus can only make objects of a relatively small size. This is because ALM apparatus are limited by the size of the surface on which powder is deposited during use. In any case, an extremely high amount of energy would be required to bond the large quantities of powder required to form such large objects making ALM unfeasible.

10

The method involves forming component 70 from six identical generally trapezoid prisms 72, 74, 76, 78, 80, 82. Prism 72 is shown in fig. 10. Prism 72 has first and second end faces 72a, 72b, and sidewalls which extend therebetween. The end faces 72a, 72b are inclined at an angle. The prisms have been formed by casting them from
15 steel using mouldings in a known way. The prisms are fully dense but in other embodiments they may not be.

20

Applying the method to form component 70 will now be described. Respective end faces 72a, 74a of two of the prisms 72, 74 are placed into abutment with one another. Spot welding is then applied circumferentially around the corresponding ends of the prisms 72, 74 to hold them together and provide a seal around the end faces 72a, 74a against any particulate matter. A further prism 76 is then connected to the free end face 72b of the prism 72 and spot welding is applied in the same way. In this manner, all six prisms are connected and arranged to form the required shape of component 70.

25

The end faces of the prisms are not directly bonded together at this stage.

30

In order to bond the end faces of the prisms together and finalise component 70, the connected prisms are placed into chamber 40 of apparatus 36. Apparatus 36 is then operated using particulate matter as a pressure transfer medium and applying heat to
30 the prisms in a similar manner to that described previously so as to urge the end faces of the prisms together and cause them to be directly bonded together. The component 70 is now a substantially integrally formed object with the prisms having been chemically bonded together. Any remaining welding can be machined or etched away as required.

35

It will be appreciated that welding need not be used and any other form of connection can be employed to hold the objects together prior to bonding the objects together. In embodiments, the objects need not be directly connected. Respective portions of the exterior surfaces thereof need only be close together or adjacent one another and
5 sealed by any other means that is sufficient to prevent the pressure transfer medium from entering into the space between the respective portions during bonding thereof.

The skilled person will understand that one or more features associated with methods described with reference to one or more aspects of the present invention may be
10 variously combined with one another.

When used in this specification and claims, the terms "comprises" and "comprising" and variations thereof mean that the specified features, steps or integers are included. The terms are not to be interpreted to exclude the presence of other features, steps or
15 components.

The features disclosed in the foregoing description, or the following claims, or the accompanying drawings, expressed in their specific forms or in terms of a means for performing the disclosed function, or a method or process for attaining the disclosed
20 result, as appropriate, may, separately, or in any combination of such features, be utilised for realising the invention in diverse forms thereof.

CLAIMS

1. A method for forming a three dimensional object including the steps of:
5 depositing successive layers of powder onto a surface;
selectively bonding the powder to form a three dimensional object;
surrounding the three dimensional object with a particulate material; and
urging the particulate matter towards the object to exert a pressure directly or
indirectly thereon and applying heat directly or indirectly to the object such that the
10 object is densified.
2. A method according to claim 1, wherein the step of selectively bonding the
powder includes forming the three dimensional object to be porous.
- 15 3. A method according to claim 1 or 2, wherein the step of selectively bonding
the powder includes forming the three dimensional object to have a density magnitude
that is higher than the tap density magnitude of the powder.
4. A method according to claim 1, 2 or 3, wherein the step of selectively bonding
20 the powder includes forming the three dimensional object to have a density magnitude
that is 5 to 25%, preferably 10 to 15%, higher than the tap density magnitude of the
powder.
5. A method according to any preceding claim, wherein the step of selectively
25 bonding the powder includes forming the three dimensional object to have a density
magnitude of between 70 and 90%, preferably 70 to 85%, and more preferably 70% or
substantially 70%.
6. A method according to any one of claims 2 to 5, wherein the three
30 dimensional object is porous and gas permeable.
7. A method according to any one of claims 2 to 6, wherein the porous three
dimensional object has an open porosity.

8. A method for forming a three dimensional object including the steps of:
depositing successive layers of powder onto a surface; selectively bonding the powder
to form a gas permeable exterior skin having a first density magnitude, wherein the
exterior skin defines an interior volume of powder having a second density magnitude,
5 and wherein the first density magnitude is higher than the second density magnitude.
9. A method according to claim 8 including the step of selectively bonding the
powder which forms the interior volume.
- 10 10. A method according to claim 9, wherein the step of selectively bonding the
powder which forms the interior volume is performed synchronously or substantially
synchronously with the selective bonding of the powder which forms the exterior skin.
11. A method according to any one of claims 8 to 10 including energising one or
15 more portions of the layers which form the exterior skin a greater amount than another
portion or portions of the layers which form the exterior skin.
12. A method according to any one of claims 8 to 11, wherein the exterior skin
varies in thickness.
- 20 13. A method according to any one of claims 8 to 11, wherein the exterior skin is
substantially uniform in thickness.
14. A method according to any one of claims 8 to 13, wherein the first density
25 magnitude is between 70 to 90%.
15. A method according to claim 14, wherein the first density magnitude is
between 70 and 80%.
- 30 16. A method according to claim 15, wherein the first density magnitude is at least
70%, preferably it is 70% or substantially 70%.
17. A method according to any one of claims 8 to 16, wherein the second density
and / or the first density magnitude(s) is / are higher than the tap density of the
35 powder.

18. A method according to any one of claims 8 to 17, wherein the second density magnitude is between 65 and 75%.

5 19. A method according to claim 18, wherein the second density magnitude is between 65 and 70%.

20. A method according to claim 19, wherein the second density magnitude is 65% or substantially 65%.

10

21. A method according to any preceding claim, wherein the step of selectively bonding includes energising the powder.

15 22. A method according to any preceding claim, including the step of energising the powder by directing an energy beam thereat.

23. A method according to claim 22, wherein the energy beam includes electromagnetic radiation and / or an electron beam.

20 24. A method according to any preceding claim, including selectively depositing a binder material onto one or more of the layers of powder.

25 25. A method according to any preceding claim, including the step of energizing one or more portions of the layer(s) which form the object a greater amount than another portion or portions of the said layer(s).

26. A method according to any preceding claim including, for one or more of the layers of powder, the step of selectively depositing more powder in a first area of the layer(s) than at a second area of said layer(s).

30

27. A method according to any preceding claim including, for one or more of the layers of powder, the step of selectively depositing at least two different powders to form the layer(s).

28. A method according any preceding to claim, wherein the powder may include one or more of: a metal powder, a ceramic powder or a composite material powder.

29. A method according to any one of claims 8 to 20, or claims 21 to 28 when
5 directly or indirectly dependent on claim 8, including the further steps of:
surrounding the exterior skin of the three dimensional object with a pressure transfer medium; and
urging the pressure transfer medium towards the exterior skin of the object to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the
10 object such that the exterior skin and interior volume are densified.

30. A method for forming a plurality of three dimensional objects including the steps of:
forming or providing a plurality of three dimensional objects each formed in
15 accordance with the method of any one of claims 8 to 20, or claims 21 to 28 when directly or indirectly dependent on claim 8;
surrounding the respective exterior skins of the plurality of the objects with a pressure transfer medium; and
urging the pressure transfer medium material towards the respective exterior skins of
20 the objects to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the objects such that the exterior skin and interior volume are densified.

31. A method for forming a plurality of three dimensional objects including
25 the steps of:
forming or providing a plurality of three dimensional objects each formed by:
depositing successive layers of powder onto a surface; and
selectively bonding the powder to form a three dimensional object;
surrounding the plurality of objects with a particulate material;
30 and urging the particulate material towards the objects to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the objects such that the objects are densified.

32. A method according to claim 31, wherein one of more of the objects has one or more or all of the features recited in claims 3 to 7 and / or the method includes one or more or all of the steps recited in claims 21 to 28.
- 5 33. A method according to any one of claims 29 to 32, including the step of providing a housing which defines a chamber and placing the three dimensional object(s) in the chamber prior to or after the pressure transfer medium / particulate material has been deposited in the chamber.
- 10 34. A method according to claim 33 including the step of applying pressure directly or indirectly on the housing in order to urge the pressure transfer medium / particulate material towards the respective exterior skin(s) / exterior surfaces of the three dimensional object(s).
- 15 35. A method according to claim 33 or 34 including the step of applying heat directly or indirectly to the housing in order to heat the three dimensional object(s).
36. A method according to claim 33, 34 or 35 including the step of applying a vacuum to the chamber once the three dimensional object(s) have been placed therein
20 and the pressure transfer medium / particulate material deposited therein.
37. A method according to claim 36 including the step of applying pressure to the housing after the chamber has been sealed.
- 25 38. A method according to any preceding claim, wherein the pressure and heat is applied synchronously or substantially synchronously.
39. A method according to any preceding claim, wherein the pressure transfer medium includes a fluid, preferably a gas.
30
40. A method according to any preceding claim, wherein the pressure transfer medium includes a particulate material.
41. A method according to claim 40, wherein the particulate material is non-tessellating.
35

42. A method according to claim 40 or 41, wherein the particulate material includes one or more of: silica, alumina.

5 43. A method according to any preceding claim comprising, after the step of urging the powder towards the object to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the object such that the object is densified a further step of removing all or part of the powder to reveal the formed three dimensional object.

10

44. A method for forming a component including the steps of: providing a first three dimensional object having an exterior surface;
providing a second three dimensional object having an exterior surface;
bringing respective portions of the exterior surfaces of the first and second three dimensional objects close to one another or into engagement;
15 urging the respective portions towards each other in order to exert a pressure directly or indirectly thereon and applying heat directly or indirectly to the objects such that the respective portions are directly bonded to each other.

20 45. A method according to claim 44 including the steps of:
surrounding the exterior surfaces of the first and second three dimensional objects with a pressure transfer medium, preferably a particulate material; and
urging the pressure transfer medium towards one or both of the exterior surfaces of the first and second three dimensional objects in order to urge the respective portions
25 towards each other.

46. A method according to claim 44 or 45, wherein one or both of the first and second three dimensional objects have been obtained from the method of any one of claims 1 to 42.

30

47. A method according to claim 44, 45 or 46, wherein one or both of the first and second three dimensional objects have:
a gas permeable exterior skin having a first density magnitude; and
an interior volume defined by the exterior powder and having a second density
35 magnitude,

wherein the first density magnitude is greater than the second density magnitude.

48. A method according to any one of claims 44 to 46 including one or more or all of the steps / features recited in claims 33 to 41.

5

49. An object or component formed or obtained from a method according to any one of claims 1 to 42.

50. A method as hereinbefore described with reference to and as shown in the accompanying drawings.

10

51. An object or component formed or obtained from the method according to claim 50.

15

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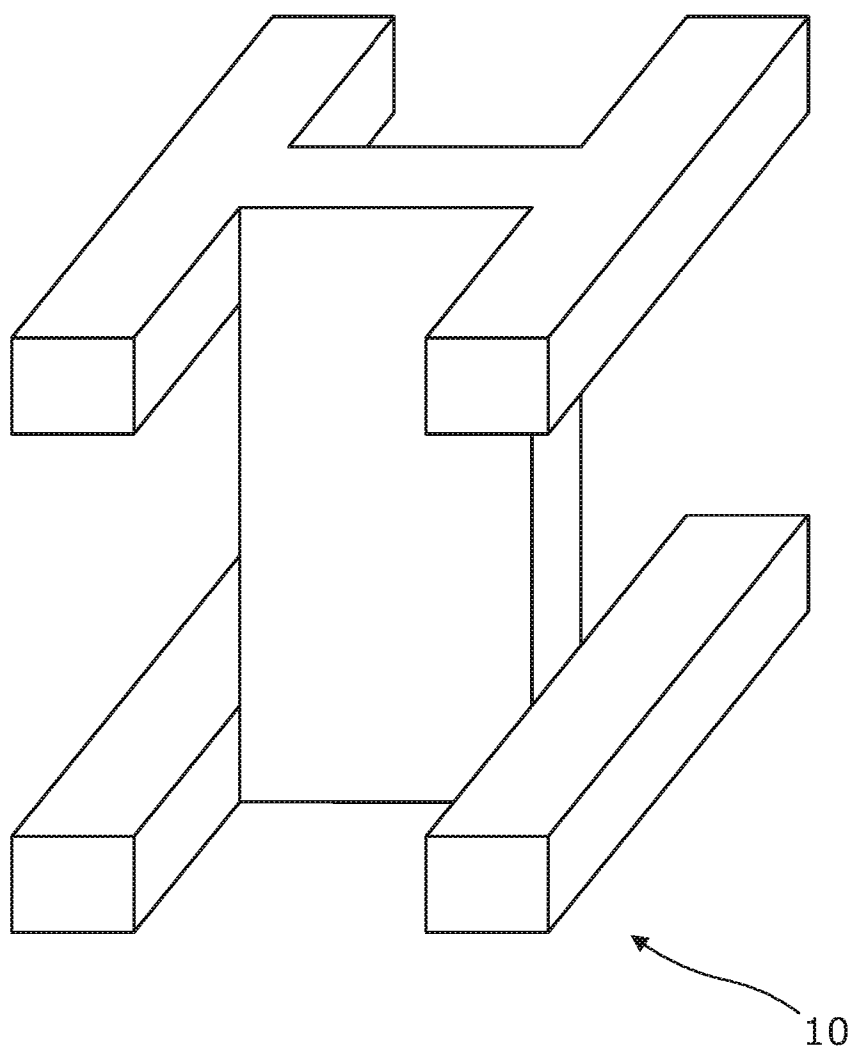


Fig. 1

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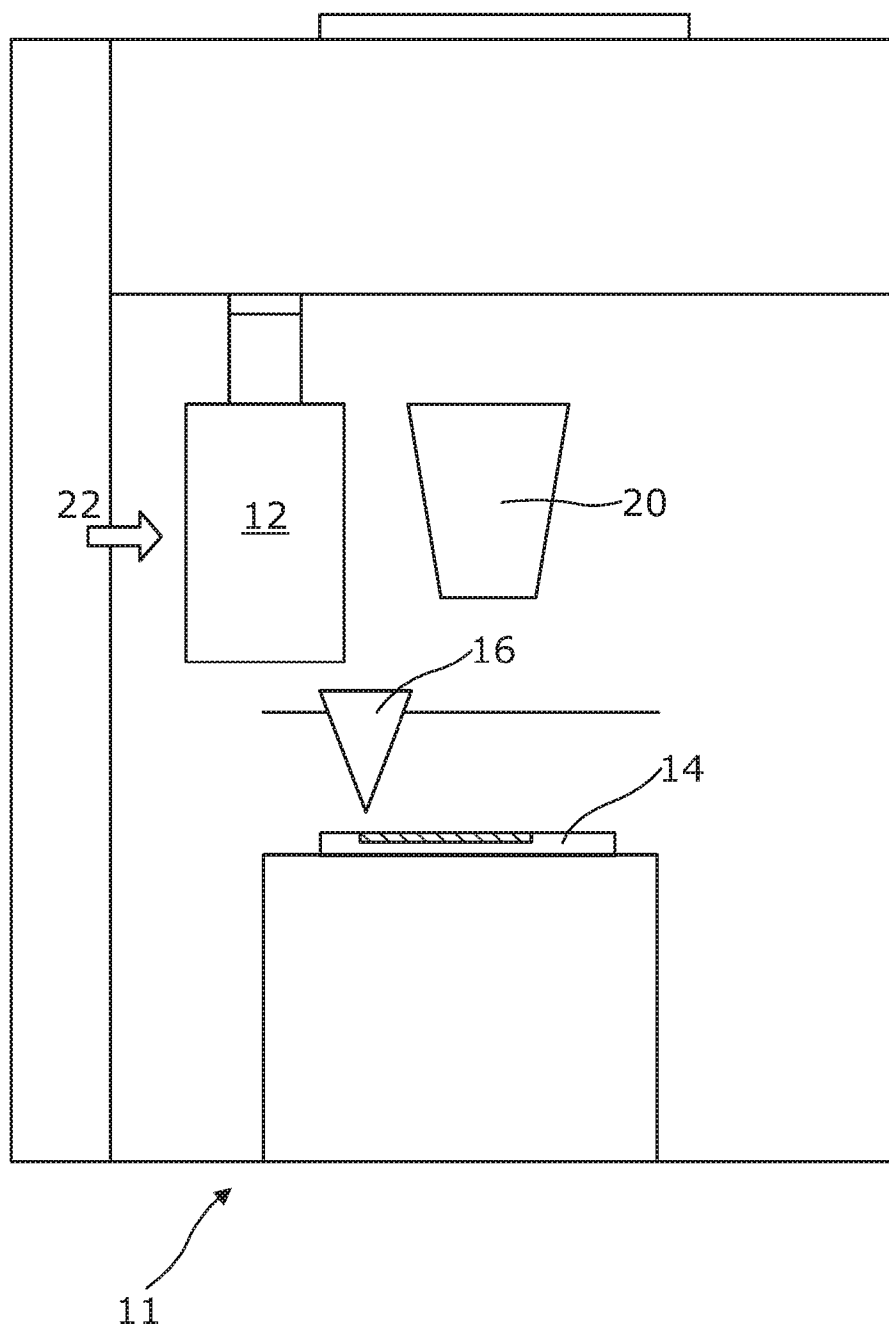


Fig. 2

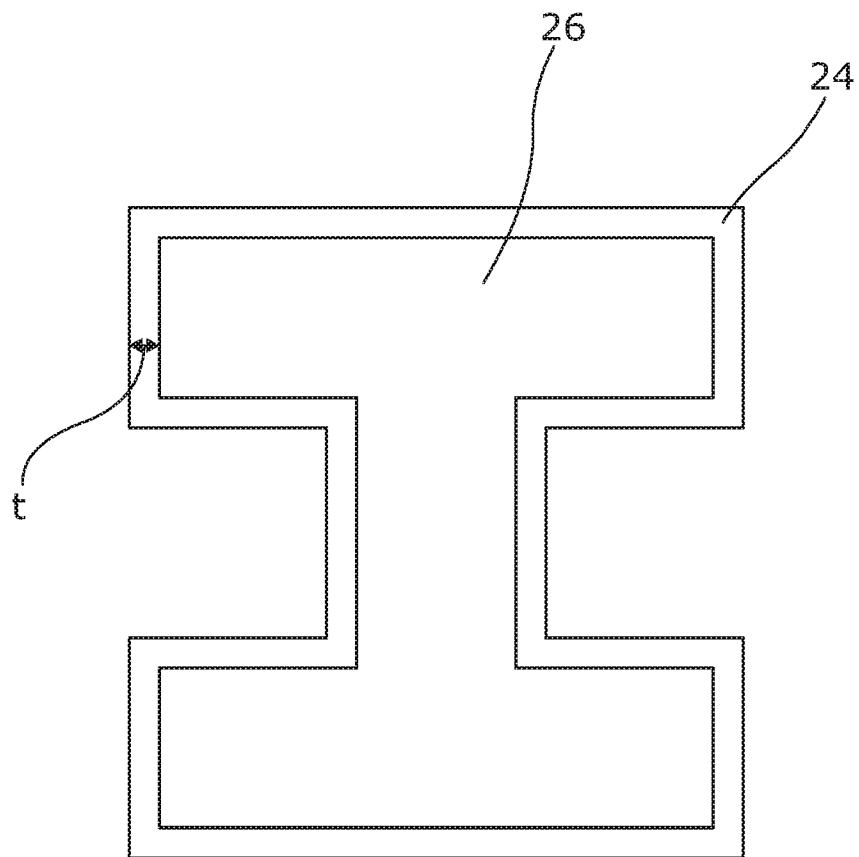


Fig. 3

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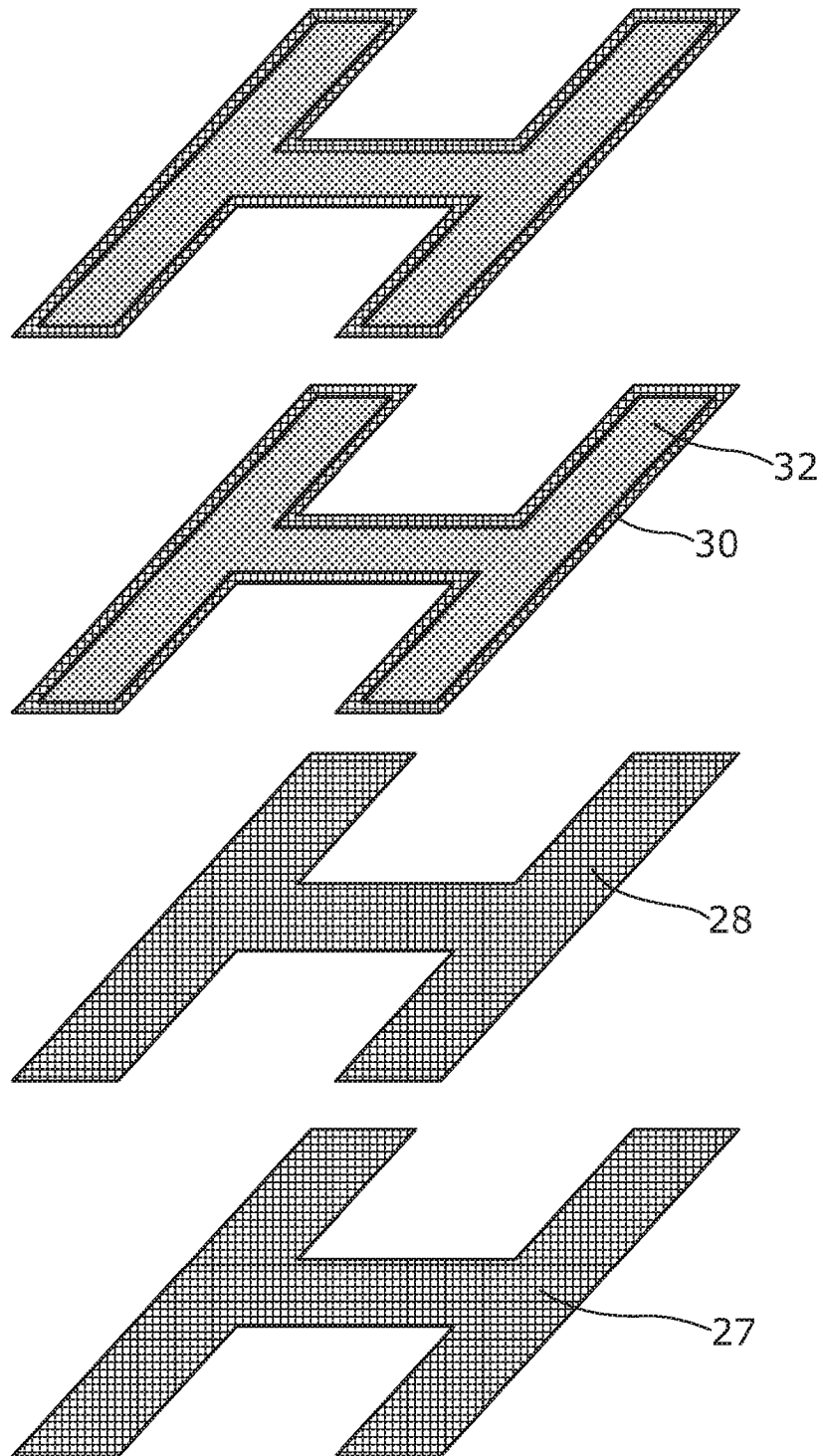


Fig. 4

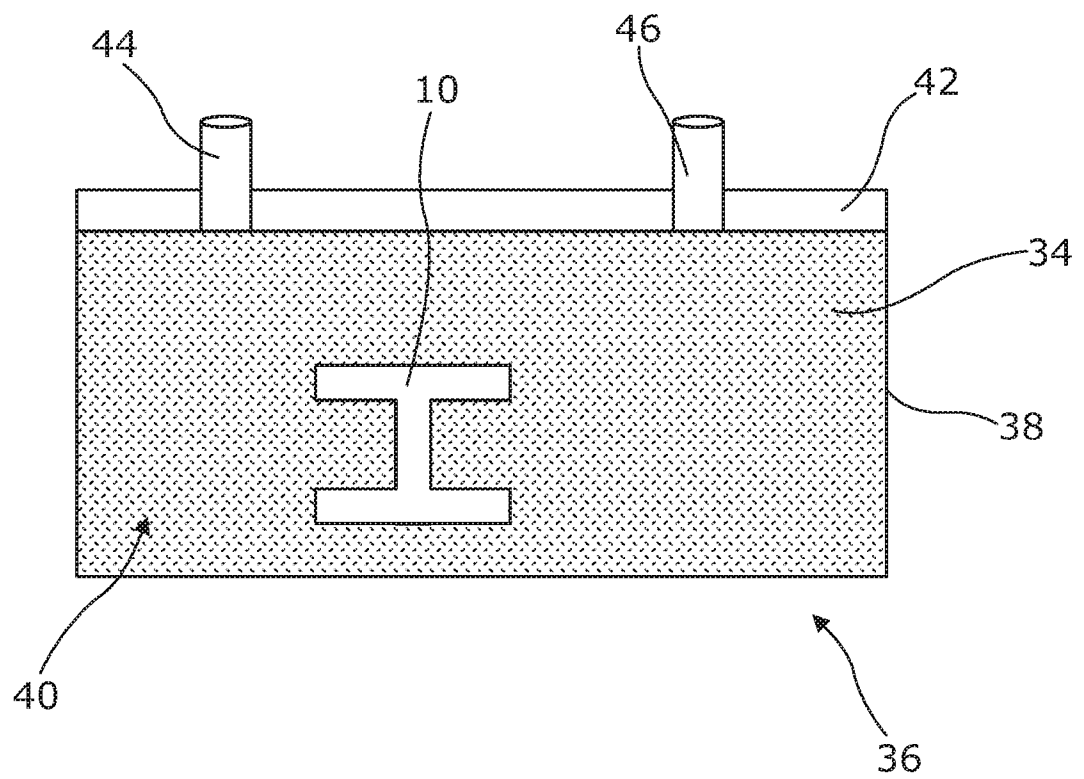


Fig. 5

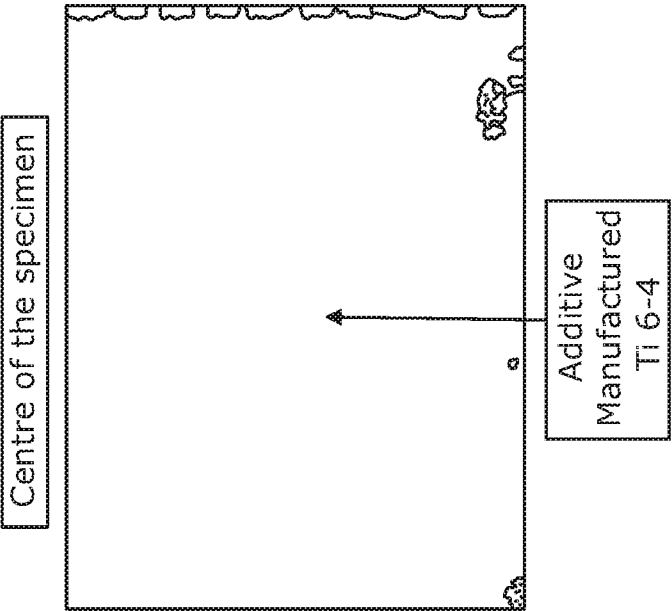


Fig. 6b

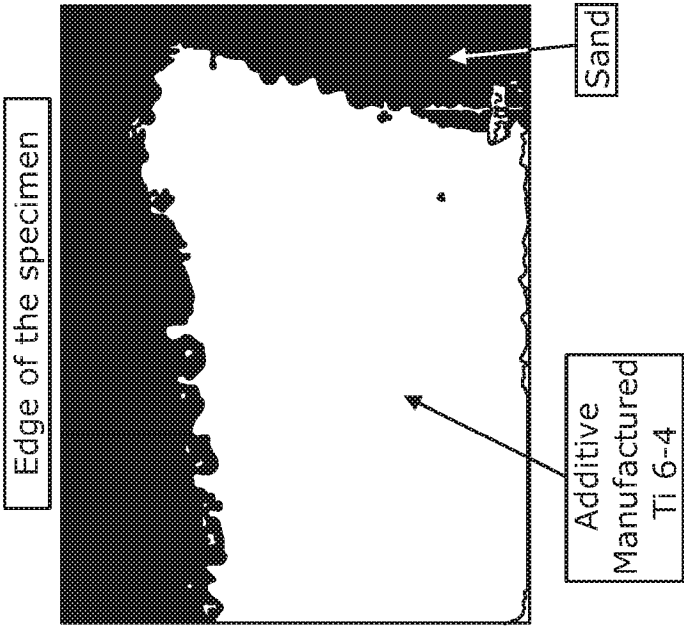


Fig. 6a

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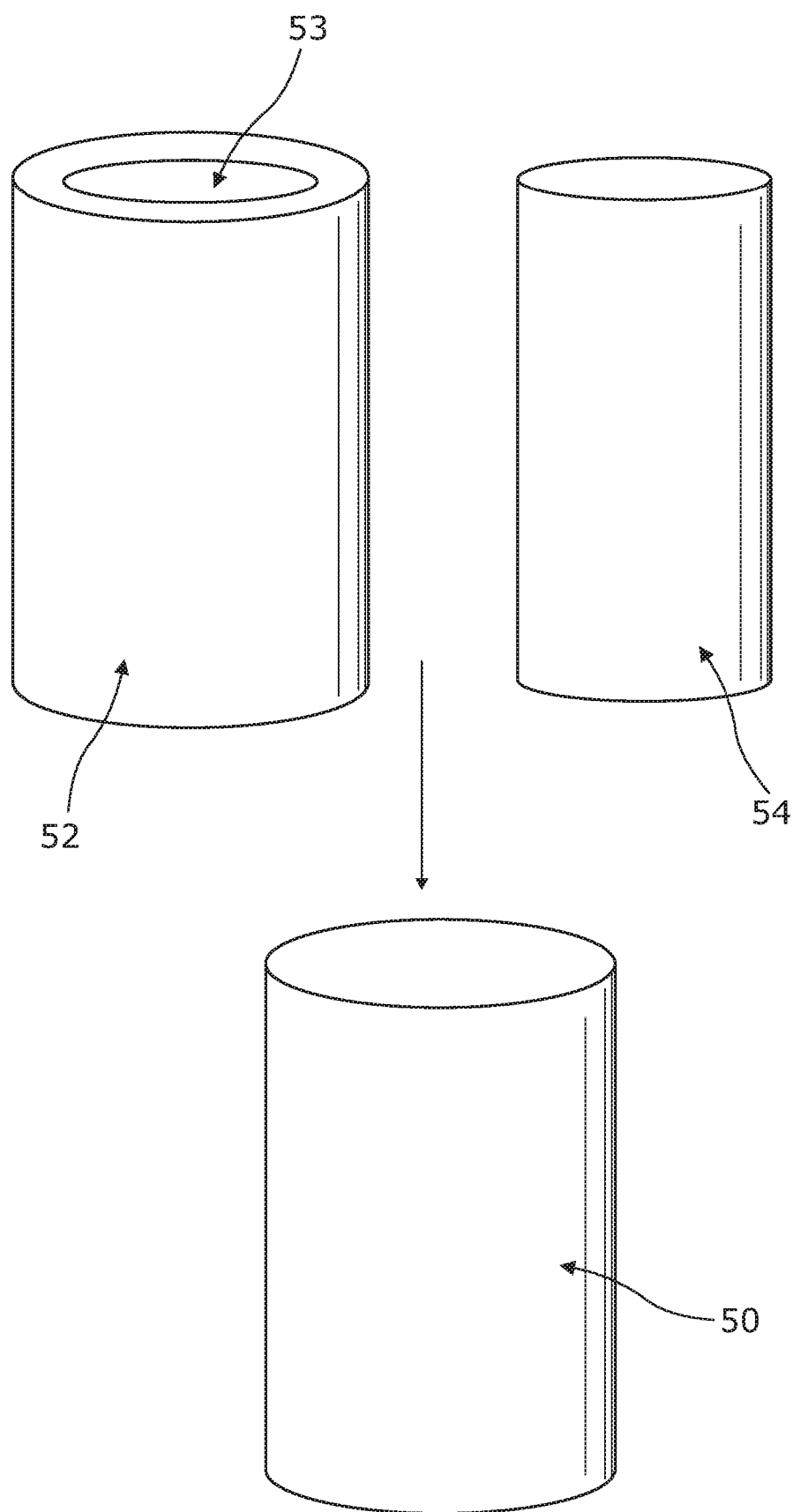


Fig. 7

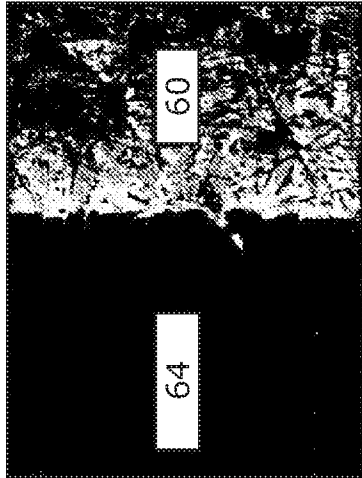


Fig. 8b

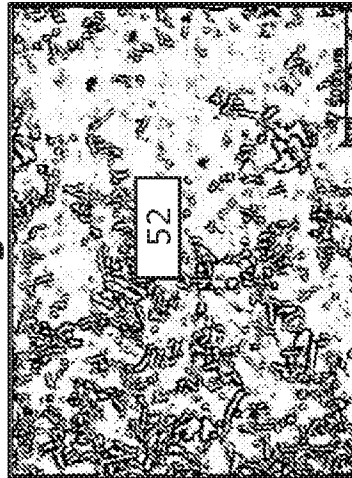


Fig. 8c

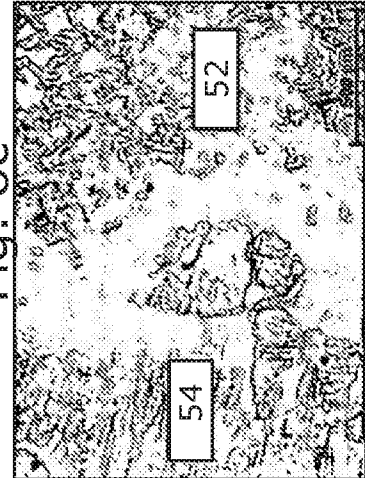


Fig. 8e

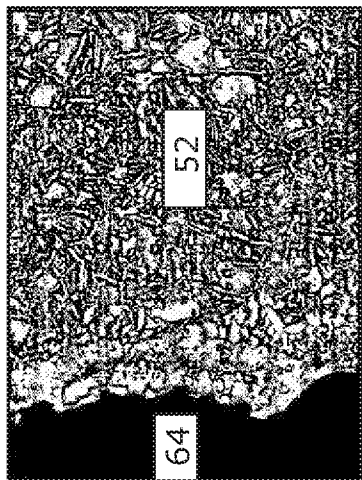


Fig. 8f

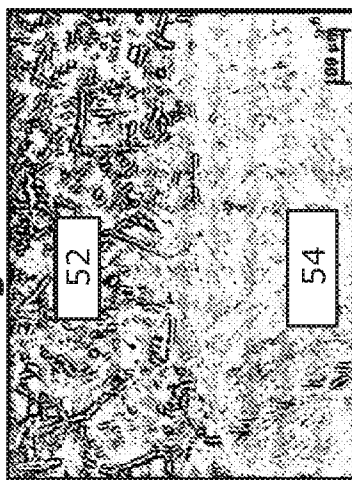


Fig. 8h

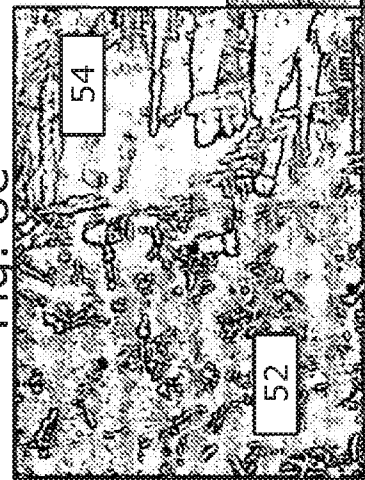


Fig. 8j

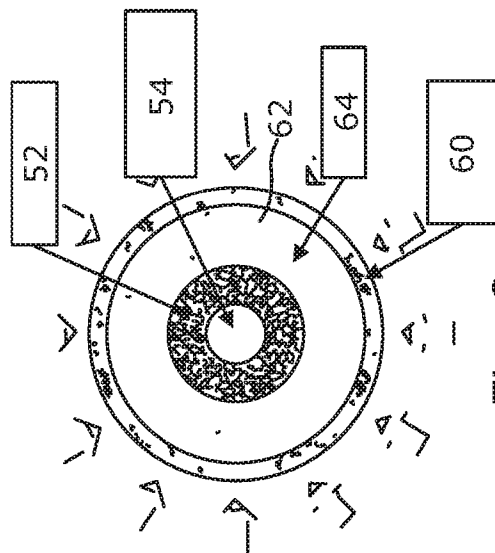


Fig. 8a

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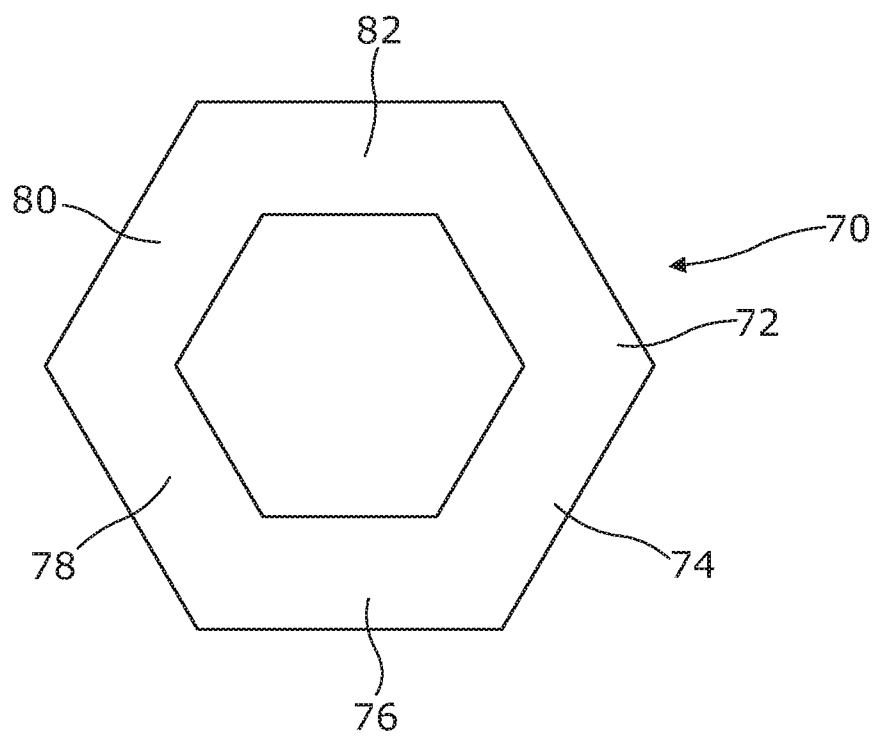


Fig. 9

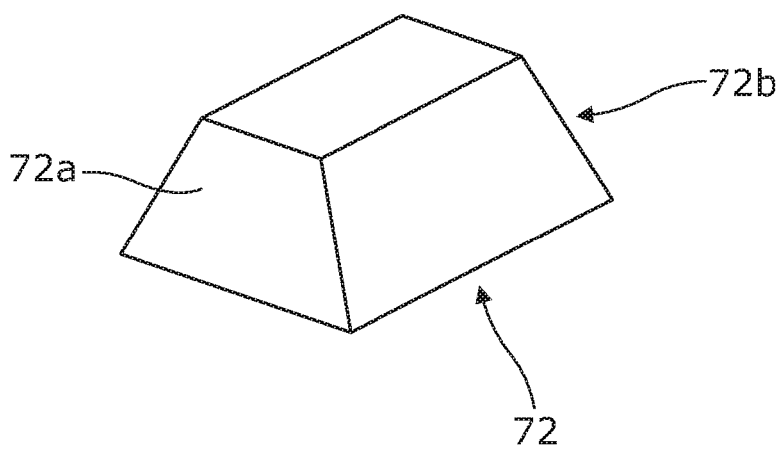


Fig. 10