United States Patent

Schoen

[15] **3,663,347**

[45] **May 16, 1972**

[54] **HONEYCOMB PANELS FORMED OF MINIMAL SURFACE PERIODIC TUBULE LAYERS**

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[73] Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**

[22] Filed: **July 16, 1970**

[21] Appl. No.: **55,537**

[52] **U.S. Cl.** **161/68,** 52/80, 52/DIG. 10, 161/7, 161/127

[51] **Int. Cl.** **B32b 3/12**

[58] **Field of Search** ....156/197; 161/68, 69, 127; 29/455 LM; 52/61 S, 80

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Assistant Examiner—Henry F. Epstein
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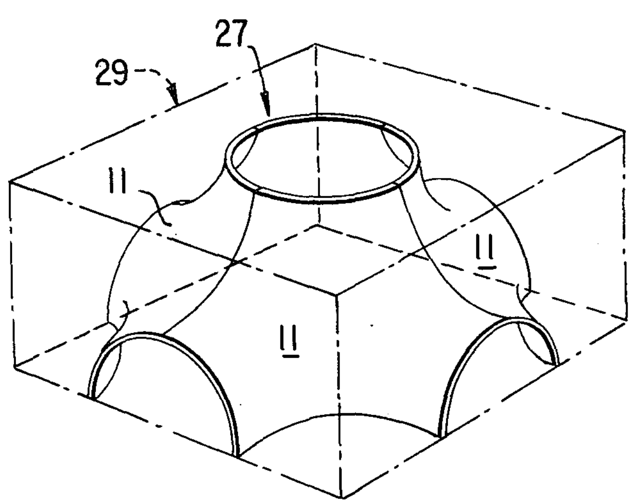
[57] **ABSTRACT**

Panels including honeycomb cores formed of minimal surface periodic tubule layers are described. Each tubule layer is defined as being formed of minimal surface elements that orthogonally intersect all of the faces of a kaleidoscopic cell at least once. In other words, for purposes of definition, the tubule layers are broken into elemental sections. The elemental sections are defined as minimal surface elements, i.e., elements having a mean curvature at all points on the surface that is equal to zero. These elements are further defined inside of kaleidoscopic cells wherein they orthogonally intersect all faces of the kaleidoscopic cell with which they are associated at least once. The minimal surface elements are smoothly interconnected to form tubule layers which are stacked in a reflection image-like manner to form a honeycomb core having no internal discontinuities.

17 Claims, 9 Drawing Figures



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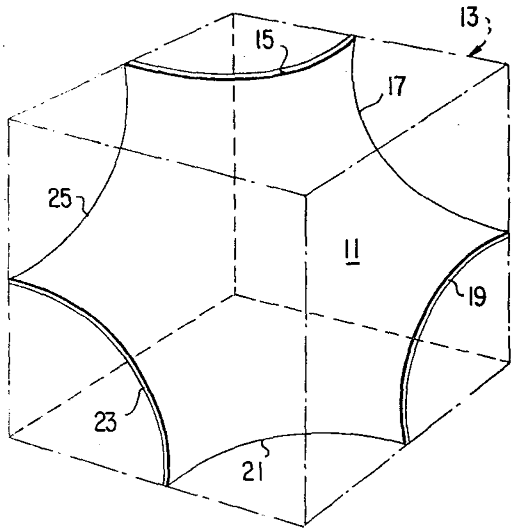

FIG. 1

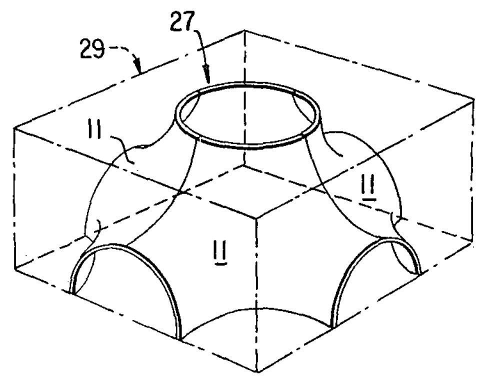

FIG. 2

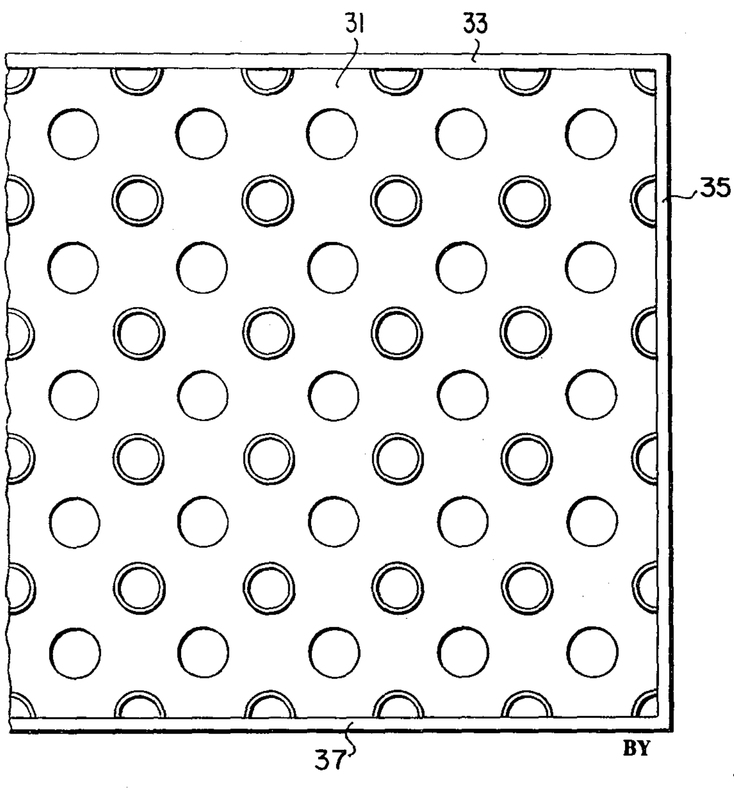

FIG. 3

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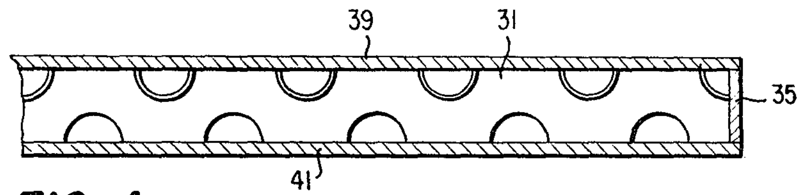

FIG. 4

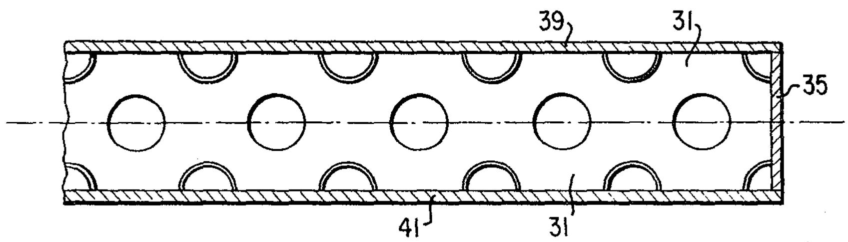

FIG. 5

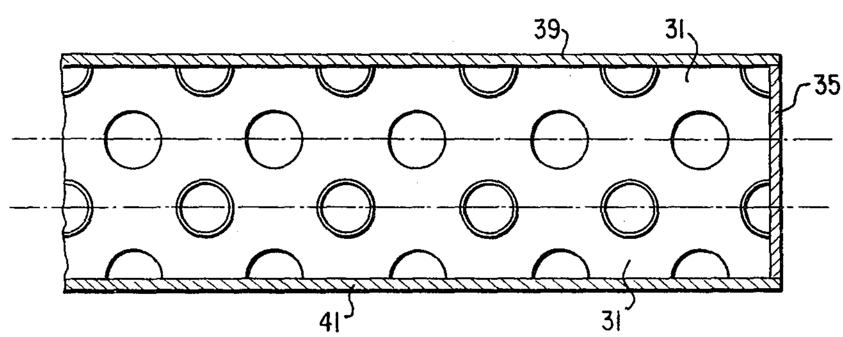

FIG. 6

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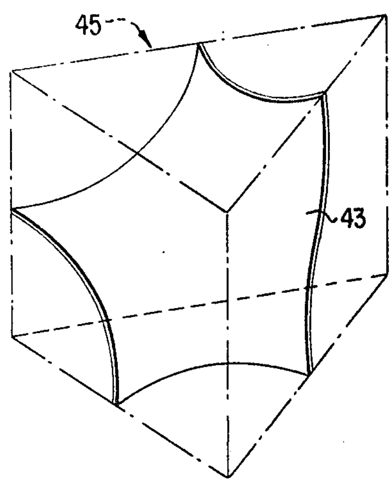

FIG. 7

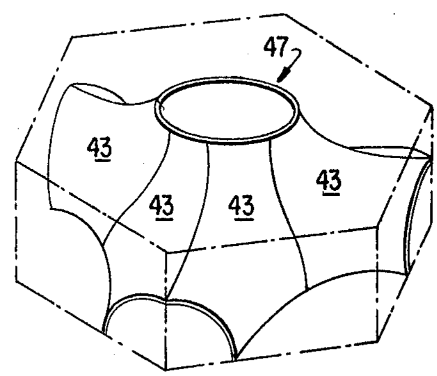

FIG. 8

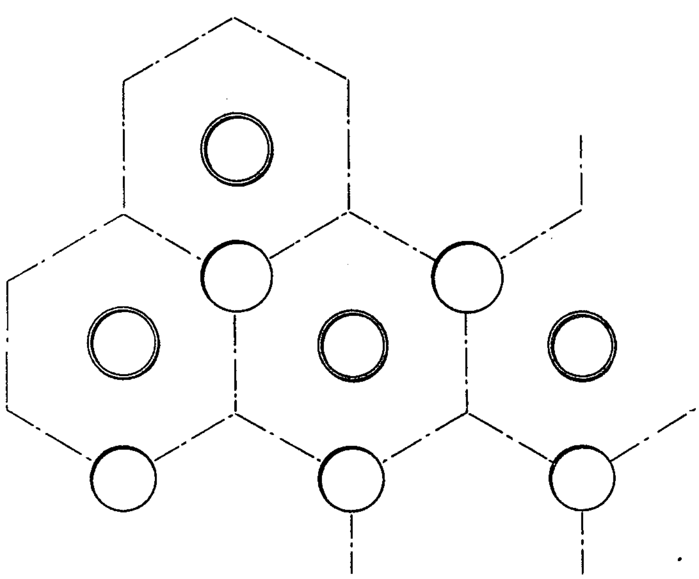

FIG. 9

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HONEYCOMB PANELS FORMED OF MINIMAL SURFACE PERIODIC TUBULE LAYERS

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

This invention relates to honeycomb core panels and more particularly, to honeycomb core panels that are light in weight while possessing high strength and rigidity.

Various types of honeycomb core panels have been proposed and are in use. They are used as walls and floors in constructing buildings, for example. In addition, they have been used as desk tops and other panels in furniture manufacture. In other words, any place where it is desired to have a relatively thick panel that is light in weight for its size, yet possesses high strength and rigidity, a honeycomb core panel is useful.

Various types of honeycomb core panels of different design have been constructed from a variety of materials, such as pressed paper, plastic, or metal. Many honeycomb core designs utilize corrugated sheets stacked in a parallel planar manner whereby hollows are formed in the resultant honeycomb core. This honeycomb core is then joined to boundary planar panels to form the resultant honeycomb core panel. The major disadvantage of honeycomb core panels of this nature is that discontinuities are created where the corrugated sheets intersect one another and where they intersect the outer panels. These discontinuities create "weak" points where rupture of the honeycomb core panel is likely. Hence, the honeycomb core panel is not as strong as desirable for its weight. More recently, honeycomb core panels utilizing curved cellular members that tend to eliminate internal intersections have been produced. While curved cellular core panels have improved the strength-to-weight ratio of honeycomb core panels, they have not been entirely satisfactory. More specifically, curved cellular cores are usually formed in planes and very often the intersection between the planes is discontinuous, whereby weak points are created. Moreover, the curves of the cellular cores do not provide core panels that have an optimum strength-to-weight ratio.

Therefore, it is an object of this invention to provide a new and improved honeycomb core panel.

It is a further object of this invention to provide new and improved honeycomb core panels that have an optimum strength-to-weight ratio.

It is a still further object of this invention to provide panels having honeycomb cores that have no internal discontinuities, are light in weight, and have a maximum strength-to-weight ratio.

SUMMARY OF THE INVENTION

In accordance with the principles of this invention, panels including honeycomb cores located between boundary surfaces are provided. The honeycomb cores are formed of minimal surface periodic tubule layers. The minimal surface tubule layers are defined as being formed of minimal surface elements that orthogonally intersect all of the faces of a kaleidoscopic cell at least once. In other words, for purposes of definition, the tubule layers are broken into minimal surface elements. Each minimal surface element is defined as having mean curvature at all points on its surface equal to zero. These elements are further defined inside of kaleidoscopic cells wherein they orthogonally intersect all faces of their related kaleidoscopic cell at least once. These minimal surface elements are smoothly interconnected to form an overall tubule layer that has no discontinuities except at the edges of the layers. In other words, the entire tubule layer has a minimal surface form and will be subsequently referred to as a minimal surface periodic tubule layer.

In accordance with a further principle of the invention, the boundaries of the honeycomb cores intersect the boundary surfaces orthogonally. As described above, the minimal surface periodic tubule layers forming the honeycomb cores are composite and sheet-like in form, not a structure of individual elements.

In accordance with still further principles of this invention, a plurality of minimal surface periodic tubule layers are stacked in a reflection image-like manner to form a relatively thick honeycomb core between the boundary surfaces of the overall panel structure.

It will be appreciated from the foregoing brief summary of the invention that panels formed of layers having no internal discontinuities are provided by the invention. Because of the lack of discontinuities, structural weak points are eliminated. Further, because the minimal surface tubule layers intersect the surfaces of the overall honeycomb core panel structure at 90°, optimum strength at the boundary discontinuity intersections are provided by the invention. In addition, the invention has the versatility of providing relatively thick panels, also with no internal discontinuities, by stacking the tubule layers of the invention in an image-like manner.

It will also be appreciated by those skilled in the art and others that because the invention uses minimal surface honeycomb cores, it optimizes core strength for the weight of the core material involved. More specifically, the honeycomb core structures are based on minimal surface forms in doubly curved surface configurations whereby the mechanism of membrane action is operative. This action leads to the maximum diffusion of applied loads throughout the entire structure away from the point of load application. Hence, maximum strength for a given weight is provided by the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing objects and many of the attendant advantages of this invention will become more readily appreciated as the same becomes better understood from the following detailed description when taken in conjunction with the accompanying drawings, wherein:

FIG. 1 is a perspective view of a minimal surface element of a tubule layer defined by a rectangular parallelopiped;

FIG. 2 is a perspective view of a portion of a tubule layer formed of minimal surface elements of the type illustrated in FIG. 1;

FIG. 3 is a top view of a honeycomb core periodic tubule layer formed of an array of tubule layer portions of the type illustrated in FIG. 2;

FIG. 4 is a side view of a honeycomb core panel including a single tubule layer of the type illustrated in FIG. 3;

FIG. 5 is a side view of a honeycomb core panel including two tubule layers of the type illustrated in FIG. 3;

FIG. 6 is a side view of a honeycomb core panel including three tubule layers of the type illustrated in FIG. 3;

FIG. 7 is a perspective view of a minimal surface element of a tubule layer defined by an equilateral triangular prism;

FIG. 8 is a perspective view of a portion of a tubule layer formed of minimal surface elements of the type illustrated in FIG. 7; and,

FIG. 9 is a top view of a periodic tubule layer formed of an array of tubule layer portions of the type illustrated in FIG. 8.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Prior to describing the preferred embodiments of the invention, reference is made to a co-pending U. S. Pat. application Ser. No. 57,253 entitled, "Honeycomb Core Structures Formed of Minimal Surface Tubule Sections", by Alan H. Schoen, filed July 22, 1970 . That patent application describes in greater detail than this application the structure and formation of honeycomb core structures utilized to form the panels of this invention. As will be better understood from the referenced co-pending patent application, the minimal surface elements that form honeycomb core structures can be defined inside of a group of seven kaleidoscopic cells which are fundamental regions of discrete groups generated by reflections. When thusly defined minimal surface elements are formed in an appropriate manner, they form honeycomb core structures which can be utilized to form the honeycomb core panels of this invention.

Turning now to a description of the drawings which illustrate preferred embodiments of the invention, FIG. 1 illustrates a minimal surface element 11 defined inside of a rectangular parallelopiped 13, one of the seven discrete kaleidoscopic geometrical figures which can be used to define the edges of a minimal surface element. The minimal surface element illustrated in FIG. 1 has six curved edges **15**, **17**, **19**, **21**, **23**, and **25**. Each of the curved edges intersects one of the faces of the rectangular parallelopiped **13** orthogonally. Moreover, the minimal surface element **11** has a mean curvature at all points that is equal to zero (i.e., a minimal value) and it is not a plane.

While the exact size and nature of the minimal surface element **11** illustrated in FIG. 1 can be mathematically determined and described, a considerably less complicated and time-consuming method of determining the exact surface configuration can be used. More specifically, a kaleidoscopic cell of the type described is constructed out of plastic or some other transparent material. A soap film is constructed inside of the transparent kaleidoscopic cell and varied in position until the desired configuration is formed. The correct configuration is obtained by blowing and sucking air through a metal tube inserted into the transparent kaleidoscopic cell through a suitable hole cut out of a corner (or corners) of the cell. The configuration of the soap film is determined to be that of the desired minimal surface by observing when the film reaches the so-called stationary state, i.e., the state of unstable mechanical equilibrium. Because of the frictional drag between the soap film and the bounding faces of the enclosed transparent kaleidoscopic cell, the soap film remains stationary in this equilibrium position long enough for detailed measurements to be made of the configuration of the soap film. These measurements may be made using various optical techniques, such as the sighting, along orthogonal axes, of a reflected laser beam.

Whenever the symmetry of the minimal surface element implies that one or more straight line segments are contained in the surface of the element, tightly stretched fine filaments are placed in the positions of these line segments. This operation transforms the unstable equilibrium of the soap film into a stable equilibrium and the film then remains absolutely stationary indefinitely. This situation is illustrated in FIG. 1. More specifically, when the enclosing rectangular parallelopiped 11 is a cube, the six-edged minimal surface element is in its most symmetrical form. At this point, all three pairs of diagonally opposite vertices of the minimal surface element 13 may be joined by straight line segments, all of which lie in the surface of the minimal surface element. By placing fine filaments along these lines, the minimal surface element remains absolutely stationary indefinitely.

As an alternate method and, in fact, preferred method for deriving the detailed configuration of a minimal surface element of the type considered herein, the following technique can be employed. In accordance with this technique, a closed polygonal boundary, composed of straight line segments which are orthogonal, respectively, to the planes containing the successive (curved) edges of the minimal surface, is constructed from fine stretched filaments. This polygonal boundary is dipped into a stable soap solution to form a stable equilibrium minimal surface spanning the boundary. A laser beam is directed onto the film at a large nuber of points very near the polygonal boundary, around the entire boundary of the soap film. Measurements are made of the orientation of a line normal to the film at all points. Then, by making use of the classical theory of Bonnet of the bending of simply connected minimal surfaces, a good approximation of the detailed shape of all of the curved edges of the desired minimal surface element is derived. When a final model of this derived boundary for the desired minimal surface element is constructed and dipped into a suitable soap solution, a stable equilibrium model of the desired minimal surface itself is obtained. From this point on, detailed optical measurements using sightings along orthogonal axes of laser-illuminated spots on the surface are employed, as described above, to determine the configuration of the desired minimal surface element.

The direct construction of a model of a given minimal surface element in the form of a soap film orthogonally bounded by the interior faces of an appropriate kaleidoscopic cell leads — in the cases described herein — to a detailed determination of the configuration of the minimal surface which does not depart significantly from the true mathematical form of the surface. Hence, for all intents and purposes, this form can be used to obtain an approximately minimal surface element. However, as stated above, the alternate method provides an independent means of determining the configuration of each minimal surface element and works for all of the minimal elements described herein.

FIG. 2 illustrates four minimal surface elements **11** of the type illustrated in FIG. 1 joined in such a manner that a portion of a minimal surface tubule layer having no internal discontinuities is provided. The minimal surface tubule layer portion **27** illustrated in FIG. 2 can further be defined inside of a rectangular parallelopiped **29**. The top and bottom of the rectangular parallelopiped **29** illustrated in FIG. 2 are squares and the sides are rectangles. By joining a plurality of tubule layer portions **27** of the type illustrated in FIG. 2 along their rectangular sides in an image-like manner (i.e., the two opposing tubule layer portions are mirror images of one another) an array or tubule layer is created. FIG. 3 is a top view of such a tubule layer **31**. While the tubule layer **31** illustrated in FIG. 3 is, broadly, essentially infinite, FIG. 3 does include side panels **33** and **37**, and an end panel **35** to illustrate the termination of the tubule layer.

FIG. 4 is a side view of a honeycomb core panel formed of a single tubule layer **31** of the type illustrated in FIG. 3, parallel boundary surfaces **39** and **41**, and end panel **35**. FIGS. 5 and 6 are side views of honeycomb core panels formed of tubule layers of the type illustrated in FIG. 3. The minimal surface periodic tubule layers are stacked in an image-like (mirror) manner to double and triple, respectively, the distance between the parallel outer surfaces **39** and **41**. The planes between layers are illustrated in FIGS. 5 and 6 as dash-dot centerlines. It will be appreciated that stacking tubule layers in an image-like (mirror) manner as illustrated in FIGS. 5 and 6 results in a relatively thick honeycomb core panel that lacks internal discontinuities.

From viewing FIGS. 3–6, it will be appreciated that the invention provides a honeycomb core panel wherein the core is formed of minimal surface periodic tubule layers. The tubule layers have no internal discontinunities per se. Moreover, the layers intersect one another in an image-like (mirror) manner whereby no discontinuities are created at the planes of intersection. While discontinunities do exist where the tubule layers intersect the outer parallel surfaces as well as the end and side panels, because these approximately circular intersections are orthogonal, optimum discontinuity strength is provided at these points. Moreover, because minimal surface forms are used by the invention, optimum strength-to-weight ratio is provided. That is, the thickness of the material forming the tubule layers can be decreased to a minimum value while maximum strength is retained because the tubule layers tend to distribute boundary panel forces in a multitude of directions on account of the membrane action which derives from the doubly curved character of the core structure. Because of this force distribution, the likelihood of panel rupture is lessened.

It will be appreciated that the minimal surface periodic tubule layers **31** heretofor described can be formed in a unitary manner in many different ways of many different materials. For example, the information concerning the detailed surface configurations previously derived can be utilized to create dies for compression forming the layers from metal, plastic, or pressed paper. In addition, injection molding techniques can be utilized with suitable dies to form the layers from plastics. Other suitable techniques will be apparent to those skilled in the art.

FIG. 7 illustrates an alternate embodiment of a minimal surface element **43** formed inside of an equilateral triangular prism **45**. As with the rectangular parallelopiped, an equilateral triangular prism falls within the seven kaleidoscopic cells described in more detail in the referenced co-pending patent application. By suitably mounting, in a composite or other manner, six minimal surface elements **43** of the type illustrated in FIG. **7**, a portion of a tubule layer **47** of the type illustrated in FIG. **8** is obtained. And, by suitably arraying a plurality of tubule layer portions of the type illustrated in FIG. **8**, a honeycomb core periodic tubule layer of the type illustrated in FIG. **9** is obtained. More specifically, FIG. **9** is a top view of an alternate embodiment of a honeycomb core periodic tubule layer formed of minimal surface tubule layer portions of the type illustrated in FIG. **8**. The minimal surface periodic tubule layer illustrated in FIG. **9** can be mounted between surfaces in the manner illustrated in FIGS. **3–6** to form an alternate embodiment of a honeycomb core panel. Again, the minimal surface periodic tubule layers can be formed in a composite unitary manner by different methods utilizing different materials.

It will be appreciated by those skilled in the art and others from the foregoing description of preferred embodiments of the invention and the referenced co-pending patent application that only two of a multitude of panels having different types of minimal surface periodic tubule layers have been described. It will also be understood, however, that other types of panels utilizing tubule cores of the general type described in the referenced co-pending patent application fall within the purview of this invention.

It will also be appreciated that the size of the tubules and the thickness of the material forming the tubule layers, as well as other parameters, will be determined by the strength, rigidity and weight requirements of the ultimate panel. These requirements and others will also determine the material to be used in the boundary panels as well as the honeycomb core structure. Hence, the invention can be practiced in many ways not specifically described herein.

What is claimed is:

1. A honeycomb core panel comprising:

first and second parallel boundary surfaces; and,

a honeycomb core located between said first and second parallel boundary surfaces, said honeycomb core comprising at least one minimal surface periodic tubule layer, said minimal surface tubule layer being defined by a plurality of approximately minimal surface elements formed in a smooth continuous manner, each of said minimal surface elements being definable within a kaleidoscopic cell.

2. A honeycomb core panel as claimed in claim **1** wherein the outer boundary of said honeycomb core intersects said first and second parallel boundary surfaces in simple closed curves.

3. A honeycomb core panel as claimed in claim **2** wherein said simple closed curved intersections between said honeycomb core and said first and second parallel boundary surfaces are substantially orthogonal at all points.

4. A honeycomb core panel as claimed in claim **3** wherein said honeycomb core comprises a plurality of tubule layers, said layers being stacked in an image-like manner whereby no internal discontinuities are formed in said honeycomb core at the junctions between said layers.

5. A honeycomb core panel as claimed in claim **4** wherein said plurality of minimal surface periodic tubule layers is two in number.

6. A honeycomb core panel as claimed in claim **4** wherein said plurality of minimal surface periodic tubule layers is three in number.

7. A honeycomb core panel as claimed in claim **3** wherein said simple closed curved intersections between said honeycomb core and said first and second parallel boundary surfaces are approximately circular.

8. A honeycomb core panel as claimed in claim **1** wherein said honeycomb core comprises a plurality of tubule layers, said layers being stacked in an image-like manner whereby no internal discontinuities are formed in said honeycomb core at the junctions between said layers.

9. A honeycomb core panel as claimed in claim **8** wherein said plurality of minimal surface periodic tubule layers is two in number.

10. A honeycomb core panel as claimed in claim **8** wherein said plurality of minimal surface periodic tubule layers is three in number.

11. A honeycomb core panel as claimed in claim **1** wherein the outer surface of said honeycomb core terminally intersects said first and second parallel boundary surfaces substantially orthogonally at all points.

12. A honeycomb core panel as claimed in claim **1** wherein each of said minimal surface elements intersects each surface of said kaleidoscopic cell at least once and each intersection is orthogonal.

13. A honeycomb core panel as claimed in claim **1** wherein said kaleidoscopic cell is a rectangular parallelopiped.

14. A honeycomb core panel as claimed in claim **1** wherein said kaleidoscopic cell is an equilateral triangular prism.

15. A honeycomb core panel comprising:

first and second parallel boundary surfaces; and

a honeycomb core located between said first and second parallel surfaces, said honeycomb core comprising at least one constant mean curvature periodic tubule layer, said constant mean curvature periodic tubule layer being defined by a plurality of approximately constant mean curvature elements formed in a smooth continuous manner, each of said constant means curvature elements being definable within a kaleidoscopic cell.

16. A honeycomb core panel as claimed in claim **15** wherein said constant is zero.

17. A honeycomb core panel as claimed in claim **15** wherein said honeycomb core comprises a plurality of tubule layers, said layers being stacked in an image-like manner, whereby no internal discontinuities are formed in said honeycomb core at the junctions between said layers.

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