ABRASIVE ARTICLES AND METHODS FOR FORMING SAME

BACKGROUND

[0001] Abrasive articles are used in material removal operations, such as cutting, grinding, or shaping various materials. Abrasive articles or green bodies of abrasive articles can be formed via additive manufacturing. There is a need to develop improved abrasive articles.

DESCRIPTION

[0002] The present disclosure is directed to methods for forming abrasive articles and the features of the resulting green abrasive articles and/or finally formed abrasive articles. While prior disclosures have provided some limited examples of forming abrasive articles via additive manufacturing, such abrasive articles are limited in their size, quantity, and quality. In fact, Applicants of the present disclosure have conducted notable empirical studies and have found that the knowledge necessary to create high quality abrasive articles according to conventional additive manufacturing techniques is noted, specifically in the context of dry powder layering and binding techniques. To-date, disclosures in the prior art are limited to micro-abrasive bodies. This is because formation of large-scale, high-quality abrasive articles via dry powder layering and binding techniques is not easily scalable. Numerous hurdles limit the advance of the technology, including, but not limited to, the capability of creating dense parts, dimensional stability during and after forming, and the empirical studies needed to fully understand and appreciate the complexities of the process variables. Such process variables include, but is not limited to, composition of the powder material, flowability of the powder material, a force applied by a compaction object to the layer or a plurality of layers of powder, a traverse speed of a compaction object, average thickness of the layer prior to compaction, a particle size distribution of the powder, number of previously formed layers underlying the layer of powder, the number of compacted layers underlying the layer of powder, the density of any layers underlying the layer of powder, the amount of binder in any layers underlying the layer of powder, the relative dimensions of the layer relative to one or more layers underlying the layer, an average thickness of the layer prior to compaction, a printhead deposition resolution, saturation limits of the binder, composition of the binder material, type of solvent or liquid vehicle used, and others. In one aspect, the additive manufacturing techniques of the embodiments herein may be part of a binder jetting manufacturing process.

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[0003] FIG. 1A includes an illustration of a portion of the process including forming one or more layers of powder material that can include abrasive particles and may include a mixture of abrasive particles and precursor bond material. The layer of powder can have an average thickness (t). The layer of powder material can be dispensed as described in embodiments herein.

[0004] FIG. 1B includes an illustration of a process of compacting at least a portion of the layer with a compaction object (120). The compaction object 120 can traverse the layer and compact the layer to form a compacted layer having an average thickness (tc). The compacted layer thickness (tc) can be less than the layer thickness (t) prior to compaction as described according to embodiments herein. As will be appreciated, in some instances, multiple layers of powder material may be formed, and compaction can be completed on more than one layer of powder material simultaneously. In some optional embodiments, a smoothing roller may traverse the surface of the layer of powder, but smoothing rollers do not apply sufficient force to cause compaction, rather they scrape the surface of the layer to remove and smooth any large undulations.

[0005] FIG. 1C includes binding at least a portion of the compacted layer of powder material with a binder material. In an embodiment, binding at least a portion of the compacted layer may include the use of a printhead 101 wherein the printhead deposition resolution impacts the amount of binder material selectively deposited. As further depicted, the layer may include a region 102 including loose or unbound powder material without binder material and a region 103 including a region of powder material and binder. The binder material can have any of the features described in the embodiments herein. The amount of binder material is sufficient to bind the powder material. The regions that do not include binder material can be loose or unbound powder, which may be removed and captured after processing is completed and used as recycled powder. Notably, at the edges of the region between the bound powder material and unbound powder material, the binder material may exist in some of the loose powder. Accordingly, as described in embodied embodiments herein, the recycled powder may include some content of organic material, such as binder material that was included in the captured loose or unbound powder material, particularly at the regions bordering the bound and unbound powder. Methods may be used to treat the loose powder material including organic material to remove a certain content of organic material prior to recycling the powder material and using in one or more subsequent additive manufacturing processes to form abrasive articles.

[0006] FIG. 1D includes a process for binding the powder material by treating the layer to convert the binder from a liquid material to a solid material to bind the powder material. The process can include curing of at least a portion of the binder material as embodied in embodiments herein.

[0007] FIG. 1E is an illustration of an abrasive article, which may represent a green body or finally-formed abrasive article. It will be appreciated that the abrasive articles of the embodiments herein can have any three-dimensional shape and FIG. 1E is illustrative of only one possible shape. The length (L) defines the longest dimension of the body, and the width (W) defines a dimension of the body substantially perpendicular to the length and may be a value less than the length and greater than the thickness (T). The thickness (T) of the body may extend in a direction perpendicular to a plane defined by the length and width. The dimensions of any body of embodiments herein may have a relationship of length, width, and thickness defined as $L \geq W \geq T$. In those instances, wherein the body is in the form of a cylinder with the axial axis being the longest, the length is the longest dimension in the axial direction, the width can be a first diameter of an end surface, and the thickness can be another diameter. In the case of an abrasive article in the form of a disk, wherein the diameter is the greatest dimension, the diameter defines the length of the body, the width defines a diameter perpendicular to the length (and may be the same as the length), and the thickness defines the dimension of the body in an axial direction perpendicular to the plane of the circular end surface.

[0008] The abrasive articles can have contents and compositions of abrasive particles, bond material, precursor bond material, and any additives as described in the embodiments herein.

[0009] FIGs. 2A and 2B include perspective view illustrations of abrasive articles, which may be green bodies or finally-formed abrasive articles according to embodiments herein. The bodies of FIGs. 2A and 2B can be formed by any of the methods of the embodiments herein and formed in a build direction 251. The body 201 can have surfaces 201 203 204 204 that are transverse relative to the build direction and surfaces that are not transverse to the build direction 202 and 207. The body 211 can be in the shape of a cylinder having a surface 213 transversely relative to the build direction and surfaces 212 and 214 that are not transverse to the build direction. It will be appreciated that the abrasive articles may be in any number of shapes and not limited to those explicitly shown herein. It will be appreciated that the bodies may be formed using a variety of build directions. In certain embodiments, the build direction may impact certain features of the abrasive articles, as green body abrasive articles and/or finally-formed abrasive articles. In certain instances, the transverse surfaces may have a different Sdr than the other surfaces. In an embodiment, the transverse surfaces may have a higher Sdr than surfaces having a different orientation to the transverse surfaces, and more specifically, surfaces having different orientations relative to the build direction 251. It will be appreciated that the build direction may be manipulated to control which surfaces have a relatively high or low Sdr. For example, an abrasive may be constructed such that the smallest surfaces are not transverse to the build direction, minimizing the amount of surface area with a low Sdr. Different Sdr values may be valuable for different applications. For example, a high Sdr surface may be useful as an abrasive working surface in low pressure grinding applications. A high or low Sdr surface may also more easily bind or adhere to a substrate or another surface using a binder, an adhesive, or other coupling means, depending on the composition of the coupling means. In an embodiment, a transverse surface can be an abrasive working surface of the body. In another embodiment, a surface that is not a transverse surface can be an abrasive working surface of the body. In embodiments, either a transverse surface or a surface that is not transverse can be coupled to another surface via a binder or adhesive. In an embodiment, the transverse surfaces may have visible layering or roughness that is not present on the other surfaces.

[0010] FIG. 3 includes an illustration of the measuring principle of the developed interfacial area ratio Sdr. The developed interfacial area ratio Sdr expresses the percent increase in surface area 301 (provided by the surface texture) in relation to a corresponding underlying projected area 302 (ideal flat plane), and was measured according to ISO standard method ISO25178-2:2012.

[0011] The developed interfacial area ratio Sdr expresses the percentage rate of an increase in a surface area A_1 301 that is related to the surface texture in comparison to a projected area A_0 702, wherein A_0 302 corresponds to an ideal plane underneath the measured surface texture. An illustration of the relation of surface area A_1 301 to projected area A_0 302 is shown in FIG. 3. The Sdr measurements were conducted with an Olympus LEXT OLS5000 laser confocal microscope. The analyzed surface area was 257 x 257μm, at a 50 times magnification, with a filter cylinder. Four measurements per sample were conducted at different locations and an average Sdr value was calculated according to the equation: =

$$\frac{1}{A}\left[\iint_A\left(\sqrt{\left[1+\left(\frac{\partial z(x,y)}{\partial x}\right)^2+\left(\frac{\delta z(x,y)}{\delta y}\right)^2\right]}-1\right)dx\,dy\right].$$

[0012] The Sdr can be also expressed by the following formula: $Sdr = [(A_1/A_0)-1] \times 100$ (%).

[0013] In an embodiment, the additive manufacturing process can be performed with a specific printer head deposition resolution that may result in improved manufacturing or performance of the abrasive body. It will be appreciated that the printhead deposition resolution may be between any of the minimum and maximum values embodied herein. Without wishing to be tied to one theory, some data suggests that manipulating the resolution may alter the Sdr on the surfaces of the body. A small resolution may lead to a smaller Sdr on surfaces transverse to the build direction, as well as a smaller difference in Sdr between transverse surfaces and surfaces that are not transverse to the build direction. The same may be true for the thickness of the layers before and/or after compaction.

[0014] In one aspect, the binder jetting can include using as starting material a powder material having a multi-modal particle distribution. The multimodal particle size distribution of the powder material may be related to different sizes of a single phase material or creation of a mixture from different powder components, including, for example, but not limited to, a mixture including a first particulate material (e.g., abrasive particles having a first particle size distribution) and a second particulate material (e.g., particulate bond material or bond material precursor having a second particle size distribution that is different from the first particle size distribution).

[0015] In one particular aspect, the powder material for the binder jetting can be bi-modal particle distribution, wherein a first plurality of particles can have an average particle size (D50) of at least 1 μm and not greater than 10 μm, and a second plurality of particles can have an average particle size (D50) of at least 20 μm and not greater than 50 μm.

[0016] In another aspect, a weight% ratio of the first plurality of particles to the second plurality of particles can be from 1:0.1 to 1:10. In certain aspects, the weight% ratio can be not greater than 1:0.3, or not greater than 1:0.5, or not greater than 1:1, or not greater than 1:2, or not greater than 1:3, or not greater than 1:4, or not greater than 1:5, or not greater than 1:6, or not greater than 1:7, or not greater than 1:8, or not greater than 1:9, or not greater than 1:10.

[0017] In an embodiment, the abrasive particles can include oxides, carbides, nitrides, borides, diamonds, or any combination thereof. In an embodiment, the abrasive particles can include alumina, zirconia, ceria, diamond, or any combination thereof.

[0018] In an embodiment, the abrasive body can include at least 2 vol% abrasive particles for a total volume of the body or at least 5 vol%, or at least 10 vol%, or at least 15 vol%, or at least 20 vol%, or at least 25 vol%, or at least 30 vol%, or at least 35 vol%, or at least 40 vol%, or at least 45 vol%, or at least 50 vol%, or at least 55 vol%, or at least 60 vol%, or at least 65 vol%, or at least 70 vol%, or at least 75 vol%, or at least 80 vol%, or at least 85 vol%, or at least 90 vol%. In an embodiment, the body can include not greater than 95 vol% abrasive particles for a total volume of the body or not greater than 90 vol%, or not greater than 85 vol%, or not greater than 80 vol%, or not greater than 75 vol%, or not greater than 70 vol%, or not greater than 65 vol%, or not greater than 60 vol%, or not greater than 55 vol%, or not greater than 50 vol%, or not greater than 45 vol%, or not greater than 40 vol%, or not greater than 35 vol%, or not greater than 30 vol%, or not greater than 25 vol%, or not greater than 20 vol%, or not greater than 15 vol%, or not greater than 10 vol%, or not greater than 5 vol%. It will be appreciated that the vol% of abrasive particles can be between any of the minimum and maximum values noted above.

[0019] In an embodiment, the body can include a bond material or bond material precursor comprising an organic material or inorganic material or any combination thereof. In an embodiment, the bond material can comprise thermoplastics, thermosets, resins, or any combination thereof. In an embodiment, the bond material can comprise phenolic resin, polyimides, polyamides, polyesters, aramids, epoxies, or any combination thereof. In an embodiment, the bond material can comprise a transition metal element. In an embodiment, the bond material comprises an amorphous phase, polycrystalline phase, or any combination thereof. In an embodiment, the bond material can comprise ceramic material, vitreous material, or any combination thereof, or wherein the ceramic material is polycrystalline, or wherein the vitreous material is amorphous. In an embodiment, the bond material can comprise an oxide. In an embodiment, the bond material can comprise an alumina-containing vitreous material. In an embodiment, the bond material can comprise silica-containing vitreous material. In an embodiment, the bond material can comprise at least one of alumina, silica, boron oxide, bismuth oxide, zinc oxide, barium oxide, magnesium oxide, calcium oxide, lithium oxide, sodium oxide, potassium oxide, cesium oxide, strontium oxide, zirconium oxide, manganese oxide, or any combinations thereof.

[0020] In an embodiment, an abrasive body can have a first surface having a first (Sdr1) and a second surface having a second developed interfacial area ratio (Sdr2). In an embodiment, Sdr1 can be greater than Sdr2. In another embodiment, Sdr1 can be less than Sdr2. In an embodiment, the first surface can be a transverse surface relative to the build direction of the abrasive article.

[0021] In an embodiment, a certain percentage of the surface area of the body can be a relatively high Sdr surface. It will be understood that a surface with a relatively high Sdr has an Sdr greater than the average Sdr of the entire body. In an embodiment, at least 5% of the exterior surface area of the body can be a relatively high Sdr surface, or at least 7%, or at least 10%, or at least 12%, or at least 14%, or at least 16%, or at least 20%, or at least 22%, or at least 24%, or at least 26%, or at least 28%, or at least 30%, or at least 32%, or at least 34%, or at least 36%, or at least 38%, or at least 40%, or at least 42%, or at least 44%, or at least 46%, or at least 48%, or at least 50%, or at least 52%, or at least 54%, or at least 56%, or at least 58%, or at least 60%, or at least 62%, or at least 64%, or at least 66%, or at least 68%, or at least 70%, or at least 72%, or at least 74%, or at least 76%, or at least 78%, or at least 80%, or at least 82%, or at least 84%, or at least 86%, or at least 88%, or at least 90%, or at least 93%, or at least 95%. In an embodiment, not greater than 95% of the exterior surface area of the body can be a relatively high Sdr surface, or not greater than 93%, or not greater than 90%, or not greater than 88%, or not greater than 86%, or not greater than 84%, or not greater than 82%, or not greater than 80%, or not greater than 78%, or not greater than 76%, or not greater than 74%, or not greater than 72%, or not greater than 70%, or not greater than 68%, or not greater than 66%, or not greater than 64%, or not greater than 62%, or not greater than 60%, or not greater than 58%, or not greater than 56%, or not greater than 54%, or not greater than 52%, or not greater than 50%, or not greater than 48%, or not greater than 46%, or not greater than 44%, or not greater than 42%, or not greater than 40%, or not greater than 38%, or not greater than 36%, or not greater than 34%, or not greater than 32%, or not greater than 30%, or not greater than 28%, or at least 26%, or not greater than 24%, or not greater than 22%, or not greater than 20%, or not greater than 18%, or not greater than 16%, or not greater than 14%, or not greater than 10%, or not greater than 7%, or not greater than 5%. It will be appreciated that the percent of surface area with a relatively high Sdr can be between any of the minimum and maximum values noted above.

[0022] In an embodiment, the first surface may have a particular Sdr1 that may facilitate improved performance and/or manufacturing of the abrasive article. In an embodiment, Sdr1 may be at least 40%, or at least 42%, or at least 44%, or at least 46%, or at least 48%, or at least 50%, or at least 52%, or at least 54%, or at least 56%, or at least 58%, or at least 60%, or at least 62%, or at least 64%, or at least 66%, or at least 68%, or at least 70%. In another embodiment, Sdr1 is not greater than 140%, or not greater than 135%, or not greater than 130%, or not greater than 125%, or not greater than 120%, or not greater than 115%, or not greater than 110%, or not greater than 105%, or not greater than 100%, or not greater than 95%, or not greater than 90%, or not greater than 85%, or not greater than 80%. It will be appreciated that Sdr1 will be between any of the minimum and maximum values noted above.

[0023] In an embodiment, the abrasive body may have a second surface with a particular Sdr2 that may facilitate improved performance of the abrasive article. In an embodiment, Sdr2 may be not greater than 110%, or not greater than 105%, or not greater than 100%, or not greater than 95%, or not greater than 90%, or not greater than 85%, or not greater than 80%, or not greater than 75%. In another embodiment, Sdr2 is at least 5%, at least 10%, at least 15%, at least 20%, at least 25%, at least 30%, or at least 35%, or at least 40%, or at least 45%. It will be appreciated that Sdr2 will be between any of the minimum and maximum values noted above.

[0024] In an embodiment, a first surface can have an Sdr1 that is different than the Sdr2 of a second surface by a particular amount that may facilitate improved manufacturing or performance of the abrasives article. In one non-limiting embodiment, Sdr1 can have a value that is greater relative to Sdr2. In an embodiment, the first surface can have an Sdr1 that is at least 1% different than Sdr2, or at least 2%, or at least 3%, or at least 4%, or at least 5%, or at least 6%, or at least 7%, or at least 8%, or at least 9%, or at least 10%, different than the Sdr2 of the second surface. In another embodiment, the first surface can have an Sdr1 that is not greater than 25% different than Sdr2, or not greater than 24%, or not greater than 23%, or not greater than 22%, or not greater than 21%, or not greater than 20%, or not greater than 19%, or not greater than 18%, or not greater than 17%, or not greater than 16%, or not greater than 15% different than Sdr2. It will be appreciated that the percent difference between Sdr1 and Sdr2 can be between any of the minimum and maximum values noted above. It will be appreciated that there may be more than two surfaces with different Sdr values, and the differences noted above in Sdr1 and Sdr2 can be equally applicable between two or more surfaces (e.g., exterior surfaces) of a body.

[0025] In an embodiment, the ratio of Sdr1: Sdr2 can be not greater than 1:2, or not greater than 1:1.9, or not greater than 1:1.8, or not greater than 1:1.7, or not greater than 1:1.6, or not greater than 1:1.5, or not greater than 1:1.4, or not greater than 1:1.3. In an embodiment the ratio of Sdr1: Sdr2 can be at least 1:1.01, or at least 1:1.03, or at least 1:1.05.

[0026] In an embodiment, the first surface, optionally a working surface, may be oriented at a particular angle relative to the second surface. The angle can be at least 2°, at least 5°, at least 8°, at least 10°, at least 12°, at least 15°, at least 18°, at least 19°, at least 20°, at least 22°, at least 25°, at least 27°, at least 30°, at least 33°, at least 35°, at least 37°, at least 40°, at least 41°, at least 43°, at least 45°, at least 47°, at least 48°, at least 50°, at least 52°, at least 55°, at least 58°, at least 60°, at least 62°, at least 64°, at least 66°, at least 68°, at least 70°, at least 72°, at least 74°, at least 76°, at least 78°, at least 80°, at least 82°, at least 85°, at least 88°, or at least 90°. In another embodiment, the angle can be at most 180°, at most 178°, at most 176°, at most 174°, at most 172°, at most 170°, at most 168°, at most 166°, at most 164°, at most 162°, at most 160°, at most 158°, at most 156°, at most 154°, at most 152°, at most 150°, at most 147°, at most 145°, at most 143°, at most 140°, at most 138°, at most 135°, at most 133°, at most 130°, at most 127°, at most 124°, at most 121°, at most 118°, at most 115°, at most 112°, at most 109°, at most 105°, at most 102°, at most 99°, at most 96°, at most 93°, at most 90°, such as at most 88°, at most 86°, at most 84°, at most 82°, at most 80°, at most 78°, at most 75°, at most 74°, at most 72°, at most 70°, at most 68°, at most 66°, at most 64°, at most 62°, at most 60°, at most 58°, at most 66°, at most 64°, at most 62°, at most 60°, at most 58°, at most 55°, at most 54°, at most 52°, at most 50°, at most 48°, at most 46°, at most 44°, at most 42°, at most 40°, at most 38°, at most 36°, at most 34°, at most 32°, or at most 30°. It will be appreciated that the angle between the first surface and the second surface may be between any of the minimum and maximum values noted above. In a non-limiting embodiment, the first surface and the second surface may be orthogonal to each other.

[0027] In an embodiment, the first surface may have a particular surface roughness (Sa1) that may facilitate improved performance and/or manufacturing of the abrasive body. In an embodiment, Sa1 may be at least 1 micron, or at least 1.5 microns, or at least 2 microns, or at least 2.5 microns, or at least 3 microns, or at least 3.5 microns, or at least 4 microns, or at least 4.5 microns, or at least 5 microns. In another embodiment, Sa1 may not be greater than 30 microns, not greater than 28 microns, not greater than 25 microns, not greater than 22 microns, not greater than 18 microns, or not greater than 15 microns. It will be appreciated that Sa1 may be between any of the minimum and maximum values noted above.

[0028] In an embodiment, the second surface may have a particular surface roughness (Sa2) that may facilitate improved performance and/or manufacturing of the abrasive body. In an embodiment, Sa2 may be at least 1 micron, at least 2 microns, at least 3 microns, at least 4 microns, or at least 5 microns. In another embodiment Sa2 may not be greater than 25 microns, not greater than 23 microns, not greater than 21 microns, not greater than 19 microns, not greater than 17 microns, or not greater than 15 microns, or not greater than 14 microns, or not greater than 13 microns. It will be appreciated that Sa2 may be between any of the minimum and maximum values noted above.

[0029] In an embodiment, a first surface can have a Sa1 that is different than the Sa2 of a second surface by a particular amount that may facilitate improved manufacturing or performance of the abrasive article. In an embodiment, the first surface can have a Sa1 that is at least 0.2 microns different than the Sdr2 of the second surface, or at least 0.4 microns, or at least 0.6 microns, or at least 0.8 microns, or at least 1 micron. In another embodiment, the first surface can have a Sa1 that is not greater than 6 microns different than Sa2, or not greater than 5.5 microns, or not greater than 5 microns, or not greater than 4.5 microns, or not greater than 4 microns, or not greater than 3.5 microns, or not greater than 3 microns, different than Sa2. It will be appreciated that the percent difference between Sa1 and Sa2 can be between any of the minimum and maximum values noted above.

[0030] The frequency domain images are obtained by utilizing the Fourier Transform through Python to process the SEM images. Three SEM images of three cross sections of a bonded abrasive body are taken. FIGs. 4A to 4E include images of a cross section of a body of a finally-formed abrasive article formed in accordance with an additive manufacturing technique. FIG. 4A includes a scanning electron microscopic image of a cross section of a body. As illustrated, the abrasive body can include abrasive particles 401 joined by a bond matrix including a bond material 402 and an infiltrant material 403, and a filler material 404. FIG. 4A can be processed by adjusting the threshold such that only the bond material remains present in the image of FIG. 4B. FIG. 4C includes an image that has been further processed by focusing on the center, the brightest area, of FIG. 4B. FIG. 4D is an image of the magnified area within the box 407 in FIG. 4C. As illustrated in FIG. 4D, noise 408 is in greyscale, and frequency signals 410 and 412 have brightness above the noise. Removing the noise from FIG. 4D, a frequency domain image is generated and illustrated in FIG. 4E. The bright dot in the center is the zero frequency component indicating the average brightness of the image in FIG. 4B, and the other two symmetrically distributed bright dots represent the frequency of the bond material 402. The Fast Fourier Transform value refers to the average number of dots other than the zero frequency components shown in frequency domain images of at least three cross-sectional images from the same body. For example, the Microstructure Feature value can be determined by dividing the sum of the number of dots that are not the center dot of each frequency domain image by the total number of the frequency domain images.

[0031] In a further embodiment, the Microstructure Feature can include a Spacing Value. The abrasive body can include an average distance determined based on frequency domain images (i.e., the image of FIG. 4E) of at least three cross-sectional images of the body of an abrasive article. As used herein, the Spacing Value can be determined using the average distance. The average distance is an averaged value of the distance between the zero frequency component (i.e., the center dot) and one other dot of frequency domain images of at least three cross-sections of the abrasive body. For example, the average distance can be calculated by dividing the total of the distance between the center dot and one other dot of each of the frequency domain images by the number of the distances that make up the total. The Spacing Value of an abrasive body can be a relative value that can be obtained by dividing the average distance of the abrasive body by the average distance of an abrasive body having layers having the printed thickness of 120 microns.

[0032] More particularly, the Spacing Value can be determined as follows. The bonded abrasive body includes layers having a printed thickness of 120 microns. All the SEM images are processed to obtain images illustrated in FIG. 4E. As illustrated in the frequency domain image of FIG. 4E, the distance from the center of the center dot to the center of one other dot is measured using Image J for each of the frequency domain images. The average of the 3 distances is calculated and referred to as Da1. The average distance is then divided by itself to have a Spacing Value of the body.

[0033] FIGs. 5A and 5B represent images from a bonded abrasive formed through conventional processing techniques of hot pressing. FIG. 5A is a cross-sectional SEM image processed in the same manner as noted above according to the Fast Fourier Transform to obtain the image of FIG. 5B. The Microstructure Feature value of the sample is 1.

[0034] FIG. 6A includes an illustration of a build box for forming an abrasive article according to an embodiment. The build box 600 is configured to contain the powder material as it is deposited. As illustrated in FIG. 6A, the build box 600 can include a portion including loose or unbound powder 601. The build box 600 can further include a portion representing a region of bound powder defining a green body abrasive article 603 surrounded by the portion of loose or unbound powder 601.

[0035] FIG. 6B includes an illustration of a process for capturing the loose powder after completing a forming operation to form the green body abrasive article. The loose powder 605 can be captured via a capturing mechanism 607, which may include suction or any other suitable means to remove the loose powder 605 and separate the green body abrasive article 603 from the portion of loose or unbound powder 601. The captured loose powder 605 can be stored in a container. Additionally, or alternatively, the loose powder 605, which may include some content of organic materials from the forming process (e.g., binder material), may be treated to remove a certain content of organic materials. Accordingly, the loose powder 605 can be recycled powder material that is suitable for use in a subsequent forming operation to form one or more green body abrasive articles.

[0036] FIG. 6C is a graphic representation of the process for recycling the unused and loose powder material.

[0037] FIG. 7A is a perspective view illustration of a body of an abrasive article. As illustrated, the body has a length, width, and thickness and can be evaluated along any of these axes by destructive or non-destructive methods to evaluate one or more properties associated with the body. Such properties can include, but are not limited to, density variation-L, density variation-W, density variation-T, dimensional variation-L, dimensional variation-W, dimensional variation-T, hardness variation-L, hardness variation-W, hardness variation-T, MOR variation-L, MOR variation-W, MOR variation-T, MOE variation-L, MOE variation-W, and MOE variation-T. FIG. 7B includes three cross-sectional images of cross-sections "a", "b" and "c" along a length of the body. Such cross-sections can be generated by cutting the samples for evaluation of one or more properties embodied herein. Alternatively, the cross-sections may be generated from 3D scans of the body to evaluate certain dimensional features and evaluate the quality and consistency of the geometric features of the body. FIG. 7C includes three cross-sectional images of cross-sections “d”, “e” and “f” along the width of the body. FIG. 7D includes three cross-sectional images of cross-sections “g”, “h” and “i” along the thickness of the body. In certain instances, the difference in cross-sectional area of each of the cross-sections may be used to quantify the geometric quality of the body.

[0038] Additionally, as illustrated, the body has four major planar surfaces and two end surfaces. Any of the four major planar surfaces extending between the two smaller end surfaces can be used to evaluate certain properties as embodied herein, including, for example, but not limited to, nWarp, nFlatness, nBow. In the instance of the property nDimensional variation, multiple measurements at random locations between two opposing major planar surfaces can be made to evaluate the nDimensional variation. Such a measurement can be made in the dimension of thickness in a direction generally perpendicular to the plane defined by the length and width of the body. A multitude of randomly selected points on the first major surface are selected and the shortest distance to the second major surface through the body is recorded as a dimension. The dimensions are averaged to define the average Dimensional variation. The average is then normalized to the surface area of the first major surface. If one of the major surfaces is smaller than the other, the smaller surface is used. The nDimensional variation is the average value of the dimensional variation normalized (divided) by the area of the smaller of the major planar surfaces.

[0039] According to another embodiment, the body of an abrasive article, which may be in the form of a green body abrasive article or a finally-formed abrasive article, may have a particular volumetric form factor that may be achieved through one or more forming processes of the embodiments herein and facilitate improved abrasive operations. In one embodiment, for a single abrasive article (green body or finally-formed body), the volumetric form factor can be a comparison between the shape of the body in three-dimensions as compared to an intended shape. In certain aspects, abrasive articles are intended to comply with strict dimensional tolerances, and deviations from the intended dimensional tolerances must be addressed by one or more methods, typically a post-forming subtractive process. In some instances, depending upon the severity of the deviation of the body from an intended shape, the body may be scrapped.

[0040] FIG. 8A includes a perspective view illustration of an intended shape of an abrasive article. The intended shape may be a well-known standard that may be stored as electronic data, such as in the form of a three-dimensional model on a computer-readable medium. FIG. 8B includes a perspective view illustration of a formed abrasive article. The volumetric form factor for a single abrasive article can be a value of how well the formed abrasive article (e.g., FIG. 8B) matches to the intended shape (e.g., FIG. 8A). One such comparison is illustrated as FIG. 8C.

[0041] According to one aspect, a detailed three-dimensional scan can be conducted on the body via 3D tomography with X-ray radiation to create a representative three-dimensional model of the abrasive article. The model of the abrasive article can be compared to the model of the intended shape. The model of the abrasive article can be compared to the model of the intended shape using slices of the body and measuring the deviations in one or more select planes through the model of the abrasive article. Additionally, or alternatively, the deviations between the two models may be evaluated for the whole of the volume.

[0042] In one particular embodiment, at least three scans are completed in three different planes on the model of the abrasive article as shown in FIG. 9A. FIG. 9A illustrates nine total planes, spaced apart from each other, and cutting through the model of the abrasive article 900 for the planes X-Y, X-Z, and Y-Z. The scanned images can be extracted as 2D images of the body and can be compared to corresponding 2D data (e.g., 903) from the model of the intended shape. Image analysis software can compare the differences in the 2D images of the abrasive article and intended shape and evaluate the difference in area between the images for each of the nine planes. As shown in FIG. 9B, additional area 901 outside of an intended surface can be given a positive value. Negative area 902 on the model of the abrasive article relative to the model of the intended shape can be given a negative value. The total of positive and negative area is summed for each scan. The values for each of the nine scans are averaged and recorded as the average volumetric form value of the model of the abrasive article. The volumetric form factor is calculated as the absolute value of the ratio of the average volumetric form value divided by the volumetric form value of the model of the intended shape. That is, $Vff = |Vav/Vmi|$, wherein Vff represents the volumetric form factor, Vav represents the average volumetric form value and Vmi represents the volumetric form value of the model of the intended shape.

[0043] According to one embodiment, the Vff can be at least 0.1, such as at least 0.2, or at least 0.25, or at least 0.3, or at least 0.35, or at least 0.4, or at least 0.45, or at least 0.5, or at least 0.55, or at least 0.6, or at least 0.65, or at least 0.7, or at least 0.71, or at least 0.72, or at least 0.73, or at least 0.74, or at least 0.75, or at least 0.76, or at least 0.77, or at least 0.78, or at least 0.79, or at least 0.80, or at least 0.81, or at least 0.72, or at least 0.73, or at least 0.74, or at least 0.75, or at least 0.76, or at least 0.77, or at least 0.78, or at least 0.79, or at least 0.80, or at least 0.81, or at least 0.82, or at least 0.83, or at least 0.84, or at least 0.85, or at least 0.86, or at least 0.87, or at least 0.88, or at least 0.89, or at least 0.90, or at least 0.91, or at least 0.92, or at least 0.93, or at least 0.94, or at least 0.95, or at least 0.96, or at least 0.97, or at least 0.98, or at least 0.99, or at least 1.0, or at least 1.01, or at least 1.02, or at least 1.03, or at least 1.04, or at least 1.05, or at least 1.06, or at least 1.07, or at least 1.08, or at least 1.09, or at least 1.10, or at least 1.11, or at least 1.12, or at least 1.13, or at least 1.14, or at least 1.15, or at least 1.16, or at least 1.17, or at least 1.18, or at least 1.19, or at least 1.20, or at least 1.21, or at least 1.22, or at least 1.23, or at least 1.24, or at least 1.25, or at least 1.26, or at least 1.27, or at least 1.28, or at least 1.29, or at least 1.30, or at least 1.31, or at least 1.32, or at least 1.33, or at least 1.34, or at least 1.35, or at least 1.36, or at least 1.37, or at least 1.38, or at least 1.39, or at least 1.40, or at least 1.45, or at least 1.50, or at least 1.55, or at least 1.60, or at least 1.65, or at least 1.70, or at least 1.75, or at least 1.80, or at least 1.85, or at least 1.90, or at least 1.95, or at least 2.00. Still, in a non-limiting embodiment, the Vff can be not greater than 10, such as not greater than 9.5, or not greater than 9, or not greater than 8.5, or not greater than 8, or not greater than 7.5, or not greater than 7, or not greater than 6.5, or not greater than 6, or not greater than 5.5, or not greater than 5, or not greater than 4.5, or not greater than 4, or not greater than 3.5, or not greater than 3, or not greater than 2.5, or not greater than 2, or not greater than 1.5, or not greater than 1.45, or not greater than 1.40, or not greater than 1.39, or not greater than 1.38, or not greater than 1.37, or not greater than 1.36, or not greater than 1.35, or not greater than 1.34, or not greater than 1.33, or not greater than 1.32, or not greater than 1.31, or not greater than 1.30, or not greater than 1.29, or not greater than 1.28, or not greater than 1.27, or not greater than 1.26, or not greater than 1.25, or not greater than 1.24, or not greater than 1.23, or not greater than 1.22, or not greater than 1.21, or not greater than 1.20, or not greater than 1.19, or not greater than 1.18, or not greater than 1.17, or not greater than 1.16, or not greater than 1.15, or not greater than 1.14, or not greater than 1.13, or not greater than 1.12, or not greater than 1.11, or not greater than 1.10, or not greater than 1.09, or not greater than 1.08, or not greater than 1.07, or not greater than 1.06, or not greater than 1.05, or not greater than 1.04, or not greater than 1.03, or not greater than 1.02, or not greater than 1.01, or not greater than 1.00, or not greater than 0.99, or not greater than 0.98, or not greater than 0.97, or not greater than 0.96, or not greater than 0.95, or not greater than 0.94, or not greater than 0.93, or not greater than 0.92, or not greater than 0.91, or not greater than 0.90, or not greater than 0.89, or not greater than 0.88, or not greater than 0.87, or not greater than 0.86, or not greater than 0.85, or not greater than 0.84, or not greater than 0.83, or not greater than 0.82, or not greater than 0.81, or not greater than 0.80, or not greater than 0.79, or not greater than 0.78, or not greater than 0.77, or not greater than 0.76, or not greater than 0.75, or not greater than 0.74, or not greater than 0.73, or not greater than 0.72, or not greater than 0.71, or not greater than 0.70. It will be appreciated that the Vff can be within a range including any of the minimum and maximum values noted above, including, for example, but not limited to at least 0.10, and not greater than 10, or within a range of at least 0.50, and not greater than 1.50, or within a range of at least 0.80, and not greater than 1.2, or within a range including at least 0.90, and not greater than 1.10, or even within a range including at least 0.95, and not greater than 1.05.

[0044] According to another aspect, a batch of abrasive articles, which may be green body abrasive articles or finally-formed abrasive articles, may have a particular batch volumetric form factor variation. The batch volumetric form factor variation (batch Vff) can be the standard deviation of the volumetric form factor for a batch of abrasive articles. According to one embodiment, the batch Vff can be not greater than 0.30, such as not greater than 0.25, or not greater than 0.20, or not greater than 0.18, or not greater than 0.16, or not greater than 0.14, or not greater than 0.12, or not greater than 0.10, or not greater than 0.09, or not greater than 0.08, or not greater than 0.07, or not greater than 0.06, or not greater than 0.05, or not greater than 0.04, or not greater than 0.03, or not greater than 0.02, or not greater than 0.01, or not greater than 0.009, or not greater than 0.008, or not greater than 0.007, or not greater than 0.006, or not greater than 0.005. Still, in one non-limiting embodiment, the batch Vff can be at least 0.00001, or at least 0.0001, or at least 0.0005, or at least 0.001, or at least 0.01, or at least 0.1, or at least 0.2, or at least 0.4, or at least 0.6. It will be appreciated that the batch Vff can be within a range including any of the minimum and maximum values noted above, including, for example, but not limited to within a range of at least 0.00001, and not greater than 0.3, such as within a range of at least 0.00001 and not greater than 0.2, or within a range of at least 0.00001 and not greater than 0.05, or even within a range of at least 0.00001 and not greater than 0.01.

[0045] It will be appreciated that a single forming operation may form a plurality of discrete green body abrasive articles, which can be formed into a plurality of finally-formed abrasive articles. A plurality of abrasive articles may be referred to as a batch of abrasive articles and may be green bodies or finally-formed abrasive articles. In one embodiment, the abrasive articles of a batch can be formed in a single forming process within the same build box. The properties noted in the foregoing and embodied herein can be used to evaluate the abrasive articles on a batch basis. That is, evaluation of one or more geometric features and/or properties of each body within a batch can be compared to evaluate the quality of a batch as a whole. According to one embodiment, a batch may include a certain minimum size or volume of material, such as described in any of the embodiments herein. In another non-limiting embodiment, a batch may include a plurality of abrasive articles formed in a single additive manufacturing build cycle, which may include a plurality of abrasive articles (green or finally-formed) that are formed in the same build box during the same build cycle.

[0046] The embodiments herein are based on empirical studies. Significant challenges exist when using certain additive manufacturing processes, including, for example, binder jetting to form abrasive articles on a commercial scale. While prior disclosures have disclosed the formation of abrasive articles via additive manufacturing, such products are not widely available because of the notable difficulties in scaling the process. The embodiments here are specifically developed based on empirical studies to advance the technology of additive manufacturing into a commercially viable option.

[0047] According to one aspect, one embodiment is a method for forming a batch of abrasive articles, particularly in the context of commercial-scale sized batches that may also include large-sized abrasive articles. According to a particular embodiment, the process can include a binder jetting operation that may include at least the steps of a) forming a plurality of green body abrasive articles defining a batch, wherein each of the green body abrasive articles comprises a precursor bond material and abrasive particles, wherein forming is conducted by: i) creating one or more layers of raw material powder (or otherwise referred to herein as powder material, ii) selectively dispensing a binder material onto portions of the layer, wherein the binder material includes a non-aqueous material, and iii) repeating at least steps i) and ii) to form a green abrasive article having a volume of at least 9 cm^3, or a length of at least 6 cm. According to one embodiment, the process may further include converting the binder material to, at least partially, solidify the binder material and bind portions of powder material from the one or more layers.

[0048] In another embodiment, the process may include moving a compaction object over the one or more layers of powder material to apply a force sufficient to compact the layer to a compacted layer thickness that is less than the thickness of the layer prior to compaction. For example, in one embodiment, the process may include controlling at least one of: a) a force applied by a compaction object to the layer or a plurality of layers of powder material; b) a traverse speed of a compaction object; c) average thickness of the layer prior to compaction; d) a particle size distribution of the powder; e) number of previously formed layers underlying the layer of powder; f) the number of compacted layers underlying the layer of powder; g) the density of any layers underlying the layer of powder; h) the amount of binder in any layers underlying the layer of powder; i) the relative dimensions of the layer relative to one or more layers underlying the layer; and any combination of a)-i).

[0049] In one particular embodiment, the process may include controlling the operation of a compacting object relative to one or more variables in the forming process, including, for example, but not limited to, the average layer thickness of a single layer of raw material powder that may be deposited before a compaction operation. In a non-limiting embodiment, the process may include controlling the compaction percentage of the average original layer thickness of the layer of raw material powder to create an abrasive article having a suitable combination of features and/or properties.

[0050] FIG. 10 includes a method for forming an abrasive article according to one embodiment. The process may optionally include step 1001, which may include forming a layer of raw material powder, wherein the raw material powder can include abrasive particles and precursor bond material as described in any embodiments herein. The process for forming the layer can include any one or more features of any of the embodiments herein. It will be appreciated that any of the abrasive articles and/or batch of abrasive articles can have any one or a combination of features of any of the embodiments herein.

[0051] The process may continue at step 1003 with selectively dispensing a binder material including a non-aqueous binder material. According to one embodiment, the binder comprises a non-aqueous material. In a more particular embodiment, the binder may include at least a majority content of non-aqueous binder material for a total volume of the binder. In another non-limiting embodiment, the binder may include least 60 vol% of the non-aqueous binder material for a total volume of the binder, such as at least 70 vol%, or at least 80 vol%, or at least 90 vol%, or at least 95 vol% of the non-aqueous binder material for a total volume of the binder. In another non-limiting embodiment, the binder may consist essentially of the non-aqueous binder material.

[0052] In a non-limiting embodiment, the binder comprises a phenolic material, and more particularly, the non-aqueous binder material may include a phenolic resin material. In one non-limiting embodiment, the non-aqueous binder material may consist essentially of phenolic resin. In another non-limiting embodiment, the binder may consist essentially of phenolic resin. In yet a more particular embodiment, the binder material is a phenolic binder, such as but not limited to, Product FB101EU available from ExOne, Phenolfuse available from ExOne, or Fluidfuse available from ExOne.

[0053] According to one aspect, the process may include binding at least a portion of the compacted layer using a binder including a non-aqueous binder material. In one aspect, a process for binding may include selecting an amount of binder to apply to one or more layers of powder material based on at least one of a) a shape of at least a portion of the green body; b) a dimension of at least a portion of the green body; c) an average particle size of the powder material; d) the material composition of one or more components of the powder material; e) a dispensing resolution of the printhead; f) the density of the layer before a compacting process; g) the density of the layer after a compacting process; h) the average thickness of the layer before a compacting process; i) the average thickness of the layer after a compacting process; or any combination of a)-i).

[0054] According to another aspect, the process of binding one or more layers of powder material may include using a binder saturation of not greater than 80%, or not greater than 70%, or not greater than 60%, or not greater than 50%, or not greater than 40%. In still another non-limiting embodiment, the process of binding may include using a binder saturation of at least 1%, or at least 5%, or at least 8%, or at least 10%, or at least 15%, or at least 20%, or at least 25%. The binder saturation used in the binding process can be within a range including any of the minimum and maximum percentages noted above, including for example, but not limited to within a range of at least 1% and not greater than 80%, or within a range of at least 1% and not greater than 60%, or even within a range of at least 1% and not greater than 50%.

[0055] According to another aspect, binding includes converting the binder or at least a portion of the binder (e.g., binder material) from a liquid to a solid or semi-solid state to bind particles of the powder material. In another embodiment, binding may include at least one of evaporation, thermal curing, chemical curing, radiation curing, or any combination thereof.

[0056] In another embodiment, the binder may include a liquid vehicle and the binder material contained therein. In certain non-limiting instances, the binder material may be dissolved in the liquid vehicle. In another embodiment, the binder material may be undissolved in the liquid vehicle.

[0057] In another embodiment, the liquid vehicle includes one or more organic solvents and/or water. In a non-limiting embodiment, the liquid vehicle includes a non-aqueous vehicle. According to another aspect, the liquid vehicle includes a polar liquid material or a non-polar liquid material. In a non-limiting embodiment, the liquid vehicle includes ethanol or isopropyl alcohol. In still another embodiment, the liquid vehicle includes isopropyl alcohol.

[0058] In another embodiment, the binder may include a binder modifier. In certain non-limiting instances, the binder modifier may be dissolved in the liquid vehicle along with the binder. In a non-limiting embodiment, the binder modifier includes Hexamethylenetetramine also known as methenamine, hexamine (HMTA or hereinafter "HEXA").

[0059] Without wishing to be tied to a particular theory, it has been demonstrated by empirical data that the type of binder, amount of binder, type of liquid vehicle, type of binder modifier, amount of binder modifier, and/or the method used to deposit the binder material may affect the properties and/or characteristics of the abrasive article or batch of abrasive articles. For example, using a binder material including a non-aqueous binder material may improve one or more features of the abrasive article or batch of abrasive articles, including for example, but not limited to the feature resolution of features (e.g., surface features, pores, etc.) formed in the body.

[0060] Furthermore, in another aspect, the dispensing mechanism may also impact the one or more features of the abrasive article or batch of abrasive articles. According to one embodiment, the dispensing mechanism may have a binding at least a portion of the compacted layer with a printhead having a dispensing resolution of not greater than 55 picoliters, such as not greater than 50 picoliters, or not greater than 45 picoliters, or not greater than 40 picoliters, or not greater than 35 picoliters, or not greater 30 picoliters, or not greater than 25 picoliters, or not greater than 20 picoliters, or not greater than 15 picoliters, or not greater than 10 picoliters, or not greater than 5 picoliters, or not greater than 1 picoliter, or not greater than 0.5 picoliters, or not greater than 0.1 picoliters. Still, in another embodiment, the dispensing resolution of the printhead may be at least

0.0001 picoliters, or at least 0.001 picoliters, or at least 0.01 picoliters, or at least 0.1 picoliters, or at least 0.5 picoliters, or at least 1 picoliter. It will be appreciated that the dispensing resolution of the printhead may be within a range including any of the minimum and maximum values noted above.

[0061] In another embodiment, the composition of the binder material may be selected based upon the wetting characteristics of the binder relative to the powder material.

[0062] In some instances, the process may optionally include a compacting process using a compacting object. In one optional embodiment, the process may include compacting the layer of powder material by at least 1% and not greater than 99% of the average original layer thickness of the layer of raw material powder. For example, in one non-limiting embodiment, the process may include compacting the layer to a by at least 1.5% of the average original layer thickness (t) of the layer of raw material powder. Stated alternatively, the average compacted layer thickness (tc) may be at least 1.5% less than the average original layer thickness (t), such that $tc \leq tc - (0.015tc)$. According to another embodiment, the process may include compacting the layer of powder material by at least 2% of the average original layer thickness of the layer of raw material powder or at least 3%, or at least 4%, or at least 5%, or at least 6%, or at least 7%, or at least 8%, or at least 9%, or at least 10%, or at least 12%, or at least 14%, or at least 16%, or at least 18%, or at least 20%, or at least 25%, or at least 30%, or at least 35%, or at least 40%, or at least 45%, or at least 50%, or at least 55%, or at least 60%, or at least 65%, or at least 70%, or at least 75%, or at least 80%, or at least 85%. Still, in another non-limiting embodiment, the process may include compacting the layer of powder material by not greater than 98% % of the average original layer thickness of the layer of raw material powder or not greater than 97%, or not greater than 96%, or not greater than 95%, or not greater than 94%, or not greater than 93%, or not greater than 92%, or not greater than 91%, or not greater than 90%, or not greater than 85%, or not greater than 80%, or not greater than 75%, or not greater than 70%, or not greater than 65%, or not greater than 60%, or not greater than 55%, or not greater than 50%, or not greater than 45%, or not greater than 40%, or not greater than 35%, or not greater than 30%, or not greater than 25%, or not greater than 20%, or not greater than 15%. It will be appreciated that the process may include compacting the layer of powder material by a percentage within a range including any of the minimum and maximum percentages noted above, including for example, but not limited to within a range of at least 1% and not greater than 90%, or within a range including at least 2% and not greater than 85%, or within a range including at least 5% and not greater than 70%.

[0063] According to another non-limiting aspect, the process may also include measuring or calculating a relative humidity or a flow characteristic of the powder material. For example, in one embodiment, the process can include measuring or calculating the relative humidity of the raw material powder material prior to and/or during the deposition of the powder material into one or more layers. The value of the relative humidity or a flow characteristic that is used to calculate or approximate the relative humidity of the powder material may be used to control the layer thickness and/or the percentage of compaction of the layer.

[0064] In another embodiment, the process may optionally include controlling one or more compaction object control variables based upon a characteristic or property of the raw material powder or the average original layer thickness. In one non-limiting aspect, the one or more compaction object control variables can include, but it not limited to a force applied by the compaction object on the layer or plurality of layers of powder material, a traverse speed of a compaction object, a size of the compaction object, a weight of the compaction object, the ratio of layer thickness (LT) to compaction thickness (CT) offset between the primary roller and job box (or build box) ($\Delta r1$), offset between primary and secondary rollers ($\Delta r2$), extra powder height above secondary roller (Δd), leveled dispensed powder thickness (DT), compaction ratio (DT/LT), or any combination thereof. FIGs. 14 and 15 provide illustrations to further illustrate some of the compaction object control variables. For example, in one non-limiting instance, the process may include controlling a compaction force of the compacting object based upon a relative humidity or a flow characteristic of the powder material. In another non-limiting embodiment, the process may include changing the compaction force based upon a measured change in a relative humidity or a flow characteristic of the powder material. In another embodiment, the process may include controlling a compaction ratio based upon a relative humidity or a flow characteristic of the powder material. In still another embodiment, the process may include changing a target compaction ratio based upon a measured change in a relative humidity or a flow characteristic of the powder material. In one embodiment, a stepped compaction process is preferred over a two-roller compaction process.

[0065] According to one aspect, the process may include selecting a target average layer thickness for one or more layers as they are formed before compacting, and selecting a compacting object control variable (e.g., compacting force, traverse speed, etc.) based upon the target average layer thickness for the one or more layers. In one particular embodiment, the process may include measuring the average original thickness of the layer of powder material after forming the layer of powder material and comparing the target average layer thickness to the measured average layer thickness and calculating a difference. In one non-limiting embodiment, the process may include changing the compaction force, translation speed, or other compacting object control variable based upon a difference in the measured average height and target average height. In one non-limiting embodiment, an alert is generated if the difference between the measured and target extend beyond a threshold value.

[0066] In still another embodiment, the process may include changing a compacting object control variable between a first compacting process and a second compacting process conducted at a different time relative to the first compacting process. For example, in one instance, the process can include conducting more than one compacting process, wherein the compacting processes can be conducted at different times. In one particular embodiment, the process may include forming a first layer of the raw material powder, compacting the first layer at a first time with a compacting object, forming a second layer of raw material powder after compacting the first layer at the first time, and compacting the second layer at a second time with a compacting object. According to one optional embodiment, the process of compacting the first layer can be different from the process of compacting the second layer based on one or more compacting object control variables.

[0067] According to one embodiment, the process can include forming an abrasive article (e.g., green body abrasive article) having a flexural strength suitable for handling. For example, in one embodiment, the flexural strength can be at least 10 MPa as measured according to ASTM 1161. In another embodiment, the flexural strength may be not greater than 100 GPa. In one non-limiting embodiment, the flexural strength may be within a range including any of the minimum and maximum values noted above.

[0068] According to another non-limiting embodiment, the process may further include forming an abrasive article (e.g., a green body abrasive article) with a particular shrinkage that may facilitate control of shape defects and/or microstructural defects. In one embodiment, the body may undergo a volume shrinkage of not greater than 20% of the volume of the green body as removed from the process and prior to significant drying as compared to the volume of the body after final treatment to create the finally-formed abrasive article. In still another embodiment, the volume shrinkage may be not greater than 18%, such as not greater than 15%, or not greater than 12%, or not greater than 10%, or not greater than 8%, or not greater than 6%, or not greater than 4%.

[0069] According to another non-limiting embodiment, the process may further include forming an abrasive article (e.g., a green body abrasive article) with a particular crush strength that may facilitate control of shape defects and/or microstructural defects. In on embodiment, the crush strength can be at least 10N or at least 11N or at least 12N or at least 13N or at least 14N or at least 15N or at least 16N or at least 17 N or at least 18N or at least 19N or at least 20N or at least 25N or at least 30 N or at least 35N or at least 40N or at least 45N or at least 50N or at least 55N or at least 60N or at least 65N or at least 70N or at least 75N or at least 80N or at least 85N or at least 90N or at least 95N or at least 100N or at least 105N or at least 110N or at least 115N or at least 120N. In still another embodiment, the crush strength should not exceed a particular limit that may effect the sintering process. It has been shown that a green body abrasive article having too high a crush strength can make the subsequent sintering process too difficult.

[0070] It will be appreciated that the foregoing processes may be used to form a batch of abrasive articles, and wherein the resulting batch of abrasive articles can have any one or combination of features of any of the embodiments herein.

[0071] In still another embodiment, any one or more processes herein can be assisted, controlled-in-part or controlled in entirety by one or more computing objects that include hardware and/or software. In such embodiments, the hardware and/or software may include capabilities to measure, evaluate, characterize, compare and/or control any one or more aspects of the process and/or products herein. In one embodiment, the hardware and/or software may utilize artificial intelligence, such as machine learning algorithms configured to evaluate and improve one or more aspects of the process and/or products. It will also be appreciated that the one or more computing objects can be commutatively coupled to one or more networks and/or the additive manufacturing apparatus. The computing objects can be configured to interface with one or more users, and present modeling information and/or suggested changes to the process based upon evaluating one or more data sets having data related to the process variables, product characteristics and/or properties, and other historical data.

[0072] In certain instances, one or more aspects of the processes of the embodiments herein may be aided by a computing device. FIG. 11 includes a schematic of a system that may be used to facilitate formation of abrasive articles via additive manufacturing. FIG. 11 includes a computing device 1151, a memory 1152, a processor 1153, and a model 1154 that may be included as hardware or software in the computing device 1151. According to one embodiment, the memory 1152 and the processor 1153 may be communicatively coupled to an additive manufacturing apparatus and/or controller of an additive manufacturing device 1155 and configured to provide instructions or control one or more operations associated with the additive manufacturing process. For example, in one embodiment, the memory 1152 may store data related to the additive manufacturing process in a machine-readable format. In another embodiment, the processor 1153 may contain one or more computer programs that are configured to evaluate the data. In one non-limiting embodiment, the processor 1153 may be configured to compare the characteristic data of one or more of the abrasive articles to historical data to create a model 1154 for the batch of abrasive articles. According to another embodiment, a model for the batch of abrasive articles may be created based on the various aspects of the batch of abrasive articles (e.g., size, composition, target properties, raw material powder properties, and characteristics, etc.), historical data, apparatus data (e.g., size of the build box, capabilities of the additive manufacturing apparatus), and the like.

[0073] In yet another embodiment, the model may be used to control the additive manufacturing process, including, but not limited to the placement and orientation of the abrasive articles relative to each other as formed in the build box and even details used to control process parameters, such as any compacting object control variables. In one instance, the model may be a scheme or plan used to build a batch of abrasive articles, and in particular, may include data on the placement and/or orientation of the abrasive articles relative to each other during the additive manufacturing process. In one embodiment, the model can be in a machine-readable format and configured to be used by one or more controllers of the additive manufacturing process, including, for example, but not limited to the movement and deposition characteristics of a printhead configured to selectively deposit binder material onto one or more layers of the powder material. In another non-limiting embodiment, the model can be in a machine-readable format and configured to be used by one or more controllers of the additive manufacturing process, including, for example, but not limited to the force and transversing speed of a compacting object relative to a layer of raw material powder. In one instance, the model may also be presented in a format suitable for a person to evaluate and confirm the proposed scheme or plan prior to it being implemented by the additive manufacturing system.

[0074] In another non-limiting embodiment, the model may be developed or evolve via a machine learning algorithm or artificial intelligence. In one embodiment, the processor 1153 may use data related to the batch of abrasive articles to develop an initial model for forming the batch of abrasive articles. For another embodiment, the initial model may be compared to historical data, which may include data from prior models and data related to the resulting properties and characteristics of the abrasive articles formed therefrom. In certain optional instances, the processor 1153 may edit the initial model based on the historical data to develop a final model to be used to form the batch of abrasive articles.

[0075] According to one embodiment, the historical data may include information of prior additive manufacturing operations including data related to the features of the abrasive articles and properties of the abrasive articles. In a more particular embodiment, data related to features of the abrasive articles may include data related to the size, shape, composition, and microstructure of the abrasive articles. In another non-limiting embodiment, the properties of the abrasive articles may include data related to the density, strength, hardness, modulus, or rupture (MOR), volumetric form factor, and any other properties of the green bodies or finally-formed bodies according to the embodiments herein.

[0076] According to another embodiment, controlling the selective dispensing of the binder may include controlling the binder saturation. In one embodiment, too little binder saturation has been demonstrated as causing deformations such as layer shifting. Still, in another non-limiting embodiment, variable saturation of the green body as evidenced by a change in the binder content in different portions of the body may be done intentionally to facilitate suitable manufacturing. For example, in one non-limiting embodiment, the binder content may vary by at least 1%, or at least 2%, or at least 3%, or at least 4%, or at least 5% for a total length, a total width or a total thickness of a body.

[0077] In another aspect, the abrasive article, such as the green body abrasive article may have a particular theoretical density, such as at least 50%, or at least 51%, or at least 53%, or at least 54%, or at least 55%, or at least 56%, or at least 57%, or at least 58%, or at least 59%, or at least 60%, or at least 61%, or at least 62%, or at least 63%, or at least 64%, or at least 65%, or at least

66%, or at least 67%, or at least 68%, or at least 69%, or at least 70%, or at least 71%, or at least 72%, or at least 73%, or at least 74%, or at least 75%, or at least 76%, or at least 77%, or at least 78%, or at least 79%, or at least 80%, or at least 81%, or at least 82%, or at least 83%, or at least 84%, or at least 85%, or at least 86%, or at least 87%, or at least 88%, or at least 89%, or at least 90%, or at least 91%, or at least 92%, or at least 93%, or at least 94%, or at least 95%, or at least 96%, or at least 97%, or at least 98%, or at least 99%. Still, in another non-limiting embodiment, the green body abrasive article may have a theoretical density of not greater than 99.9%, such as not greater than 99.5%, or not greater than 99%, or not greater than 96%, or not greater than 94%, or not greater than 90%, or not greater than 85%, or not greater than 80%, or not greater than 75%, or not greater than 70%, or not greater than 65%, or not greater than 60%, or not greater than 55%, or not greater than 50%. It will be appreciated that the green body abrasive article may have a theoretical density within a range including any of the minimum and maximum percentages noted above.

[0078] In another aspect, the processes of the embodiments herein may facilitate formation of abrasive articles or batches of abrasive articles having a suitable microstructure. In one embodiment, the body of an abrasive article may have a particular Linear Feature Factor, which is a measure of the homogeneity of the microstructure. FIG. 12 includes a cross-sectional image of an abrasive article formed under certain conditions as provided in the Examples. As illustrated in FIG. 12, the cross-sectional image of the body of the abrasive article has evidence of lines associated with porosity that has been aligned substantially perpendicular to an applied force of compaction during the forming process. FIG. 13 includes a cross-sectional image of an abrasive article sample formed according to an embodiment having less evidence of lines of porosity extending through the body and having a more uniform microstructure and a different Linear Feature Factor.

[0079] The Linear Feature Factor can be measured according to the following sample preparation and testing conditions. The process would start with images taken in 3 planes, or alternatively, with X-ray CT scans of the body. Image analysis could be done in 3D or 2D. In one instance, the process includes picking a plurality of random points in the body (or plane) and then count the number and size of intersections with porosity. In an isotropic body, there would be no dependence of the average size/number of pores on direction. Where there is alignment of pores, the analysis demonstrates a statistically significant peak along certain directions.

[0080] In one aspect, the abrasive article or batch of abrasive articles formed according to the embodiments herein may have suitable homogeneity of microstructure. In one embodiment, the body may be essentially free of one or more Linear Features as viewed in cross-section. For example, the body of sample in FIG. 13 is essentially free of one or more Linear Features, whereas the body of the sample in FIG. 12 demonstrates a plurality of Linear Features. In certain instances, the Linear Features appear as lines or alignment of elongated pores giving the microstructure the appearance of layers or having lines as viewed in cross-section, which is a plane that is perpendicular to the length of the body.

[0081] According to another embodiment, the body of an abrasive article or a batch of abrasive articles may have a particular type of porosity having a particular shape. In certain instances, it has been observed that elongated porosity may be created by certain compacting processes. In certain instances, the elongated porosity may be beneficial. However, in other instances, it may not be suitable. In one embodiment, the shape and orientation of the porosity in the body may be controlled by controlling the placement and/or orientation of the body relative to the compacting process.

[0082] In one embodiment, the abrasive article or batch of abrasive articles may have porosity having an average aspect ratio (L:W) of not greater than 100 as viewed in cross-section, such as not greater than 90, or not greater than 80, or not greater than 70, or not greater than 60, or not greater than 50, or not greater than 40, or not greater than 30, or not greater than 20, or not greater than 10. In one non-limiting embodiment, the average aspect ratio of the porosity as viewed in cross-section can be at least 1, or at least 1.2, or at least 1.5, or at least 1.8, or at least 2, or at least 2.5, or at least 3, or at least 3.5, or at least 4. It will be appreciated that the average aspect ratio can be within a range including any of the minimum and maximum values noted above.

[0083] The average aspect ratio of the porosity in the body may be evaluated by obtaining 3 or more randomly selected cross-sectional images and using imaging analysis software to isolate the pores as viewed from the cross-sectional images and measure the length and width of the pores. The average length and average width of the pores can be used to calculate the average aspect ratio of the porosity in the body.

[0084] In another embodiment, the placement and/or orientation of the abrasive article or batch of abrasive articles in the build bed and the compacting process may be controlled to control the orientation of the porosity in the body. In some instances, some alignment of the porosity may be desired and the process of placement and/or orientation and the compacting process may be controlled to create some alignment of the porosity in the body. In still another embodiment, the porosity may be substantially randomly oriented porosity as viewed in cross-section.

[0085] According to one aspect, the body of an abrasive article or a batch of abrasive articles may have not greater than 80% of the porosity having a longitudinal axis within +-5 degrees of a direction parallel to any surface of the body as viewed in cross-section. For example, turning to FIG. 12, the pores 1202 or the body 1201 are extending generally in the direction 1205, which is substantially parallel to the surface 1203 of the body 1201. In one embodiment, the surface 1203 and direction 1205 may be substantially perpendicular to the direction of force applied by the compacting object during a compaction process, such that the force applied created a certain content of elongated porosity within the body 1201 having longitudinal axes substantially parallel to the surface 1203 and in the direction 1205. According to one non-limiting embodiment, the not greater than 70% of the porosity may have a longitudinal axis within +- (plus or minus) 5 degrees of a direction parallel to any surface of the body, such as not greater than 60%, or not greater than 50%, or not greater than 40%, or not greater than 30%, or not greater than 20%, or not greater than 10%, or not greater than 5%. Still, in another non-limiting embodiment, the percentage of porosity in the body having a longitudinal axis aligned with a direction parallel to any surface of the body may be at least 1%, or at least 3%, or at least 5%, or at least 10%, or at least 15%, or at least 20%, or at least 25%, or at least 30%, or at least 35%, or at least 40%, or at least 45%, or at least 50%, or at least 60%, or at least 70%, or at least 80%. It will be appreciated that the percentage of porosity in the body having a longitudinal axis aligned with a direction parallel to any surface of the body may be within a range including any of the minimum and maximum percentages noted above.

[0086] According to another embodiment, the abrasive article is part of a batch, and wherein the batch of abrasive articles comprise an average batch Linear Feature Factor that is notable improved as compared to a batch of abrasive articles formed using a poorly controlled process.

[0087] According to another embodiment, the abrasive article may be part of a batch, and wherein the batch of abrasive articles comprises an average batch flexural strength within a range of at least 10 MPa according to the ASTM standard noted herein. In one non-limiting embodiment, the average batch flexural strength can be not greater than 100 GPa. It will be appreciated that the average batch flexural strength can be within a range including any of the minimum and maximum values above.

[0088] The processes of the embodiments herein are developed by empirical studies that have identified certain elements leading to improved abrasive articles. One non-limiting example of a property of the abrasive articles (green or finally-formed) that may be improved includes batch density variation. According to one embodiment, the process may facilitate formation of a batch of abrasive articles having a batch density variation of not greater than 20% of an average density value of the batch, or not greater than 19%, or not greater than 18%, or not greater than 17%, or not greater than 16%, or not greater than 15%, or not greater than 14%, or not greater than 13%, or not greater than 12%, or not greater than 11%, or not greater than 10%, or not greater than 9%, or not greater than 8%, or not greater than 7%, or not greater than 6%, or not greater than 5%, or not greater than 4%, or not greater than 3%, or not greater than 2%, or not greater than 1%, or not greater than 0.5%, or not greater than 0.3%, or not greater than 0.1%. The batch density variation can be measured using the techniques described herein.

[0089] The method for forming a batch of abrasive articles as described in the embodiments herein may also be suitable for minimizing a batch volumetric form factor. Some data indicates that the batch volumetric form factor of the abrasive articles may be impacted by the position and/or orientation of the abrasive articles relative to each other and/or the position and/orientation of the abrasive articles relative to the walls of the build box. According to one embodiment, the embodiments herein may facilitate formation of a batch of abrasive articles having a batch volumetric form factor (batch Vff) of not greater than 0.30, such as not greater than 0.25, or not greater than 0.20, or not greater than 0.18, or not greater than 0.16, or not greater than 0.14, or not greater than 0.12, or not greater than 0.10, or not greater than 0.09, or not greater than 0.08, or not greater than 0.07, or not greater than 0.06, or not greater than 0.05, or not greater than 0.04, or not greater than 0.03, or not greater than 0.02, or not greater than 0.01, or not greater than 0.009, or not greater than 0.008, or not greater than 0.007, or not greater than 0.006, or not greater than 0.005. Still, in another non-limiting embodiment, the batch Vff can be at least 0.00001, or at least 0.0001, or at least 0.0005, or at least 0.001, or at least 0.01, or at least 0.1, or at least 0.2, or at least 0.4, or at least 0.6. It will be appreciated that the batch Vff can be within a range including any of the minimum and maximum values noted above, including, for example, but not limited to within a range of at least 0.00001, and not greater than

0.3, such as within a range of at least 0.00001 and not greater than 0.2, or within a range of at least 0.00001 and not greater than 0.05, or even within a range of at least 0.00001 and not greater than 0.01. The batch Vff can be measured as described herein.

[0090] According to one embodiment, the process may include using at least 10% of the total volume of powder material in the build box to form a batch of abrasive articles while minimizing at least one of a batch density variation and/or a batch volumetric form factor of the batch of abrasive articles. In another embodiment, the method for forming the batch of abrasive articles may include using at least 15% of the total volume of the powder material in the build box to form the batch, such as at least 20%, or at least 25%, or at least 30%, or at least 35%, or at least 40%, or at least 45%, or at least 50%, or at least 55%, or at least 60%, or at least 65%, or at least 70%, or at least 75%, or at least 80%, or at least 85%. Still, in one non-limiting embodiment, the method may include using not greater than 99% of the total volume of powder material in the build box to form a batch of abrasive articles, such as not greater than 95%, or not greater than 90%, or not greater than 85%, or not greater than 80%. It will be appreciated that the volume of powder material used to form the batch of abrasive articles may be within a range including any of the minimum and maximum percentages noted above.

[0091] In one non-limiting embodiment, the method for forming an abrasive article may further include controlling the position and/or orientation of two or more abrasive articles of a batch relative to each other in the build box and more particularly with respect to a direction of translation of a compacting object. It will be appreciated that for any of the embodiments herein a compaction object can be configured to traverse one or more layers of powder material and apply a force sufficient to compact the one or more layers and reduce the thickness of the one or more layers. As used herein, a direction of translation of the compacting object is generally in a direction that is parallel to the length of the build box or in a direction that is parallel to a width of the build box.

[0092] In still another embodiment, the method for forming an abrasive article may include controlling a binder material or saturation percentage of the binder material based upon one or more variables associated with the compacting object. For example, in one embodiment, the binder material composition and/or saturation percentage may be used to control one or more compacting object control variable, including, for example, but not limited to, the force applied to one or more layers by the compacting object, a traverse speed of the compacting object, or any combination thereof.

[0093] According to one embodiment, the process can include forming one or more bodies each having a longitudinal axis that is substantially parallel to a direction of translation of a compaction object. Still, in an alternative embodiment, one or more bodies may each have a longitudinal axis that is substantially perpendicular to a direction of translation of a compaction object. Substantially perpendicular is used to mean the same thing as described in other embodiments herein.

[0094] In yet another aspect, the abrasive article or batch of abrasive articles made via the methods of the embodiments herein may have improved properties or characteristics. For example, in one embodiment, the abrasive article may have improved feature resolution. According to one embodiment, a green body abrasive article or finally-formed abrasive article may have a feature resolution value that is at least 5% better than a feature resolution value of an article formed using a different binder material and/or different binder process. For example, in one embodiment, the improvement in feature resolution may be at least 8% better, or at least 10% better, or at least 15% better, or at least 20% better, or at least 30% better, or at least 40% better, or at least 50% better as compared to a feature resolution value of a green body using a different binder material or binder process.

[0095] According to another embodiment, the green body abrasive article or batch of green body abrasive articles may include a particular binder material, such as those described in embodiments herein. According to one embodiment, the green body abrasive article or batch of green body abrasive articles may include a binder material binder material including a non-aqueous material. According to one embodiment, the binder material is a non-aqueous material. In another embodiment, the binder material comprises a phenolic material. In yet a more particular embodiment, the binder material may include a phenolic binder.

[0096] In another aspect, the green body abrasive article or batch of green body abrasive articles can include a particular content of binder that may facilitate improved properties and/or performance. The binder material may be partially or fully cured in the green body abrasive article. In one instance, the green body may include an average content of binder material of at least 0.01 wt% for a total weight of the body, such as at least 0.02 wt%, or at least 0.05 wt%, or at least 0.1 wt%, or at least 0.2 wt%, or at least 0.53 wt%, or at least 1 wt%, or at least 2 wt%, or at least 3 wt%, or at least 4 wt%, or at least 5 wt%. Still, in another non-limiting embodiment, the green body or batch of green bodies may have an average weight percent of binder material that is not greater than 30 wt%, or not greater than 25 wt%, or not greater than 20 wt%, or not greater than 15 wt%, or not greater than 10 wt%, or not greater than 8 wt%, or not greater than 6 wt%. It will be appreciated that the average weight percent of the binder material in the green body may be within a range including any of the minimum and maximum percentages noted above.

[0097] In another non-limiting embodiment, the distribution of any one or more features of the abrasive articles can be evaluated. The shape of the distribution for such measured features, particularly dimensional features, may be evaluated via kurtosis.

[0098] The methods of the embodiments herein facilitate improved formation of abrasive articles. Notably, the empirical studies conducted by the Applicant facilitate methods that have a superior forming ratio (Add/Sub), which can define the ratio of the material added to form the body versus the material subtracted in any post-forming finishing techniques. The methods of the embodiments herein facilitate a forming ratio that is advantageous compared to conventional forming techniques and/or less sophisticated additive manufacturing techniques.

[0099] The improvement in forming ratio is also evident in the limited residual stress and/or subsurface damage on one or more exterior surfaces of the finally-formed abrasive articles. Given the enhancements in the forming process, much less effort, if any, is needed to finish the abrasive articles to suitable shapes and/or tolerances for their intended applications. Accordingly, the amount of residual stress and/or subsurface damage in the finally-formed abrasive articles is less as compared to conventional products or other less sophisticated additive manufacturing techniques.

<u>EXAMPLES</u>

[0100] The following non-limiting examples illustrate the present invention.

<u>EXAMPLE 1</u>

[0101] A mixture is prepared by combining two individual dry powder materials: a precursor bond material and abrasive particles. The precursor bond material is an oxide-containing material that forms a vitreous phase material upon further processing.

[0102] The additive manufacturing process is conducted according to embodiments described herein. The additive manufacturing process may be characterized as a binder jetting operation, wherein layers of the powder material are deposited into a build box, the layers are smoothed, compacted, and selectively bound with a binder material to form a batch of green body abrasive articles contained a bed of unbound or loose powder. Each of the green body abrasive articles has any one or more of the features embodied in the embodiments herein. The batch of green body abrasive articles has any one or more of the features embodied in the embodiments herein. The green body abrasive article is converted to finally-formed abrasive article via heating, as provided below. Example 1 was formed using an ExOne Innovent+. The printing conditions are summarized in Table 1.

Table 1:

Parameter	**Samples S1**
Saturation (%)	10-200%
Layer Thickness [μm]	1-1000
Foundation Layer Count	0-200
Oscillator on Delay (sec)Dispenser Delay	0-20
Dispense coverage parameter (% of bed length for dispensing powder material)	0-100%
Binder Set Time (sec)	0-30
Recoater Dry Speed (mm/s)	1-120
Target Bed Temperature (°C)	20-100
Recoat Speed (mm/s)	1-200
Smoothing Roller Rotation Rate(rpm)	1-1000
Smoothing Roller Speed (mm/s)	1-200
Binder Droplet Volume (pL)—	10-80
Binder Droplet Frequency (Hz)—	955-10,000
Compaction Roller Speed (mm/s)	1-150
Compaction thickness Δ (μm)	5-300

[0103] The build box has dimensions of length of at least 150 mm, a width of at least 60 mm, and a depth of at least 60 mm. The forming process creates a green body abrasive article having dimensions of a length of at least 6 cm and/or a width of at least 2.8 cm and /or a solid volume of at least 9 cm^3. The green body abrasive article has a thickness of at least 1 mm.

[0104] After forming, the green body is heated at a rate of 5°C/min up to a temperature of 550°C under air and held for one hour at 550°C to remove the binder. Thereafter, the air is replaced with argon, and the body is heated at a ramp rate of 5°C/min up to a maximum temperature of 1000°C. The temperature is held for four hours at 1000°C, and cooling is conducted at a rate of 5°C/minute.

<u>EXAMPLE 2</u>

[0105] A mixture is prepared by combining two individual dry powder materials: a precursor bond material and abrasive particles. The precursor bond material is a metal-containing material.

[0106] The process for forming the green body abrasive article of Example 2 is conducted using an ExOne25 Pro. Printing conditions are provided in Table 2 below.

<u>Table 2:</u>

Parameter	**Samples S2**
Saturation (%)	10-200%
Layer Thickness [µm]	1-1000
Foundation Layer Count	0-200
Oscillator on Delay (sec)Dispenser Delay	0-20
Dispense coverage parameter (% of bed length for dispensing powder material)	0-100%
Binder Set Time (sec)	0-30
Recoater Dry Speed (mm/s)	1-120
Target Bed Temperature (°C)	20-100
Recoat Speed (mm/s)	1-200
Smoothing Roller Rotation Rate(rpm)	1-1000
Smoothing Roller Speed (mm/s)	1-200
Binder Droplet Volume (pL)	10-80
Binder Droplet Frequency (Hz)	955-10,000
Compaction Roller Speed (mm/s)	1-150
Compaction thickness Δ (µm)	5-300

[0107] The build box has dimensions of length of at least 150 mm, a width of at least 60 mm, and a depth of at least 60 mm. The forming process creates a green body abrasive article having dimensions of a length of at least 6 cm and/or a width of at least 2.8 cm and /or a solid volume of at least 9 cm^3. The green body abrasive article has a thickness of at least 1 mm.

COMPARATIVE EXAMPLE 1

[0108] A sample was prepared using a binder jetting operation as generally described in Example 1. However, the powder material was 20 wt% of SP1086 glass powder from Specialty Glass Inc., in Oldsmar, Florida, and 80 wt% of 200/230 Mesh, D76 diamond powder from Pinnacle Abrasives (Santa Rosa, CA). The binder used was PM-B-SR1-04 from ExOne. The forming conditions are detailed below in Table 3 and were formed using a Innovent ExOne Printer. FIG. 16 includes an image of CS1 samples.

Table 3:

Parameter	**Samples CS1**
Saturation (%)	70
Layer Thickness [µm]	100
Foundation Layer Count	5
Oscillator on Delay (sec)	2
Binder Set (sec)	1
Dry Time (sec)	45
Target Temperature (°C)	60
Recoat Speed (rpm)	10
Oscillator Speed (rpm)	2800
Roller Speed (rpm)	60
Roller Speed (mm/s)	1

[0109] The body was then cured in an ambient atmosphere oven for 2 hours at 195°C. After curing and cooling to 23°C the cured bodies are placed into a furnace and burned out at 400°C for 2 hours, followed by sintering at 700°C for 4 hours, to produce comparative sample CS1.

[0110] SDR AND SURFACE ROUGHNESS

[0111] The Sdr and surface roughness (Sa) of transverse surfaces and other surfaces of representative samples ("Sample") and Sample CS1 were measured and detailed below in Table 4.

Table 4:

Sample	Sdr[%] Transverse	Sdr[%] Top	Sdr[%] Difference	Sa[microns] Transverse	Sa[microns] Top
Sample	76.5	64.7	11.8	11	9.112
CS1	130	100	30		

[0112] Notably, Sample had a much smaller transverse Sdr and Sdr difference than CS1.

[0113] EXAMPLE 3

[0114] Two groups of samples were created using different binder contents. The first set of samples, Sample S3, was formed using an ExOne (now Desktop Metal) Innovent+ with stepped compaction system) printer according to the parameters in Table 5 below from a mixture prepared by combining two individual dry powder materials: a bond material and abrasive particles. The bond material is a vitreous material.

Table 5:

Parameter	Samples S3
Saturation (%)	60%
Layer Thickness [µm]	1-1000
Foundation Layer Count	0-200
Oscillator on Delay (sec)Dispenser Delay	0-20
Dispense coverage parameter (% of bed length for dispensing powder material)	0-100%
Binder Set Time (sec)	0-30
Recoater Dry Speed (mm/s)	1-120
Target Bed Temperature (°C)	20-100
Recoat Speed (mm/s)	1-200
Smoothing Roller Rotation Rate(rpm)	1-1000
Smoothing Roller Speed (mm/s)	1-200
Binder Droplet Volume (pL)	10-80
Binder Droplet Frequency (Hz)	955-10,000
Compaction Roller Speed (mm/s)	1-150
Compaction thickness Δ (µm)	5-300

[0115] The second sample set, Sample S4, was formed using an ExOne (now Desktop Metal) Innovent+ with stepped compaction system) printer according to the parameters in Table 6 below from the same mixture used to form the samples of Sample S3.

Table 6:

Parameter	**Samples S2**
Saturation (%)	40%
Layer Thickness [µm]	1-1000
Foundation Layer Count	0-200
Oscillator on Delay (sec)Dispenser Delay	0-20
Dispense coverage parameter (% of bed length for dispensing powder material)	0-100%
Binder Set Time (sec)	0-30
Recoater Dry Speed (mm/s)	1-120
Target Bed Temperature (°C)	20-100
Recoat Speed (mm/s)	1-200
Smoothing Roller Rotation Rate(rpm)	1-1000
Smoothing Roller Speed (mm/s)	1-200
Binder Droplet Volume (pL)	10-80
Binder Droplet Frequency (Hz)	955-10,000
Compaction Roller Speed (mm/s)	1-150
Compaction thickness Δ (µm)	5-300

[0116] Samples S3 included two different abrasive article types. A first portion of the batch of Sample S3 was segments having the dimensions provided in FIG. 18. A second portion of the batch of Sample S3 were in the shape of cubes having the dimensions of length of at least 1.27 cm, a width of at least 1.27 cm, a thickness of 1.27 cm, and a solid volume of at least 2.05 cm^3.

[0117] Sample S4 included a batch of abrasive articles of two different portions, wherein each portion had different shapes. A first portion having the same shape and dimensions as the first portion of Sample S3 as provided in FIG. 18. A second portion of the batch of Sample S4 were in the shape of cubes having the dimensions of length of at least 1.27 cm, a width of at least 1.27 cm, a thickness of 1.27 cm, and a solid volume of at least 2.05 cm^3.

[0118] FIG. 17A includes a plot of sample-to-sample variation for the different portions in each of Samples S3 and Samples S4. The thickness (Z-direction dimension in the build direction) for each of the samples was measured using calipers and the difference between the smallest measurement and the largest measurement were recorded for each of the different portions in each of Samples S3 and S4. For example, in the portion of Sample S3 representing the segment shapes, the difference between the smallest and largest measurements of thickness was approximately 0.25 mm. FIG. 17B includes a plot of standard deviation of the thickness dimensions for each of the bodies for Samples S3 and Samples S4.

[0119] According to the embodiments herein, abrasive articles may be created that have a controlled difference in surface features (e.g., Sdr, etc.) between two surfaces, notably two different exterior surfaces of the abrasive articles. Research into the process variables that may be used to control difference in such surface features is complex and not predictable. Certain surface features, such as the difference in Sdr are understood to be related to build direction and orientation of the body during the forming process. Accordingly, the empirical data generated demonstrates that it is possible to engineer abrasive articles having selective surface features on various surfaces by controlling the build direction and build parameters. Such surface features are thought to be technically beneficial with respect to improved abrasive performance and/or anchoring of the abrasive articles with a bond system or other component for formation of a fixed abrasive article.

[0120] EXAMPLE 4

[0121] Two green body samples were formed using commercially available phenolic binder systems in two different liquid vehicles (i.e., solvents). Sample S5 was made using 75 grams of Phenolfuse phenolic binder available from ExOne dissolved in an isopropyl alcohol liquid vehicle and Sample S6 was made using 75 grams of Fluidfuse phenolic binder available from ExOne dissolved in an ethanol liquid vehicle. Table 7 shows the amount of HEXA% and solvent type for each of Samples S5 and S6.

Table 7:

Sample	HEXA%	Solvent Type
S5	0.63	IPA
S6	0.57	Ethanol

[0122] The mixtures were then used to perform a droplet test on the samples and various parameters were measured including crush strength. For the droplet test, measurements were performed with a Biolin® Scientific Attention Theta Flow optical tensiometer, using the parameters listed in Table 8.

Table 8:

Instrument Name:	Attension Theta Flow
Make:	Biolin Scientific
Pipette name:	Automatic single liquid dispenser
Make of Pipette:	Biolin Scientific
Size Range of Pipette:	8.5"x1.25"x1"
Disposable tip type:	Finntip non-filtered universal pipette tips
Size of disposable tip type:	2" in length, 250 uL in capacity

[0123] To perform the droplet test, the automated micropipette dispenser is installed onto the tensiometer equipment. The tensiometer is turned on and the One Attention software is opened on the desktop connected to the tensiometer. A disposable pipette tip is attached to the bottom of the micropipette dispenser. The pipette tip is inserted into the vial containing the sample to be measured. The dispenser is initiated from the software, so the binder fills into the pipette tip. The vial is removed from the micropipette dispenser. A prepared powder bed is placed on the sample stage, underneath the dispenser. The focus of the camera is adjusted on the equipment so that the process can be clearly recorded by the software. Recording on the software is started and a 15 μL binder droplet of the sample is immediately dispensed onto the powder bed. If the droplet infiltrates into the powder bed, record the process and stop when the droplet fully penetrates and disappears. If the droplet stays on the powder bed, record the process and calculate the contact angle on the software. Infiltration time is measured from when the droplet contacts the powder bed to when it is fully dissolved. This process is repeated to record at least 4 droplets for each sample. FIG. 19 shows a top down view of the droplet test set-up.

[0124] To measure the crush strength, the droplets were cured and removed from the powder bed and an Instron 3366 dual column tabletop testing system was used with the parameters as shown in Table 9.

Table 9:

Load Cell:	100 lbf load cell
Advanced Vid Extensometer:	No
Test Speed:	1 mm/min
Temperature:	Room Temperature
Distance between grips:	Equivalent to droplet diameter
Target Gauge length:	N/A

[0125] All samples were stood up diametrically using steel supports and the supports were removed before testing once the sample was gripped between the jaws of the machine. In these tests, the crush strength is defined as the max load after which the load starts to drop. This point coincides with a visual "crushing" of the sample (cracks seen in some samples, flakes chipping off in others, and most just crumbled into powder). The crush strengths of Samples S5 and S6 can be seen below in Table 10.

Table 10:

Sample	Crush Strength (N)
S5	28.8
S6	6.160

[0126] As can be seen, Sample S5 and S6 made with similar amounts of binder and hexa but made with different solvents resulted in different crush strengths. Sample S5 made with isopropyl alcohol showed improved crush strength compared to Sample S6 made with ethanol.

[0127] EXAMPLE 5

[0128] Three more samples, S7, S8, and S9 were made according to the same methods of Example 4. All three samples, S7, S8, and S9 were made using the phenolic binder Phenolfuse available from ExOne in an isopropyl alcohol (IPA) liquid vehicle and various amounts of a binder modifier, Hexa(methoxymethyl)melamine (HEXA). Sample S7 included 75g of Phenolfuse dissolved in 75g of IPA. Sample S8 included 150g of Phenolfuse +3g of HEXA. Sample S9 included 150g of Phenolfuse +8g of HEXA.

[0129] Table 11 shows the hexa% for each of S7, S8 and S9. The Crush Strength for each sample was also measured for according to the same methods of Example 4 and is shown in Table 11.

Table 11

Sample	Hexa%	Crush Strength
S7	0.18	12.275
S8	2.1	35.155
S9	5.2	43.933

[0130] As can been seen, Sample S9 having an increased Hexa content showed improved crush strength.

[0131] Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any feature(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature of any or all the embodiments. Reference herein to a material including one or more components may be interpreted to include at least one embodiment wherein the material consists essentially of the one or more components identified. The term "consisting essentially" will be interpreted to include a composition including those materials identified and excluding all other materials except in minority contents (e.g., impurity contents), which do not significantly alter the properties of the material. Additionally, or in the alternative, in certain non-limiting embodiments, any of the compositions identified herein may be essentially free of materials that are not expressly disclosed. The embodiments herein include a range of contents for certain components within a material, and it will be appreciated that the contents of the components within a given material total 100%.

[0132] The specification and illustrations of the embodiments described herein are intended to provide a general understanding of the structure of the various embodiments. The specification and illustrations are not intended to serve as an exhaustive and comprehensive description of all of the elements and features of apparatus and systems that use the structures or methods described herein. Separate embodiments may also be provided in combination in a single embodiment, and conversely, various features that are, for brevity, described in the context of a single embodiment, may also be provided separately or in any subcombination. Further, reference to values stated in ranges includes each and every value within that range. Many other embodiments may be apparent to skilled artisans only after reading this specification. Other embodiments may be used and derived from the disclosure, such that a structural substitution, logical substitution, or another change may be made without departing from the scope of the disclosure. Accordingly, the disclosure is to be regarded as illustrative rather than restrictive.

FIG. 1A

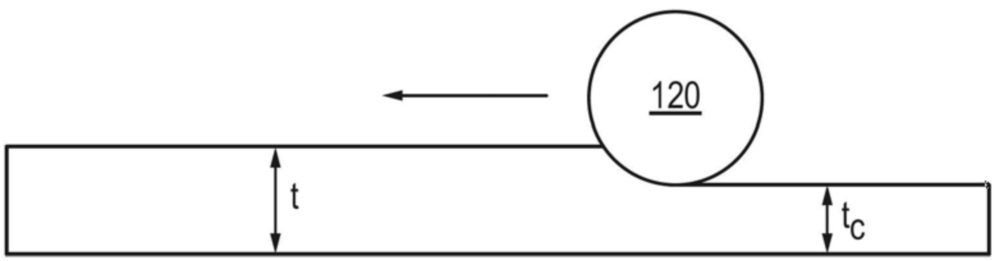


FIG. 1B

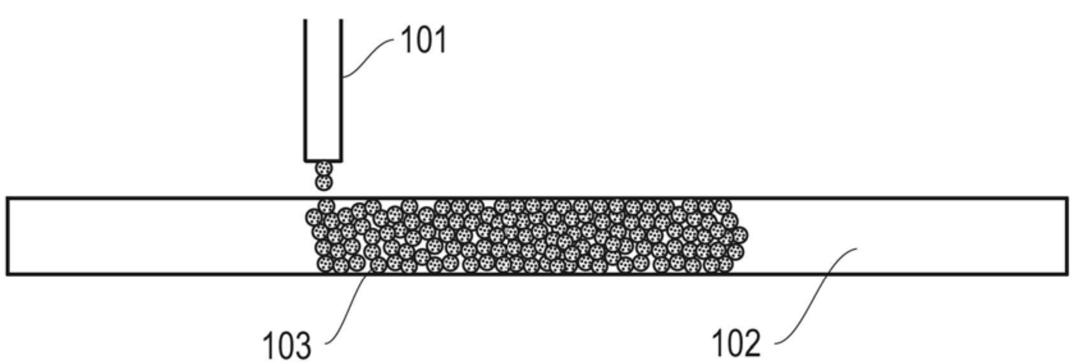


FIG. 1C

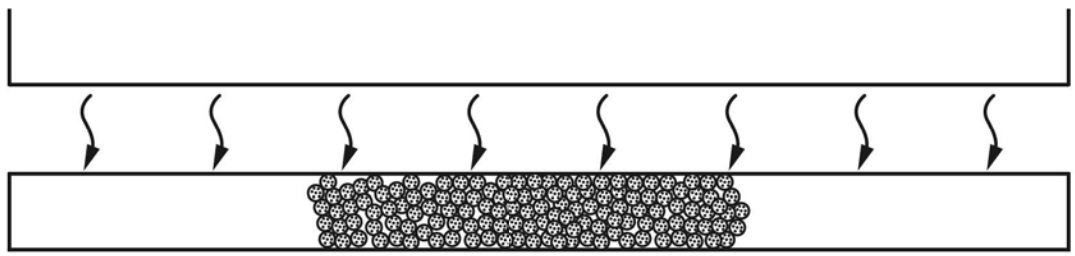


FIG. 1D

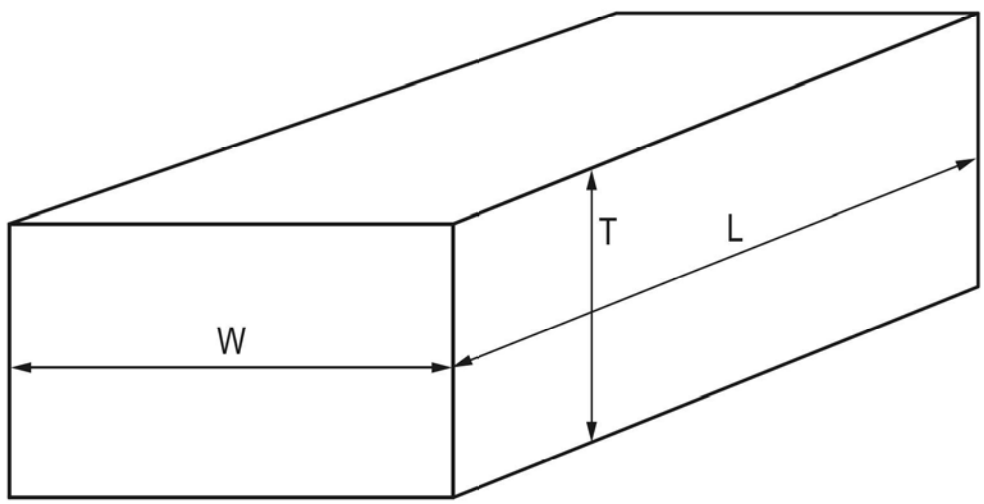


FIG. 1E

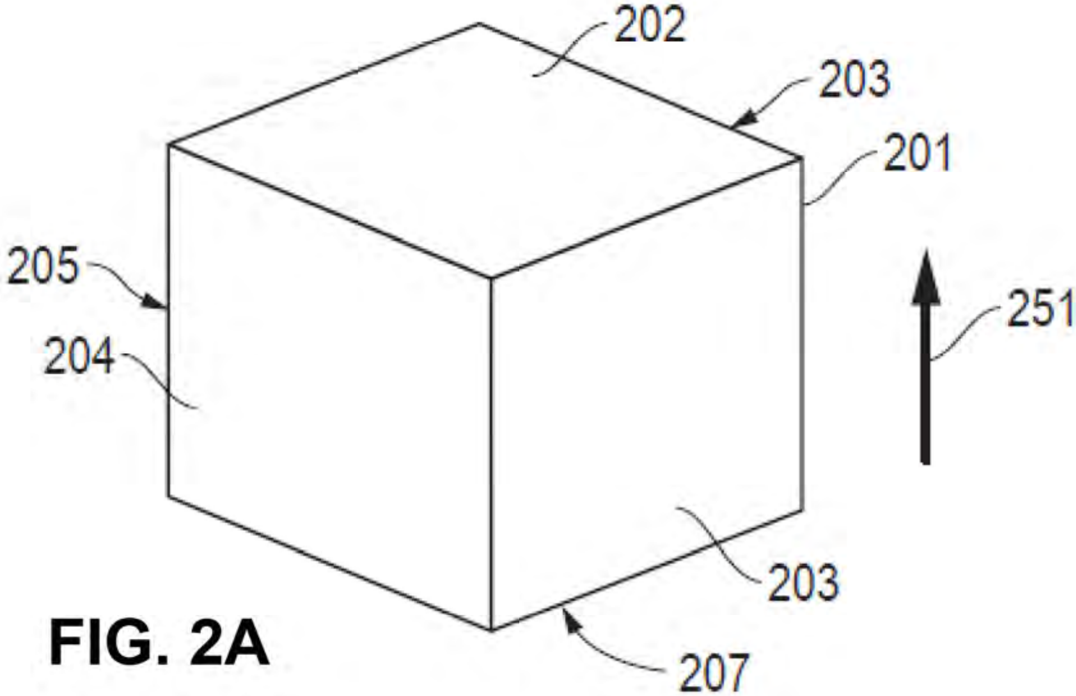


FIG. 2A

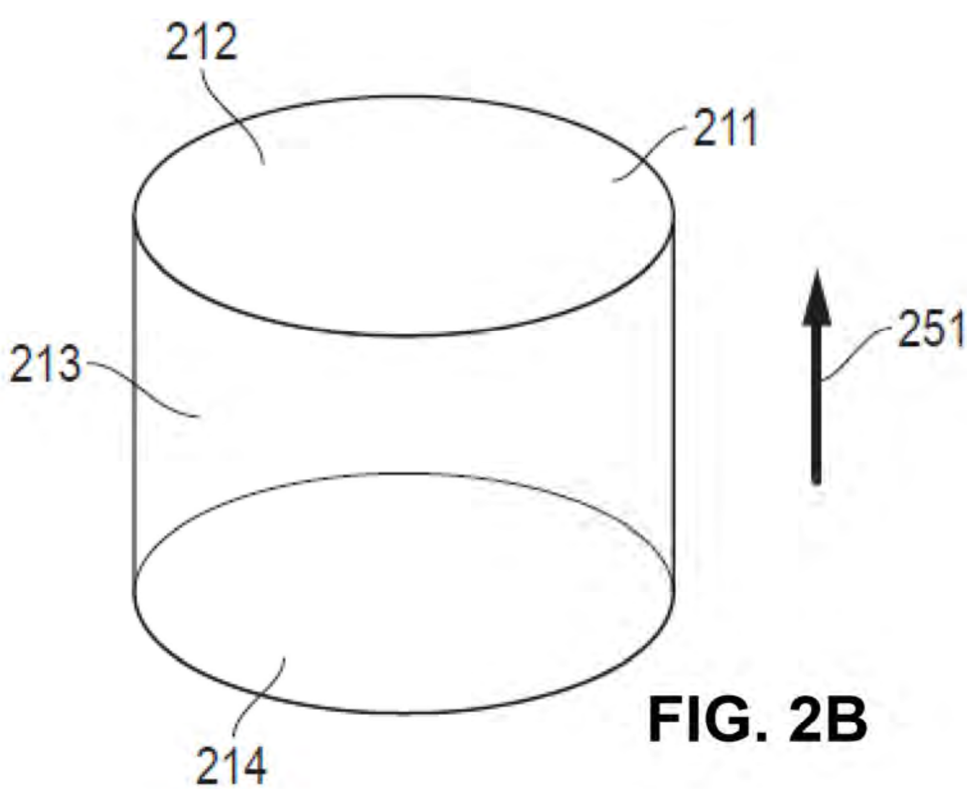


FIG. 2B

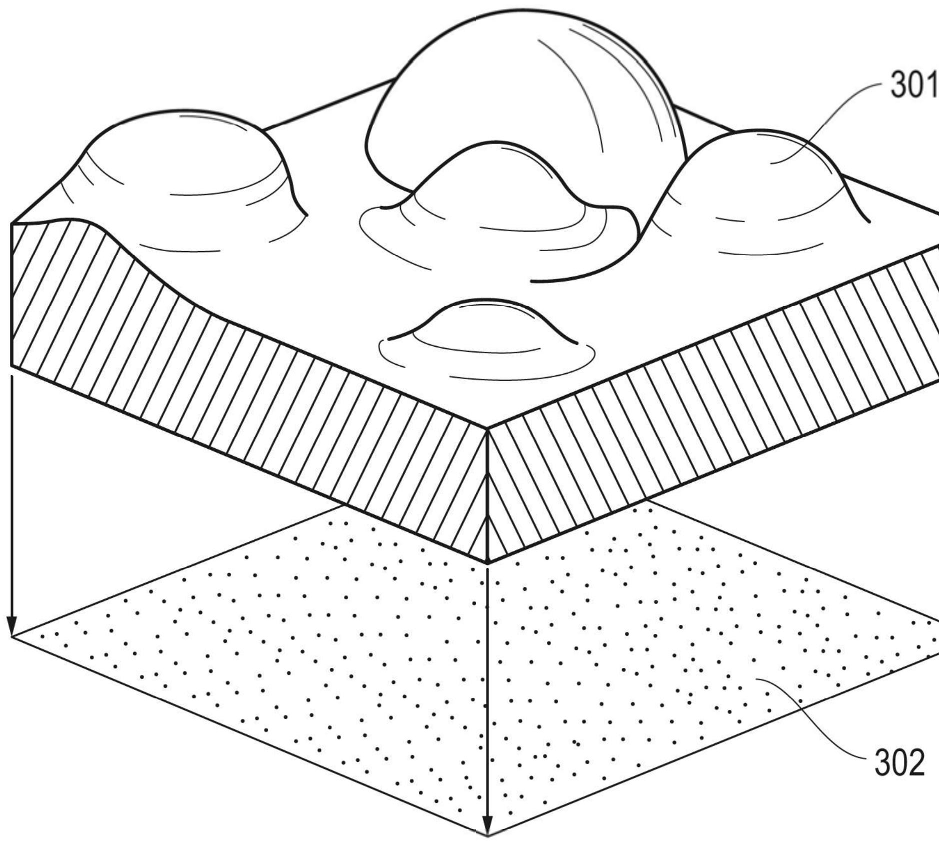


FIG. 3

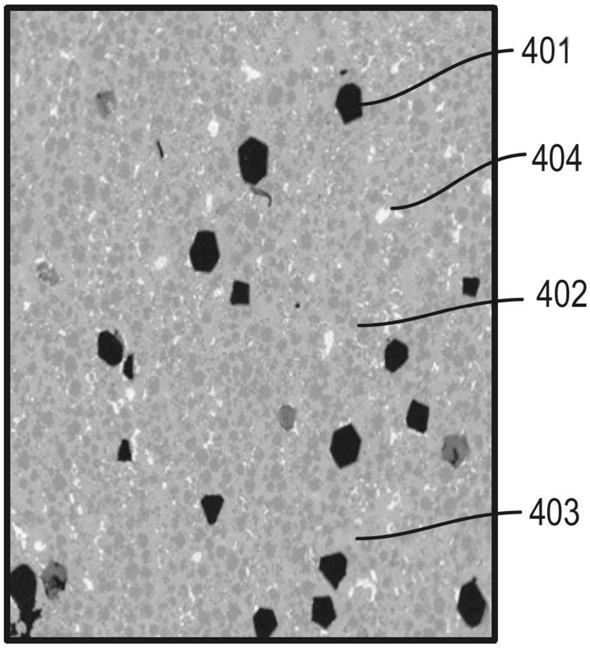


FIG. 4A

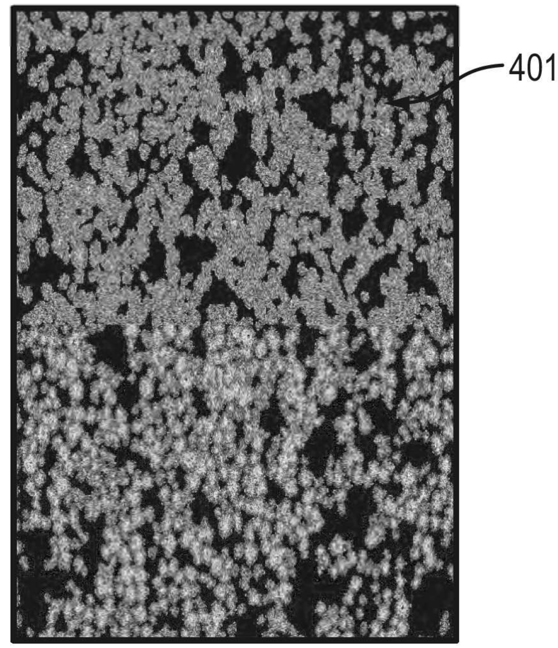


FIG. 4B

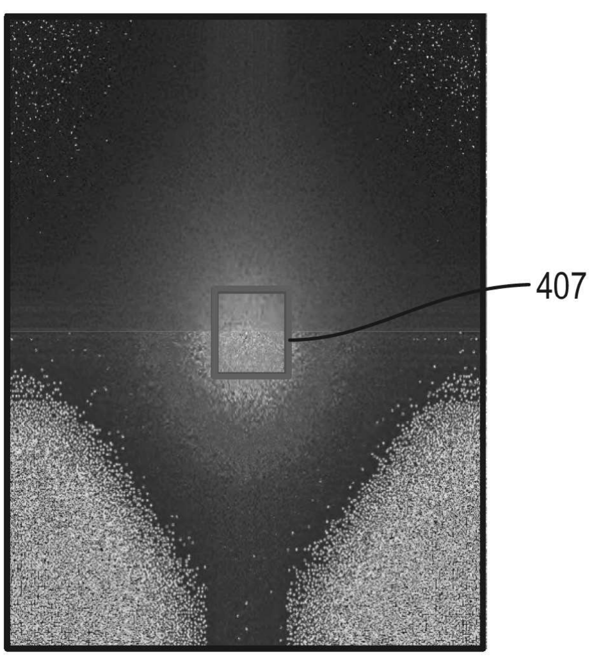


FIG. 4C

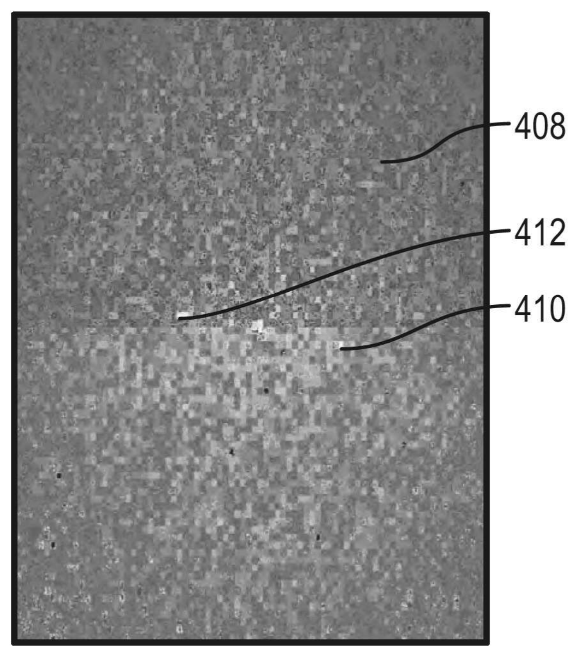


FIG. 4D

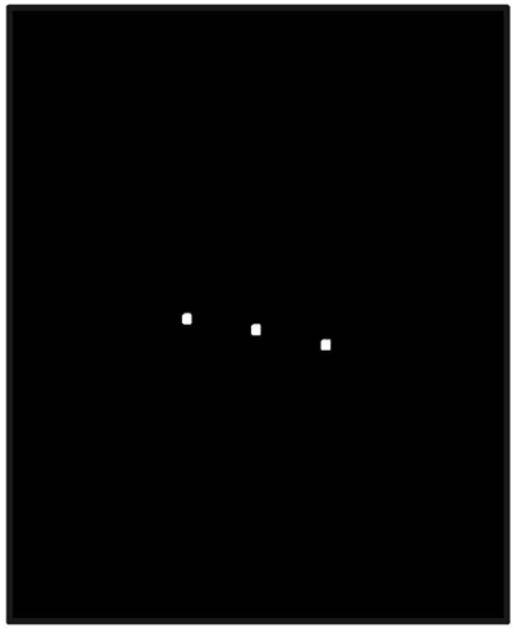


FIG. 4E

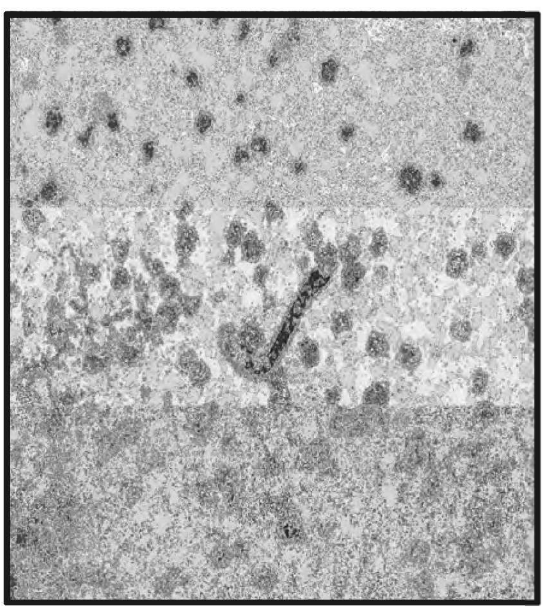


FIG. 5A

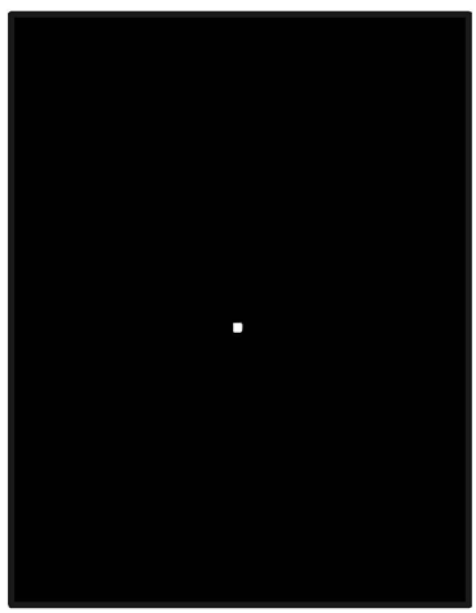


FIG. 5B

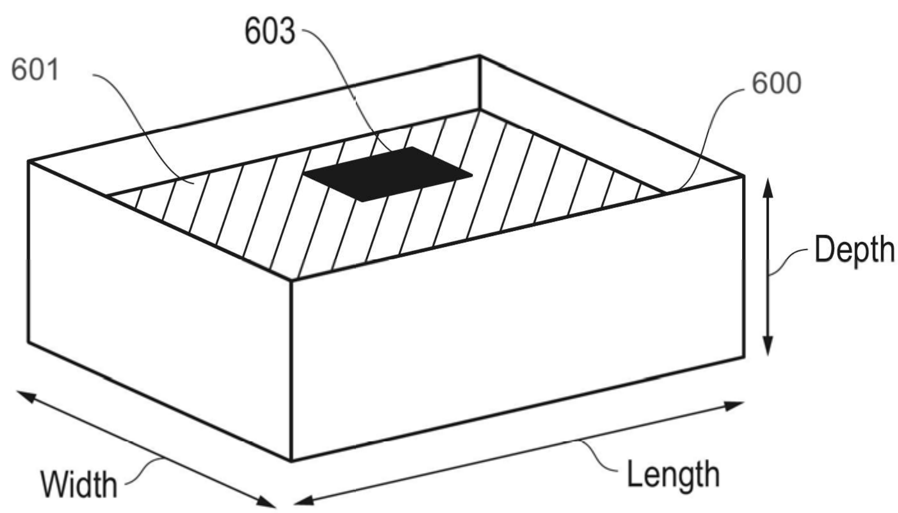


FIG. 6A

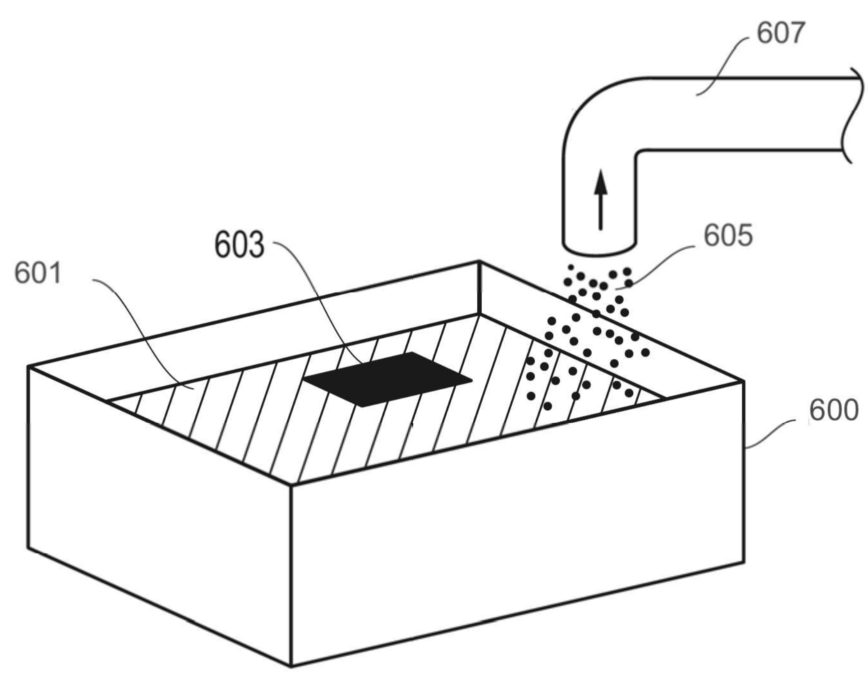


FIG. 6B

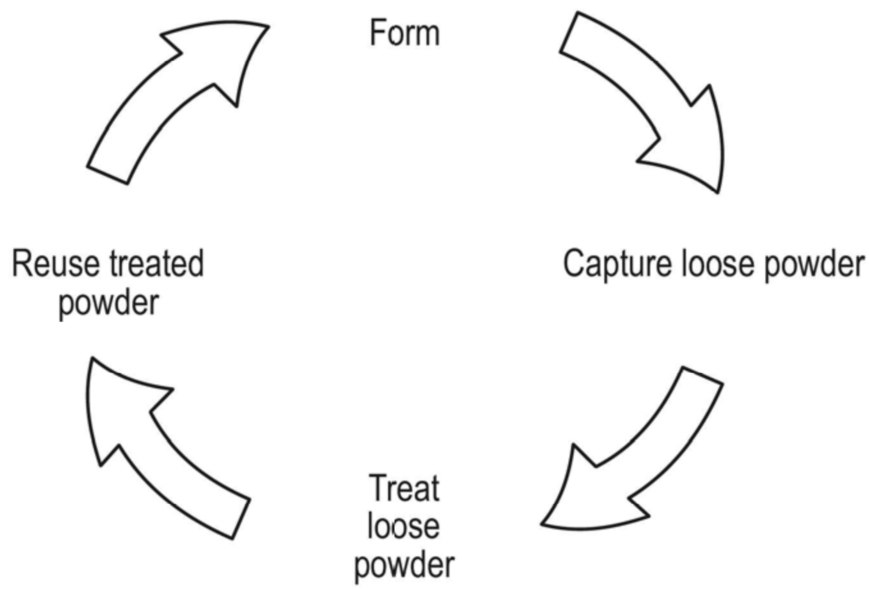

Form
Capture loose powder
Treat loose powder
Reuse treated powder

FIG. 6C

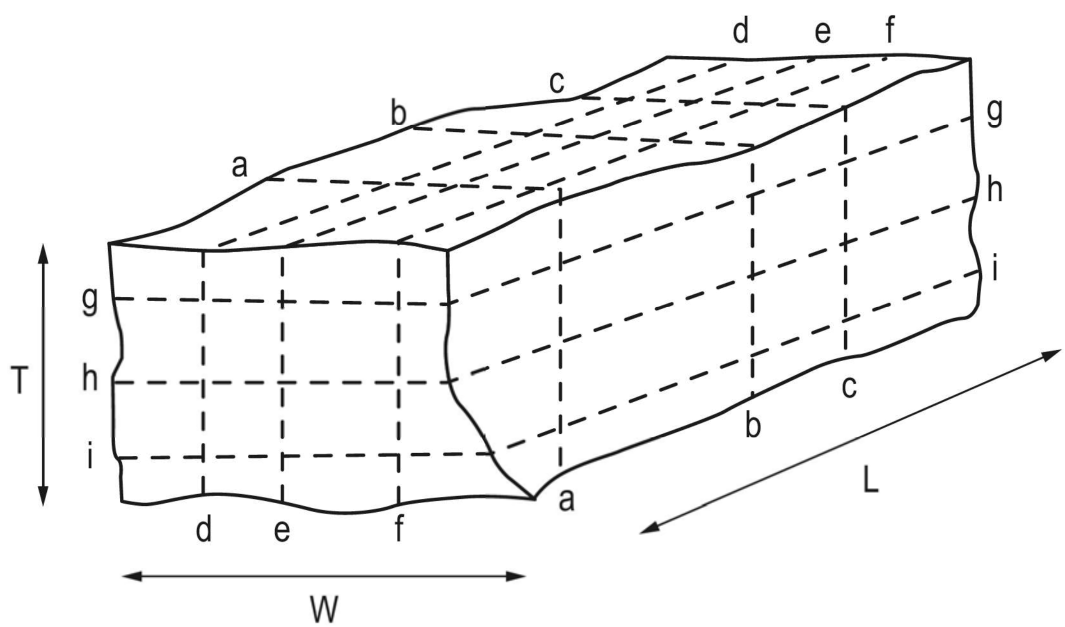

a
b
c
d
e
f
g
h
i
T
W
L

FIG. 7A

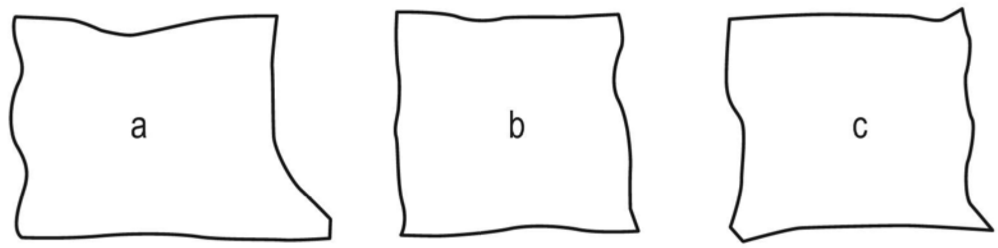


FIG. 7B

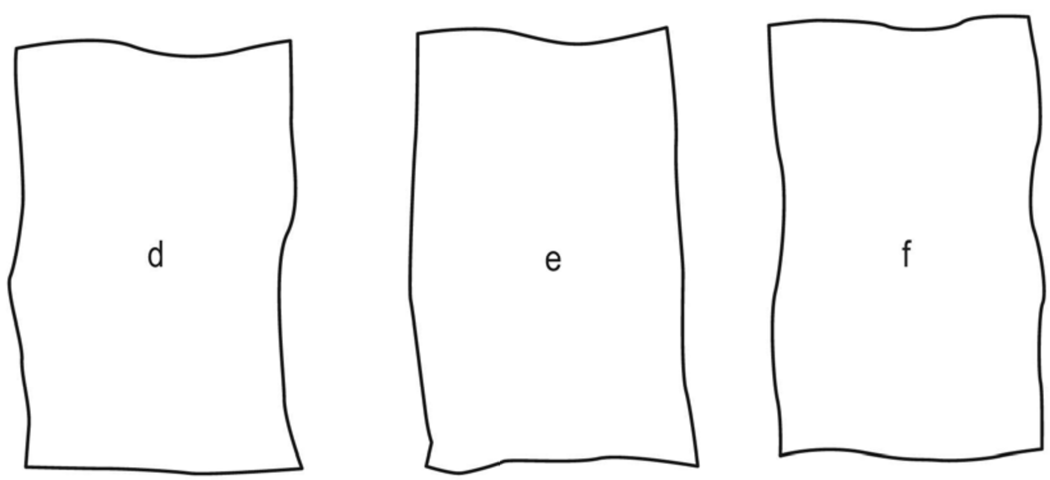


FIG. 7C

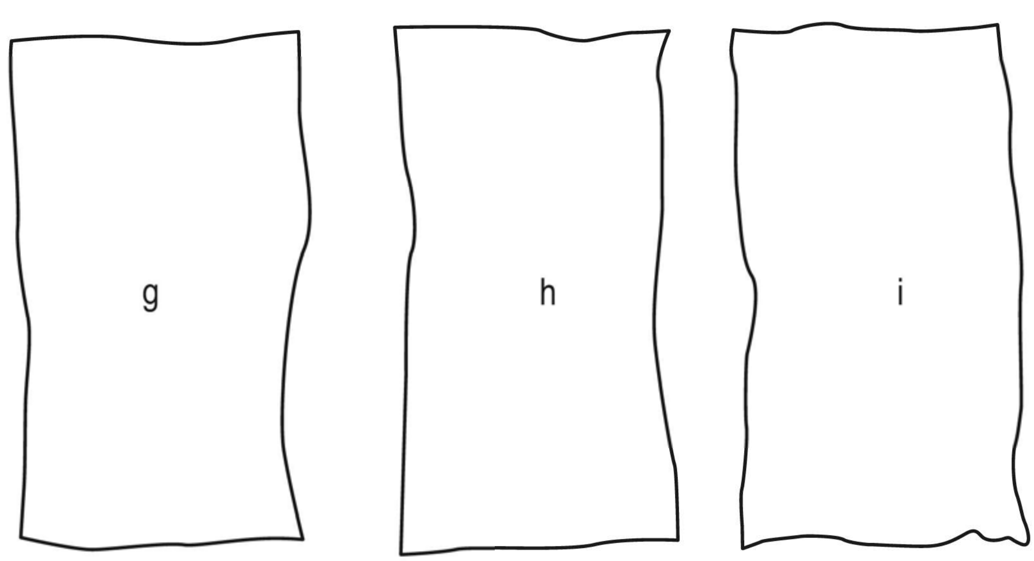


FIG. 7D

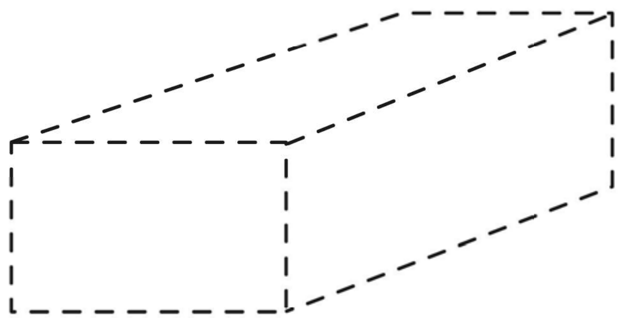


FIG. 8A

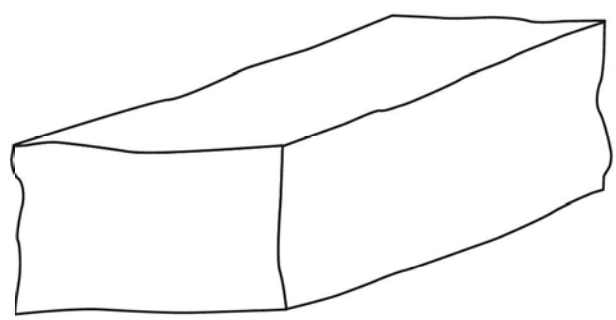


FIG. 8B

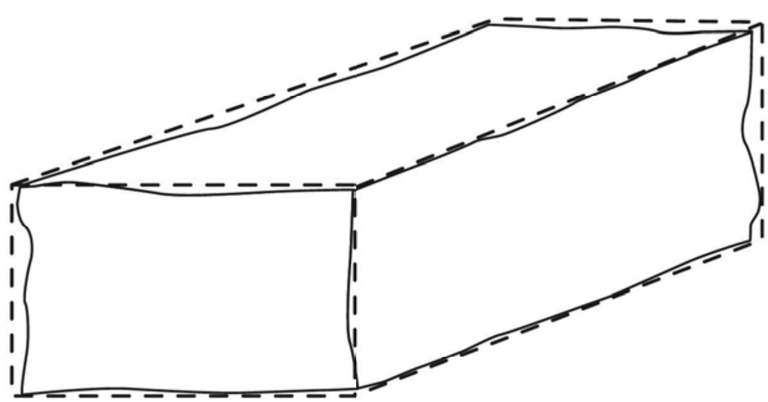


FIG. 8C

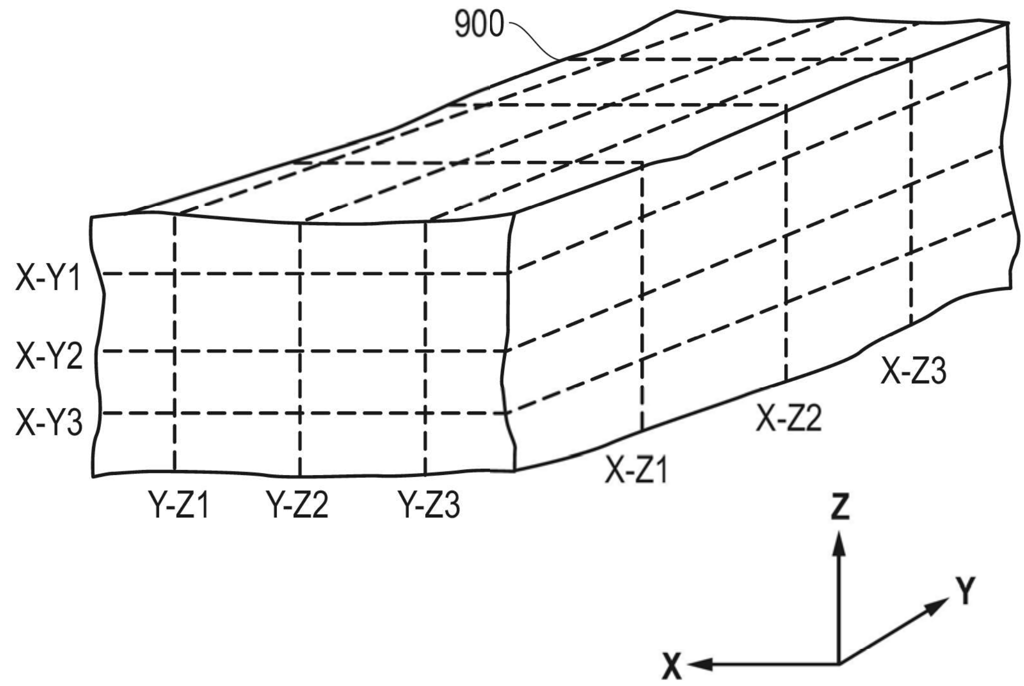

900
X-Y1
X-Y2
X-Y3
Y-Z1
Y-Z2
Y-Z3
X-Z1
X-Z2
X-Z3
Z
Y
X

FIG. 9A

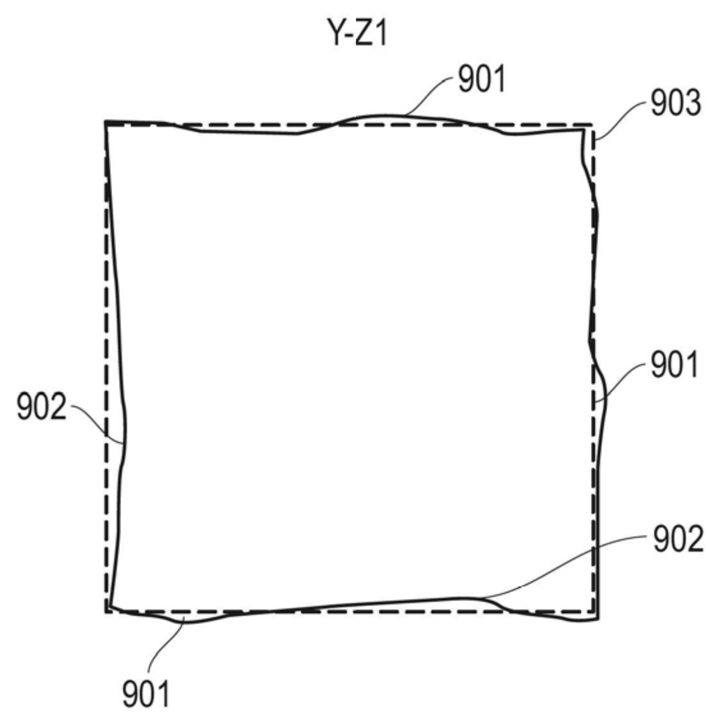

Y-Z1
901
903
901
902
902
901

FIG. 9B

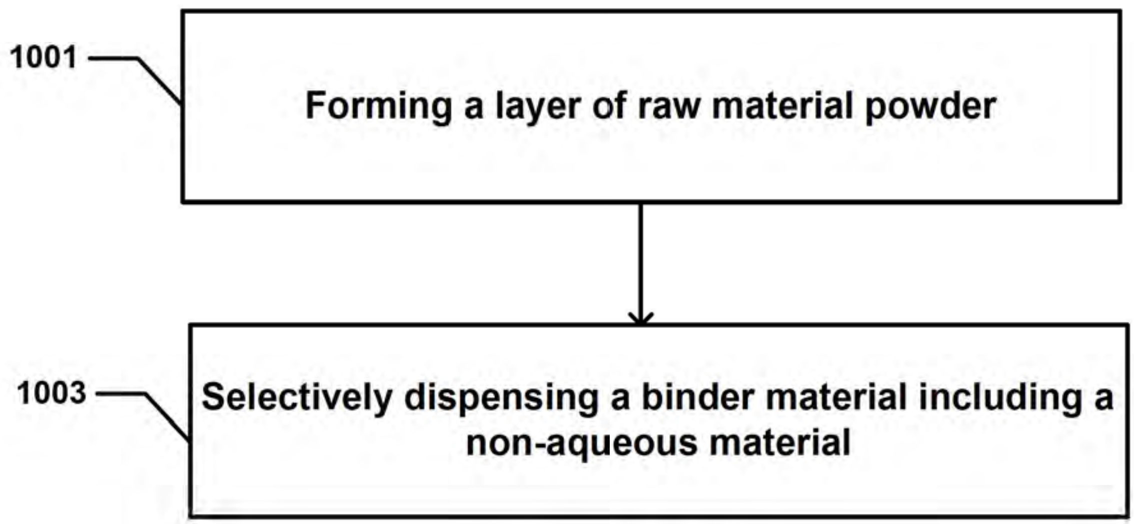

1001
Forming a layer of raw material powder
1003
Selectively dispensing a binder material including a non-aqueous material

FIG. 10

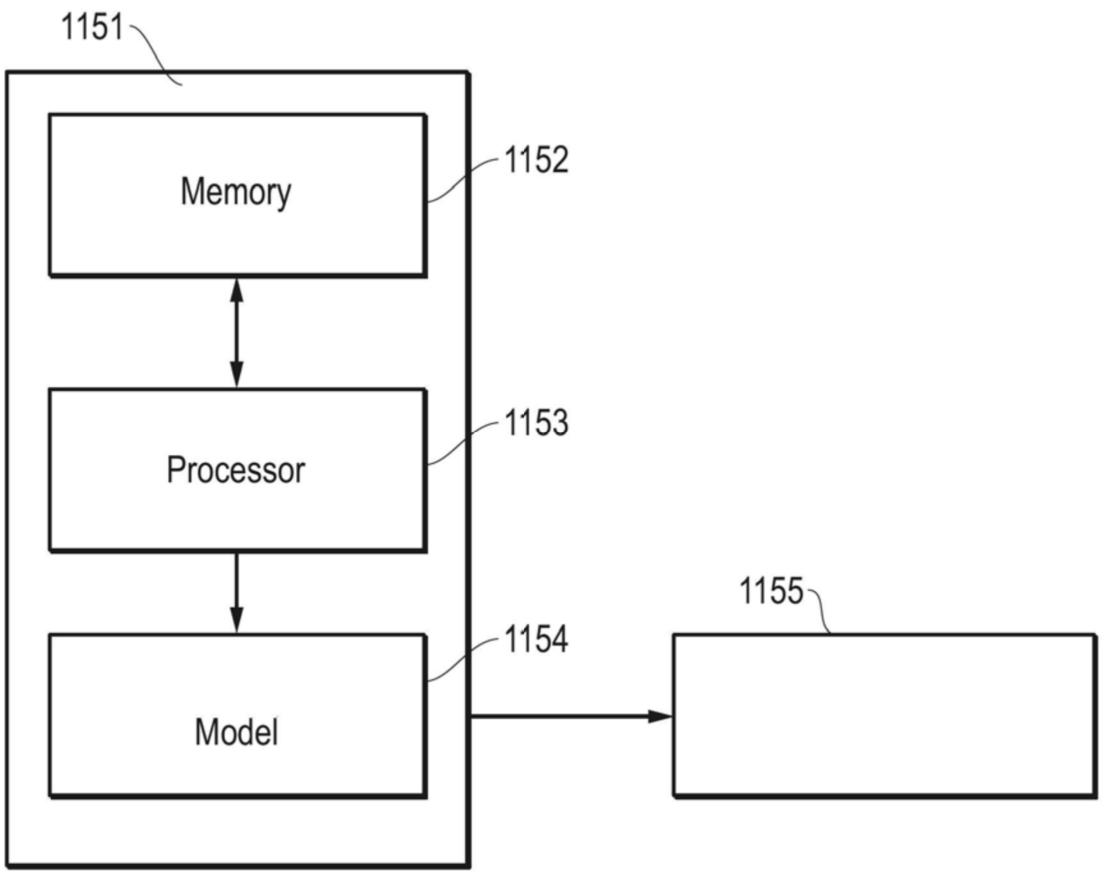


FIG. 11

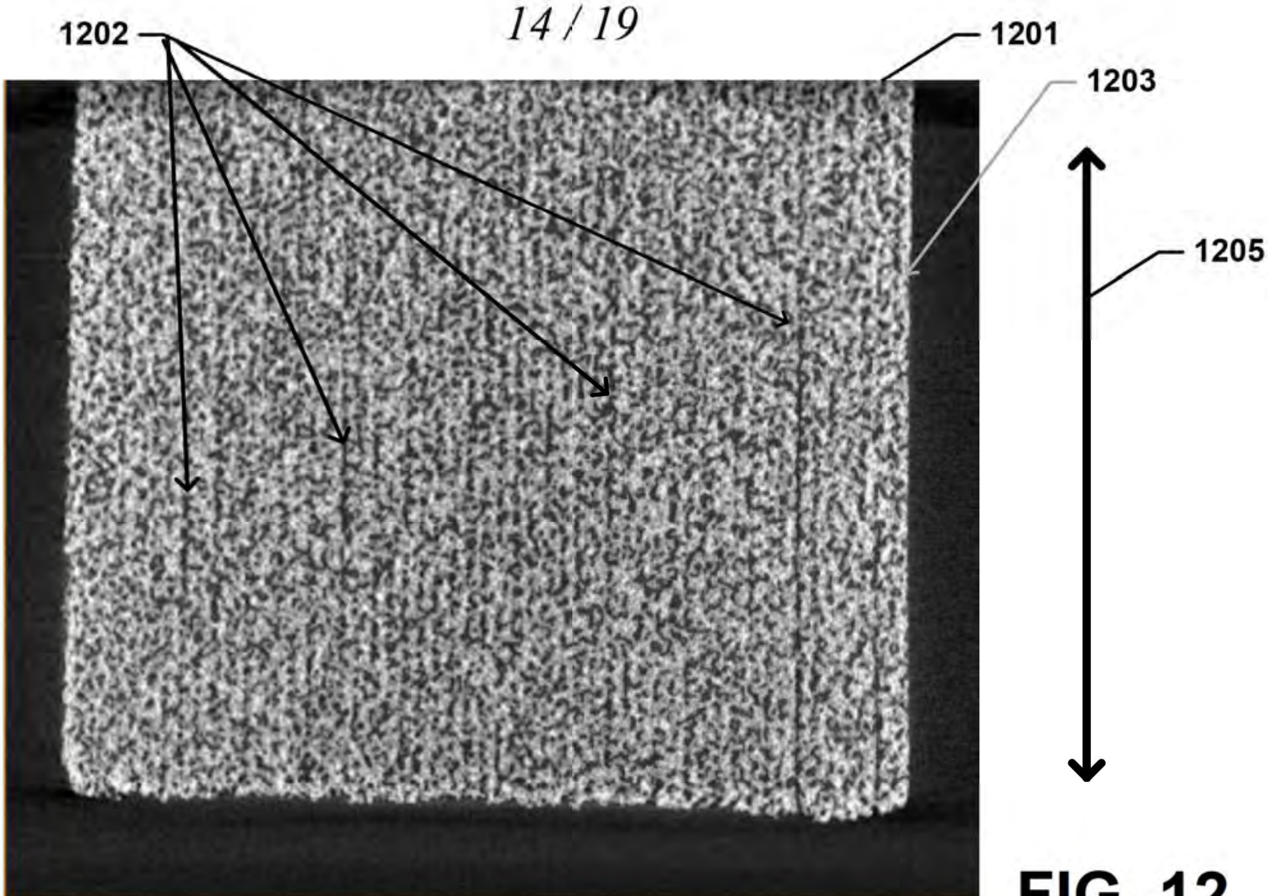


FIG. 12

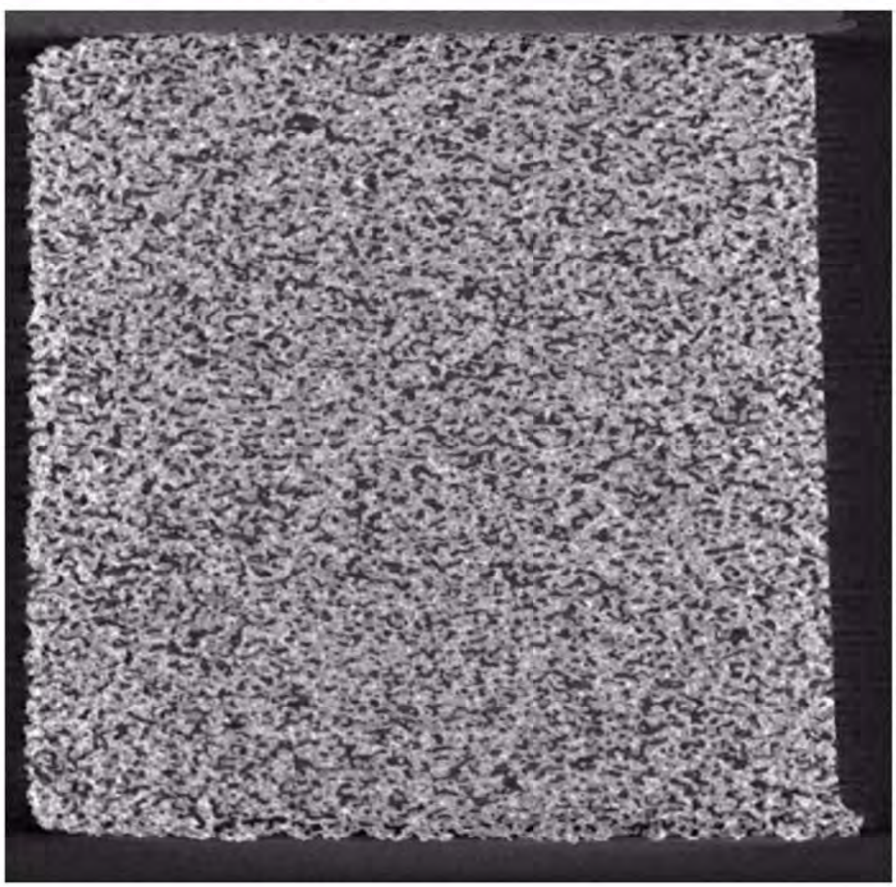
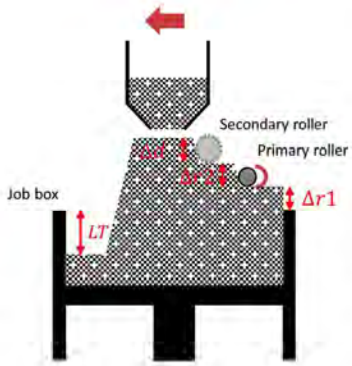


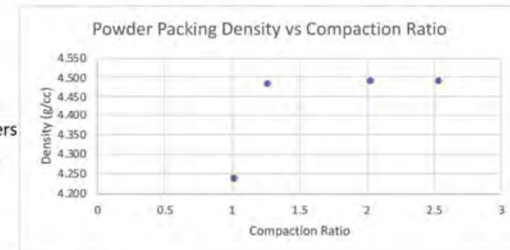
FIG. 13

- Purpose: providing same amount of powder for primary roller to spread powder

$$Compaction\ ratio = \frac{DT}{LT} - 1 = \frac{LT + \Delta r1 + \Delta r2}{LT} - 1 = \frac{\Delta r1 + \Delta r2}{LT}$$



$\Delta r1$	Offset between primary roller and job box
$\Delta r2$	Offset between primary and secondary rollers
Δd	Extra powder height above secondary roller
LT	Layer thickness
DT	Leveled dispensed powder thickness



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1

FIG. 14

CT	Compaction thickness
n	Compaction pass count

- Purpose: forcing powder downward by forward rotating roller

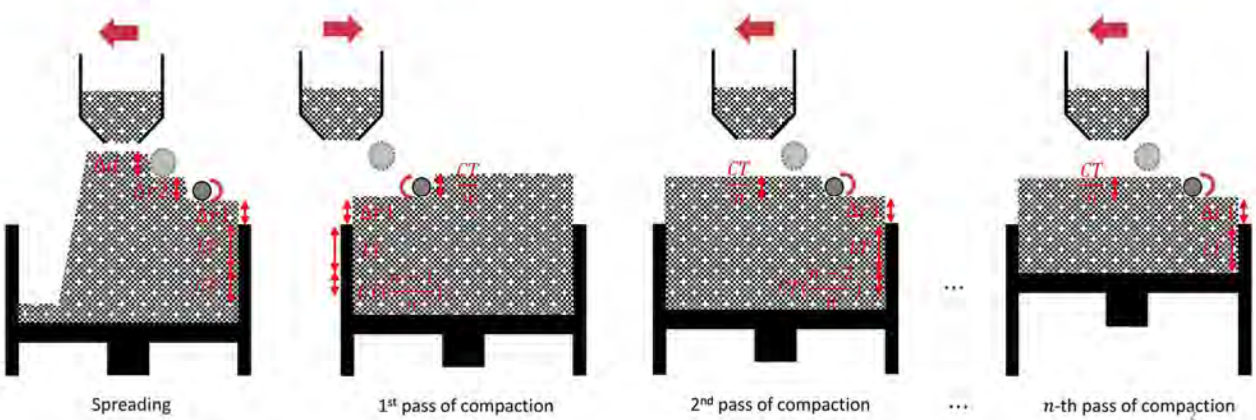

FIG. 15

FIG. 16

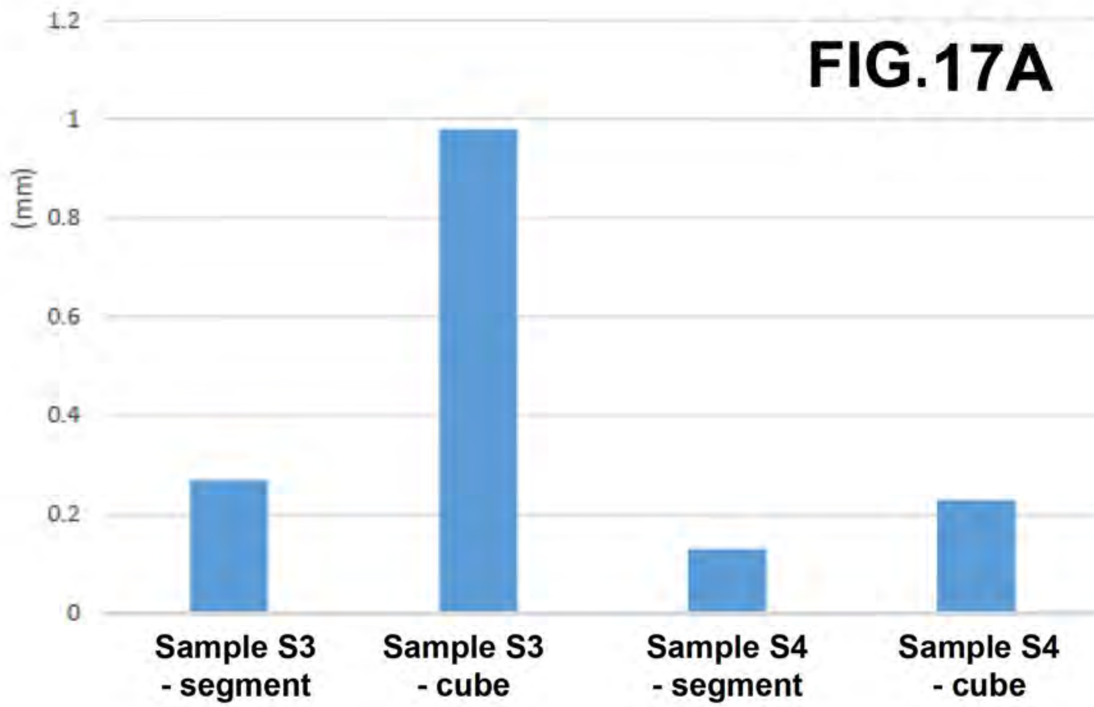

FIG.17A

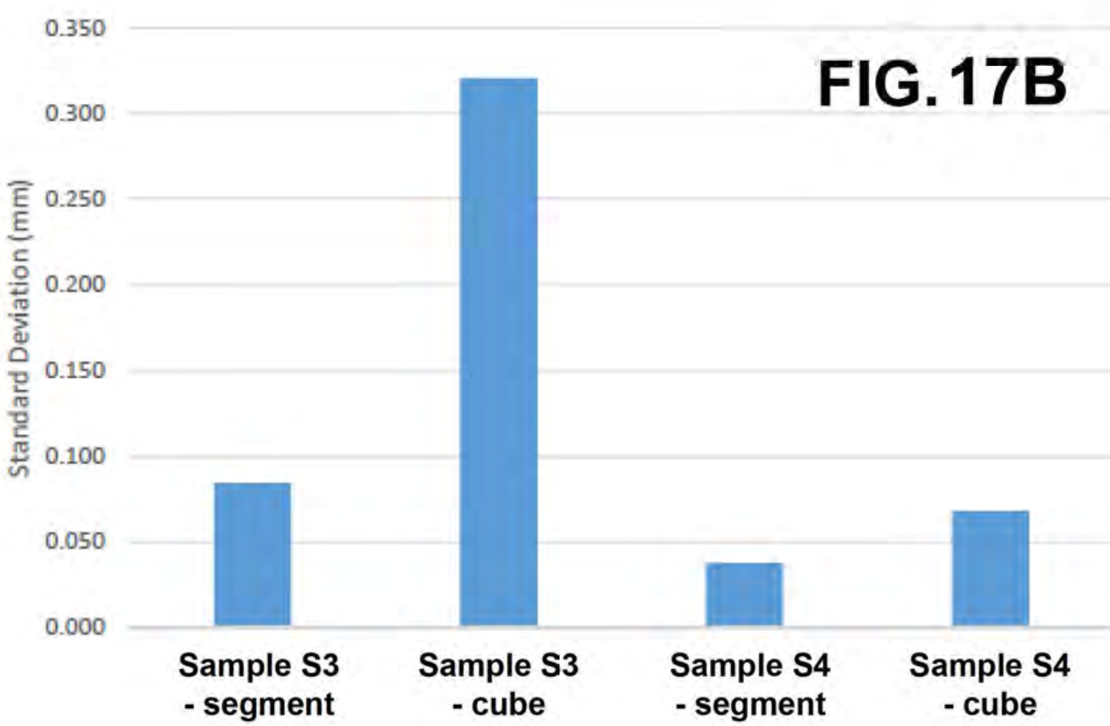

FIG.17B

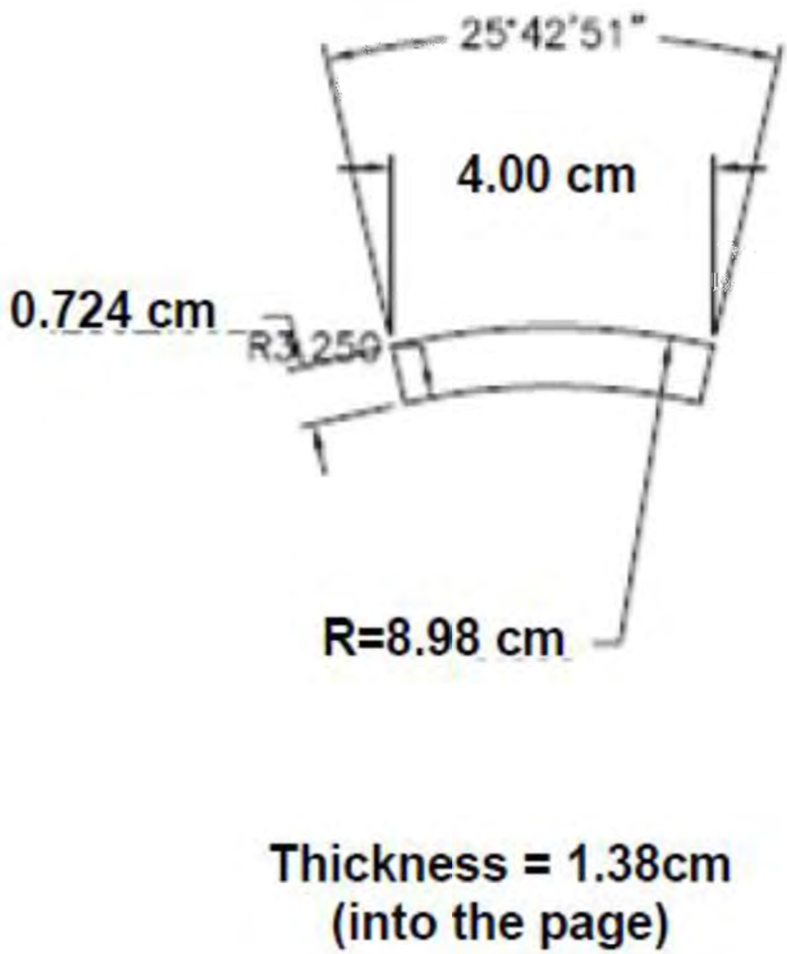
25°42'51"
4.00 cm
0.724 cm
R3.250
R=8.98 cm
Thickness = 1.38cm
(into the page)

FIG. 18

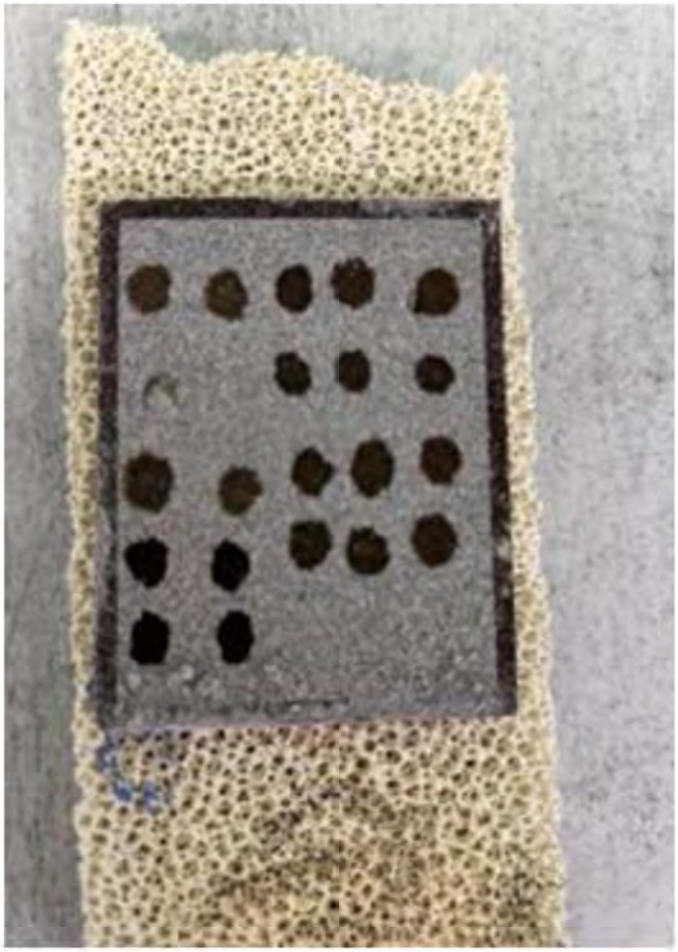

FIG. 19