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Bertoldi et al.

(54) **AUXETIC STRUCTURES WITH DISTORTED PROJECTION SLOTS IN ENGINEERED PATTERNS TO PROVIDE NPR BEHAVIOR AND IMPROVED STRESS PERFORMANCE**

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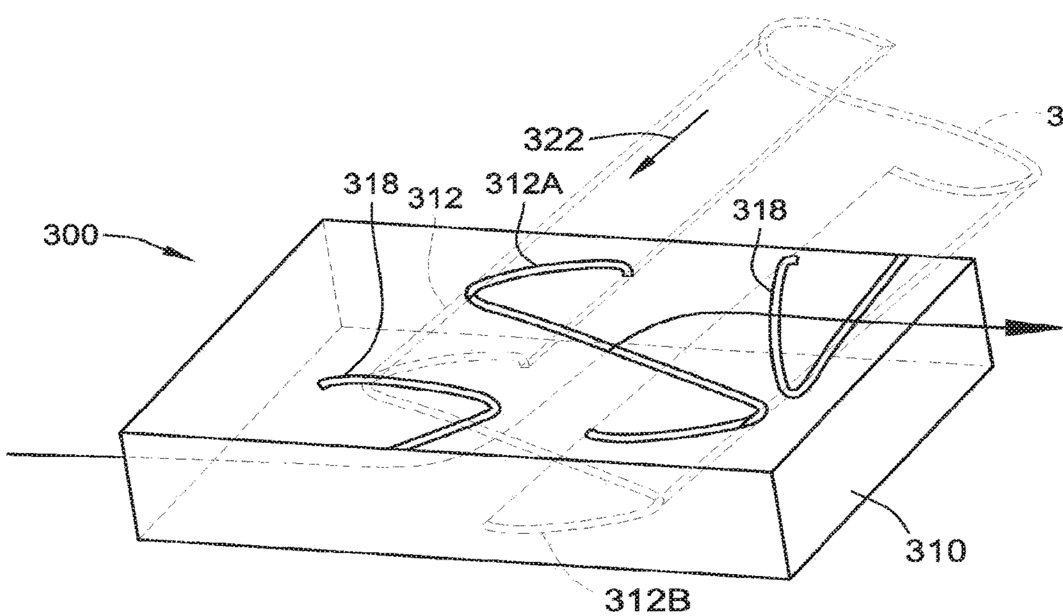
(57) **ABSTRACT**

Auxetic structures, effusion-cooling auxetic sheets, systems and devices with auxetic structures, and methods of using and methods of making auxetic structures are disclosed. An auxetic structure is disclosed which includes an elastically rigid body with opposing top and bottom surfaces. First and second pluralities of elongated apertures extend through the elastically rigid body from the top surface to the bottom surface. The first plurality of elongated apertures extends transversely with respect to the second plurality of elongated apertures. The first and/or second pluralities of elongated apertures have distorted shapes projected through the elastically rigid body at an oblique angle. The elongated apertures are cooperatively configured to provide a desired stress performance while exhibiting negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions. By way of example, the auxetic structure may exhibit a reduction in stress concentration proximate the elongated apertures and a Poisson's Ratio of approximately −0.0001 to −0.9%.



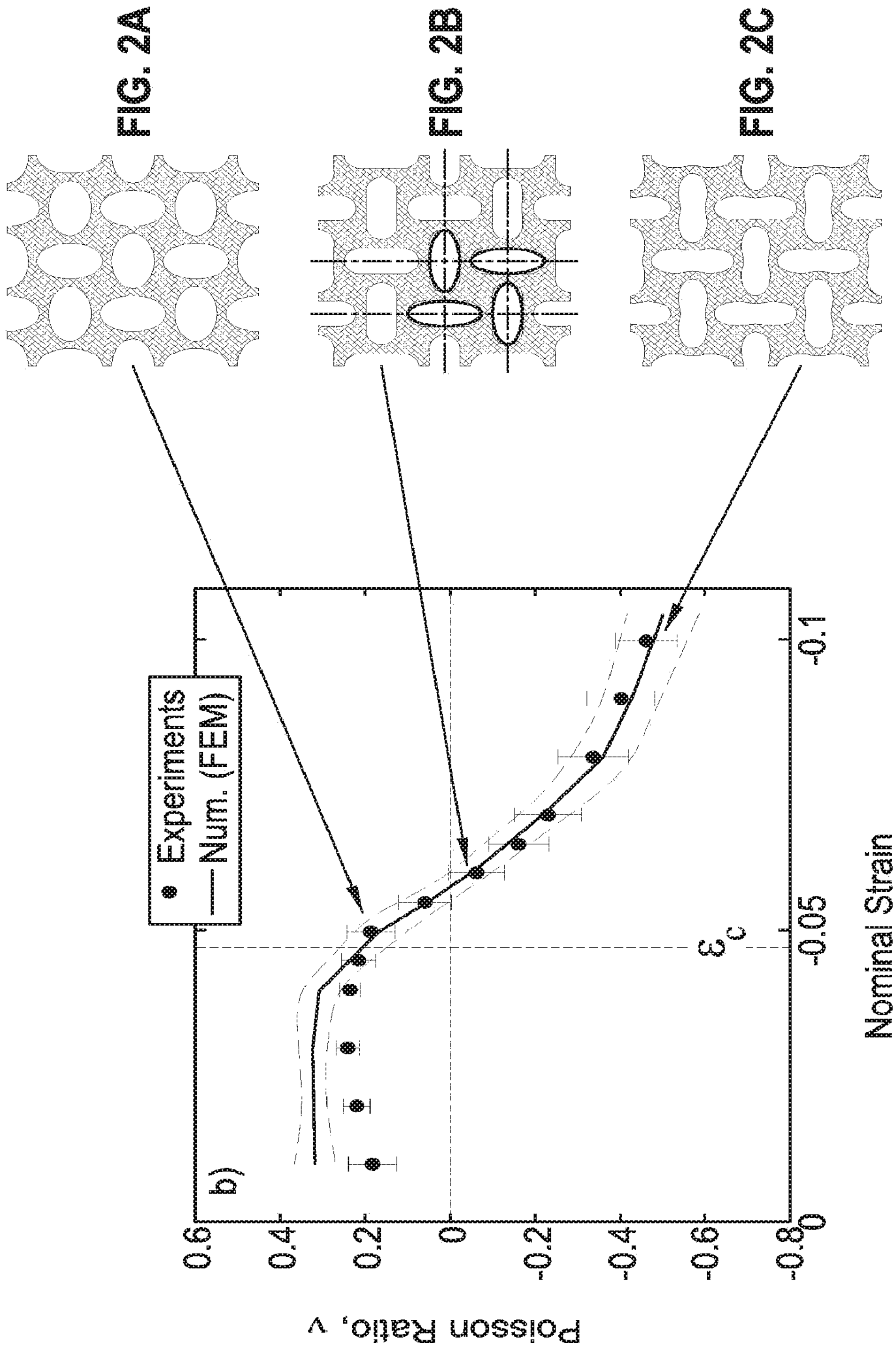


FIG. 1

FIG. 2A

FIG. 2B

FIG. 2C

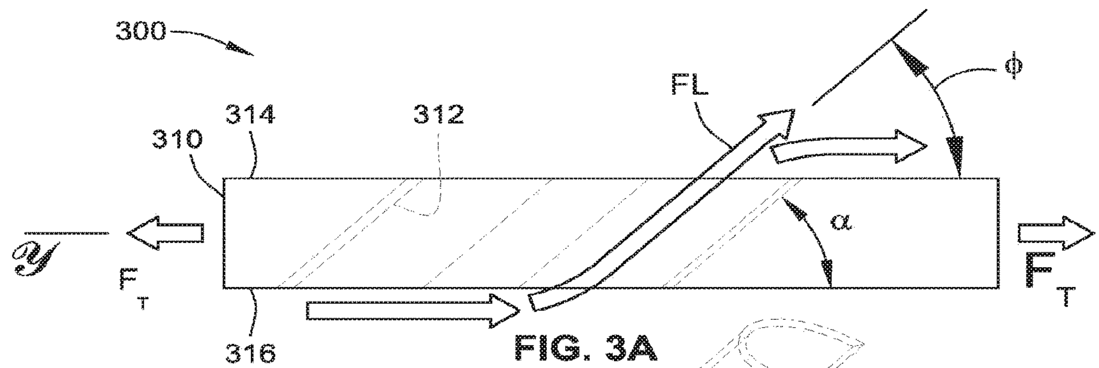


FIG. 3A

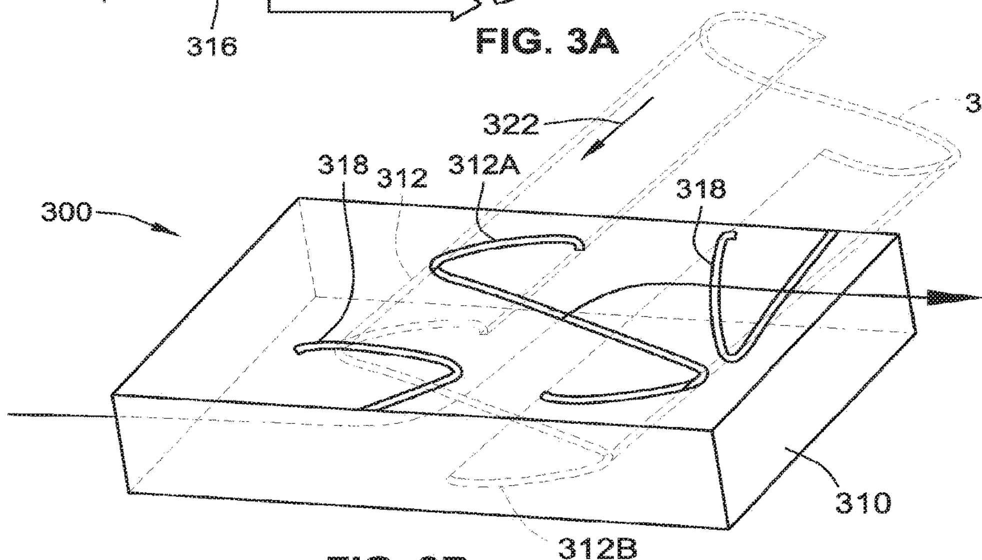


FIG. 3B

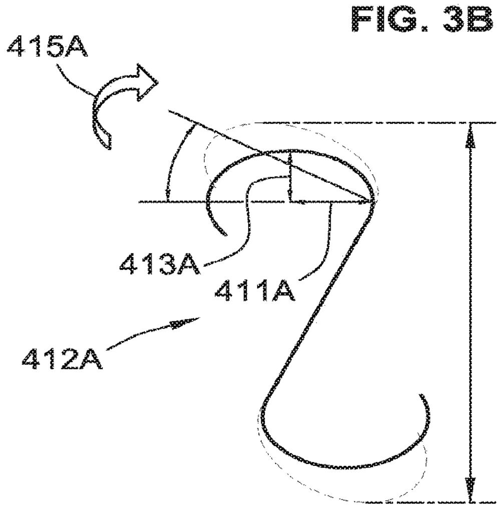


FIG. 4A

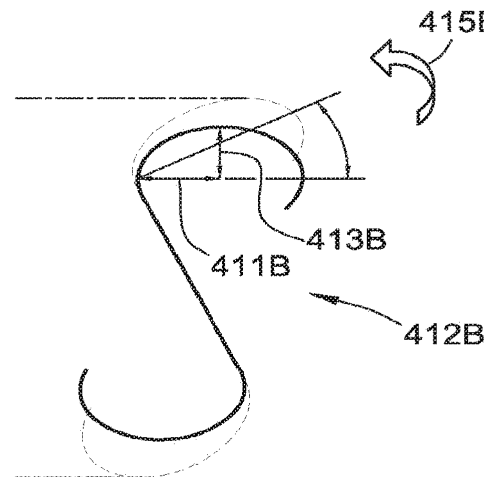


FIG. 4B

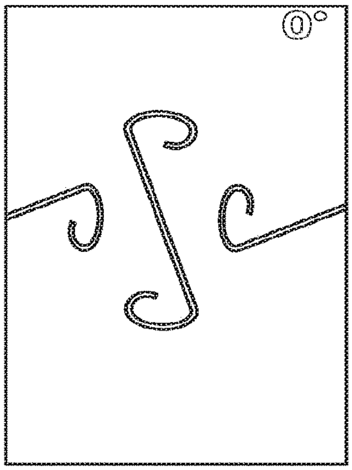


FIG. 5A

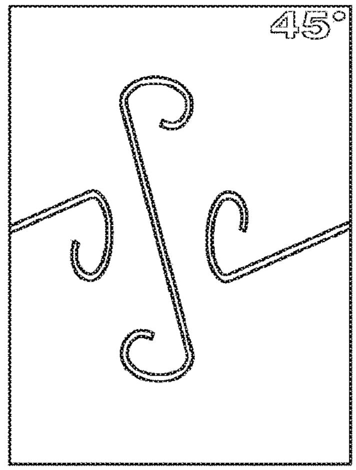


FIG. 5B

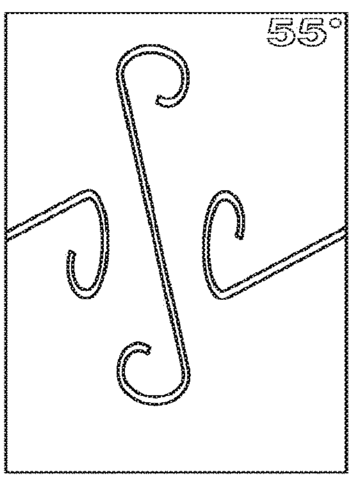


FIG. 5C

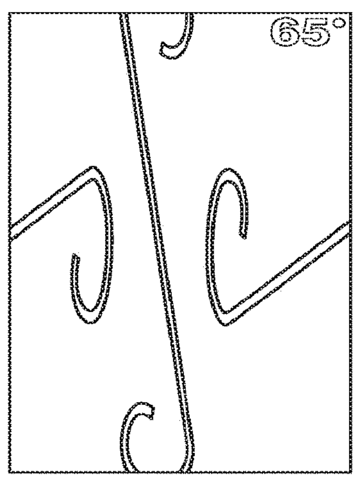


FIG. 5D

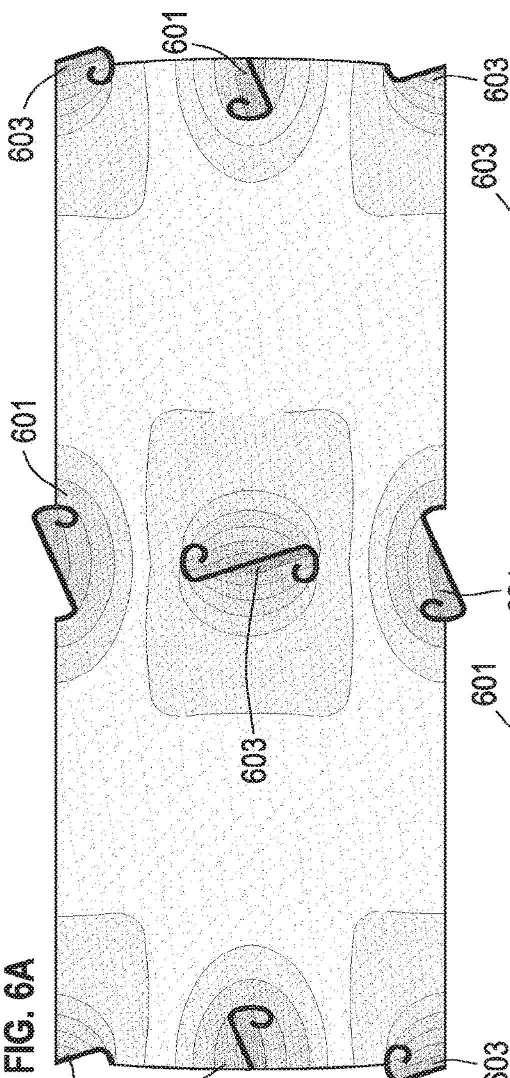
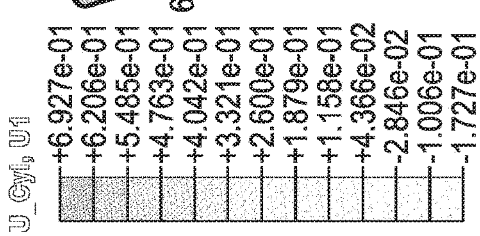


FIG. 6A



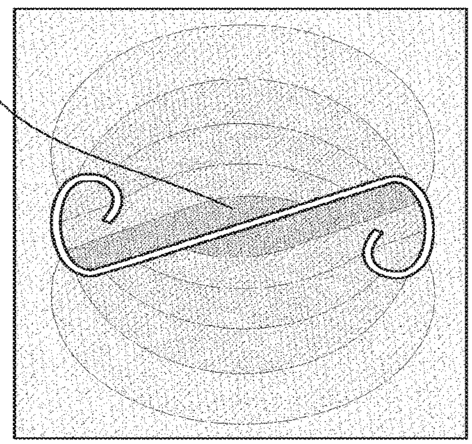


FIG. 6C

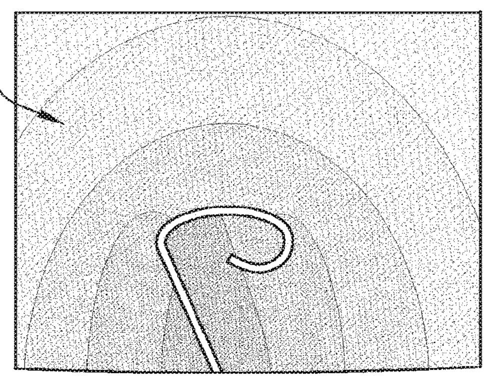


FIG. 6B

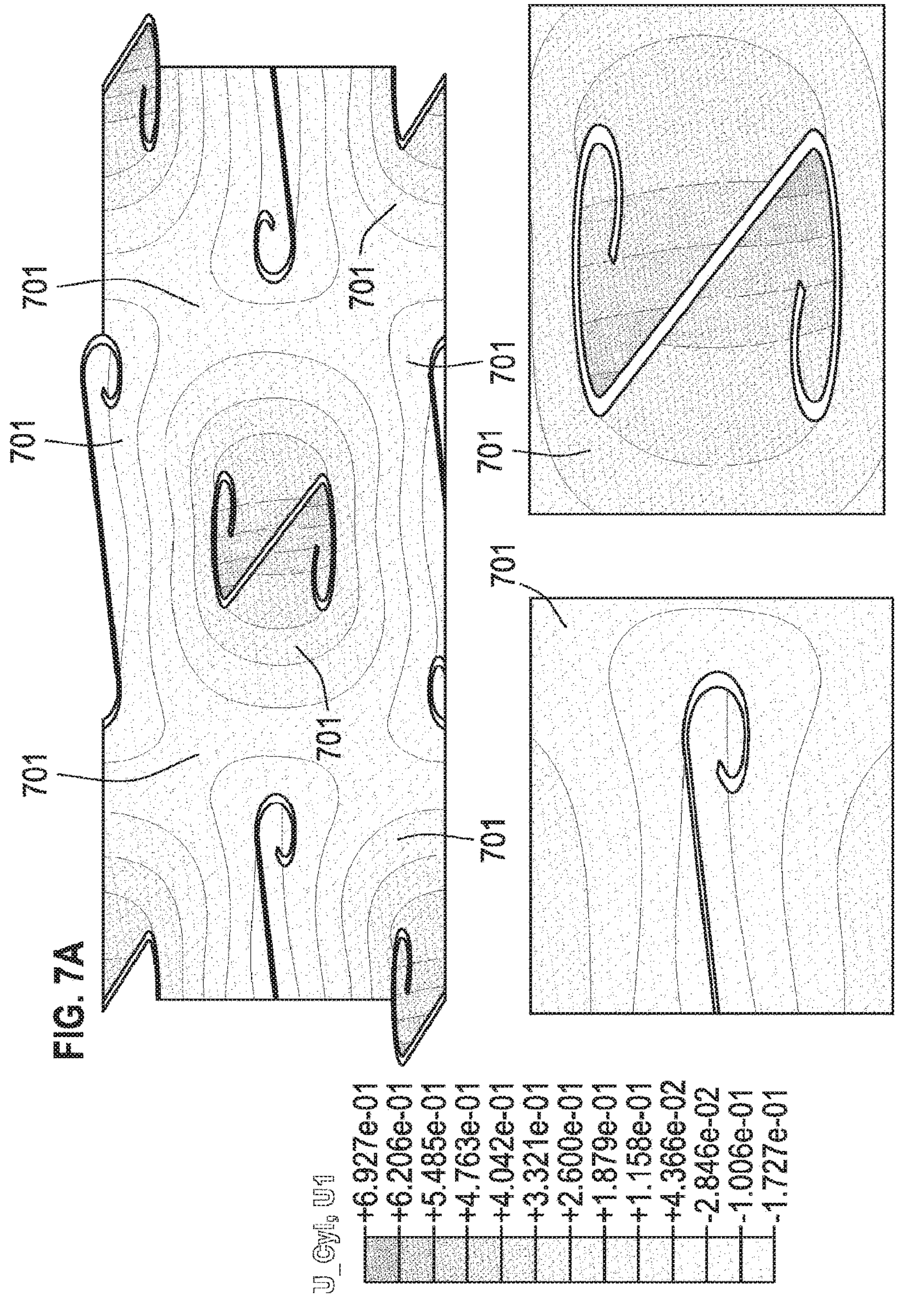


FIG. 7A

FIG. 7B

FIG. 7C

AUXETIC STRUCTURES WITH DISTORTED PROJECTION SLOTS IN ENGINEERED PATTERNS TO PROVIDE NPR BEHAVIOR AND IMPROVED STRESS PERFORMANCE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the right of priority to U.S. Provisional Patent Application No. 62/118,830, filed on Feb. 20, 2015, and U.S. Provisional Patent Application No. 62/101,852, filed on Jan. 9, 2015, both of which are incorporated herein by reference in their respective entireties.

TECHNICAL FIELD

[0002] The present disclosure relates generally to porous materials and cellular solids with tailored isotropic and anisotropic Poisson's ratios. More particularly, aspects of this disclosure relate to auxetic structures with engineered patterns that exhibit negative Poisson's Ratio (NPR) behavior, as well as systems, methods and devices using such structures.

BACKGROUND

[0003] When materials are compressed along a particular axis, they are most commonly observed to expand in directions transverse to the applied axial load. Conversely, most materials contract along a particular axis when a tensile load is applied along an axis transverse to the axis of contraction. The material property that characterizes this behavior is known as the Poisson's Ratio, which can be defined as the negative of the ratio of transverse/lateral strain to axial/longitudinal strain under axial loading conditions. The majority of materials are characterized by a positive Poisson's Ratio, which is approximately 0.5 for rubber, approximately 0.3 for aluminum, brass and steel, and approximately 0.2 for glass.

[0004] Materials with a negative Poisson's Ratio (NPR), on the other hand, will contract (or expand) in the transverse direction when compressed (or stretched) in the axial direction. Materials that exhibit negative Poisson's Ratio behavior are oftentimes referred to as "auxetic" materials. The results of many investigations suggest that 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, ferroelectric 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 materials which were fabricated using soft lithography and at the nanoscale with sheet assemblies of carbon nanotubes.

[0005] A significant challenge in the fabrication of auxetic materials is that it usually involves embedding structures with intricate geometries within a host matrix. As such, the manufacturing process has been a bottleneck in the practical development towards applications. A structure which forms the basis of many auxetic materials is that of a cellular solid. Research into the deformation of these materials is a relatively mature field with primary emphasis on the role of buckling phenomena, on load carrying capacity, and energy absorption under compressive loading. Very recently, the results of a combined experimental and numerical investigation demonstrated that mechanical instabilities in 2D periodic porous structures can trigger dramatic transformations of the original geometry. Specifically, uniaxial loading of a square array of circular holes in an elastomeric matrix is found to lead to a pattern of alternating mutually orthogonal ellipses while the array is under load. This results from an elastic instability above a critical value of the applied strain. The geometric reorganization observed at the instability is both reversible and repeatable and it occurs over a narrow range of the applied load. Moreover, it has been shown that the pattern transformation leads to unidirectional negative Poisson's Ratio behavior for the 2D structure, i.e., it only occurs under compression.

[0006] U.S. Pat. No. 5,233,828 ("828 Patent") shows an example of an engineered void structure—a combustor liner or "heat shield"—utilized in high temperature applications. Combustor liners are typically used in the combustion section of a gas turbine. Combustor liners can also be used in the exhaust section or in other sections or components of the gas turbine, such as the turbine blades. In operation, 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 provided in the interior of the combustor to insulate the surrounding engine. To minimize temperature and pressure differentials across a combustor liner, cooling feature have conventionally been provided, such as is shown in the '828 Patent, in the form of spaced cooling holes disposed in a continuous pattern. As another example, U.S. Pat. No. 8,066,482 B2 presents an engineered structural member having elliptically-shaped cooling holes to enhance the cooling of a desired region of a gas turbine while reducing stress levels in and around the cooling holes. European Patent No. EP 0971172 A1 likewise shows another example of a perforated liner used in a combustion zone of a gas turbine. None of the above patent documents, however, provide examples disclosed as exhibiting auxetic behavior or being engineered to provide NPR effects.

[0007] U.S. Patent Application Pub. No. 2010/0009120 A1 discloses various 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. Said transformation alters the geometric pattern, changing the spacing and the shape of the features within the transformative periodic structure. Upon removal of the critical macroscopic stress or strain, these elastomeric periodic solids recover their original form. By way of comparison, U.S. Patent Application Pub. No. 2011/0059291 A1 discloses structured porous materials, where the porous structure provides a tailored Poisson's ratio behavior. These porous structures consist of a pattern of elliptical or elliptical-like voids in an elastomeric sheet which is tailored, via the mechanics of the deformation of the voids and the mechanics of the deformation of the material, to provide a negative or a zero Poisson's ratio. All of the foregoing patent documents are incorporated herein by reference in their respective entireties and for all purposes.

SUMMARY

[0008] Aspects of the present disclosure are directed towards auxetic structures with repeating patterns of elongated apertures (also referred to herein as "voids" or "slots") that are engineered to provide a desired negative Poisson's Ratio (NPR) behavior and enhanced stress performance. Unlike prior art NPR void shapes that extend through the structure material, traversing the material's thickness with a constant three-dimensional (3D) geometry and in a direction normal to the material's plane, NPR voids disclosed herein traverse the material's thickness with a variable 3D-geometry (e.g., a distorted shape projected through the material at an oblique angle). These void configurations enhance the stress performance of the structure while retaining a low porosity and providing a desired NPR behavior. Other aspects of the present disclosure are directed to multi-functional NPR structures with variable 3D-geometry air passages in the hot section of a gas turbine. Additional aspects are directed towards gas turbine combustors that are made with walls from a material with engineered variable 3D-geometry void features that provide particular thermal, damping and/or acoustic functionalities. Such functionalities include, for example, acoustic attenuation (or noise damping), stress reduction (or load damping), and thermal cooling (or heat damping).

[0009] According to aspects of the present disclosure, auxetic structures with distorted NPR slots are disclosed. In an example, an auxetic structure includes an elastically rigid body, such as a metallic sheet or other sufficiently elastic solid material, with opposing top and bottom surfaces. First and second pluralities of elongated apertures extend through the elastically rigid body from the top surface to the bottom surface. The first plurality of elongated apertures extends transversely (e.g., orthogonally) with respect to the second plurality of elongated apertures. The first and/or second pluralities of elongated apertures have distorted shapes projected through the elastically rigid body at an oblique angle. In an example, the profile of each angled NPR slot that appears on an outer (top or bottom) surface can be a distorted projection of an original, unadulterated image. Moreover, each slot traverses the thickness of a sheet material at an angle that is oblique (e.g., approximately 40-75 degrees) to the material's plane. The elongated apertures are cooperatively configured to provide a desired stress performance while exhibiting a negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions. By way of example, the elongated apertures are engineered with a predefined porosity, a predetermined pattern, and/or a predetermined aspect ratio to achieve the desired NPR behavior. The auxetic structure may exhibit a reduction in stress concentration proximate the longitudinal ends of one or more or all of the elongated apertures, a porosity of about 0.3 to about 9%, and a Poisson's Ratio of about −0.0001 to about −0.9%.

[0010] In accordance with other aspects of this disclosure, effusion-cooling auxetic sheet structures are featured. In an example, an effusion-cooling auxetic sheet structure is presented which includes a metallic sheet with opposing top and bottom surfaces. First and second pluralities of elongated apertures extend through the metallic sheet from the top surface to the bottom surface. The first plurality of elongated apertures has a first set of geometric characteristics and is arranged in a first pattern. Likewise, the second plurality of elongated apertures has a second set of geometric characteristics and is arranged in a second pattern. The elongated apertures of the first plurality are orthogonally oriented with respect to the elongated apertures of the second plurality. The elongated apertures have distorted shapes projected through the elastically rigid body at an oblique angle. The geometric characteristics and pattern of the first plurality of elongated apertures are cooperatively configured with the geometric characteristics and pattern of the second plurality of elongated apertures to provide a desired stress performance while exhibiting negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions.

[0011] Other aspects of the present disclosure are directed to methods of manufacturing and methods of using auxetic structures. In an example, a method is presented for manufacturing an auxetic structure. Said method includes: providing an elastically rigid body with opposing top and bottom surfaces; adding to the elastically rigid body a first plurality of apertures extending through the elastically rigid body from the top surface to the bottom surface, the first plurality of apertures being arranged in rows and columns; and, adding to the elastically rigid body a second plurality of apertures extending through the elastically rigid body from the top surface to the bottom surface, the second plurality of apertures being arranged in rows and columns. Each aperture of the first and/or second pluralities of elongated apertures has a distorted shape that is projected through the elastically rigid body at an oblique angle. The first and second pluralities of apertures are cooperatively configured to provide a desired stress performance while exhibiting a negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions. By way of example, the elongated apertures are engineered with a predefined porosity, a predetermined pattern, and/or a predetermined aspect ratio to achieve the desired NPR behavior. The auxetic structure may exhibit a reduction in stress concentration proximate one or more or all of elongated apertures and a Poisson's Ratio of about −0.0001 to about −0.9%. The elastically rigid body may take on various forms, such as a metallic sheet or other sufficiently elastic solid material.

[0012] The above summary is not intended to represent every embodiment or every aspect of the present disclosure. Rather, the foregoing summary merely provides an exemplification of some of the novel aspects and features set forth herein. The above features and advantages, and other features and advantages of the present disclosure, which are considered to be inventive singly and in any combination, will be readily apparent from the following detailed description of representative embodiments and modes for carrying out the present disclosure when taken in connection with the accompanying drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a graph of Nominal Strain vs. Poisson's Ratio illustrating the Poisson's Ratio behavior of representative structures with elongated through holes according to aspects of the present disclosure.

[0014] FIGS. **2**A-**2**C are illustrations of the representative structures of FIG. **1** corresponding to specific data points from the graph.

[0015] FIGS. **3**A and **3**B are side-view and perspective-view illustrations, respectively, of a distorted projection NPR slot according to aspects of the present disclosure.

[0016] FIGS. 4A and 4B are plan-view illustrations of a distorted NPR S-shaped through slot and a distorted NPR Z-slot, respectively, with variable cap rotation in accordance with aspects of the present disclosure.

[0017] FIGS. 5A-5D are plan-view illustrations of an NPR S-shaped through slot exhibiting a 0-degree angle, a distorted projection NPR S-shaped through slot exhibiting a 45-degree angle, a distorted projection NPR S-shaped through slot exhibiting a 55-degree angle, and a distorted projection NPR S-shaped through slot exhibiting a 65-degree angle, respectively, in accordance with aspects of the present disclosure.

[0018] FIG. 6A-6C are finite element (FE) models illustrating radial displacement under axial tension of a cylindrical structure with S-shaped through slots in accordance with aspects of the present disclosure.

[0019] FIGS. 7A-7C are finite element (FE) models illustrating radial displacement under axial tension of a cylindrical auxetic structure with distorted NPR S-shaped through slots in accordance with aspects of the present disclosure.

[0020] The present disclosure is susceptible to various modifications and alternative forms, and some representative 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 inventive aspects of this disclosure are not limited to the particular forms illustrated in the drawings. Rather, the disclosure is to cover all modifications, equivalents, combinations and subcombinations, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

[0021] This disclosure is susceptible of embodiment in many different forms. There are shown in the drawings, and will herein be described in detail, representative embodiments with the understanding that the present disclosure is to be considered as an exemplification of the principles of the present disclosure and is not intended to limit the broad aspects of the disclosure 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. For purposes of the present detailed description, unless specifically disclaimed or logically prohibited: the singular includes the plural and vice versa; and the words "including" or "comprising" or "having" means "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.

[0022] Aspects of the present disclosure are directed towards auxetic structures which include repeating patterns of angled slots that provide negative Poisson's Ratio (NPR) behavior when macroscopically loaded. Poisson's Ratio (or "Poisson coefficient") can be generally typified as the ratio of transverse contraction strain to longitudinal extension strain in a stretched object. Poisson's Ratio is typically positive for most materials, including many alloys, polymers, polymer foams and cellular solids, which become thinner in cross section when stretched. The auxetic structures disclosed herein exhibit a negative Poisson's Ratio behavior.

[0023] According to aspects of the disclosed concepts, when an auxetic structure is compressed along one axis (e.g., in the Y-direction), coaxial strain results in a moment around the center of each cell because of the way the adjacent apertures are arranged. This, in turn, causes the cells to rotate. Each cell rotates in a direction opposite to that of its immediate neighbors. This rotation results in a reduction in the transverse axis (X-direction) distance between horizontally adjacent cells. In other words, compressing the structure in the Y-direction causes it to contract in the X-direction. Conversely, tension in the Y-direction results in expansion in the X-direction. At the scale of the entire structure, this mimics the behavior of an auxetic material. But many of the structures disclosed herein are composed of conventional materials. Thus, the unadulterated material itself may have a positive Poisson's Ratio, but by modifying the structure with the introduction of the distorted-NPR-slot patterns disclosed herein, the structure behaves as having a negative Poisson's Ratio.

[0024] FIG. 1 is a graph of Poisson's Ratio (PR) against Nominal Strain illustrating the Poisson's Ratio behavior of three representative void structures shown in FIGS. 2A-2C. The chart of FIG. 1 shows the Poisson's Ratio of each test piece under load. At a certain level of deformation, the "instantaneous" PR can be determined and plotted against a parameter (e.g., nominal strain) representing the level of deformation. When a designer has a desired NPR for an intended application, the level of deformation corresponding to that PR can be determined and the geometry of the holes at that condition determined. This hole shape pattern can then be machined (manufactured) on an unstressed part to achieve a component with the desired PR.

[0025] As seen in FIGS. 2B and 2C, the NPR aperture patterns can consist of horizontally and vertically oriented, elongated holes (also referred to as "apertures" or "voids" or "slots"), shown as elliptical through slots. These elongated holes are arranged on horizontal and vertical lines (e.g., rows and columns of a square array in FIG. 2B) in a way that the vertical lines are equally spaced and the horizontal in both dimensions lines are equally spaced (also $\Delta x = \Delta y$). The center of each slot is on the crossing point of two of the lines. Horizontally oriented and vertically oriented slots alternate on the vertical and horizontal lines such that any vertically oriented slot is surrounded by horizontally oriented slots (and vice versa), while the next vertically oriented slots are found on both diagonals. These voids can also act as cooling and/or damping holes and, due to their arrangement, also as stress reduction features. One or more of the slots shown herein can be replaced by elongated NPR protrusions or semispherical NPR dimples.

[0026] Also disclosed are gas turbine combustors that are made with one or more walls from a material with any of the specific auxetic structure configurations disclosed herein. In some embodiments, the NPR slots are generated in a metal body directly in a stress-free state such that the apertures are equivalent in shape to collapsed void shapes found in rubber under external load in order to get NPR behavior in the metal body without collapsing the metallic structure in manufacturing. Various manufacturing routes can be used to replicate the void patterns in the metallic component. The manufacturing does not necessarily contain buckling as one of the process steps. The auxetic structures disclosed herein are not limited to the combustor wall; rather, these features can be incorporated into other sections of a turbine (e.g., a blade, a vain, etc.).

[0027] In a conventional combustor wall, holes used for cooling air flow and damping also act as stress risers. In some of the disclosed embodiments, as the wall material at a hot spot presses against its surrounding material, e.g., in a vertical direction, the negative Poisson's Ratio (NPR) behavior will make the wall material contract in the horizontal direction, and vice versa. This behavior will reduce the stresses at the hotspot significantly. This effect is stronger than just the impact of the reduced stiffness. Stress at hot spot gets reduced, for example, by 50% which, in turn, leads to an increase in stress fatigue life by several orders of magnitude. The stress reduction by the NPR behavior does not increase the air consumption of the combustor wall. The longer life could be used as such or the wall material could be replaced by a cheaper one in order to reduce raw material costs.

[0028] It has also been demonstrated that the replacement of circular combustor cooling holes with a fraction of elongated and angled air passages of 2-3% reduces thermo-mechanical stress by a factor of at least five, while maintaining cooling and damping performance. For example, elliptical cooling holes in the combustor have been predicted to result in a five-fold decrease in the worst principal stress. Inducing NPR behavior, thus, adds further functionality to the cooling holes of the combustor in that the NPR behavior generates a five-fold reduction in worst principal stress as compared to traditional cooling holes. In stress fatigue of a combustor-specific superalloy, halving the component stress increases the fatigue life by more than an order of magnitude. In some embodiments, the superalloy may be a nickel-based superalloy, such as 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.

[0029] It has been shown that optimized porosity offers increased cooling function. As used herein, "porosity" can be defined to mean the surface area of the apertures, AA, divided by the surface area of the structure, AS, or Porosity=AA/AS. It may be desirable, in some embodiments, that the porosity of a given void structure be approximately 0.3-9.0% or, in some embodiments, approximately 1-4% or, in some embodiments, approximately 2%. By comparison, many prior art arrangements require a porosity of 40-50%.

[0030] There may be a predetermined optimal aspect ratio for the elongated apertures to provide a desired NPR behavior. As used herein, "aspect ratio" of the apertures can be defined to mean the length divided by the width of the apertures, or the length of the major axis divided by the length of the minor axis of the apertures. It may be desirable, in some embodiments, that the aspect ratio of the apertures be approximately 5-40 or, in some embodiments, approximately 20-30. An optimal NPR may comprise, for example, a PR of about 0 to about −0.9 or, for some embodiments, about −0.5. Aspects of the disclosed concepts can be demonstrated on structural patterns created with a pattern lengthscale at the millimeter, and are equally applicable to structures possessing the same periodic patterns at a smaller lengthscale (e.g., micrometer, submicrometer, and nanometer lengthscales) or larger lengthscales so far as the unit cells fit in the structure.

[0031] Turning next to FIGS. **3-5**, there are shown various examples of distorted-slot auxetic structures which exhibit desired NPR behaviors and enhanced stress-mitigating performance in accordance with the present disclosure. FIGS. **3**A and **3**B, for example, illustrate an auxetic structure, designated generally at **300**, which utilizes an alternating pattern of elongated asymmetrical slots. The foregoing slots are elongated in that each has a major axis (e.g., a length) that is larger than and perpendicular to a minor axis (e.g., a width). As shown, the auxetic structure **300** comprises an elastically rigid body **310**, which may be in the form of a metallic sheet or other solid material with adequate elasticity to return substantially or completely to its original form once macroscopic loading conditions are sufficiently reduced or eliminated. Elastically rigid body **310** has a first (top) surface **314** in opposing spaced relation to a second (bottom) surface **316**. Fabricated into the elastically rigid body **310** is a first plurality of S-shaped through slots (also referred to herein as "apertures" or "voids" or "slots"), represented herein by slot **312**, which extend through the body **310** from the top surface **314** to the bottom surface **316**. A second plurality of S-shaped through slots/apertures, represented herein by slots **318**, also extends through the elastically rigid body **310** from the top surface **314** to the bottom surface **316**. The pattern of elongated apertures present in the elastically rigid body **310** may be similar in arrangement to what is seen in FIGS. **2**B and **2**C.

[0032] S-shaped through slots **312**, **318** are arranged in an array or matrix of rows and columns, with the first plurality of elongated apertures **312** extending transversely with respect to the second plurality of elongated apertures **318**. Note that hidden lines indicating the internal structural configuration of slots **318** have been omitted from FIGS. **3**A and **3**B for clarity to better show the internal structural configuration of slots **312**. For at least some embodiments, the rows are equally spaced from each other and, likewise, the columns are equally spaced from each other. According to the illustrated embodiment of FIGS. **3**A and **3**B, for example, each row and each column comprises vertically oriented S-shaped through slots **312** interleaved with horizontally oriented S-shaped through slots **318**. In effect, each vertically oriented through slot **312** is neighbored on four sides by horizontally oriented through slots **318**, while each horizontally oriented through slot **318** is neighbored on four sides by vertically oriented through slots **312**. With this arrangement, the minor axes of the first plurality of S-shaped through slots **312** are parallel to the rows of the array, whereas the minor axes of the second plurality of S-shaped through slots **318** are parallel to the columns of the array. Thus, the major axes of the through slots **318**, which are parallel to the rows of the array, are perpendicular to the major axes of the through slots **312**, which are parallel to the columns of the array. It is also envisioned that other patterns and arrangements for achieving NPR behavior are within the scope and spirit of the present disclosure.

[0033] The illustrated pattern of elongated, angled slots provides a specific porosity (e.g., a porosity of about 0.3 to about 9.0%) and a desired stress performance (e.g., lower stress concentration factors) while exhibiting a desired negative Poisson's Ratio behavior (e.g., a PR of about −0.0001 to about −0.9) under macroscopic planar loading conditions (e.g., when tension or compression is applied in the plane of the sheet). When the auxetic structure **300** is stretched, for example via tensile force F_T along a vertical axis Y, axial strain in the vertical direction results in a moment around the center of each cell, which causes the cells to rotate. A cell may consist of two laterally adjacent vertical slots aligned with two vertically adjacent horizontal slots to form a square-shaped unit. Each cell rotates in a direction opposite to that of its immediate neighboring cells. This rotation increases the X-direction distance between horizontally adjacent cells such that stretching the structure in the Y-direction causes it to stretch in the X-direction. The first plurality of S-shaped through slots **312** have (first) engineered geometric characteristics, including a predefined geometry and a predefined aspect ratio, while the second plurality of S-shaped through slots **318** have (second) engineered geometric characteristics, including a predefined geometry and a predefined aspect ratio, that are cooperatively configured with (third) engineered geometric characteristics of the aperture pattern, including NPR-slot density and cell arrangement, to achieve a desired NPR behavior under macroscopic loading conditions.

[0034] Each slot of the first and/or second pluralities of elongated S-shaped through slots **312**, **318** has a distorted shape that is projected through the elastically rigid body at an oblique angle. By way of explanation, the profile of each angled NPR slot that appears on an outer surface of the auxetic structure's body can be a distorted projection of an original, unadulterated image. According to the illustrated example, top-surface and bottom-surface profiles **312**A and **312**B, respectively, of S-shaped through slot **312** are generated by projecting a standard "S" shape **320** at a desired oblique angle through the thickness of the elastically rigid body **310**. In so doing, the profiles **312**A, **312**B of the NPR slot **312** that appear on the top and bottom surfaces **314**, **316** of the body **310** are distorted from the original image **320**. The degree of distortion can be varied depending, for example, on the desired angle and/or the desired orientation of the slot, e.g., to provide a desired cooling performance or a desired stress-mitigation. Top-surface and bottom-surface profiles of S-shaped through slots **318** can be generated in a similar manner. It is envisioned that the surface profiles of S-shaped through slots **312** are identical to the surface profiles of S-shaped through slots **318**, e.g., for applications where the body **310** of the auxetic structure is relatively flat and the angle of projection is common for both sets of through slots. Contrastingly, the surface profiles of S-shaped through slots **312** can be distinct from the surface profiles of S-shaped through slots **318**, e.g., for implementations where the body **310** of the auxetic structure is curved and/or the angle of projection of S-shaped through slots **312** is distinct from the angle of projection of S-shaped through slots **318**.

[0035] Slot **312** is shown in FIG. **3**A traversing the entire thickness of the body **310** at an angle that is oblique to the material's horizontal plane. For at least some embodiments, each aperture has an angle Φ of approximately 20-80 degrees or, in some embodiments, approximately 45-75 degrees with the top and bottom surfaces **314**, **316** of the auxetic structure's body **310**. These macroscopically patterned NPR voids—i.e., S-shaped angled slots (or, equivalently, I-shaped angled slots, barbell-shaped angled slots, elliptical angled slots, Z-shaped angled slots, C-shaped angled slots, etc.)—serve as effusion cooling holes which allow a cooling fluid FL to traverse one surface of the auxetic structure, pass through the body at an inclination angle α, as shown in FIG. **3**A, and traverse the opposing surface of the auxetic structure. This configuration enhances film cooling performance as compared to traditional cooling slots/holes that are normal to the thickness of the body and, thus, more restrictive of cooling fluid flow. Inclination angle α can be defined as the angle between the injection vector and its projection on the material plane. This inclination angle α can be varied in a 360° rotational angle of freedom using three rotational axis to achieve numerous desired combinations of auxetic behavior and film cooling performance. Inclination angle α can be varied with respect to any plane, or the compound of any two planes, giving the transverse direction of the shape three rotational degrees of freedom. Patterned angled NPR-slot features have been shown to cool significantly better than conventional right-angled (normal) circular holes and cooling slots as the internal surface area of the slots is larger than that of normal circular holes or slots. Adiabatic film cooling effectiveness is also increased compared to traditional normal cooling holes and slots, for example, due to a more even distribution of cooling air over the surface and reduced coolant jet penetration into the mainstream flow.

[0036] Auxetic structure **300** provides a reduction in stress concentration proximate one or more of all of the elongated apertures **312**, **318**. Patterned angled S-shaped slot structures provide significantly better effusion cooling characteristics than conventional circular holes while providing lower stress concentration factors. Projecting cooling holes onto a surface of an auxetic structure forms elongated through slots (e.g., ellipses or s-shaped slots), which can result in high stress concentrations at the opposing tips of the slots. Macroscopic patterned voids, such as those illustrated in FIGS. **3**A and **3**B, have smoother curvature when projected, and hence lower stress concentration factors. To reduce the stress concentration caused by the distorted shape when projecting onto an outer surface of an elastically rigid body, such as a cylindrical surface of a tubular component, a projection vector **322** of each aperture can be substantially or completely parallel to a direction of loading of the elastically rigid body. FIGS. **5**A-**5**D illustrate slot distortion on an outer surface of a tubular auxetic structure. FIG. **5**A, for example, illustrates normal NPR S-shaped through slots exhibiting a 0-degree projection angle. By comparison, FIG. **5**B illustrates angled NPR S-shaped through slots exhibiting a 45-degree projection angle with the projection vector placed parallel to the loading direction, while FIG. **5**C illustrates angled NPR S-shaped through slots exhibiting a 55-degree projection angle with the projection vector placed parallel to the loading direction, and FIG. **5**D illustrates angled NPR S-shaped through slots exhibiting a 65-degree projection angle with the projection vector placed parallel to the loading direction. Since tensile loading acts to separate the through holes, projecting along the loading direction acts to keep the voids interacting throughout deformation of the rigid body.

[0037] Projecting the distorted slots along the loading direction allows a void arrangement that would otherwise exhibit a significantly positive Poisson's ratio (e.g., FIGS. **6**A-**6**C illustrate slots with an inclination angle α=0 degrees, resulting in a Poisson's Ratio=0.27) to achieve a negative Poisson's ratio (e.g., FIGS. **7**A-**7**C illustrate slots with an inclination angle α=75 degrees, resulting in a Poisson's Ratio=−0.0001). Distorted and angled S-shaped through slots help retain NPR behavior at much lower porosity than normal NPR S-shaped slots. When normal NPR S-shaped slots are separated by the required distance to achieve a low-porosity-level requirement, the horizontal and vertical S-shaped through slots tend to stop interacting during deformation, making the structure lose its NPR behavior. With the distorted, angled S-shaped through slot structure, the S-shaped slots are elongated within the thickness of material, allowing them to be placed further apart than the normal S-shaped slots while still retaining the NPR behavior. With the improved film cooling effectiveness of the angle S-shaped through slot structure, the temperature on the structure is reduced, leading to a decrease in thermal stress

[0038] Distorted NPR slot shapes, for instance, Z-shaped slots **412**A (FIG. **4**A) and S-shaped slots (FIG. **4**B), can be developed by changing cap length **411**A and **411**B and/or cap height **413**A and **413**B to provide a horizontal projection that is dissimilar to an existing or "standard" S-shape/Z-shape. The size and shape of the caps can be varied to achieve a desired combination of auxetic behavior and film cooling performance. Film cooling performance of angled effusion S-shaped slots or, equivalently, Z-shaped slots can be improved by producing a longer cooling thermal layer above the hot surface. A longer cooling thermal layer can be created by increasing the lateral area of the slots normal to the free mainstream fluid by rotating the S-shaped slot cap in the counter-clockwise direction (or clockwise direction for Z-shaped slot caps). This cap rotation angle **415**A and **415**B can be varied to achieve a desired combination of auxetic behavior and film cooling performance. By rotating the caps of the S-shaped slots in the counter-clockwise direction, the maximum mechanical stress at the top of the caps will be reduced and the film cooling performance of the effusion slots will be improved due to the increased coverage of the cooling thermal layer above the hot surface.

[0039] As an exemplary implementation of the disclosed features, one can consider a combustor liner with sheet metal walls, in which conventional round effusion holes or normal effusion slots are replaced with a pattern of angled, distorted S-shaped through slots forming an auxetic structure. Cooling air fed through the slots removes the heat from the structure and produces an even distribution of cooling air over the surface. These angled slots, which have an increased internal surface area, enhance film cooling performance and improve mechanical response. Moreover, angled and distorted NPR slots are capable of sustaining higher flame temperatures, and help impart to the sheet a much longer life compared to the conventional sheet with normal effusion voids.

[0040] FIG. **6**A-**6**C are finite element (FE) models illustrating radial displacement under axial tension of a cylindrical structure with normal S-shaped through slots. By way of comparison, FIGS. **7**A-**7**C are finite element (FE) models illustrating radial displacement under axial tension of a cylindrical auxetic structure with distorted NPR S-shaped through slots. The longitudinal axes of the cylinders are horizontal in the illustrated examples, as are the directions of the tensile forces applied to these cylinders. As indicated above, the void configuration of FIGS. **6**A-**6**C consists of S-shaped through slots that are normal to the thickness of the structure (i.e., an inclination angle α=0 degrees) resulting in a positive Poisson's Ratio of PR=0.27. Contrastingly, the void configuration of FIGS. **7**A-**7**C consists of distorted S-shaped NPR slots that are oblique to the thickness of the structure (i.e., an inclination angle α=75 degrees) resulting in a negative Poisson's Ratio of PR=−0.0001. Further angling of the slots will further decrease the Poisson's Ratio value. Blue regions **601**, **701** indicate NPR-type behavior, whereas red regions **703** indicate non-NPR-type behavior. In FIG. **6**A, there is no projection vector as the voids are cut at a zero-degree angle. FIG. **6**B is a close-up of one of the horizontal S-shaped slots while FIG. **6**C is a close-up of one of the vertical S-shaped slots. In FIG. **7**A, the projection vector of the slots is parallel to the direction of tensile loading.

[0041] Aspects of this disclosure are also directed to methods of manufacturing and methods of using auxetic structures. By way of example, a method is presented for manufacturing an auxetic structure, such as the auxetic structures described above with respect to FIGS. **3**-**5**. The method includes, as an inclusive yet non-exclusive set of acts: providing an elastically rigid body, such as the elastically rigid body **310** of FIGS. **3**A and **3**B, with opposing top and bottom surfaces; adding to the elastically rigid body a first plurality of apertures, such as the elongated S-shaped slots **312** of FIGS. **3**A and **3**B, extending through the elastically rigid body from the top surface to the bottom surface; and, adding to the elastically rigid body a second plurality of apertures, such as the elongated S-shaped slots **318** of FIGS. **3**A and **3**B, extending through the elastically rigid body from the top surface to the bottom surface. The first and second pluralities of apertures are arranged in rows and columns. The apertures of the first and/or second plurality have distorted shapes projected through the elastically rigid body at oblique angles. The first and second pluralities of apertures are cooperatively configured to provide a desired stress performance while exhibiting a negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions. By way of example, the elongated apertures are engineered with a predefined porosity, a predetermined pattern, and/or a predetermined aspect ratio to achieve the desired NPR behavior.

[0042] In some embodiments, the method includes at least those steps enumerated above and illustrated in the drawings. It is also within the scope and spirit of the present invention to omit steps, include additional steps, and/or modify the order presented above. It should be further noted that the foregoing method can be representative of a single sequence for designing and fabricating an auxetic structure. However, it is expected that the method will be practiced in a systematic and repetitive manner.

[0043] The present invention is not limited to the precise construction and compositions disclosed herein. Rather, any and all modifications, changes, combinations, permutations and variations apparent from the foregoing descriptions are within the scope and spirit of the invention as defined in the appended claims. Moreover, the present concepts expressly include any and all combinations and subcombinations of the preceding elements and aspects.

1. An auxetic structure comprising:

an elastically rigid body with opposing top and bottom surfaces and first and second pluralities of elongated apertures extending through the elastically rigid body from the top surface to the bottom surface, the first plurality of elongated apertures extending transversely with respect to the second plurality of elongated apertures, each aperture of the first plurality of elongated apertures having a distorted shape projected through the elastically rigid body at an oblique angle,

wherein the first and second pluralities of elongated apertures are cooperatively configured to provide a desired stress performance while exhibiting a desired negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions.

2. The void structure of claim **1**, wherein each aperture of the first plurality of elongated apertures is angled approximately 40-75 degrees with the top surface of the elastically rigid body.

3. The void structure of claim **1**, wherein a projection vector of each aperture of the first plurality of elongated apertures is at least substantially parallel to a direction of loading of the elastically rigid body.

4. The void structure of claim **1**, wherein each aperture of the second plurality of elongated apertures has a distorted shape projected through the elastically rigid body at an oblique angle.

5. The void structure of claim **4**, wherein a projection vector of each aperture of the second plurality of elongated apertures is at least substantially parallel to a direction of loading of the elastically rigid body.

6. The void structure of claim **1**, wherein the desired stress performance includes a reduction in stress concentration proximate the plurality of elongated apertures.

7. The void structure of claim **1**, wherein the NPR behavior includes a Poisson's Ratio of about −0.0001 to about −0.9%.

8. The void structure of claim **1**, wherein the elongated apertures have a predetermined porosity of about 0.3 to about 9%.

9. The void structure of claim **1**, wherein the elongated apertures are engineered with a predefined porosity, a predetermined pattern, or a predetermined aspect ratio, or any combination thereof, to achieve the NPR behavior.

10. The void structure of claim **1**, wherein each of the elongated apertures has an aspect ratio of approximately 5-40.

11. The void structure of claim **1**, wherein the first or the second plurality of elongated apertures, or both, each has an S-shaped plan-view profile.

12. The void structure of claim **11**, wherein the first and second pluralities of elongated apertures are arranged in an array of rows and columns.

13. The void structure of claim **12**, wherein the rows are equally spaced from each other and the columns are equally spaced from each other.

14. The void structure of claim **1**, wherein each of the elongated apertures has a major axis perpendicular to a minor axis, the major axes of the first plurality of elongated apertures being substantially perpendicular to the major axes of the second plurality of elongated apertures.

15. An effusion-cooling auxetic sheet structure comprising:

a metallic sheet with opposing top and bottom surfaces and first and second pluralities of elongated apertures extending through the metallic sheet from the top surface to the bottom surface, the first plurality of elongated apertures having a first set of geometric characteristics and a first pattern, the second plurality of elongated apertures having a second set of geometric characteristics and a second pattern, the first plurality of elongated apertures being orthogonally oriented with respect to the second plurality of elongated apertures, the elongated apertures having distorted shapes projected through the elastically rigid body at an oblique angle, wherein the first geometric characteristics and pattern of the first plurality of elongated apertures are cooperatively configured with the second geometric characteristics and pattern of the second plurality of elongated apertures to provide a desired stress performance while exhibiting negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions.

16. A method of manufacturing an auxetic structure, the method comprising:

providing an elastically rigid body with opposing top and bottom surfaces;

adding to the elastically rigid body a first plurality of apertures extending through the elastically rigid body from the top surface to the bottom surface, the first plurality of apertures being arranged in rows and columns, each aperture of the first plurality of elongated apertures having a distorted shape projected through the elastically rigid body at an oblique angle; and

adding to the elastically rigid body a second plurality of apertures extending through the elastically rigid body from the top surface to the bottom surface, the second plurality of apertures being arranged in rows and columns,

wherein the first and second pluralities of apertures are cooperatively configured to provide a desired stress performance while exhibiting a negative Poisson's Ratio (NPR) behavior under macroscopic planar loading conditions.

17. The method of claim **16**, wherein each aperture of the first plurality of elongated apertures is angled approximately 40-75 degrees with the top surface of the elastically rigid body.

18. The method of claim **16**, wherein a projection vector of the first plurality of elongated apertures is at least substantially parallel to a direction of loading of the elastically rigid body.

19. The method of claim **16**, wherein each aperture of the second plurality of elongated apertures has a distorted shape projected through the elastically rigid body at an oblique angle.

20. The method of claim **19**, wherein a projection vector of the second plurality of elongated apertures is at least substantially perpendicular to a direction of loading of the elastically rigid body.

21-29. (canceled)

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