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[Continued on next page]

(54) Title: ZERO-POROSITY NPR STRUCTURE AND TUNING OF NPR STRUCTURE FOR PARTICULAR LOCALITIES

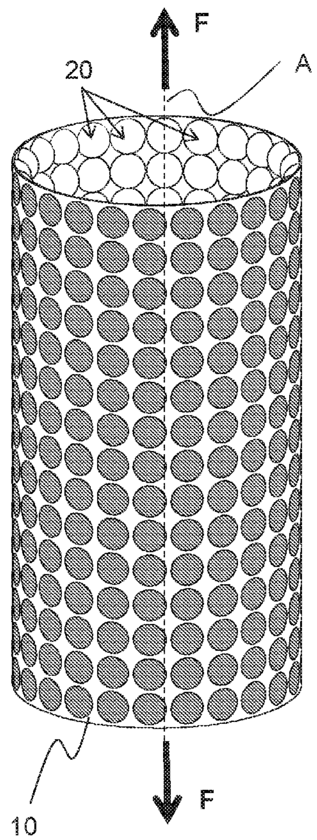

FIG. 1(d)

(57) Abstract: The present concepts include a zero-porosity structure having a plurality of structural elements arranged to provide a negative Poisson's ratio and, further, a new mechanism to generate negative Poisson's ratio is single material, zero-porosity structure. The present disclosure is directed to transformation of a sheet structure, or one or more subparts thereof, having a Positive Poisson's Ratio (PPR) to a Negative Poisson's Ratio (an "auxetic" structure) along one or more axes.

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ZERO-POROSITY NPR STRUCTURE AND TUNING OF NPR STRUCTURE FOR PARTICULAR LOCALITIES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the right of priority to U.S. Provisional Patent Application No. 62/118,819, filed on February 20, 2015, and U.S. Provisional Patent Application No. 62/101,823, filed on January 9, 2015, both of which are incorporated herein by reference in their respective entireties.

TECHNICAL FIELD

[0002] The present disclosure relates generally to materials possessing a Negative Poisson's Ratio ("NPR"), as well as systems, methods and devices using such materials.

BACKGROUND

[0003] When materials are compressed along a particular axis they are most commonly observed to expand in directions orthogonal to the applied load. The property that characterizes this behavior is the Poisson's Ratio, which can be defined as the ratio between the negative transverse and longitudinal strains. The majority of materials are characterized by a positive Poisson's Ratio, which is approximately 0.5 for rubber and 0.3 for glass and steel.

[0004] Materials with a Negative Poisson's Ratio will contract (or expand) in the transverse direction when compressed (or stretched) and, although they can exist in principle, demonstration of practical examples is relatively recent. Materials that exhibit negative Poisson's Ratio behavior are oftentimes referred to as "auxetics". The results of many investigations suggest that the auxetic behavior involves an interplay between the microstructure of the material and its deformation. Examples of this are provided by the discovery that metals with a cubic lattice, natural layered ceramics, ferro-electric polycrystalline ceramics, and zeolites may all exhibit negative Poisson's Ratio behavior. Moreover, several geometries and mechanisms have been proposed to achieve negative values for the Poisson's Ratio, including foams with reentrant structures, hierarchical laminates, polymeric and metallic foams. Negative Poisson's Ratio effects have also been demonstrated at the micrometer scale using complex structures which were fabricated using soft lithography and at the nanoscale with sheets assemblies of carbon nanotubes.

[0005] U.S. Patent No. 5,233,828 ("'828 Patent"), to Phillip D. Napoli, shows an example of an engineered structural member - a combustor liner - utilized in high temperature applications. Combustor liners are generally used in the combustion section of a gas turbine, but can also be used in the exhaust section or in other sections of or components of the gas turbine, such as the turbine blades. In operation, the combustors burn gas at intensely high temperatures, such as around 3,000°F or higher. To prevent this intense heat from damaging the combustor before it exits to a turbine, the combustor liner is inserted in the combustor to insulate the surrounding engine. To minimize temperature and pressure differentials across the combustor liners, cooling slots have conventionally been provided, such as is shown in '828 Patent. The '828 Patent shows a portion of an annular combustor liner having spaced cooling holes disposed in a continuous pattern, angled through the wall of the liner. U.S. Patent No. 8,066,482 B2, to James Page Strohl et al., shows another example of an engineered structural member having cooling holes shaped to enhance the cooling of a desired region of a gas turbine and to reduce stress levels in and around the cooling holes. European Patent No. EP 0971172 A1, to Dr. Jakob Keller, likewise shows another example of a perforated liner used in a combustion zone of a gas turbine. In yet another example, U.S. Patent Application Pub. No. 2010/0009120 A1, to Mary C. Boyce et al., discloses a number of transformative periodic structures which include elastomeric or elasto-plastic periodic solids that experience transformation in the structural configuration upon application of a critical macroscopic stress or strain. PCT patent application PCT/US2014/025324, to the President and Fellows of Harvard College, discloses, *inter alia*, void structures with repeating elongated-aperture patterns providing Negative Poisson's Ratio behavior. PCT patent application PCT/US2014/024830, to the President and Fellows of Harvard College, discloses, *inter alia*, a solid having an engineered void structure that causes the solid (having a positive Poisson's ratio) to exhibit pseudo-auxetic (NPR) behavior upon application of stress to the solid. The engineered void structure provides a porosity amenable to, for example, applications involving gas turbine combustors. All of the foregoing patent documents are incorporated herein by reference in their respective entireties for all purposes.

SUMMARY OF THE INVENTION

[0006] The present disclosure is directed to transformation of a sheet structure, or one or more subparts thereof, having a Positive Poisson's Ratio (PPR) to a Negative Poisson's Ratio (an "auxetic" structure) along one or more axes.

[0007] In at least some aspects of the present concepts, a zero-porosity structure comprises a zero-porosity material comprising a plurality of structural elements arranged to provide a negative Poisson's ratio. In some aspects, the structure comprises a sheet material such as, but not limited to a sheet-steel, strip steel, sheet-metal. In other aspects, the structure may comprise, but is not limited to, a casting or plate metal. In still other aspects, the structure may comprise other form factors and materials including, but not limited to composite materials, polymers and metal alloys.

[0008] In at least some other aspects of the present concepts, a zero-porosity structure comprises a first material portion comprising a first tiling of a first plurality of structural elements, and a second material portion comprising a second tiling of a second plurality of structural elements, wherein the first tiling is different from the second tiling and wherein at least one of the first material portion or the second material portion provides, responsive to the respective tiling configuration, at least one of a predetermined local negative Poisson's ratio or a predetermined global negative Poisson's ratio.

[0009] In yet other aspects of the present concepts, a method for constructing a zero-porosity structure comprises acts of establishing design constraints for the zero-porosity structure and determining, within the design constraints, at least one tiling pattern bearing a plurality of structural elements having one or more shapes that provide, in the aggregate a resultant negative Poisson's ratio for the structure. The method also includes the act of constructing the zero-porosity structure consistent with the act of determining.

[0010] In yet another aspect of the present concepts, a zero-porosity structure comprises a thin-walled structure having formed therein a plurality of structural elements defined which may comprise spherical caps or may be defined by the function

$$z = f(x, y) = exp\left(\delta\left[1 - \frac{1}{1 - \left|\frac{x}{a}\right|^{\alpha} - \left|\frac{y}{b}\right|^{\beta}}\right]\right)$$

restricted to:

$$\left|\frac{x}{a}\right|^{\alpha} + \left|\frac{y}{b}\right|^{\beta} < 1$$

[0011] wherein a and b control the aspect ratio of the ellipsoid in the $f(x,y) = 0$ plane, δ shows the structural element's maximum depth, and α, β vary the out-of-plane curvature, and wherein the structural elements, as a whole, provide the structure with a negative Poisson's ratio.

[0012] The above summary is not intended to represent each embodiment or every aspect of the present disclosure. Rather, the summary merely provides an exemplification of some of the novel features presented herein. The above features and advantages, and other features and advantages of the present disclosure, will be readily apparent from the following detailed description of exemplary embodiments and modes for carrying out the present invention when taken in connection with the accompanying drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1(a) presents isometric and side depictions, respectively, of a sheet patterned with a plurality of structural elements exiting a plane of the sheet in the same direction according to at least some aspects of the present disclosure.

[0014] FIG. 1(b) presents isometric and side depictions, respectively, of a sheet patterned with a plurality of structural elements having differing (e.g., alternating as shown) concavities according to at least some aspects of the present disclosure.

[0015] FIG. 1(c) shows a different representation of the sheet according to FIG. 1(b), wherein the sheet is patterned with a series of structural elements with differing (e.g., alternating as shown) concavities.

[0016] FIG. 1(d) shows a tubular thin-walled structure patterned with a series of inwardly-directed structural elements according to at least some aspects of the present disclosure.

[0017] FIGS. 2(a)-2(h) show a variety of non-limiting tiling patterns for sheets bearing a plurality of structural elements, such as those shown in FIGS. 1(a)-1(d), according to at least some aspects of the present disclosure.

[0018] While aspects of this disclosure are susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail herein. It should be understood, however, that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

[0019] The drawings and description herein provide representative embodiments of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspects of the invention to the embodiments illustrated. To that extent, elements and limitations that are disclosed, for example, in the Abstract, Summary, and Detailed Description sections, but not explicitly set forth in the claims, should not be incorporated into the claims, singly or collectively, by implication, inference or otherwise.

[0020] For purposes of the present detailed description, unless specifically disclaimed: the singular includes the plural and vice versa; the words “and” and “or” shall be both conjunctive and disjunctive; the word “all” means “any and all”; the word “any” means “any and all”; and the words “including” and “comprising” mean “including without limitation.” Moreover, words of approximation, such as “about,” “almost,” “substantially,” “approximately,” and the like, can be used herein in the sense of “at, near, or nearly at,” or “within 3-5% of,” or “within acceptable manufacturing tolerances,” or any logical combination thereof, for example.

[0021] Aspects of the present disclosure are directed towards structures possessing a plurality of structural elements such as, but not limited to concave and/or convex structures or “dimples,” formed in a pattern that, in the aggregate, provide a local and/or a global Negative Poisson’s Ratio (NPR) or auxetic behavior.

[0022] Contrary to the type of NPR structure disclosed in, for example, those described in WO 2014/151045 A1 and US 2011/0059291 A1, incorporated herein by reference in their respective entireties for all purposes, the NPR structures disclosed herein have no porosity.

[0023] FIGS. 1(a)-1(b) present isometric and side depictions, respectively, of (a) a structure 10 (e.g., a sheet material, etc.) patterned with a plurality of structural elements 20 (e.g., “dimples”) exiting a plane of the material in the same direction and (b) a structure 10 patterned with a first plurality of structural elements 20 configured to exit a plane of the material in a first direction (e.g., normal to the plane of the sheet, etc.) and a second plurality of structural elements 20’ configured to exit a plane of the material in a second direction (e.g., normal to the plane of the sheet in a direction opposite to the first direction, etc.).

[0024] In various aspects, the structure comprises a metal, aluminum, steel, and/or an alloy, as appropriate for a particular application. By way of example, in certain high temperature applications, a suitable material may comprise, but is not limited to, a “superalloy” such as a nickel-based superalloy (e.g., Inconel (e.g. IN100, IN600, IN713), Waspaloy, Rene alloys (e.g. Rene 41, Rene 80, Rene 95, Rene N5), Haynes alloys, Incoloy, MP98T, TMS alloys, and CMSX (e.g. CMSX-4) single crystal alloys, etc.).

[0025] The structural element 20, or combination(s) of different structural elements (e.g., 20, 20'), transform the underlying structure 10 from a Positive Poisson's Ratio (PPR) to a Negative Poisson's Ratio (NPR) responsive to stresses acting along one or more axes such as, but not limited to, tensile force F represented in FIG. 1(a) or FIG. 1(d).

[0026] As shown in FIG. 1(b), the first structural elements 20 and the second structural elements 20' are shown in an alternating relationship. However, this exemplary arrangement is non-limiting and the present concepts expressly including any tiling arrangement of one or more structural elements, as disclosed herein, that provide a Negative Poisson's Ratio (NPR). By way of example, further non-limiting tiling patterns for sheets bearing a plurality of structural elements are shown in FIGS. 2(a)-2(h).

[0027] FIG. 1(c) shows a different representation of the sheet according to FIG. 1(b), wherein the sheet is patterned with first structural elements 20 (illustrated as white circles) exiting or extending beyond a plane of the structure 10 in a first direction (e.g., normal to the plane of the sheet, etc.) and second structural elements 20' (illustrated as shaded circles) exiting or extending beyond a plane of the material in a second direction (e.g., normal to the plane of the sheet in a direction opposite to the first direction, etc.).

[0028] The convention of white circles and shaded circles will further be used in FIGS. 1(d) and 2(a)-2(h) to visually represent structural elements 20, 20' respectively exiting a plane of the structure 10 in different directions (e.g., opposite directions). By way of example, the white circles represent, from a particular reference frame, a convex structure, whereas the shaded circles represent, from that same vantage of the reference frame, a concave structure.

[0029] FIG. 1(d) shows an example of a structure 10 formed into a cylindrical shape and patterned with a plurality of structural elements 20 (e.g., dimples) exiting a plane of the sheet in the same direction (inwardly toward a central axis "A" of the cylinder in the example shown). By virtue of the structural elements, in the configuration depicted, the structure 10 is formed to possess a Negative Poisson's Ratio (NPR) rather than a Positive Poisson's Ratio (PPR).

[0030] In at least some aspects, the structural elements 20, 20' in FIGS. 1(a)-1(d) comprise spherical caps. As defined herein, "spherical cap" refers to one of the sections resulting from cutting a sphere along a given plane. In the examples shown in FIGS. 1(a)-1(d), the spherical cap structural elements 20, 20' are shown with arbitrarily chosen cross-sections, depth, and out-of-plane profiles for purposes of illustration and these parameters may be varied in accord with various aspects of the present concepts. Specifically, while the illustrated examples show uniformity in the structural elements 20 and 20' (i.e., the examples all show spherical cap structural elements), the present concepts expressly include utilization of different structural elements (e.g., spherical, spheroidal or ellipsoidal caps) on or side or on both sides of the structure 10 . The structural elements could comprise, for example, entirely elliptical structural elements a combination of different structural elements, such as a combination of spherical cap structural elements and elliptical structural elements. For any of these structural elements, the structural element can vary in depth, aspect ratio, and steepness of incline, among other design variables.

[0031] The structural elements 20, 20', however, could be arranged in different shapes including triangular, square, rhomboidal, and hexagonal lattices. In all cases the structural elements 20, 20' can extend from one side or both sides of the material, which may comprise a flat sheet or a curved or curvilinear material. Some non-limiting arrangements of structural elements 20, 20' are illustrated in FIGS. 2(a)-2(h). It is to be noted, however, that not all these tiling patterns necessarily lead to a global NPR behavior. Instead, some tiling patterns are advantageously utilized to generate special patterns of shrinkage or expansion in the displacement field of the structure. As in the aforementioned cases, such structural elements (e.g., dimples, etc.) are not restricted to spherical caps, but can vary greatly in depth, aspect ratio, and steepness of incline, among other features.

[0032] As noted above with respect to FIG. 1(a), one aspect of the present concepts comprises a square lattice of identical structural elements 20 exiting a plane of the structure 10 in the same direction. The structure of FIG. 1(a) exhibits auxetic behavior in cylindrical structures, such as is shown in FIG. 1(d), when subjected to loading, such as is represented by axial forces F. The structure of FIGS. 1(b) and 1(c), on the other hand, shows NPR behavior in planar structures under uniaxial loading.

[0033] Although the cross-section, depth and/or out-of-plane profiles can vary significantly in accord with the present concepts, not all possible combinations lead to NPR behavior. The NPR behavior was observed in thin shell structures where the thickness of the material was around 10 times smaller than the other dimensions. In the simulations performed by the inventors, it was observed that the NPR behavior fades away if the radius of the structural element (e.g., spherical cap) cross-section is less than 10 times that of the plate thickness. It was further determined that the cross-sectional area of the structural elements needed to cover a large area of the material surface (e.g., in general, more than about 50%). A pseudo-porosity for structural elements can be defined as the ratio between the combined structural element's cross-sectional area (A_{SE}) and the area (A_S) of the entire structure (i.e., Pseudo-porosity = A_{SE} / A_S). In a local area (e.g., a unit cell), the pseudo-porosity can be understood as the ratio between the area of one of the structural elements (e.g., a white circle shown in FIG. 1 (c)) and that of an imaginary geometric element (e.g., square) surrounding it, such as is shown by the dashed-line square 25 in FIG. 1(c). For a spherical structural element, the pseudo-porosity of the structure is desirably around 50% or higher to ensure NPR behavior. Finally, as noted, the depth of the structural element(s) can also affect the NPR behavior. For example, in spherical structural elements, the optimal value for depth of the structural element is around half that of the radius of the structural element.

[0034] As noted above, the structural elements can assume a variety of shapes (including a plurality of shapes for a given material or sub-portion of a material) and can be optimized to impart desired mechanical properties to the material or sub-portion thereof. In addition to the aforementioned geometric shapes such as spherical and spheroidal caps, many different functions can be used to create the structural element profile. For example, a structural element can be generated using the following function:

$$z = f(x, y) = exp\left(\delta\left[1 - \frac{1}{1 - \left|\frac{x}{a}\right|^{\alpha} - \left|\frac{y}{b}\right|^{\beta}}\right]\right)$$

Restricted to:

$$\left|\frac{x}{a}\right|^{\alpha} + \left|\frac{y}{b}\right|^{\beta} < 1$$

[0035] This structural element can then be tiled on a plane in order to achieve the desired structural element configuration. Alternatively, this structural element can be tiled and alternately inverted on a plane in order to achieve a desired structural element configuration. In the function presented above, a and b control the aspect ratio of the ellipsoid in the $f(x,y) = 0$ plane, δ shows the structural element's (e.g., dimple's) maximum depth, and α, β vary the out-of-plane curvature. The NPR structures can take the form of any material characterized by structural elements sharing a similar shape to those which can be created using the above function.

[0036] The main advantage of the proposed structures lies in their non-porousness and the low stress values exhibited under displacement-controlled loading. Since the disclosed zero-porosity NPR materials are non-porous and permit no fluids to pass, they present an excellent candidate for utilization in any structure for which porosity would be disadvantageous such as, but not limited to, turbine components, heat exchangers, piping, supports, fuselages, automotive or vehicular components, or any other structure or component subjected to mechanical and/or thermal loading.

[0037] Moreover, tiling patterns may be varied along a particular material or structure to provide tailored localized auxetic behavior and accommodate optimization for more complex applications where different behaviors are required in different sections of a structure. For example, a particular structural element (e.g., a gas turbine combustor component, combustor liner, etc.) may comprise a first material portion having a first tiling pattern comprising one or more distinct structural element types (e.g., arrangement, shape(s), density/densities, depth(s), etc.), a second material portion having a second tiling pattern comprising one or more distinct structural element types, a third material portion having a third tiling pattern comprising one or more distinct structural element types, to an n^{th} material portion having an n^{th} tiling pattern comprising one or more distinct structural element types.

[0038] The disclosed structures show very low stress values under displacement-controlled cases and demonstrate relatively high structural stiffness, which make them very good candidates for use in both load- and displacement-controlled loading conditions.

[0039] Regarding the process for selection of specific structural elements, tilings, and shapes, such process is largely informed by external design constraints. The following general concepts are not intended to be restrictive in nature, but are disclosed to illustrate some considerations of the design process. Some initial considerations are generally the dimension limitation on the out-of-plane size (e.g., depth or height) of the structural elements and the thickness of the material (e.g., metal sheet, etc.) The shape type of the structural element (e.g., whether spherical, ellipsoidal, or another shape) is determined by (1) the required negativity of the Poisson's ratio and (2) the maximum allowable stress for the application. If very low negative PRs are required, ellipsoidal structural elements are preferred over spherical ones. Further, the local shape of the structure (e.g., cylindrical, planar, curved, etc.) will influence the direction(s) in which the structural elements exit the plane of the material in that location and/or the tiling pattern. If the maximum stress is a major contributor to the structure's design, spherical dimples are preferred. In view of the above considerations, the size(s) of the microstructure of the structural elements are determined, as is the spacing thereof to arrive at the necessary local and global Poisson's ratio(s). Of course, the order of operations may be freely changed in accord with the present concepts in view of the available design information and imposed constraints. Purely for illustrative purposes, the present concepts even include trial and error optimization techniques in which a variety of tiling patterns, structural element shapes and structural element orientations are iteratively applied for a particular structure to determine an optimal combination of structural element features and placements to attain a desired local and/or global NPR characteristic.

[0040] Although the present concepts are disclosed in relation to a variety of patterns or tilings, the present concepts are not limited to utilization of a pattern or tiling. By way of example, the present concepts may even advantageously adopt a local or global randomized distribution, subject to local or global constraints (allowable stress, loading, unloading, peak stress, etc.) to achieve a desired global local or global NPR. Thus, in a given area of a material, locations of structural elements could be disposed in a manner that produces an asymmetrical pattern and yields a desired global local NPR.

[0041] Each of these embodiments and obvious variations thereof is contemplated as falling within the spirit and scope of the claimed invention, which is set forth in the following claims. Moreover, the present concepts expressly include any and all combinations and subcombinations of the preceding elements and aspects.

CLAIMS

What is claimed:

1. A zero-porosity structure comprising:

a zero-porosity material comprising a plurality of structural elements arranged to provide a negative Poisson's ratio.

2. The zero-porosity structure according to claim 1,

wherein the structural elements comprise at least a first plurality of structural elements configured to exit a plane of the material in a first direction.

3. The zero-porosity structure according to claim 2,

wherein the structural elements comprise at least a second plurality of structural elements configured to exit a plane of the material in a second direction different than the first direction.

4. The zero-porosity structure according to claim 3,

wherein the first direction is a normal direction to a first side of the material, and

wherein the second direction is a normal direction to a second side of the material.

5. The zero-porosity structure according to claim 2,

wherein the first plurality of structural elements are arranged in at least one tiling pattern on the material.

6. The zero-porosity structure according to claim 3,

wherein the first plurality of structural elements and the second plurality of structural elements are arranged in at least one tiling pattern on the material.

7. The zero-porosity structure according to any one of claims 1, 2 or 5,

wherein at least one of the first plurality of structural elements comprise a spherical cap.

8. The zero-porosity structure according to any one of claims 1, 2 or 5,

wherein at least one of the first plurality of structural elements comprise an ellipsoidal structure.

9. The zero-porosity structure according to any one of claims 1-6,

wherein at least one of the first plurality of structural elements or at least one of the second plurality of structural elements comprises a spherical cap.

10. The zero-porosity structure according to any one of claims 1-6,

wherein at least one of the first plurality of structural elements or at least one of the second plurality of structural elements comprises an ellipsoidal structure.

11. The zero-porosity structure according to any one of claims 1-6,

wherein at least one of the first plurality of structural elements or at least one of the second plurality of structural elements has a shape defined by the function

$$z = f(x,y) = exp\left(\delta\left[1 - \frac{1}{1 - \left|\frac{x}{a}\right|^{\alpha} - \left|\frac{y}{b}\right|^{\beta}}\right]\right)$$

wherein

$$\left|\frac{x}{a}\right|^{\alpha} + \left|\frac{y}{b}\right|^{\beta} < 1$$

wherein a and b control the aspect ratio of the ellipsoid in the $f(x,y) = 0$ plane,

wherein δ shows the structural element's maximum depth, and

wherein α, β vary the out-of-plane curvature.

12. The zero-porosity structure according to claim 11,

wherein a configuration of all of the first plurality of structural elements are governed by said function.

13. The zero-porosity structure according to claim 12,

wherein a configuration of all of the second plurality of structural elements are governed by said function.

14. The zero-porosity structure according to any one of claims 1-13,
wherein a pseudo-porosity of the structure is about 50% or higher.

15. The zero-porosity structure according to claim 7 or claim 9,
wherein a depth of the spherical cap structural element is around half that of the radius of the spherical cap structural element.

16. A zero-porosity structure comprising:
a first material portion comprising a first tiling of a first plurality of structural elements, and
a second material portion comprising a second tiling of a second plurality of structural elements,
wherein the first tiling is different from the second tiling, and
wherein at least one of the first material portion or the second material portion provides, responsive to the respective tiling configuration, at least one of a predetermined local negative Poisson's ratio or a predetermined global negative Poisson's ratio.

17. The zero-porosity structure according to claim 16,
wherein the first plurality of structural elements comprise a plurality of structural elements configured to exit a plane of the first material portion in a first direction.

18. The zero-porosity structure according to claim 17,
wherein the first plurality of structural elements comprise a plurality of structural elements configured to exit a plane of the first material portion in a second direction different than the first direction.

19. The zero-porosity structure according to claim 18,
wherein the first direction is a normal direction to a first side of the first material portion, and
wherein the second direction is a normal direction to a second side of the first material portion.

20. The zero-porosity structure according to claim 17,

wherein the second plurality of structural elements comprise a plurality of structural elements configured to exit a plane of the second material portion in the first direction.

21. The zero-porosity structure according to claim 20,

wherein the second plurality of structural elements comprise a plurality of structural elements configured to exit a plane of the second material portion in the second direction different than the first direction.

22. The zero-porosity structure according to claim 21,

wherein the first direction is a normal direction to a first side of the second material portion, and

wherein the second direction is a normal direction to a second side of the second material portion.

23. The zero-porosity structure according to any one of claims 16-22,

wherein a pseudo-porosity of the structure is about 50% or higher.

24. The zero-porosity structure according to any one of claims 16-22,

wherein at least one of the first plurality of structural elements comprise a spherical cap or an ellipsoidal structure, and

wherein at least one of the second plurality of structural elements comprise a spherical cap or an ellipsoidal structure.

25. A method for constructing a zero-porosity structure comprising the acts of:

establishing design constraints for the zero-porosity structure,

determining, within the design constraints, at least one tiling pattern bearing a plurality of structural elements having one or more shapes that provide, in the aggregate a resultant negative Poisson's ratio for the structure, and

constructing the zero-porosity structure consistent with the act of determining.

26. The method for constructing a zero-porosity structure according to claim 25,

wherein the at least one tiling pattern comprises a plurality of tiling patterns.

27. The method for constructing a zero-porosity structure according to claim 25,

wherein the design constraints comprise a dimension limitation on an out-of-plane dimension of the structural elements, a thickness of the material, or combination of the out-of-plane dimension of the structural elements and the thickness of the material.

28. The method for constructing a zero-porosity structure according to claim 25,

wherein a shape of the structural elements is determined at least in part by the required negativity of the Poisson's ratio.

29. The method for constructing a zero-porosity structure according to claim 28,

wherein a shape of the structural elements is determined at least in part by the maximum allowable stress for the application of the zero-porosity structure.

30. The method for constructing a zero-porosity structure according to claim 27,

wherein an out-of-plane direction of the structural elements is determined by a local curvature of the zero-porosity structure.

31. The method for constructing a zero-porosity structure according to claim 27,

wherein a shape of the structural elements is determined by a maximum stress of the zero-porosity structure.

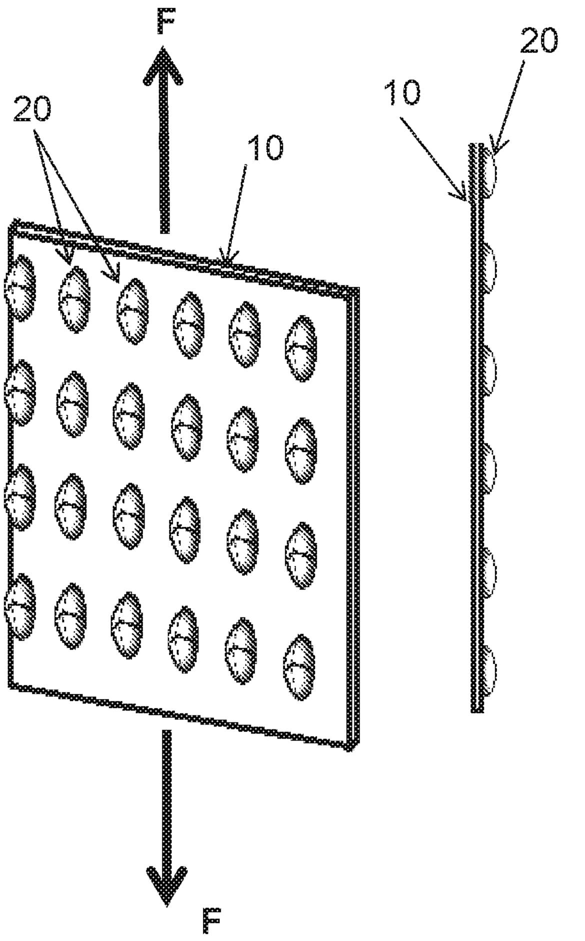
F
20
10
10
20
F

FIG. 1(a)

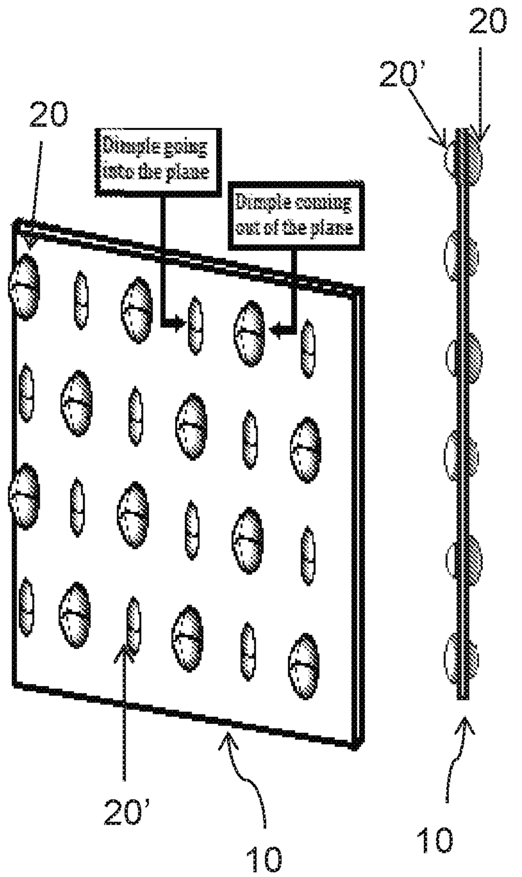
20
Dimple going into the plane
Dimple coming out of the plane
20'
20
20'
10
10

FIG. 1(b)

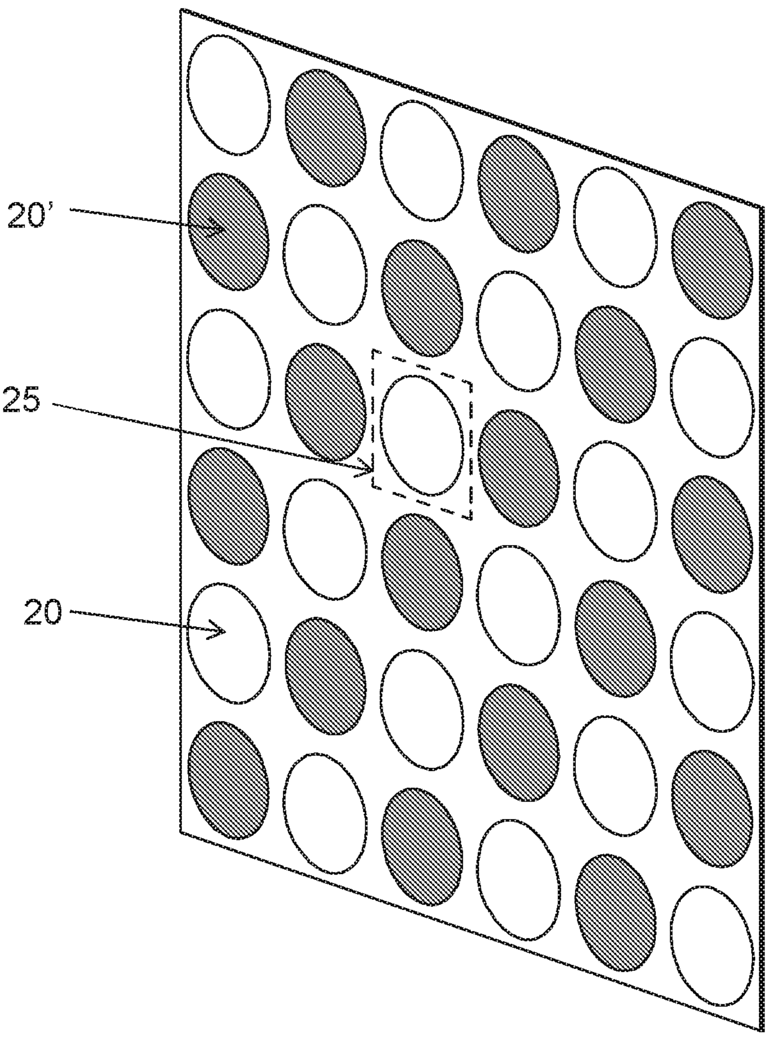

FIG. 1(c)

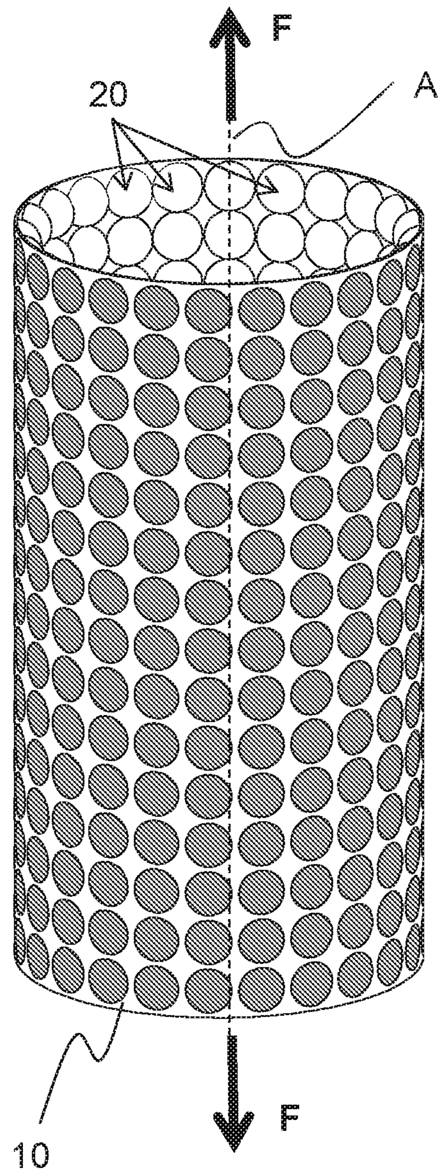

FIG. 1(d)

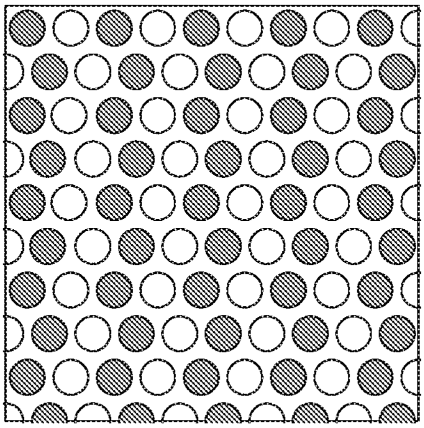

FIG. 2(a)

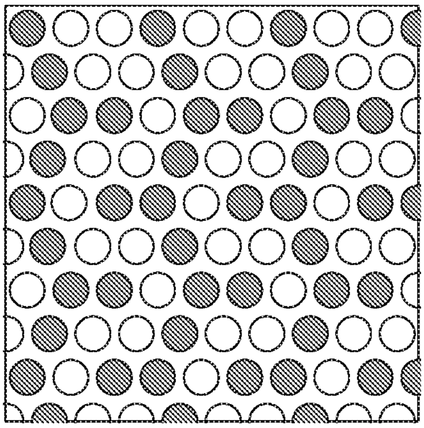

FIG. 2(b)

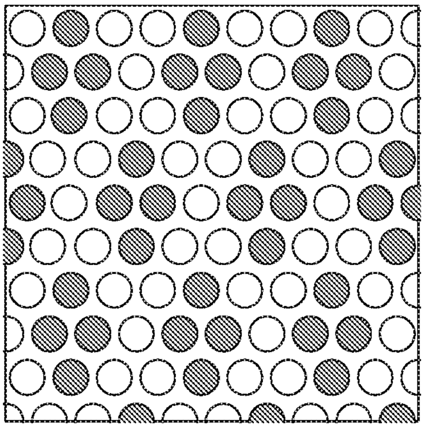

FIG. 2(c)

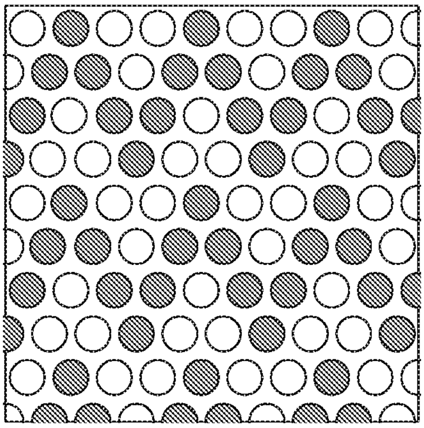

FIG. 2(d)

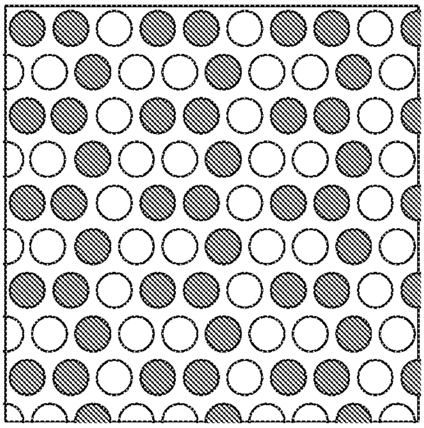

FIG. 2(e)

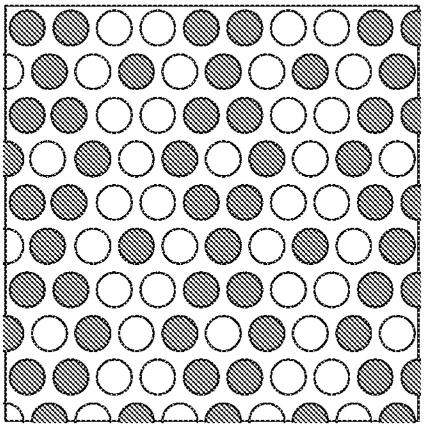

FIG. 2(f)

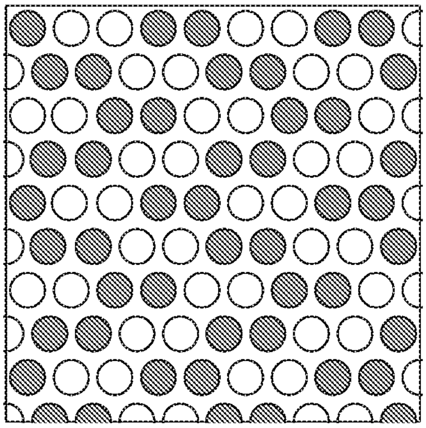

FIG. 2(g)

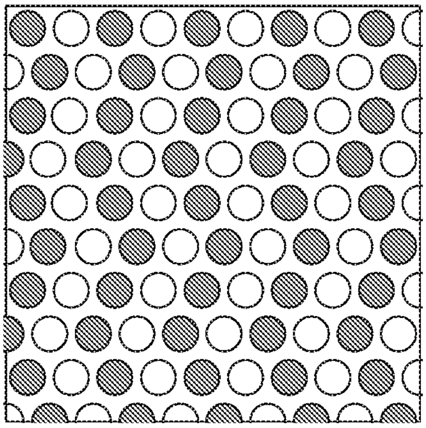

FIG. 2(h)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/012765

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B32B 3/26 (2016.01)
CPC - B32B 3/26 (2016.02)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - B32B 3/10, 3/12, 3/24, 3/26 (2016.01)
CPC - B32B 3/10, 3/12, 3/26, 3/266; F05B 2220/302, 2240/35; F23R 3/002, 3/08 (2016.02)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC- 148/563; 257/415; 428/131, 136 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Patbase, Google Patents, Google, Google Scholar
Search terms used: material, pattern, dimple, indent, protrusion, porous, poisson, auxetic, local, global, tile

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	LI et al. Temperature insensitive negative Poisson's ratios in isotropic alloys near a morphotropic phase boundary. Applied Physics Letters. 19 December 2012. [retrieved 2016-02-26]. Retrieved from the Internet. <http://silver.neep.wisc.edu/~lakes/PoissonPhaseAPL12.pdf>. entire document	1-13, 16-31
Y	US 2,738,297 A (PFISTERSHAMMER) 13 March 1956 (13.03.1956) entire document	1-13, 16-31
A	SCHENK. Folded Shell Structures. University of Cambridge. 31 August 2011. [retrieved on 2016-02-26]. Retrieved from the Internet: <http://www.markschenk.com/research/files/PhD%20thesis%20-%20Mark%20Schenk.pdf>. entire document	1-13, 16-31
A	US 6,780,361 B1 (SRIDHARAN et al) 24 August 2004 (24.08.2004) entire document	1-13, 16-31
A	US 2005/0153634 A1 (PRASAD et al) 14 July 2005 (14.07.2005) entire document	1-13, 16-31
A	US 2011/0059291 A1 (BOYCE et al) 10 March 2011 (10.03.2011) entire document	1-13, 16-31

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 February 2016	14 MAR 2016

Name and mailing address of the ISA/	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No. PCT/US2016/012765

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 14, 15
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.