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(54) AN IMPACT ABSORBING STRUCTURE AND A HELMET COMPRISING SUCH A STRUCTURE

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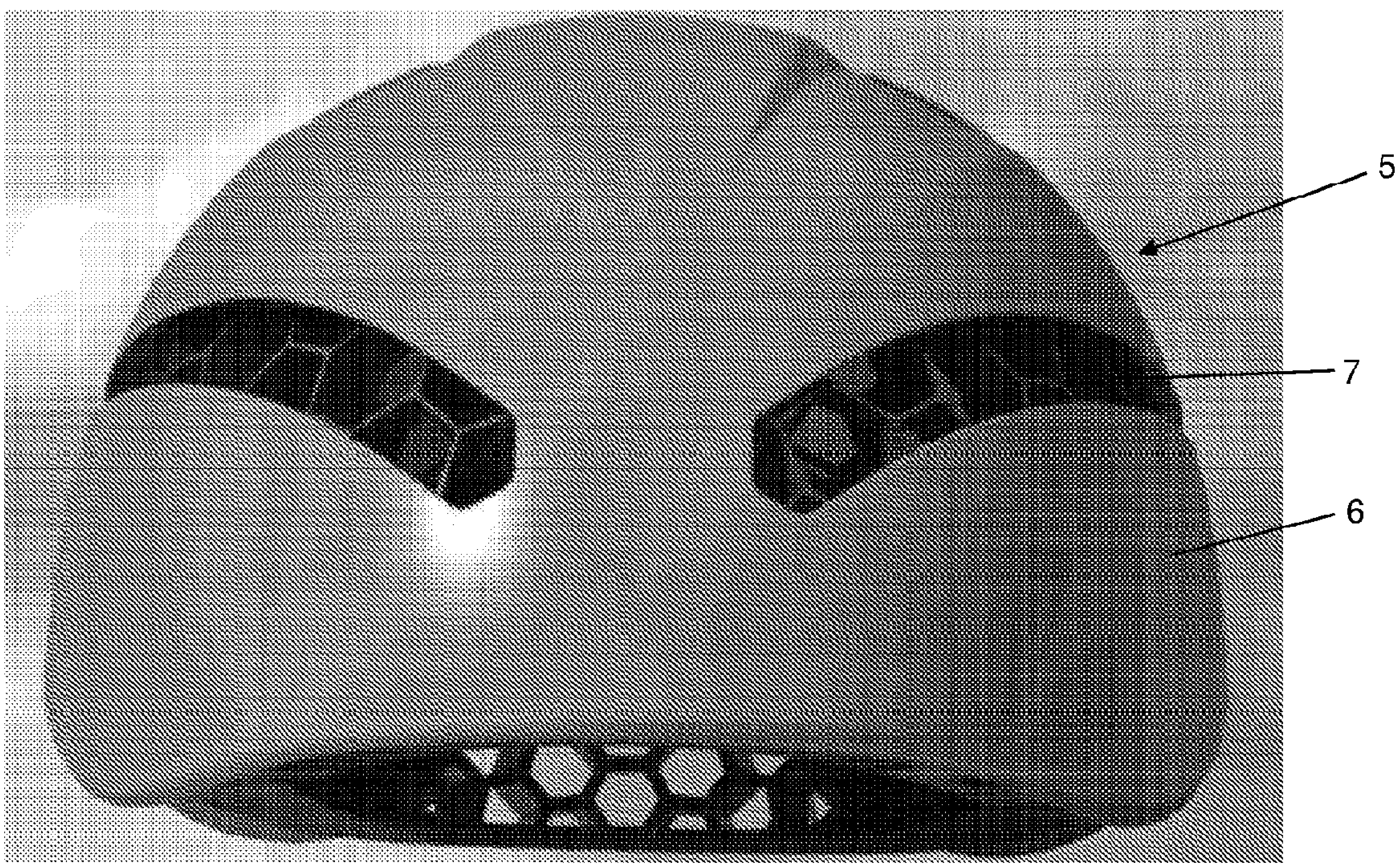
(57) **ABSTRACT**

An impact absorbing structure comprises a unitary material formed as a stretch-dominated hollow cell structure and a helmet comprising such a structure as an inner impact resistant liner.



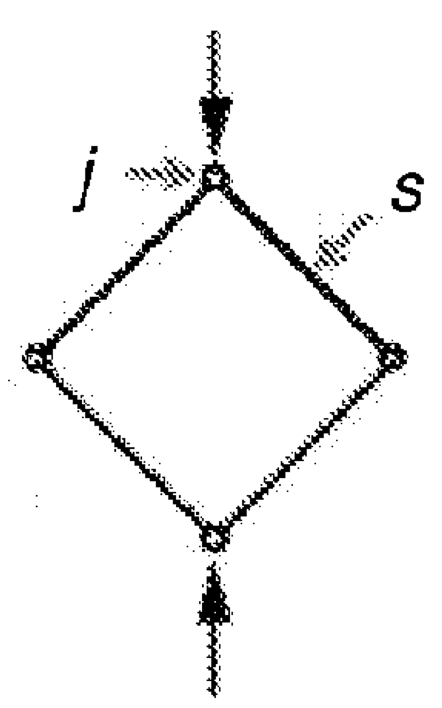


Figure 1A

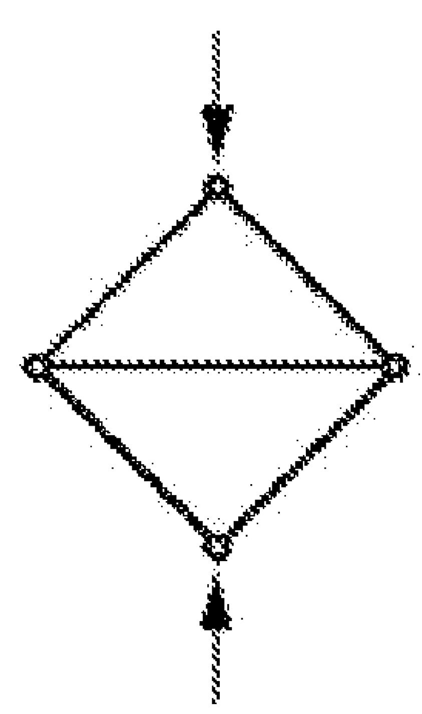


Figure 1B

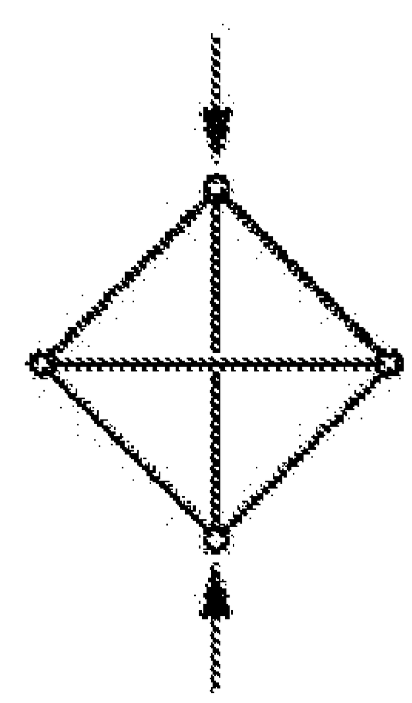
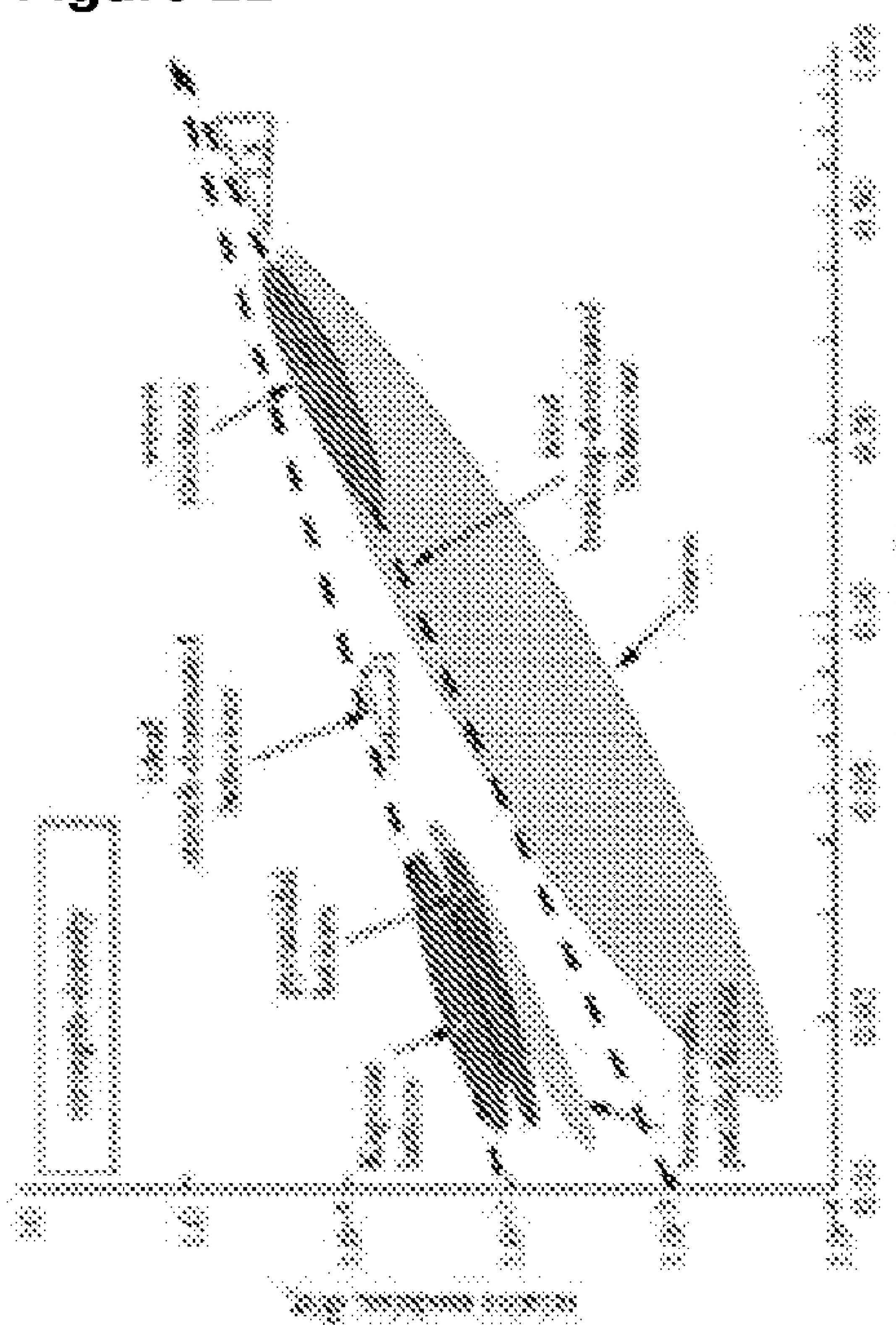


Figure 1C

Figure 2B



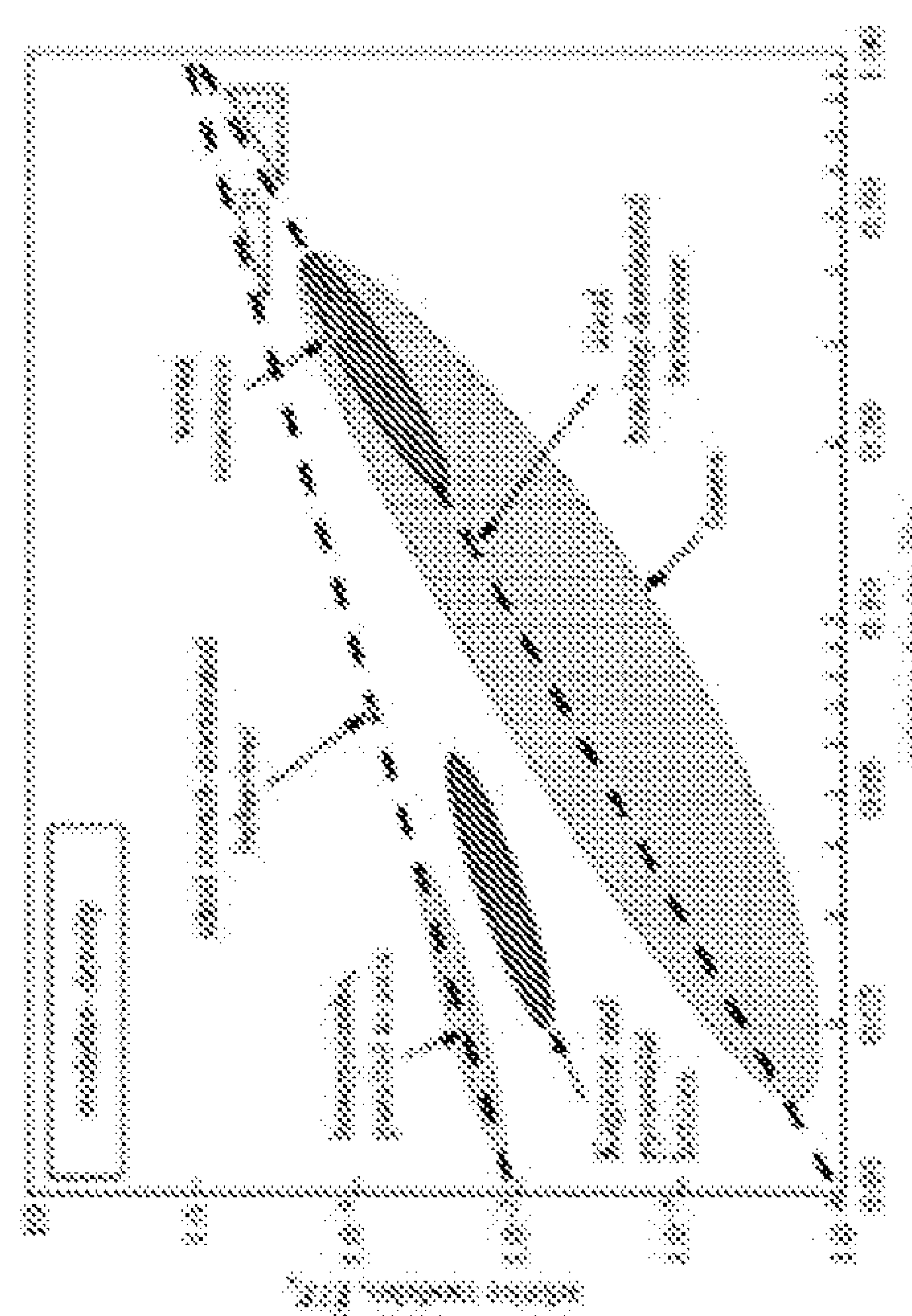


Figure 2A

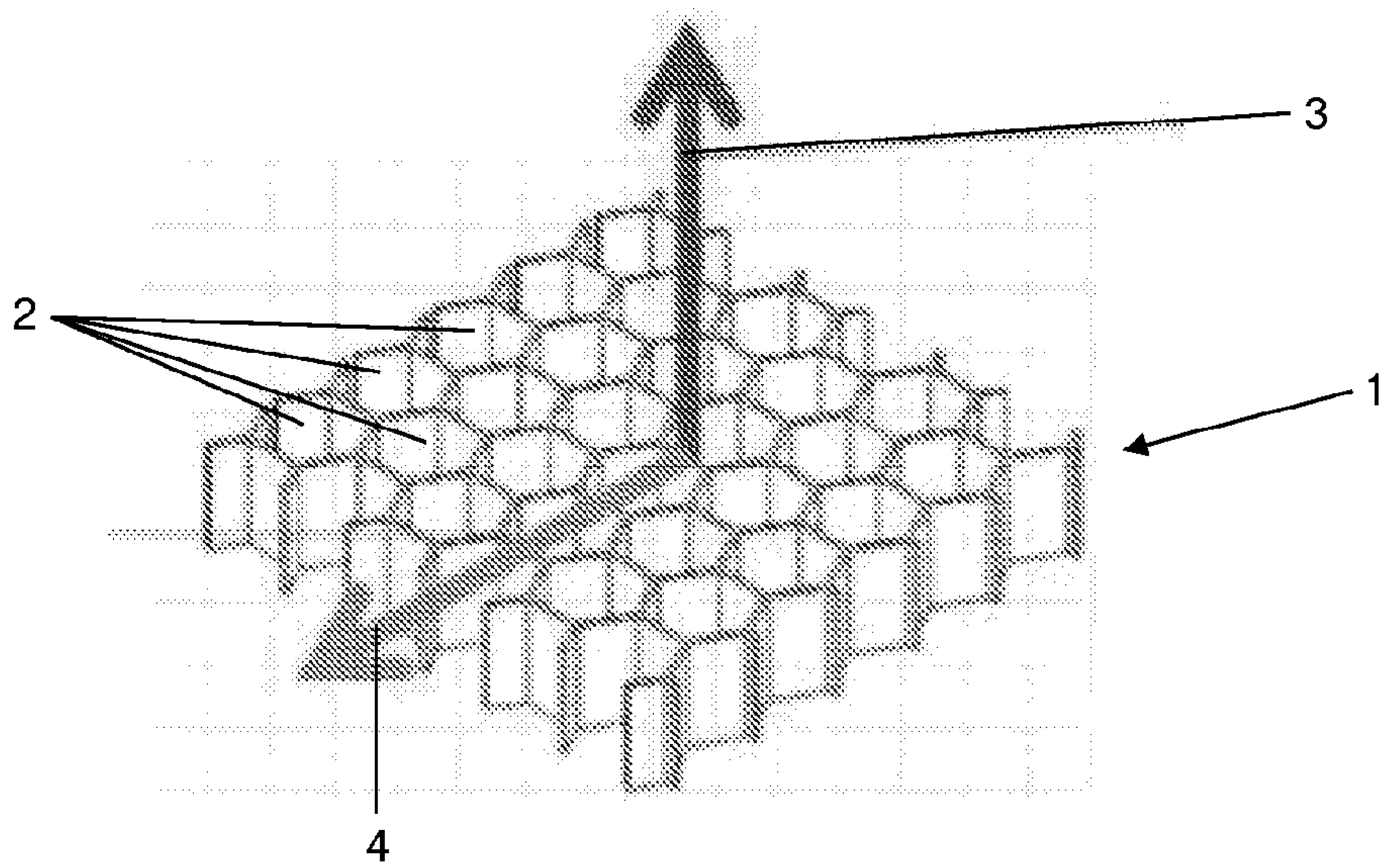


Figure 3

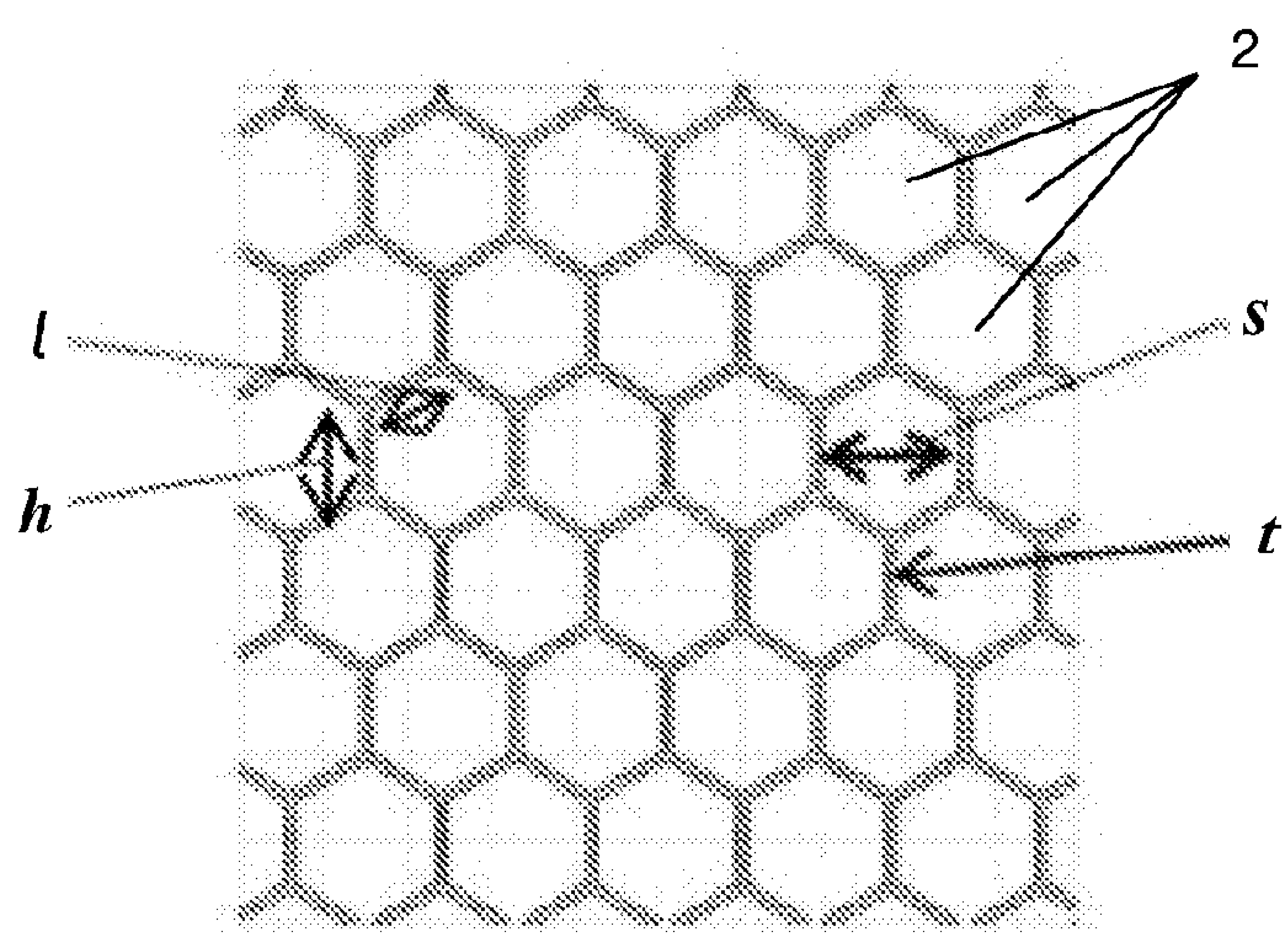


Figure 4

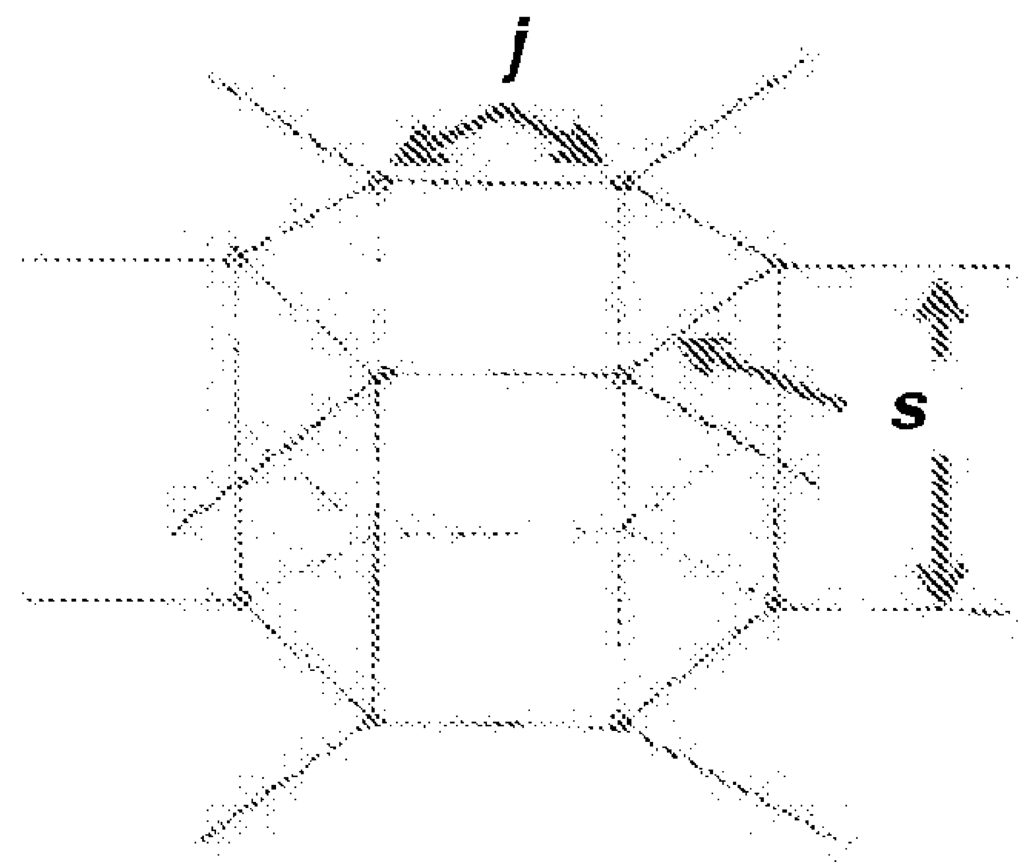


Figure 5

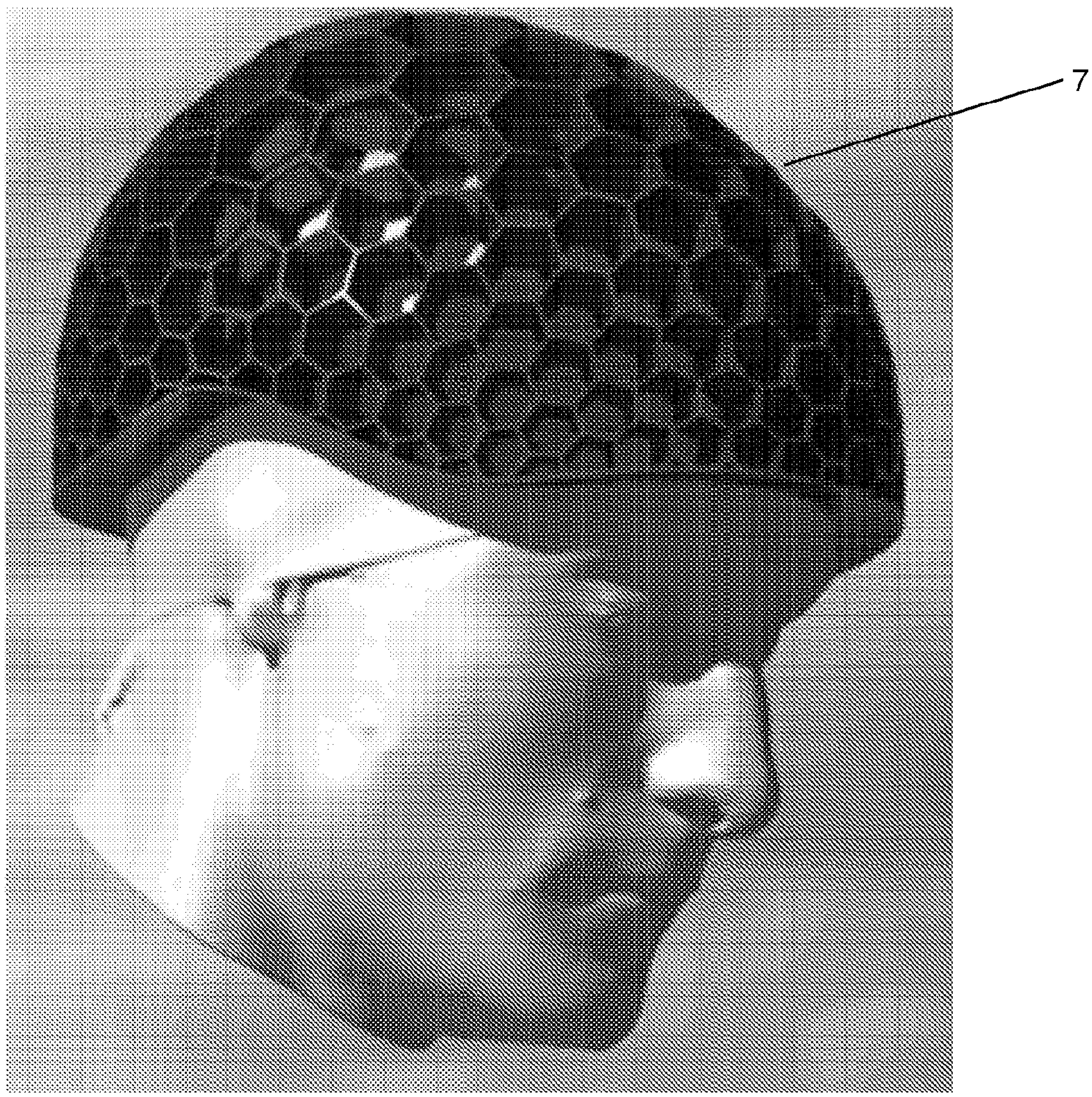


Figure 6

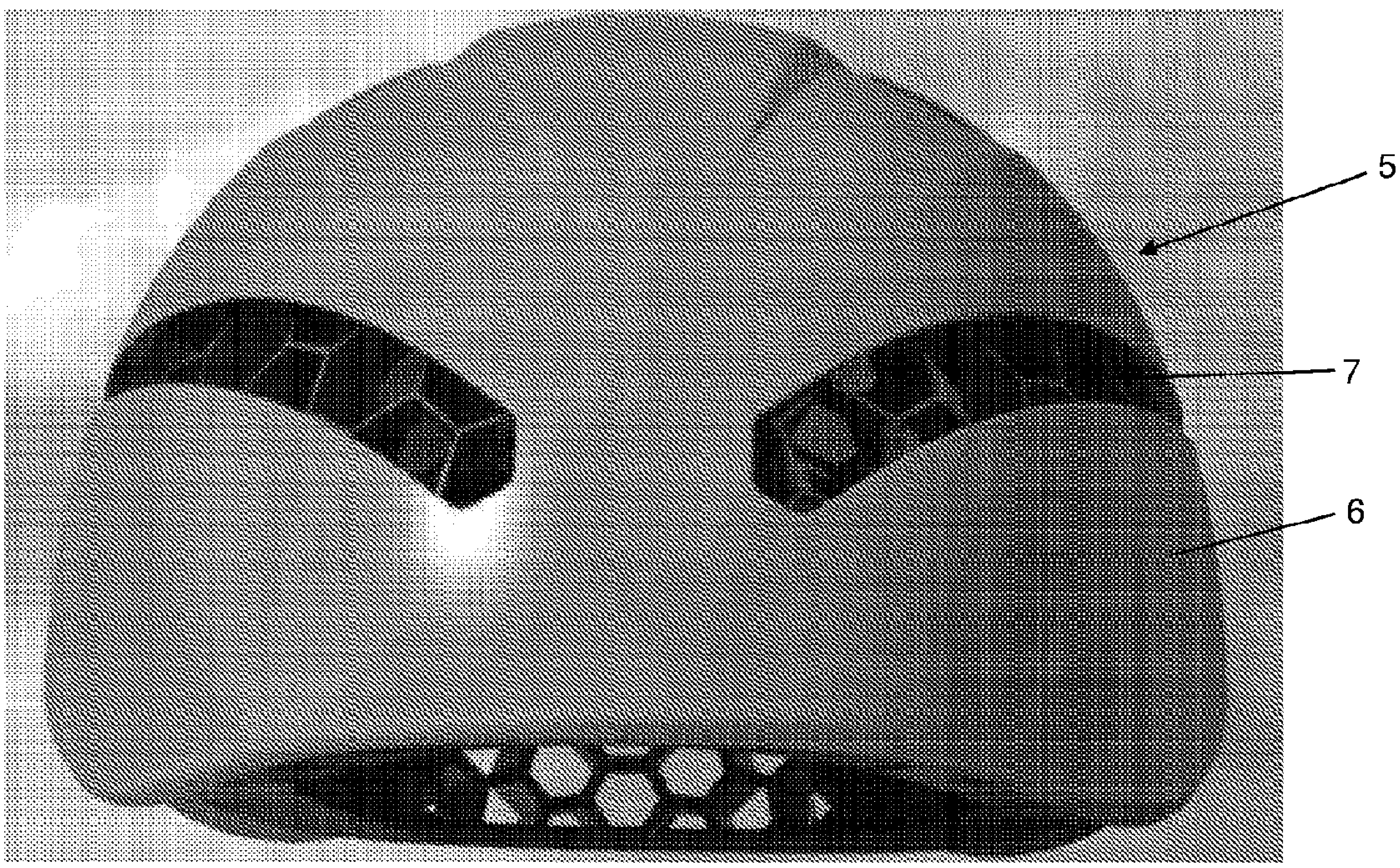


Figure 7

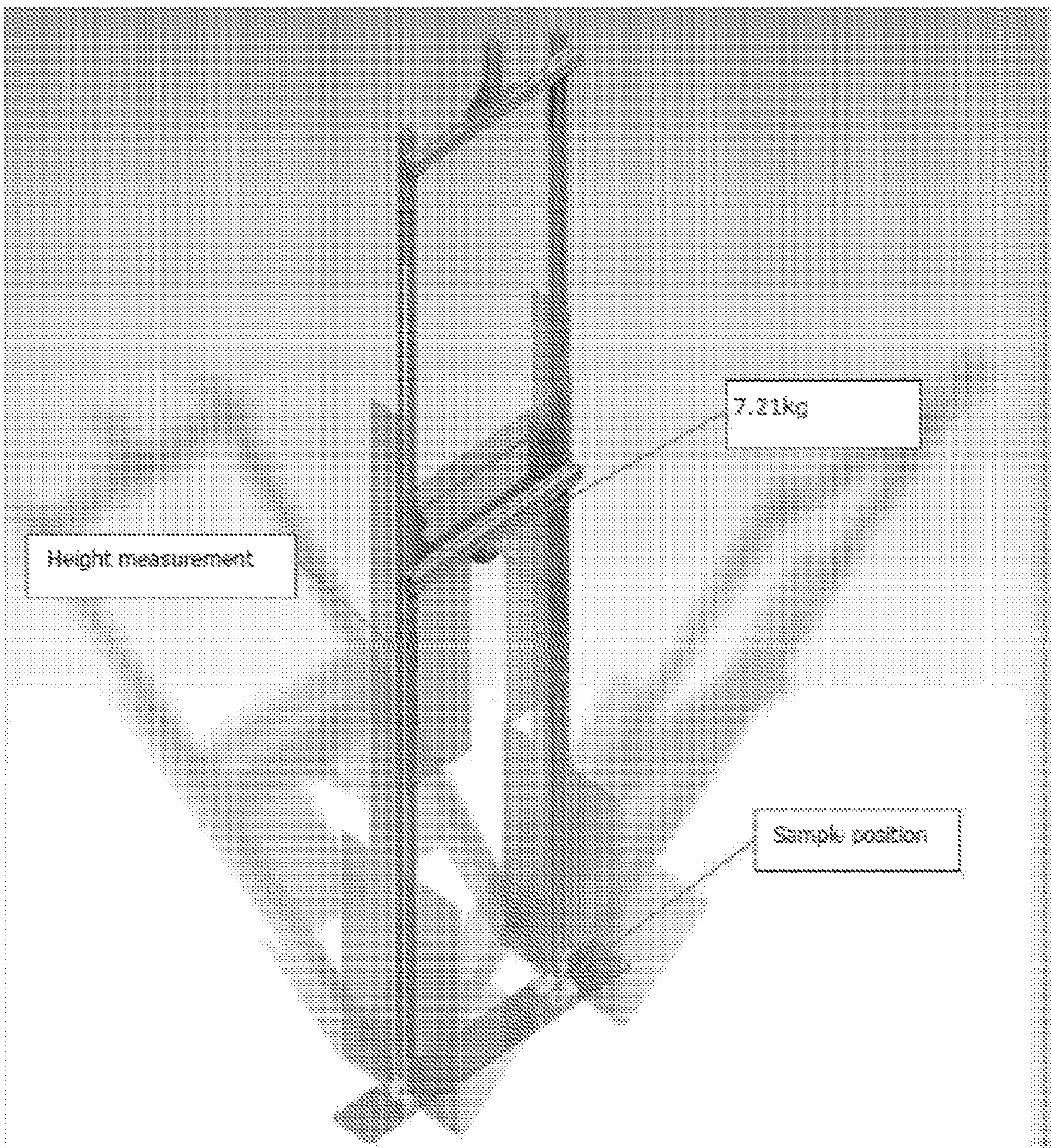


Figure 8

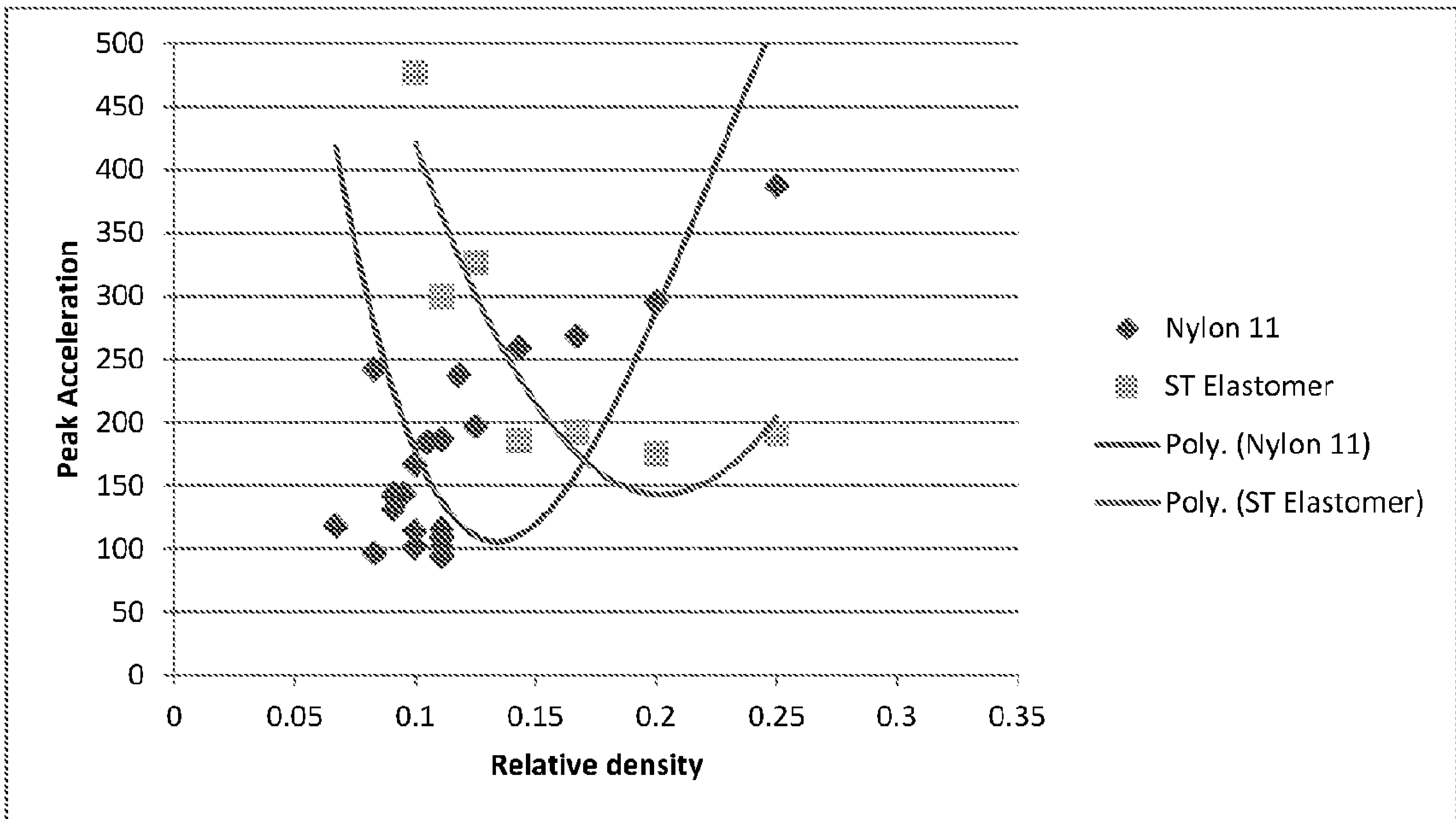

500
450
400
350
300
250
200
150
100
50
0
Peak Acceleration
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Relative density
Nylon 11
ST Elastomer
Poly. (Nylon 11)
Poly. (ST Elastomer)

Figure 9

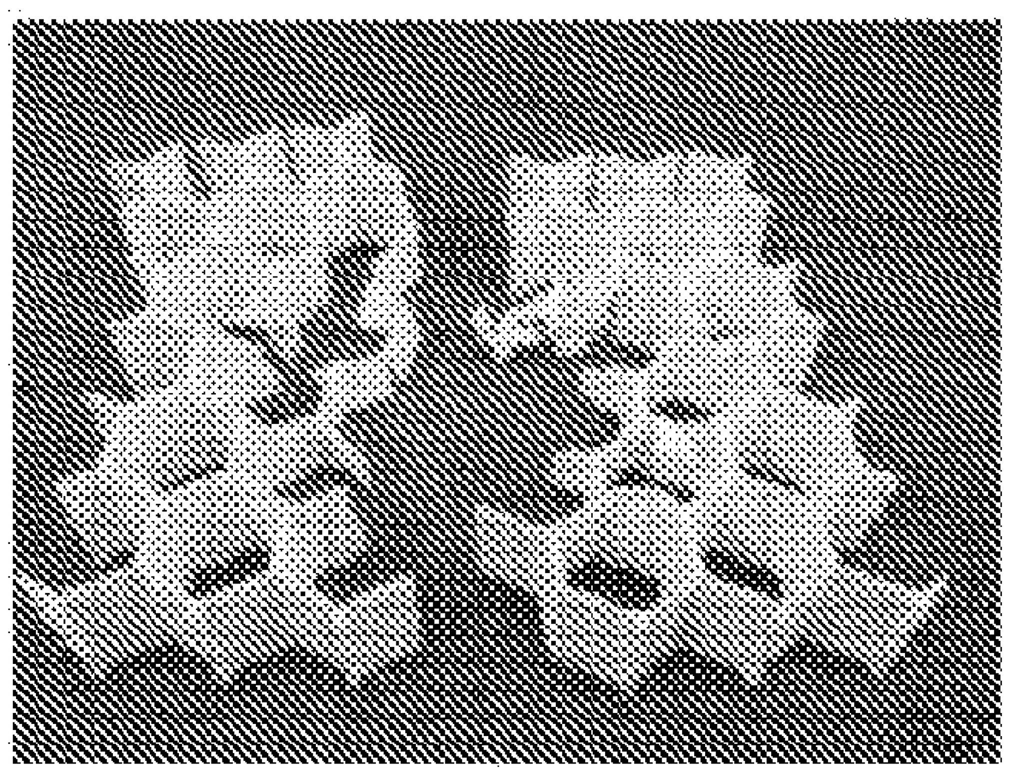


Figure 10

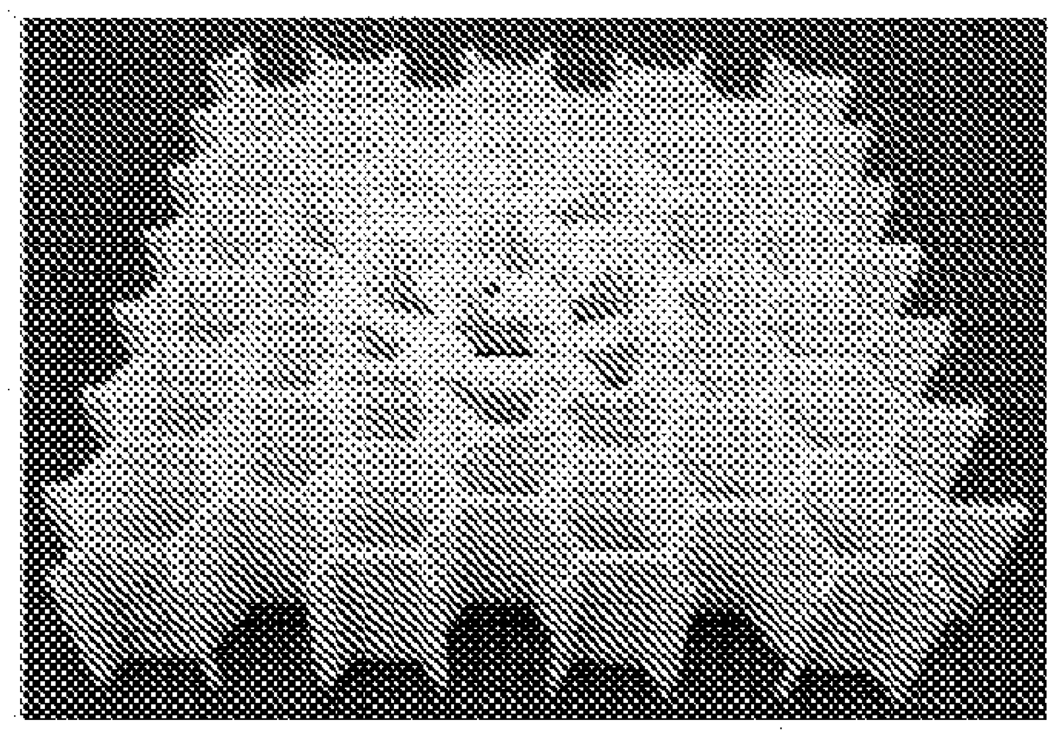


Figure 11

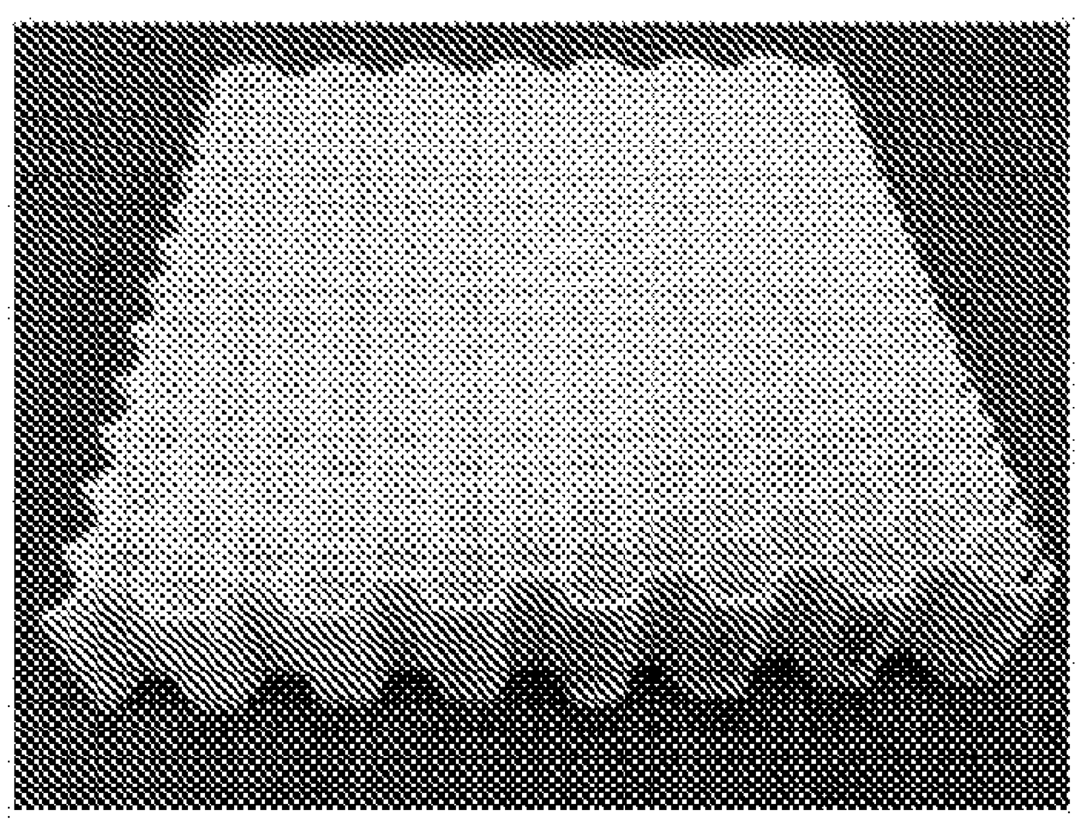
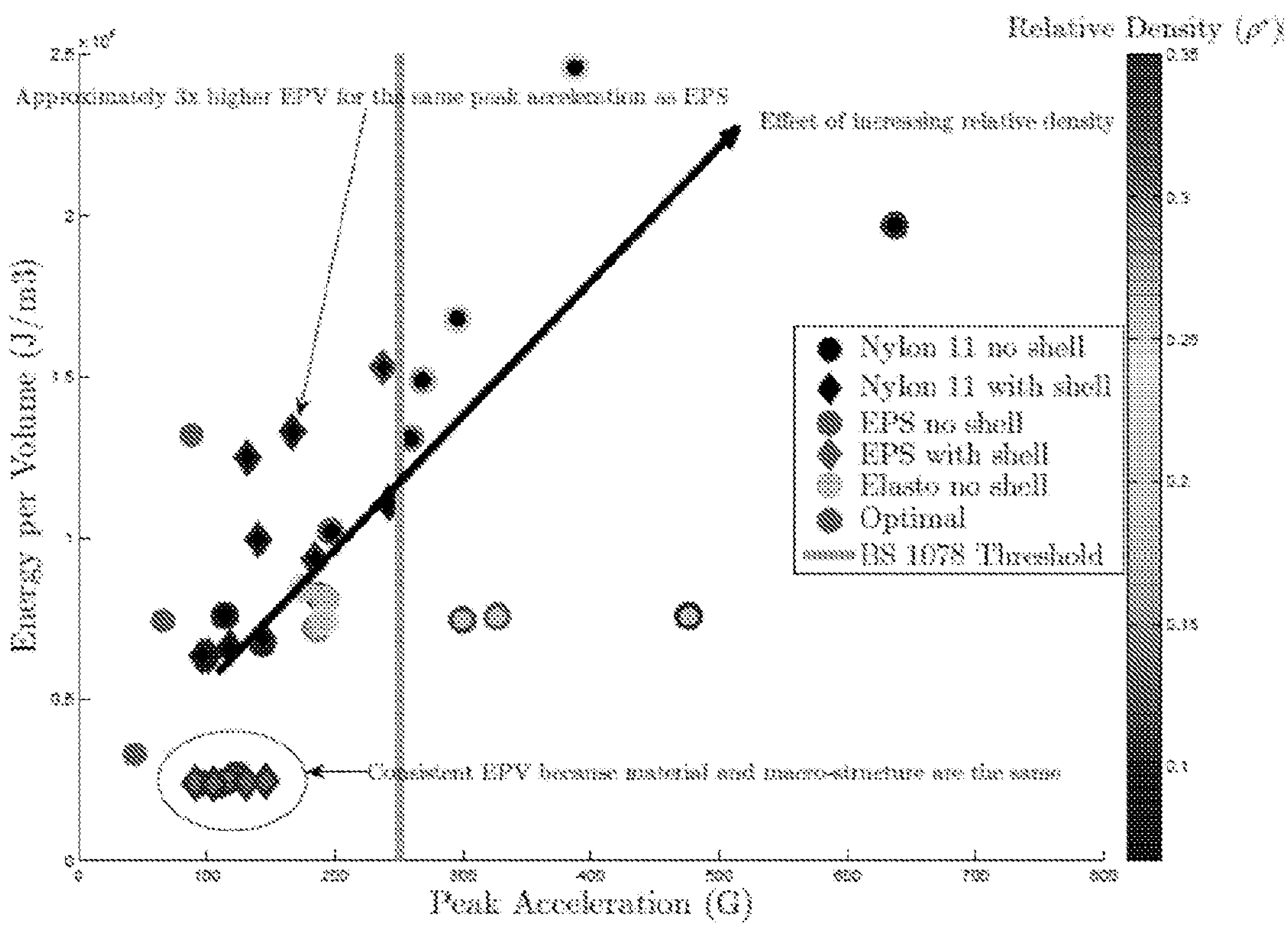


Figure 12



Relative Density (ρ^*)
Approximately 3x higher EPV for the same peak acceleration as EPS
Effect of increasing relative density
Nylon 11 no shell
Nylon 11 with shell
EPS no shell
EPS with shell
Elasto no shell
Optimal
BS 1078 Threshold
Consistent EPV because material and macro-structure are the same
Energy per Volume (J/m3)
Peak Acceleration (G)

Figure 13

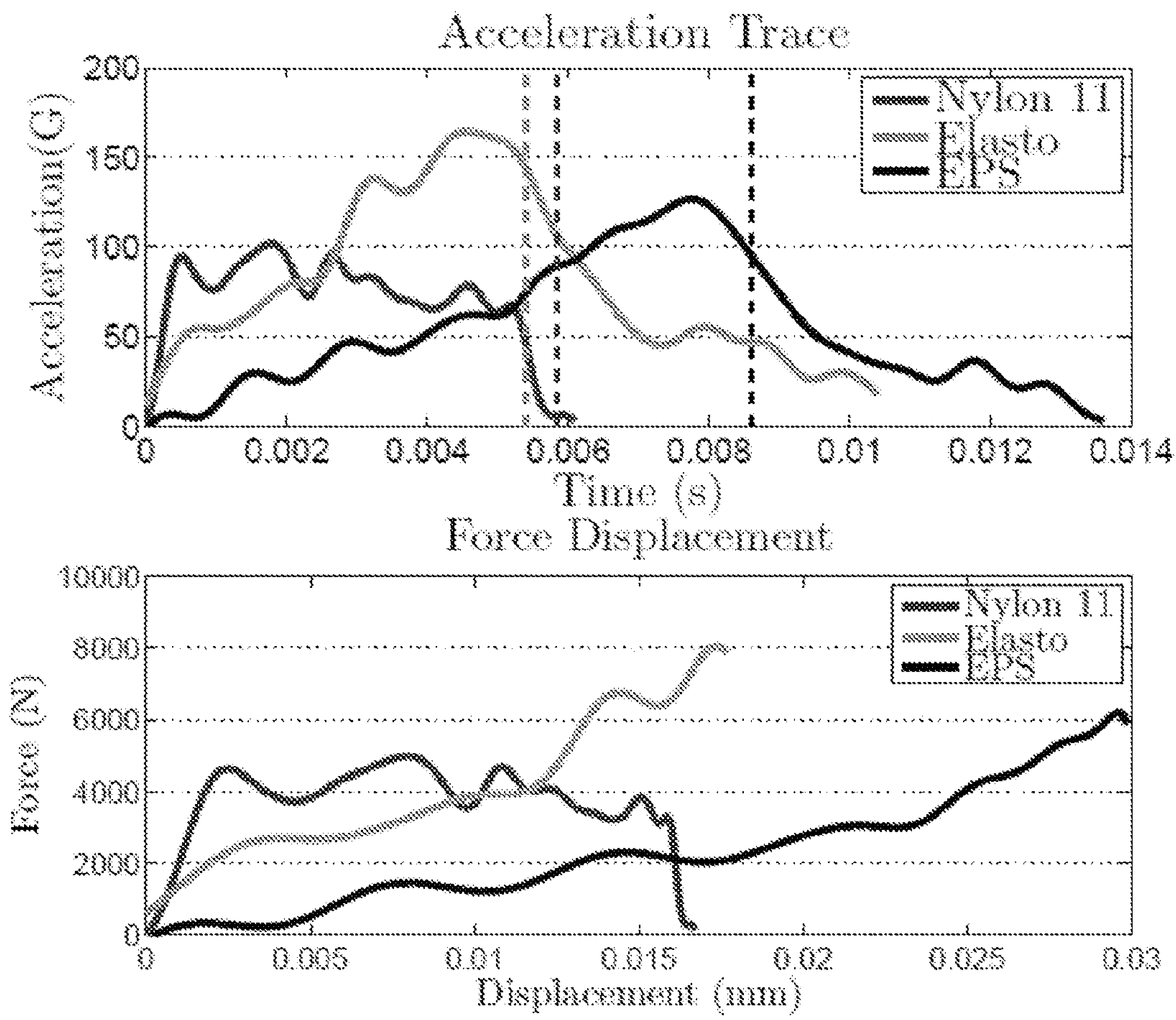
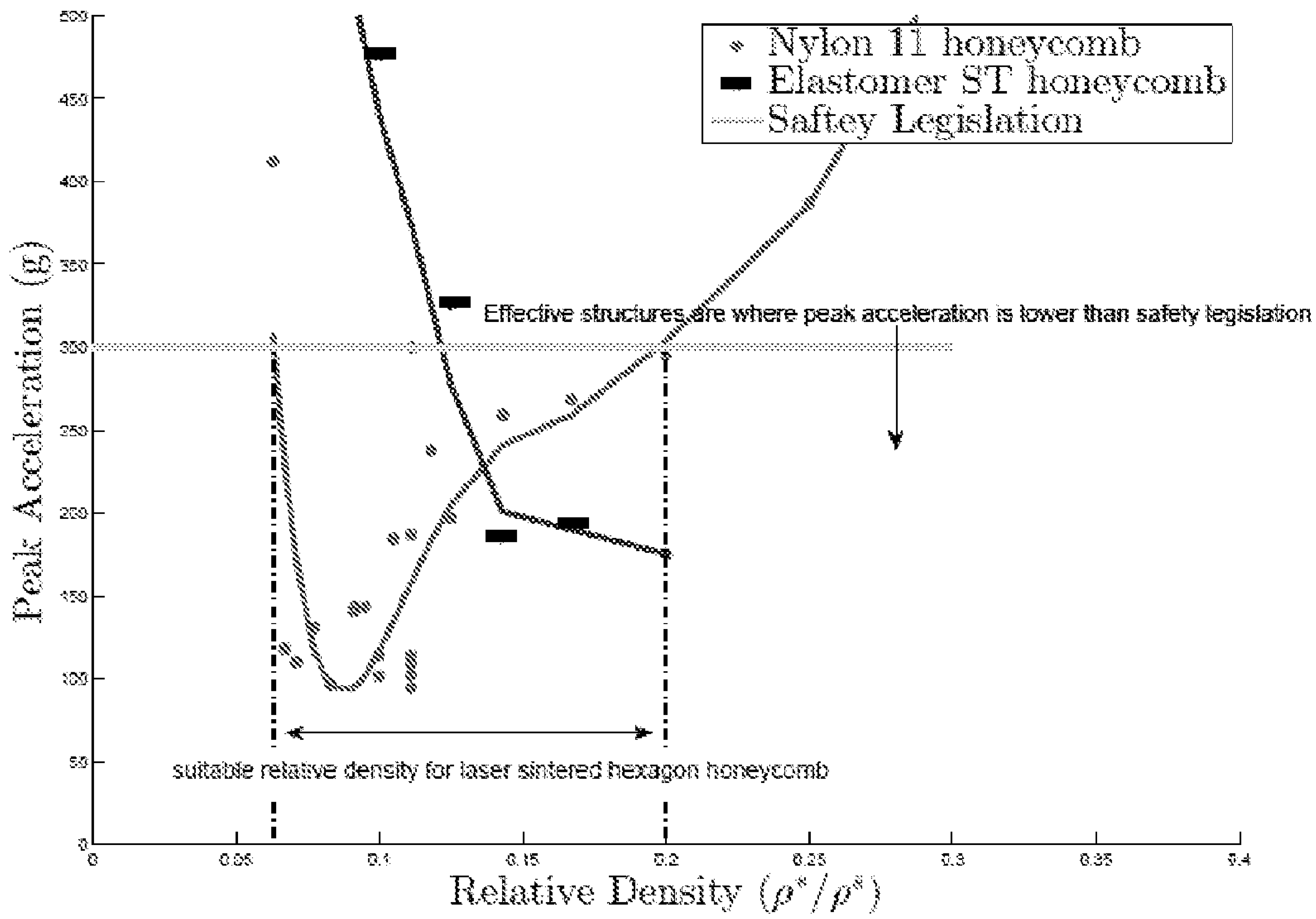
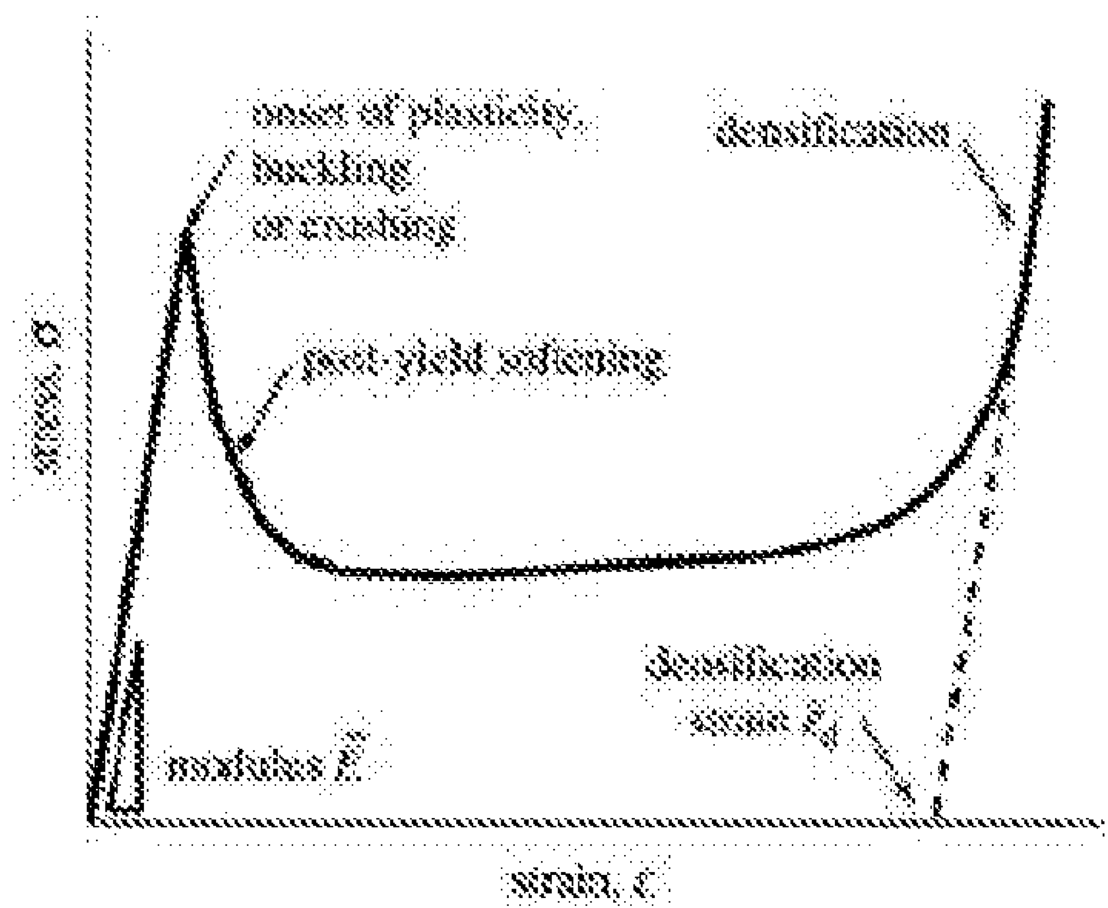
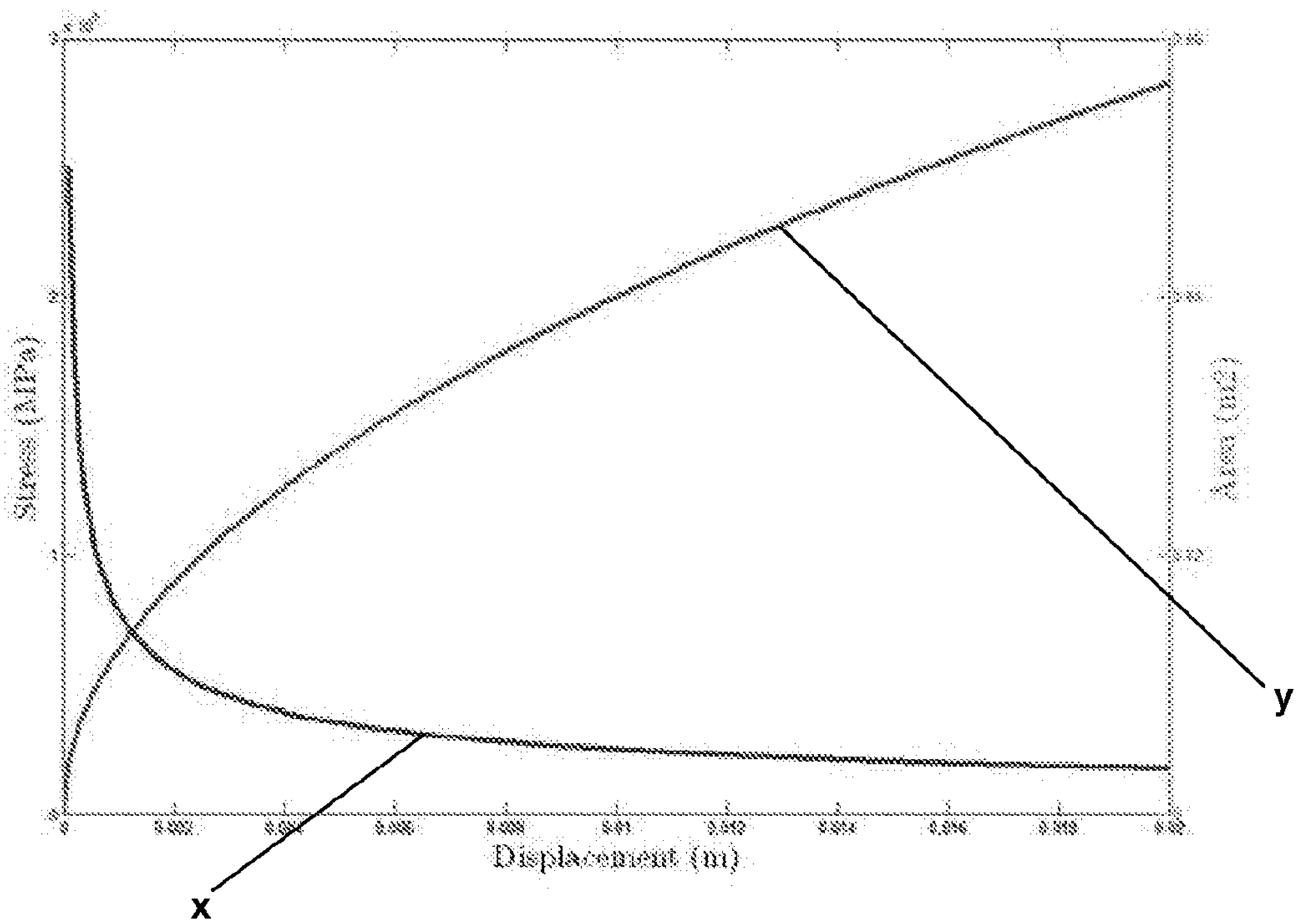
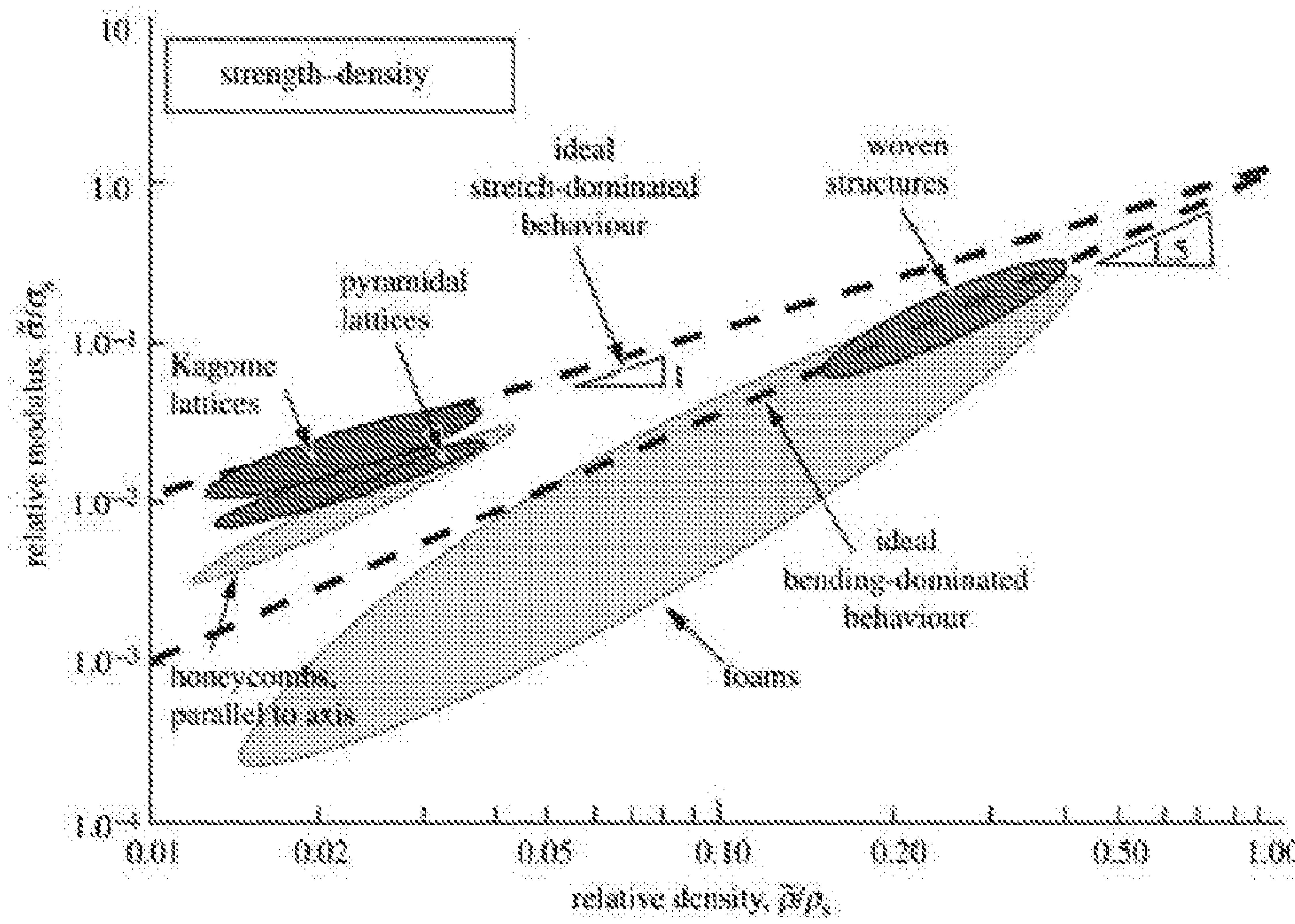

Acceleration Trace
Acceleration(G)
200
150
100
50
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Time (s)
Nylon 11
Elasto
EPS
Force Displacement
Force (N)
10000
8000
6000
4000
2000
0
0
0.005
0.01
0.015
0.02
0.025
0.03
Displacement (mm)
Nylon 11
Elasto
EPS

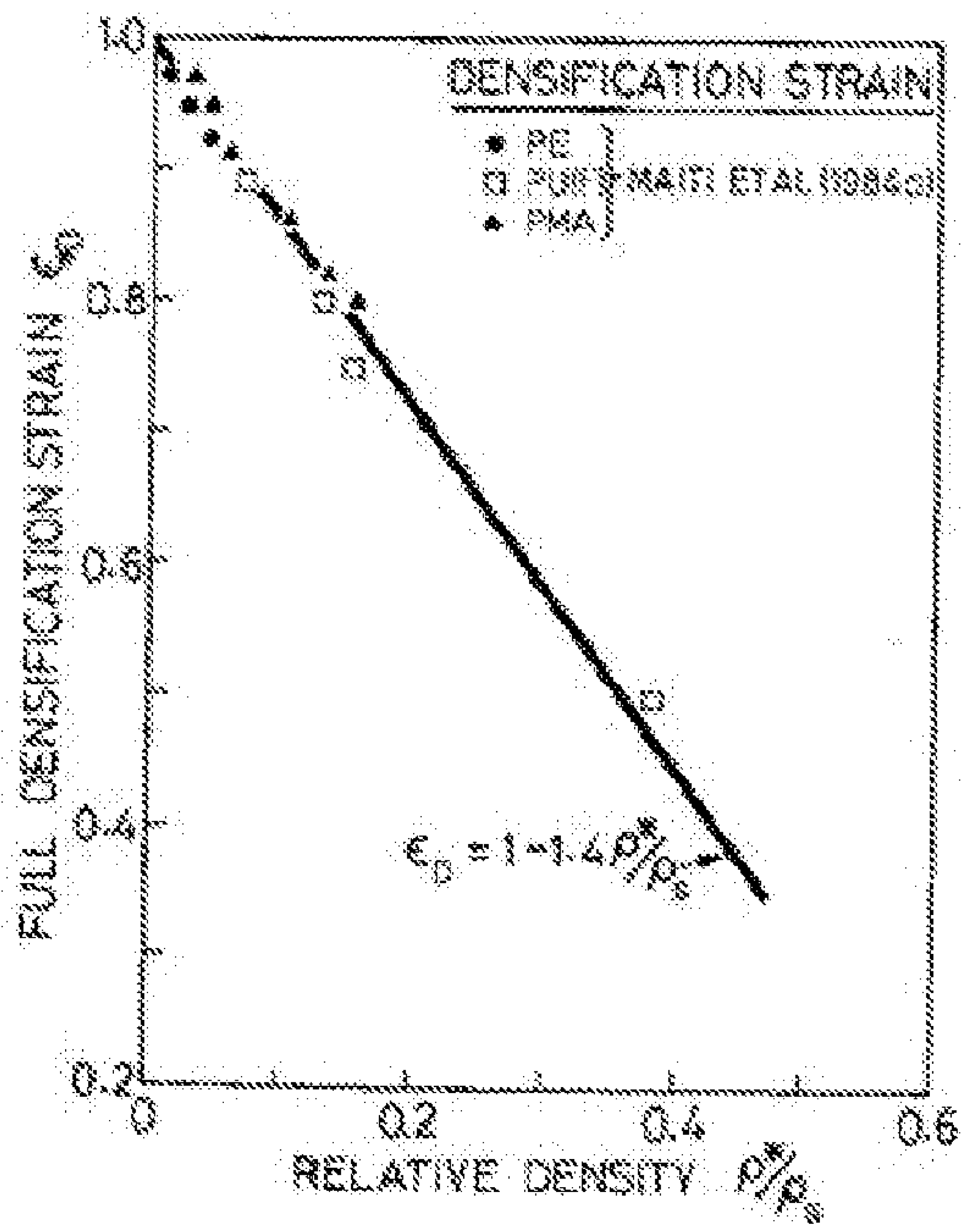
Figure 14


Nylon 11 honeycomb
Elastomer ST honeycomb
Saftey Legislation
Effective structures are where peak acceleration is lower than safety legislation
suitable relative density for laser sintered hexagon honeycomb
Peak Acceleration (g)
Relative Density (ρ*/ρs)

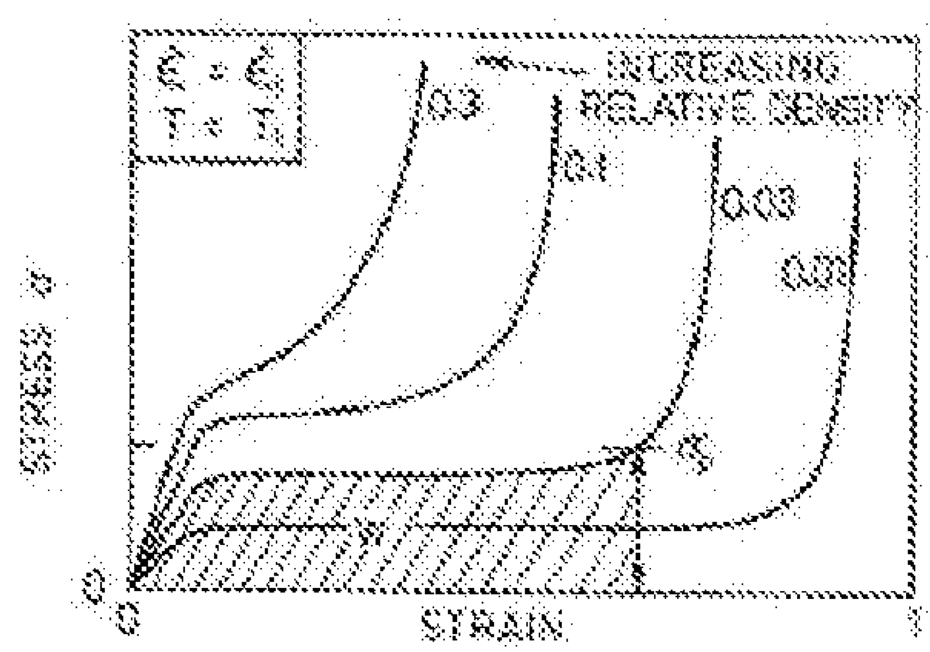

onset of plasticity,
buckling
or crushing
densification
post-yield softening
stress, σ
densification
strain ε_d
modulus $\tilde{E}$
strain, ε


Stress (MPa)
Area (m2)
Displacement (m)
x
y

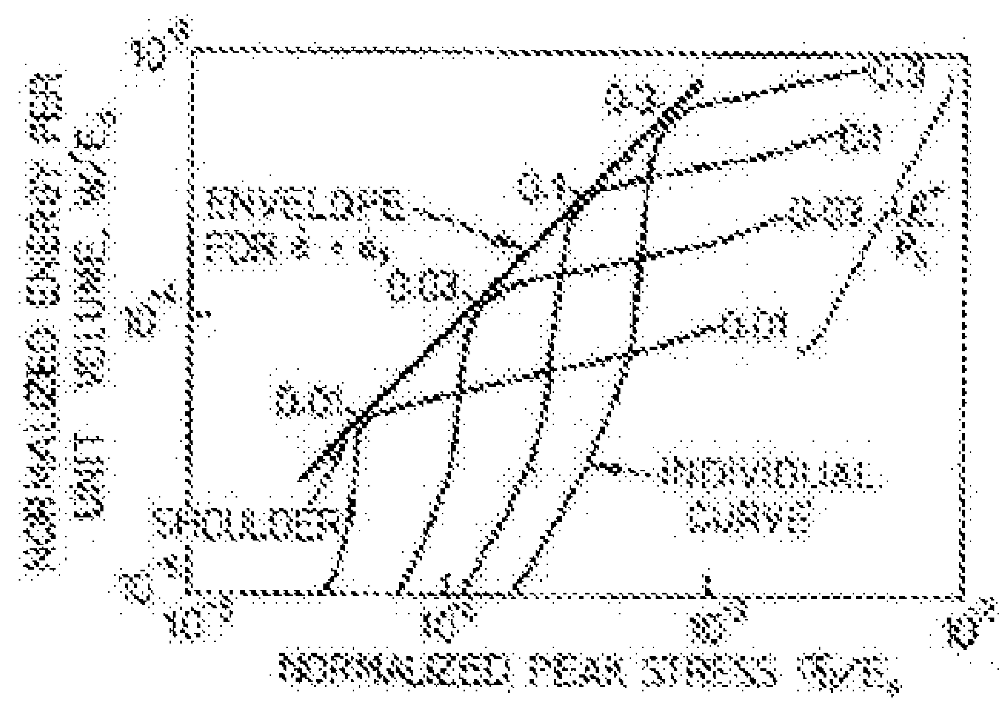

strength–density
ideal
stretch-dominated
behaviour
woven
structures
pyramidal
lattices
Kagome
lattices
1
1.5
ideal
bending-dominated
behaviour
foams
honeycombs,
parallel to axis
relative density, $\bar{\rho}/\rho_s$
10
1.0
1.0^{-1}
1.0^{-2}
1.0^{-3}
1.0^{-4}
0.01
0.02
0.05
0.10
0.20
0.50
1.00


DENSIFICATION STRAIN
PE
PUR
PMA
MAITI ET AL (1984a)
FULL DENSIFICATION STRAIN ϵ_D
RELATIVE DENSITY ρ^*/ρ_s
$\epsilon_D = 1 - 1.4\rho^*/\rho_s$
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6

Energy Absorbing diagrams



(a) Energy absorbed per unit volume



(b) Normalised W plotted against normalised peak stress

AN IMPACT ABSORBING STRUCTURE AND A HELMET COMPRISING SUCH A STRUCTURE

FIELD

[0001] The present invention relates to an impact absorbing structure. More particularly, the present invention relates to a hollow-cell impact absorbing structure. Even more particularly, the present invention relates to an impact absorbing structure formed as a stretch-dominated hollow-cell structure. The present invention also relates to impact absorbing structures where the impact surface is curved, such as a sports helmet or aerospace nose bumpers, at least part of the structure formed from a hollow-cell impact absorbing structure, and even more particularly a stretch-dominated hollow-cell impact absorbing structure.

BACKGROUND

[0002] Injury to a person or damage to an object can occur when the person or object is subjected to an impact of sufficient force. Considerable developmental effort has been expended in order to produce materials and structures that provide protection from potentially damaging or injurious impacts.

[0003] Impact protection is particularly important for preventing head injury. A blow to the head can result in severe traumatic brain injury (TBI). It is common for brain trauma to occur as a consequence of either a focal impact upon the head, or by a sudden acceleration/deceleration within the cranium, or from a combination of both impact and movement. Traumatic brain injury can cause long-term issues, and there are limited treatment options.

[0004] One of the most common causes of head injury is participation in sports. For example, a fall from a bicycle when riding may result in the head striking against a solid unyielding object or surface such as a road surface or similar. In order to help prevent injury, helmet usage is customary or mandatory in many sports such as bicycle, motorcycle and horse riding, rock climbing, American football and also winter or ice sports such as skating, ice hockey, and skiing. Another common cause of head injury is an impact caused by a falling object on a building or construction site.

[0005] Sports helmets and safety helmets are individually designed so as to be particularly suited to their particular use. However, most or all of the helmets have common design elements such as a hard outer shell (formed from a stiff thermoplastic or composite) and a lining/liner, softer than the outer shell, but still stiff enough to retain it's shape when unsupported. In combination, the shell and liner act to absorb the force of an impact and to help prevent this force being transmitted to the head and brain. Virtually all helmets use expanded polystyrene as the energy absorbing liner. The expanded polystyrene is formed as a unitary structure (that is, without gaps) in the required shape.

[0006] U.S. Pat. No. 3,447,163 describes and shows a safety or crash helmet intended for use by motorcyclists and/or racing motorists. The helmet has an outer shell formed as a double-skinned member, the two skins of the shell joined to one another around the periphery of the shell by a gently curved peripheral portion that has no sharp edges, and the space between the skins contains a layer of a honeycomb type of material, the cells of the honeycomb layer filled with an energy-absorbing foamed material.

[0007] U.S. Pat. No. 7,089,602 describes and shows an impact absorbing, modular helmet having layers on the outer side of a hard casing that increase the time of impact with the intention of reducing the intensity of the impact forces. The layers are made up of a uniformly consistent impact absorbing polymer material, a polymer layer filled with air or a polymer structure. These impact-absorbing layers can also be made and used as an independent, detachable, external protective cover that can be attached over a hard casing helmet.

[0008] U.S. Pat. No. 6,247,186 describes and shows a helmet having a housing, an inner impact resistant layer shaped to the head of rider, a protective covering spaced above and formed integrally with the housing, and a chamber enclosed by the housing and protective covering that is open in the front for ventilation. The chamber has a net strap in the front side for preventing foreign objects from entering and one or more inner channels in communication with the inner space of helmet through a passageway. In use, fresh air flows through the passageway and into the impact resistant layer.

[0009] Sports helmets and safety helmets often have to be worn for extended periods, and the weight of the helmet is an important design consideration. When designing a helmet, there will generally be a trade-off between the overall weight (and shape and size) of the helmet, and the impact-absorbing properties. Increasing the amount of impact-absorbing material will increase the overall weight of the helmet, and may also result in an increase in the external dimensions, which can in turn make wearing the helmet relatively more unwieldy and uncomfortable to wear, especially where aerodynamic considerations may also be important. Conversely, impact protection can be compromised if the helmet has too little impact-absorbing material.

[0010] Foams such as the foams used in helmets are typically excellent energy absorbers because they are characterised by a long plateau stress, and in most impacts the area is constant so the stress can be directly converted to force, providing a long plateau force. This means all the energy can be absorbed whilst maintaining a low peak force and acceleration, optimal in reducing brain damage. However, in an oval shape helmet, the area when crushing is not constant.

[0011] In this specification where reference has been made to patent specifications, other external documents, or other sources of information, this is generally for the purpose of providing a context for discussing the features of the invention. Unless specifically stated otherwise, reference to such external documents is not to be construed as an admission that such documents, or such sources of information, in any jurisdiction, are prior art, or form part of the common general knowledge in the art.

SUMMARY

[0012] It is an object of the present invention to provide a range of optimised impact absorbing structures for improved impact absorption, or which at least provide the public or industry with a useful choice. It is a further object of the invention to provide a range of optimised impact absorbing structures that can be used to reduce traumatic brain injury by reducing peak acceleration and force to the brain and directing energy away from vulnerable areas of the brain, or which at least provide the public or industry with a useful choice. It is a yet still further object of the invention to provide a helmet at least partly formed from an optimised impact absorbing structure that assists with reducing traumatic brain injury by reducing peak acceleration and force to the brain and directing energy away from vulnerable areas of the brain, or which at least provides the public or industry with a useful choice. It is a yet still further object of the present invention to provide a method of optimising an impact absorbing structure for improved impact absorption.

[0013] The term "comprising" as used in this specification and indicative independent claims means "consisting at least in part of", and is intended as an inclusive rather than exclusive term. When interpreting each statement in this specification and indicative independent claims that includes the term "comprising", features other than that or those prefaced by the term may also be present. Related terms such as "comprise" and "comprises" are to be interpreted in the same manner.

[0014] As used herein the term "and/or" means "and" or "or", or both.

[0015] As used herein "(s)" following a noun means the plural and/or singular forms of the noun.

[0016] Accordingly, in a first aspect the present invention may broadly be said to consist in an impact absorbing structure, comprising a unitary material formed as a stretch-dominated hollow cell structure.

[0017] In an embodiment, substantially all the cells of the hollow cell structure are 2D hollow-cells.

[0018] In an embodiment, substantially all the cells are aligned substantially out of plane.

[0019] In an embodiment, the cells are formed as a micro-truss lattice.

[0020] In an embodiment, the cells are formed as a crystal lattice structure.

[0021] In an embodiment, at least a plurality of the cells are configured to tessellate.

[0022] In an embodiment, at least a plurality of the cells are configured to tessellate with a cell axis normal to the surface or out-of-plane.

[0023] In an embodiment, at least a plurality of the cells are hexagonal.

[0024] In an embodiment, at least a plurality of the cells are triangular.

[0025] In an embodiment, at least a plurality of the cells are square.

[0026] In an embodiment, at least a plurality of the cells are a combination of octagons and squares co-located in a tessellating pattern.

[0027] In an embodiment, the unitary material is formed to have a relative density substantially between 0.05 and 0.15.

[0028] In an embodiment, the cell shape, size, cell wall thickness, cell width and cell length can be freely varied relative to one another.

[0029] In an embodiment, the ratio of cell wall thickness to cell length is significantly small.

[0030] In an embodiment, the wall has a maximum thickness of substantially 1 mm.

[0031] In an embodiment, the unitary material is a polymer material.

[0032] In an embodiment, the unitary material is an elastomer.

[0033] In an embodiment, the unitary material is elastic-plastic and elastic-brittle.

[0034] In an embodiment, the unitary material is Nylon 11.

[0035] In an embodiment, the unitary material is ST Elastomer.

[0036] In an embodiment, the hollow cell structure is manufactured by Laser Sintering.

[0037] In a second aspect, the present invention may broadly be said to consist in a helmet, comprising an inner impact resistant liner at least partly formed form an impact absorbing structure as claimed in any one of the preceding statements.

[0038] In an embodiment, the helmet further comprises an outer shell formed to substantially cover the inner impact resistant liner.

[0039] In an embodiment, the outer shell is at least partly formed from a composite material.

[0040] In an embodiment, the outer shell is at least partly formed from a thermoplastic material.

[0041] In an embodiment, at least one vent slot is formed in the outer shell.

[0042] In a third aspect, the invention may broadly be said to consist in a method of optimising an impact absorbing structure for improved impact absorption, comprising the steps of:

- **[0043]** (i) choosing a material;
- **[0044]** (ii) forming the material into a stretch-dominated hollow cell structure.

[0045] In an embodiment of the method, substantially all the cells of the hollow cell structure are formed as 2D hollow-cells.

[0046] In an embodiment of the method, substantially all the cells are formed so as to be aligned substantially out of plane.

[0047] In an embodiment of the method, the cells are formed as a micro-truss lattice.

[0048] In an embodiment of the method, the cells are formed as a crystal lattice structure.

[0049] In an embodiment of the method, at least a plurality of the cells are formed so as to tessellate.

[0050] In an embodiment of the method, at least a plurality of the cells are formed so as to tessellate with a cell axis normal to the surface or out-of-plane.

[0051] In an embodiment of the method, the hollow cells are formed to have a topology that propagates radially to a curved surface.

[0052] In an embodiment of the method, at least a plurality of the cells are formed as hexagons.

[0053] In an embodiment of the method, at least a plurality of the cells are formed as triangles.

[0054] In an embodiment of the method, at least a plurality of the cells are formed as squares.

[0055] In an embodiment of the method, at least a plurality of the cells are formed as a combination of octagons and squares co-located in a tessellating pattern.

[0056] In an embodiment of the method, the material is formed in such a manner that the material has a relative density substantially between 0.05 and 0.15.

[0057] In an embodiment of the method, the cells are formed so that the cell shape, size, cell wall thickness, cell width and cell length can be freely varied relative to one another.

[0058] In an embodiment of the method, the cells are formed so that the ratio of cell wall thickness to cell length is significantly small.

[0059] In an embodiment of the method, the cells are formed so that the wall has a maximum thickness of substantially 1 mm.

[0060] In an embodiment of the method, the unitary material is a polymer material.

[0061] In an embodiment of the method, the unitary material is an elastomer.

[0062] In an embodiment of the method, the unitary material is elastic-plastic and elastic-brittle.

[0063] In an embodiment of the method, the unitary material is Nylon 11.

[0064] In an embodiment of the method, the unitary material is ST Elastomer.

[0065] In an embodiment of the method, the hollow cell structure is manufactured by Laser Sintering.

[0066] With respect to the above description then, it is to be realised that the optimum dimensional relationships for the parts of the invention, to include variations in size, materials, shape, form, function and manner of operation, assembly and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention.

[0067] This invention may also be said broadly to consist in the parts, elements and features referred to or indicated in the specification of the application, individually or collectively, and any or all combinations of any two or more said parts, elements or features, and where specific integers are mentioned herein which have known equivalents in the art to which this invention relates, such known equivalents are deemed to be incorporated herein as if individually set forth.

[0068] Therefore, the foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation shown and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

BRIEF DESCRIPTION OF THE FIGURES

[0069] Further aspects of the invention will become apparent from the following description which is given by way of example only and with reference to the accompanying drawings which show an embodiment of the device by way of example, and in which:

[0070] FIGS. **1***a-c* show schematic views of single cells that form part of a cellular solid, showing the joints j and struts s which the cell shares with adjoining cells, the struts s forming surrounding faces that enclose the cells, FIG. **1***a* showing a bending-dominated structure where the joints are locked and the frame bends as the structure is loaded, stretch-dominated structures shown in FIGS. **1***b* and **1***c* where the members carry tension or compression when loaded, giving higher modulus and strength.

[0071] FIGS. **2***a* and **2***b* show plots summarising the difference between stretch and bending-dominated structures in terms of relative modulus E/E_s and relative strength σ/σ_s against relative density p/p_s.

[0072] FIG. **3** shows a perspective view from above, looking downwards and sideways, of a honeycomb hollow cell structure according to an embodiment of the present invention.

[0073] FIG. **4** shows a top view from directly above of the hollow cell structure of FIG. **3**.

[0074] FIG. **5** shows a section of a periodic lattice of hexagonal cells, showing the positions of the joints j and struts s for this stretch dominated structure.

[0075] FIG. **6** shows a perspective view from one side of an inner impact resistant liner of a cycle helmet, the inner impact resistant liner formed from a hollow cell structure similar to that shown in FIGS. **3**, **4**, and **5**, the liner shaped to follow and substantially conform to the top portion of a user's head.

[0076] FIG. **7** shows a perspective view directly from the rear of the inner impact resistant liner of FIG. **3**, with an outer shell covering the inner impact resistant liner, vent slots formed in the outer shell to allow air to circulate within the inner impact resistant liner.

[0077] FIG. **8** shows a perspective schematic view from the front and to one side of a test rig used to test samples of a hollow cell structure.

[0078] FIG. **9** is a graph showing the Head Injury Criterion (HIC) and peak acceleration for a range of test samples.

[0079] FIGS. **10** to **12** show test samples of honeycomb hollow cell structure according to embodiments of the present invention post-testing, each sample having a different relative density, FIG. **10** showing brittle failure at a relative density of 0.111, FIG. **11** showing plastic work at a relative density of 0.143, and FIG. **12** showing linear elastic deformation at a relative density of 0.25.

[0080] FIG. **13** shows a graphical plot of energy per volume vs peak acceleration for a range of test materials and conditions.

[0081] FIG. **14** shows graphical plots of acceleration vs time and force vs displacement for test pieces formed from Nylon 11, Elasto and EPS.

DETAILED DESCRIPTION

[0082] Embodiments of the present invention will now be described with reference to the figures. As outlined above in the background section certain structures are known to be suited for impact absorption. However, it has not been fully understood how these could be structured in order to optimise the impact absorption properties. Outlined below are examples of optimised structures for improved impact absorption. These can be used to form items intended to reduce traumatic brain injury such as bicycle helmets. A method of optimising the structure for improved impact absorption is also described.

[0083] Previously, it has been assumed when assessing energy dissipation in helmets or similar impact absorbing structures that the liner foam is entirely responsible for dissipating the impact energy. The reaction force is determined by the compressive strength of the foam. A foam lattice is assumed to have a flat plateau compressive strength over its densification strain. However, the foam only provides an ideal force-displacement curve if the compressed region is uniform in area. In a curved structure such as a helmet with a substantially ovoid shape, the impact area or crush area is not constant, or planar: the contact area increases with displacement. This causes the reaction force to also increase. Furthermore, if the curved helmet surface impacts another curved surface, the force-displacement gradient will be further reduced. The consequence of this is that a foam liner needs to be thicker in order to provide adequate energy absorption by maintaining the peak acceleration below the safety legislation. The consistent plateau stress of foam limits it's effectiveness as an energy absorbing structure when used as a curved structure (such as for example in a helmet) due to the inherent curved contact surface. The other assumption is that the liner is formed as a unitary structure (that is, without gaps).

[0084] As outlined below, it is possible to create a structure that has a stiffness and strength higher than would otherwise be the case if creating the structure as a unitary structure formed from e.g. foam, for a given relative density p/p_s (where p is the density of the foam and p_s that of the bulk material), and this allows more energy to be dissipated per volume. It is also possible to create a structure that provides an initially high strength when the contact area is very low and which has a gradual post-yield softening proportional to the increase in contact area.

[0085] This is achieved by forming the impact-absorbing structure as a hollow-cell structure which is stretch-dominated, such as for example a micro-truss lattice or out-of-plane honeycomb.

[0086] In this type of structure, the mechanism of deformation involves 'hard' modes such as compression and tension rather than bending. For the same relative density as foam, stretch dominated structures have a comparatively higher modulus and yield stress. This is discussed below.

[0087] In stretch-dominated hollow-cell structures, yield stress occurs due to localised plastic buckling and brittle collapse of the struts. This is also known as the bifurcation point because the structure becomes unstable and a post yield softening regime ensues.

[0088] The stress rises steeply at the densification strain (ϵ_d), which can be calculated from

$$\varepsilon_d = 1 - \left(\frac{\rho}{\rho_s}\right) / \left(\frac{\rho_{crit}}{\rho_s}\right)$$

where p is the density of the structure and p_s that of the bulk material, and where p_{crit}/p_s is the relative density (or volume fraction solid) at which the structure locks up.

[0089] Apart from light weight and ventilation, there are potentially two key benefits of using hollow-cell stretch-dominated structures as an impact absorbing structure. Firstly, the post-yield softening counteracts the area increase of a oval shaped helmet dissipating energy at a more uniform plateau force. Secondly, for a given yield stress, the relative density of a stretch-dominated structure can be much lower providing a greater densification strain and therefore increasing the potential energy dissipated over the same displacement.

[0090] One particular form of stretch-dominated structure is a cellular solid. A cellular solid is one made up of an interconnected network of solid struts or plates that form the edges and faces of cells. Typically the mechanical behaviour of cellular solids can be distinguished by bending-(foam) and stretch-(lattice) dominated mechanisms. The Maxwell stability criterion is used to distinguish between bending- and stretch-dominated structures. Cellular solids can be thought of as joints j, joined by struts s, which surround faces that enclose cells, as shown in FIG. **1**.

[0091] The effect of material in the faces stiffens the structure by a constant. In FIG. **1***a,* when the frame is compressed it has no stiffness or strength in the loading direction. If the joints are frozen (locked) the frame in FIG. **1***a* will bend as the structure is loaded and can be called a bending-dominated structure. In the stretch-dominated structures in FIG. **1***b* and **1***c,* the members carry tension or compression when loaded, giving higher modulus and strength. This is shown in FIGS. **2***a* and **2***b*, which summarise the difference between stretch and bending-dominated structures in terms of relative modulus E/E_s and relative strength σ/σ_s against relative density p/p_s. In the structures in FIGS. **1***a* and **1***b,* the structure carries self-stress, which means the struts carry stress even though the structure carries no external load (this is prevalent in FIG. **1***c*). For example if the vertical strut is shortened, it pulls the other struts into compression.

[0092] The two key benefits of using stretch-dominated structures as impact absorbing structures are as follows: firstly, the post-yield softening counteracts the area increase of a oval shaped helmet dissipating energy at a more uniform plateau force, and; secondly, for a given yield stress, the relative density of a stretch-dominated structure can be much lower providing a greater densification strain and therefore increasing the potential energy dissipated over the same displacement. This is discussed in detail in Appendix E.

[0093] In the embodiments described below, the impact absorbing structure is formed as a lattice—i.e. from interconnected hollow cells. Also, in order to simplify manufacture, a periodic lattice is described (i.e. the cells are regularly shaped and sized). Hexagonal cells were used as this shape has the largest number of side and which will still regularly tessellate—i.e. without requiring a second shape to fill gaps (for example, if a regular octagon lattice was chosen, a regular square shape would be inherent). Hexagonal honeycomb cells have the highest number of cell walls for each cell, and therefore the lowest connectivity. which has been shown to be effective in high specific strength.

[0094] Other shapes (e.g. triangles and squares) will also tessellate, but have fewer sides. However, the number of sides has been shown to correlate positively with the dissipated energy per unit mass of the structure (SAE).

[0095] The types of lattice structure described above can be generally described as 2D hollow cell structures. Where these are referred to in this specification, this indicates a three-dimensional structure, with the cells of the structure formed in such a way as to have depth, but so that when viewed at a certain angle the cells will have a uniform or identical cross-section at any position perpendicular to the view angle. That is, a cross section taken at any position would be identical to one taken at any other position. For example, a honeycomb cell structure viewed in plan or from directly above will provide a uniform cross-section at any depth through the cells. This can be translated to curved shapes such as the ovoid shape necessary to form a helmet, for example. When viewed at any particular point looking inwards towards the centre of the interior, the cells will appear identical to those viewed from another point also looking inwards towards the centre of the interior.

[0096] It should be noted that other types of structure, formed as stretch dominated structures, will also provide the same advantages. For example, 3-D stretch-dominated structures such as a truss structure or a structure similar to a crystal lattice structure can also be formed, which will provide the same impact absorption benefits.

[0097] As shown in FIGS. **3** and **4** the hollow cell stretch dominated structure **1** used in a first embodiment of the present invention is a unitary material formed into a honeycomb structure. It is preferred that the cells are hexagonal, as hexagonal cells **2** such as those used in the hollow cell structure **1** tessellate and so form a structure where each cell wall is common with an adjacent cell. A grid formed from hexagonal cells also provides a balance between overall grid density (the total amount of material), and the layout/location of the cell wall material and the empty space which the cell walls encompass. That is, tessellation is achieved with the cell walls distributed over a given planar or curved surface as evenly as possible, with no overloaded focal areas, or over-large uncovered areas.

[0098] Hexagonal honeycomb can be thought of as a stretch dominated structure by applying the Maxwell criterion:

$$M_{honeycomb}=30-3\times12+6=0$$

[0099] FIG. **4** shows a section of a periodic lattice of hexagonal cells, showing the positions of the joints j and struts s for this stretch-dominated structure.

[0100] In practical use, and when experiencing an impact, the honeycomb structure will experience both in-plane and out-of-plane loading. Stretch-dominated structures such as the hexagonal hollow cell structure **1** are generally used in a planar or sheet form, either flat or curved, and the impacts received by the hollow cell structure have a primary force component directed into the plane perpendicular to the point of impact. That is, in the opposite direction to out-of-plane arrow **3** in FIG. **1**. However, as noted there will frequently be a force component at an angle to this, and the theory behind this is discussed in detail in Appendix C.

[0101] The impact absorption properties of a stretch-dominated structure such as the hollow cell structure **1** are determined by the material used to form the structure, and the specific geometry of the structure: i.e. cell size, cell wall thickness, cell width and cell length as shown in FIG. **4**.

[0102] If used in an impact-absorbing structure such as a helmet, the lattice is designed so that the axial part of the cell is always perpendicular to the surface of the head. This is important as the crush strength of honeycomb significantly diminishes as the impact angle increases away from perpendicular to the axial part of the cell.

[0103] If the cell dimensions are known, a value of hollow cell relative density (or volume fraction solid) can be calculated using the equation shown below:

$$\frac{p^*}{p_s}=\left\{\frac{\frac{h}{l}+2}{2*\left(\frac{h}{l}+\sin\theta\right)\cos\theta}\right\}\frac{t}{l}=\frac{2}{\sqrt{3}}\frac{t}{l}\left(1-\frac{1}{2\sqrt{3}}\frac{t}{l}\right)=\frac{2}{\sqrt{3}}\frac{t}{l}$$

[0104] For the particular embodiments of the honeycomb structure **1** of the invention described, h is assigned a value of 1, θ has a value of 30 (degrees), and the ratio of cell wall thickness (t) to cell length (l) is significantly small.

[0105] A proposed use for the hollow cell structure **1** would be in bicycle helmets. The material used to create the hollow cell structure **1** in this embodiment is Nylon 11 and ST Elastomer. This is a readily available material, which is lightweight, easily formed and malleable, and is therefore suitable or at least analogous to the type of material that would be used for mass-manufactured helmets.

[0106] The hollow cell structure **1** was manufactured by additive manufacturing. The process is briefly described in Appendix B.

[0107] Tests were carried out as detailed in Appendix A, and Appendix D, with the objective of determining how varying the relative density of the honeycomb hollow cell structure **1** (this type of structure also known as 'out-of-plane honeycomb') would affect the hollow cell structure **1** when subjected to impact testing. As shown in Appendix A, the relative density was varied between 0.1 and 0.33 by changing the cell size (s) from between a minimum of 6 mm and a maximum of 20 mm, with the wall thickness maintained at a constant 1 mm.

[0108] The results indicate that an acceptable range of optimum relative densities lies between 0.125 and 0.175 for this material and for the particular cell/lattice size and shape used during testing, for the reasons outlined in the 'Results from Impact Testing' section of Appendix A, and Appendix D. The results indicate that the cell size, cell wall thickness, cell width and cell length can be freely varied relative to one another, and as long as the relative density lies between 0.03 and 0.17, then the structure will provide optimised impact absorption properties.

[0109] As outlined in the 'background' section, helmet design is generally a trade-off between the overall weight of a helmet, and the impact-absorbing properties. Based on the results of the tests detailed in Appendix A and Appendix D, a helmet such as helmet **5** shown in FIGS. **3** and **4**, constructed using a structure the same as or similar to the inner impact resistant liner **7** (formed as a hexagonal hollow-cell stretch-dominated structure) covered by an outer shell **6**, formed from nylon 12 or a similar material, will provide a lightweight structure capable of meeting and exceeding the relevant standards for impact absorption, in particular BS EN 1078. The test results indicate the elastic-plastic honeycomb has a 3× greater EPV than a typical expanded polystyrene helmet. This is clearly shown by the plots of the experimental results shown in FIGS. **13** and **14**.

[0110] The reasons can be summarised as follows:

- **[0111]** Stretch dominated structures rely on 'hard' modes of deformation through compression and tension. A long plateau force is achieved, as the stress response softens as the area increases.
- **[0112]** Stretch dominated structures have higher specific strength for the same relative density, so it is possible to increase the densification strain, as the relative density is lower in a stretch dominated structure.
- **[0113]** All stretch dominated structures have similar mechanical responses. Therefore, an impact-absorbing structure can be formed from any appropriate material and at any shape and size (e.g. all honeycomb topology and materials), and will still provide the advantages as outlined above.

[0114] As briefly noted above, where 2D hollow cells are referred to in this specification, this indicates a three-dimensional structure, with the cells of the structure formed in such a way as to have depth, but so that when viewed at a certain angle the cells will have a uniform or identical cross-section at any position perpendicular to the view angle. That is, a cross section taken at any position would be identical to one taken at any other position. For example, a honeycomb cell structure viewed in plan or from directly above will provide a uniform cross-section at any depth through the cells. It should also be noted that when a structure is referred to as 'stretch-dominated', this is according to the Maxwell criterion as outlined herein. It should further be noted that the phrases 'relative density' and 'volume fraction solid' essentially have the same meaning and are used interchangeably within this specification.

APPENDIX A - TEST METHODOLOGY AND RESULTS

A range of hollow cell structures were manufactured from nylon 12 by Selective Laser Sintering. Each sample had a cross-sectional area of 100cm^2, and a depth of 10cm.

Testing was carried out using a drop test. An aluminium head form weighing 7.21 Kg was dropped a vertical distance of 1.48m onto the samples. The sample was released using a handle, and was directed using guides on a test rig as shown in figure 8.

A single axis accelerometer was placed in the head form, at the Centre of Mass. The sampling rate was set to 1000Hz in LabView.

It was found that relative densities between 0.125 and 0.23 would pass the relevant British Standards under this test. At relative densities around 0.15, the peak acceleration is reduced to 53% of the maximum threshold. As the relative density increases, so too does the consistency of results. The HIC was calculated by post-processing software Diadem©, the HIC value has a similar trendline to the peak acceleration.

According to the results (see the table below, and Figure 9), for a honeycomb of 0.15 relative density, an injury of AIS level 3 (moderate) would occur, whilst the risk of serious head injury would be minimalised to 5%. At the British Standards threshold an injury of AIS level 4 (severe) would occur, whilst the risk of serious injury would be increased to 24%.

The results suggest an optimum relative density between 0.125 and 0.175. Figures 10, 11, and 12 show the deformation mode for relative densities 0.111, 0.143 and 0.25 respectively. Sample 8 shows fracture couple with plastic deformation, which seems to be the most effective form of deformation.. No permanent deformation mode could be seen for the relative density of 0.33 suggesting only linear behaviour occurred.

The Head Injury Criterion (HIC) is used to measure the likelihood of head injury due to impact measurements. HIC is currently the most widely used computational predictor of head injury. The HIC plots resultant translational acceleration of a head vs time duration at that acceleration.

Hexagonal cellular structure optimisation

The impact performances of an elastomer and elastic-plastic hexagonal honeycomb structure in the out-of-plane were investigated by varying the relative density and cell height. These results were compared with foam sections cut from a conventional bicycle helmet liner.

A kerbstone shape was used as the impacting projectile in a drop weight system. The geometric parameters of the honeycomb was varied in each impact: cell width, cell wall thickness, cell height and cell liner. Each honeycomb sample had a constant cross sectional area of 100 mm×100 mm, and was placed so the cell walls were always axial to the z direction shown in the test rig schematic. Polycarbonate sheets of 0.375 mm, 0.5 mm, 1 mm and 2 mm thickness were laid on top of the sample to represent the shell. For testing of EPS materials, a helmet was sectioned into nine parts, each having a surface area approximately the same as the honeycomb structures. As the EPS sections were not flat, a hard Polyfiller was moulded to provide a curved support. The impact speed for the kerbstone anvil is 4.57 ± 0.1 ms^{-1} with a mass of 5 kg.

A drop tower was used to replicate the 1078 standard shock absorption test. High speed photography at 2000 frames per second was used to trace the impact of the anvil and film the response of the honeycomb structure. The high speed camera was triggered using a light gauge 15 mm before impact. The impactor anvil was connected to a rod that is suspended in a rigid cage, ensuring that it can only travel in the z axis. When the anvil and rod impact, the rigid cage continues to move freely until contact is made with dampers.

Since foams theoretically have a constant plateau stress, the force increases proportionally to the displacement.

Commonly used head injury criterion were used to analyse the likelihood of potential brain damage. The head injury criterion (HIC) is a measurement of magnitude and duration of deceleration, above 750 - 1000 $s{\cdot}g^{2.5}$ represents a 16% risk of severe injury.

The table below represents the 'best' structures s found by testing different material samples.

Material & Structure	**Time Period** (ms)	**HIC** ($sg^{2.5}$)
Elastomer honeycomb	2	54
	5	247
	10	431
EPS	2	18
	5	70
	10	148
Nylon 11 honeycomb	2	5
	5	21
	10	44

The table above lists the HIC values for EPS foam, Elastomer honeycomb and elastic-plastic (PA11) honeycomb for 2, 5 and 10 ms. The three variations showed an unusually low HIC value with PA11 delivering the lowest HIC value at 44. A higher HIC value is predicted when the helmet is conditioned to +50°C and −20°C given in the safety legislation. The relationship between magnitude of acceleration and duration has been shown to be significant in causing brain damage. The Wayne State Tolerance curve (WSTC) was used to plot magnitude against duration for an impact, a threshold curve in red describes the fatal tolerance limit of the brain. Standard impact profiles for Elastomer, PA11 honeycomb and EPS foam are plotted on the WSTC. All curves are below the fatal threshold. Interestingly, EPS is consistently the furthest away from the threshold, suggesting that a slowly graduating force displacement curve could be more effective in preventing brain damage. However, its duration of acceleration is nearly double compared to PA11.

The Energy absorbed Per Volume (EPV) is the amount of kinetic energy lost from the projectile across the maximum displaced volume of the structure, this was measured using digital image correlation. At a higher EPV, the structure dissipates or stores more kinetic energy over the same volume. This is also equivalent to the integral of the stress-strain curve used by Gibson and Ashby to create a continuous energy absorption diagram.

For an EPV equivalent to EPS, the optimal peak acceleration is more than 60% lower, highlighting the suitability of this type of structure and material for a helmet. It is clear that above 0.15 relative density the elastic-plastic (Nylon 11) honeycomb structure was too stiff and responded with extremely high peak accelerations, for example at 0.33 density, a peak acceleration of 650 g was obtained. However, at around 0.1 density (in blue) the peak acceleration was similar to EPS but with a three times greater EPV. The response of Nylon 11 honeycomb was both plastic buckling and fracturing of the cell walls.

Laser sintered PA 12 showed both strain rate and temperature dependence, confirming that the polymer was amorphous. Above energy density 0.37 J/mm2 the mechanical properties worsened at low, medium and high strain rate. /3 transition could be found at approximately 1000 s^{-1} and -50° C, between the T_g and /3 there is a natural temperature dependence.

Elastomer and elastic-plastic material was produced as a honeycomb through Additive Manufacturing as outlined in Appendix B. The structure was impacted in the out-of-plane under safety legislation impact conditions and compared with sections of expanded polystyrene cut from a bicycle helmet. The elastomer honeycomb showed elastic buckling deformation, whilst the elastic-plastic honeycomb saw plastic buckling through localised plastic hinges and fracture of the cell wall. The elastomer honeycomb and EPS foam showed very similar force-displacement curves, where force is proportional to displacement. However, the elastic-plastic honeycomb attained a higher initial force that was maintained across the sample, which meant that the impact energy was dissipated at a lower peak load over a shorter duration. The acceleration-time profiles for the three different mechanisms were analysed by the Head Injury Criterion, where the elastic-plastic honeycomb achieved the lowest value of predicted head injury and was well within the Wayne State Tolerance Curve. When plotting the energy absorption per volume (EPV) against peak acceleration, elastic-plastic honeycomb was found to have a 3x greater EPV than the expanded polystyrene helmet.

Summary of testing data

Sample Number	Material	Geometry								Weight	Theoretical Testing conditions					Accelerometer data
		Cell Width (mm)	Free wall length: l (mm)	node width: h (mm)	web thickness: t (mm)	t/l	relative density: ρ*/ρ	expansion angle: θ (deg)	cell wall height: b (mm)	Mass: (g)	Height dropped: (m)	Impact velocity: (m/s)	Impact energy (J)	Ambient Temperature (deg)	Radius of striking edge (mm)	Peak acceleration (m/s2)
1.01	Nylon 11	32	18.5	18.5	1	0.05	0.063	30	20	11.25	1.2	4.62	53.361	22	15	412.2
1.02	Nylon 11	30	17.3	17.3	1	0.06	0.067	30	20	11.7	1.2	4.62	53.361	22	15	118.2
1.03	Nylon 11	28	16.2	16.2	1	0.06	0.071	30	20	15.0	1.2	4.62	53.361	22	15	110.4
1.04	Nylon 11	26	15.0	15.0	1	0.07	0.077	30	20	13.5	1.2	4.62	53.361	22	15	131.0
1.05	Nylon 11	24	13.9	13.9	1	0.07	0.083	30	20	14.5	1.2	4.62	53.361	22	15	96.7
1.06	Nylon 11	22	12.7	12.7	1	0.08	0.091	30	20	15.9	1.2	4.62	53.361	22	15	140.4
1.07	Nylon 11	20	11.5	11.5	1	0.09	0.100	30	20	17.5	1.2	4.62	53.361	22	15	101.6
1.08	Nylon 11	18	10.4	10.4	1	0.10	0.111	30	20	19.5	1.2	4.62	53.361	22	15	94.8
1.09	Nylon 11	18	10.4	10.4	1	0.10	0.111	30	20	19.5	1.2	4.62	53.361	22	15	109.2
1.1	Nylon 11	18	10.4	10.4	1	0.10	0.111	30	20	19.5	1.2	4.62	53.361	22	15	102.3
1.11	Nylon 11	18	10.4	10.4	1	0.10	0.111	30	20	19.5	1.2	4.62	53.361	22	15	114.3
1.12	Nylon 11	20	11.5	11.5	1	0.09	0.100	30	15	17.5	1.2	4.62	53.361	22	15	114.2
1.13	Nylon 11	22	12.7	12.7	1	0.08	0.091	30	15	15.9	1.2	4.62	53.361	22	15	143.5
1.17	Nylon 11	18	10.4	10.4	1	0.10	0.111	30	20	19.5	1.2	4.62	53.361	22	15	186.9
1.18	Nylon 11	16	9.2	9.2	1	0.11	0.125	30	20	21.9	1.2	4.62	53.361	22	15	197.0
1.19	Nylon 11	14	8.1	8.1	1	0.12	0.143	30	20	25.0	1.2	4.62	53.361	22	15	259.1
1.2	Nylon 11	12	6.9	6.9	1	0.14	0.167	30	20	29.2	1.2	4.62	53.361	22	15	256.5
1.21	Nylon 11	10	5.8	5.8	1	0.17	0.200	30	20	35.0	1.2	4.62	53.361	22	15	235.6
1.22	Nylon 11	8	4.6	4.6	1	0.22	0.250	30	20	43.8	1.2	4.62	53.361	22	15	387.4
1.23	Nylon 11	6	3.5	3.5	1	0.29	0.333	30	20	58.4	1.2	4.62	53.361	22	15	697.9
1.24	Nylon 11	34	19.6	19.6	2	0.10	0.128	30	20	20.6	1.2	4.62	53.361	22	15	237.8
1.25	Nylon 11	38	21.9	21.9	2	0.09	0.105	30	20	18.4	1.2	4.62	53.361	22	15	134.5
1.26	Nylon 11	42	24.2	24.2	2	0.08	0.095	30	20	16.7	1.2	4.62	53.361	22	15	143.3
1.01	ST Elastomer	26	15.0	15.0	1	0.07	0.077	30	20	14.3	1.2	4.62	53.361	22	15	857.6
1.02	ST Elastomer	24	13.9	13.9	1	0.07	0.083	30	20	15.0	1.2	4.62	53.361	22	15	612.2
1.03	ST Elastomer	22	12.7	12.7	1	0.08	0.091	30	20	16.7	1.2	4.62	53.361	22	15	530.0
1.04	ST Elastomer	20	11.5	11.5	1	0.09	0.100	30	20	17.5	1.2	4.62	53.361	22	15	476.3
1.05	ST Elastomer	18	10.4	10.4	1	0.10	0.111	30	20	20	1.2	4.62	53.361	22	15	299.7
1.06	ST Elastomer	16	9.2	9.2	1	0.11	0.125	30	20	21.9	1.2	4.62	53.361	22	15	326.7
1.07	ST Elastomer	14	8.1	8.1	1	0.12	0.143	30	20	25.0	1.2	4.62	53.361	22	15	195.5
1.08	ST Elastomer	12	6.9	6.9	1	0.14	0.167	30	20	29.1	1.2	4.62	53.361	22	15	182.5
1.09	ST Elastomer	10	5.8	5.8	1	0.17	0.200	30	20	34.9	1.2	4.62	53.361	22	15	175.2
1.1	ST Elastomer	8	4.6	4.6	1	0.22	0.250	30	20	49.7	1.2	4.62	53.361	22	15	191.4

Appendix B - Additive Manufacturing

Additive Manufacturing provides a fast process for creating complex geometries that would be impossible or highly expensive compared to conventional subtractive/formative methods. Additive Manufacturing works by directly building computer aided designs by depositing material in a layer by layer process. Laser Sintering is a form of Additive Manufacturing whereby a thin layer of powder is deposited onto a preheated build area, a CO_2 laser is then used to selectively consolidate the powder. Laser Sintering was chosen as the process to manufacture the hexagon structures because of the comparatively higher mechanical properties. Laser Sintering is still a relatively young manufacturing technique and requires a specific thermal window to consolidate, so only a selection of materials were available. However, the microstructure can be varied by using a range of different processing conditions.

The mechanical properties of Laser Sintering can in part be attributed to the degree of particle melt (DPM), which defines the quantity variations in the consolidation of sintering.

Appendix C - Discussion of in-plane and out-of-plane mechanics

In-plane

In compression the cell walls initially bend, giving linear elasticity. But when a critical stress is reached the cells begin to collapse: in elastomeric materials collapse is by the elastic buckling of the cell walls and so is recoverable; in materials with a plastic yield point it is by the formation of plastic hinges at the section of maximum moment in the bent members; and in brittle materials it is by brittle fracture of cell walls; the last two are not recoverable. Eventually, at high strains, the cells collapse sufficiently that opposing cell walls touch (or broken fragments pack together) and further deformation compresses the cell wall material itself. This gives the final, steeply rising portion of the stress-strain curve called densification.

Out-of-plane

In compression the cell walls initially compress axially, so that the Young's modulus varies linearly with the relative density and the Poisson's ratio is that of the solid. In elastomeric material the cell walls will buckle, once the elastomer is unloaded the honeycomb recover the buckling (typically there is a hysteresis effect as energy is loss through heat). Ductile materials have a yield point, after which permanent deformation occurs through localised plastic hinges (buckling of cell wall). Ceramic material typically fail through fracture of cell walls.

The honeycomb material used to gather the test results was a laser sintered viscoelastic polyamide and elastomer. The plasticity and fracture of polymers is dependent on temperature and strain rate. At lower temperatures ($T << T_g$) polymers are linear-elastic to fracture. At higher temperatures ($T \approx 0.8T_g$) the mode of failure changes from brittle to ductile, characterised by a yield point. *Failure-mechanisms diagrams* are used to summarize the plastic and fracture response in an amorphous polymer and elastomer respectively.

For an elastomer if the cell walls are constrained parallel to the cell face, the elastic buckling load is determined from Euler's buckling of columns formula

$$P_{critical} = \frac{KE_s}{(1-v_s^2)}\frac{t^3}{l}$$

the constant K is an end constraint factor, typically equal to 4. If the cell height is large compared with l (> 3l), then K is independent of the cell height. Walls with single thickness t will maintain the same load after they reach their initial collapse load P_{crit}, the total collapse load is $6P_{crit}$ divided by the load bearing cross sectional area:

$$\sigma_{el} = 5.2 \cdot E_s \left(\frac{t}{l}\right)^3$$

where σ_{el} is the elastic buckling stress, 5.2 is the value found from the cell geometry of regular honeycomb where v_s is assumed to be 0.3.

For elastic-plastic materials, Wierzbicki found that in compression the lowest plastic collapse strength (and so most likely to occur) is due to plastic buckling. Plastic buckling dissipates energy by a permanent rotation of the cell wall. Wierzbicki derived an approximation based on an isolated cell wall. The plastic collapse stress for regular hexagons with uniform wall thickness t is

$$\sigma_{pl} = 6.6 \cdot \sigma_{ys} \left(\frac{t}{l}\right)^{\frac{5}{3}}$$

where σ_{ys} is the yield stress.

In brittle materials if the net section stress σ_3 exceeds the tensile fracture strength σ_{fs} of the cell wall solid, the honeycomb will fail in tension. Brittle solids are stronger in compression than in tension because compressive stresses close the small cracks or flaws that ultimately determine the strength. But even though they close, the flaws can shear and the shearing concentrates stress in a way which still leads to fracture. The result is that the crushing strength σ_{cr} of a cell wall in the out-of-plane was found experimentally to be 12 times greater than failure strength

$$\sigma_{cr} = 12 \cdot \sigma_{fs} \frac{t}{l}$$

Bending-dominated structures such as foam are analysed through energy-absorbing diagrams. The energy absorbed per unit volume W, is given by the area under the stress-strain curve in graph (a) below.

In an elastomer material, the failure mechanism is elastic buckling and so most of the energy is stored elastically. In plastic and brittle materials, the energy is stored elastically up to the yield point, after which energy is then dissipated through plastic bending or fracture of cell walls. In graph (a) as we move along the strain axis, the amount of energy absorbed W (dissipated or stored) increases with little change in peak stress σ_p. At densification the peak stress rises drastically with little change in W. Optimal use of the foam's energy absorbing capabilities is achieved by exploiting the shoulder of this curve, i.e: absorb as much energy as possible for a given peak stress. The envelope of shoulders for different foam densities is plotted in graph (b). The envelope describes a relationship between W and σ_p to pick the optimum relative density, at a particular strain rate and temperature.

Modelling of the energy-absorbing diagrams can be applied for both elastomer and elastic-plastic materials where the linear elastic region is very small. The modelling process is identical between elastomer and elastic-plastic material, the final equation is in the form

$$\frac{W_{max}}{E_s} = \frac{\sigma D}{E_s}\left(1 - 6.26\left(\frac{\sigma D}{E_s}\right)^{1/2}\right)$$

Where *σD* is the densification stress, which for a bending-dominated structure is assumed to be at the same level as the plateau stress. *Wmax* is the maximum energy that can be absorbed. The equation developed above show that $\frac{W_{max}}{E_s}$ depends only on $\frac{\sigma_D}{E_s}$ and $\frac{\sigma_D}{E_s}$, that is the diagram describes all elastomeric foams of all densities and material properties.

Appendix D - Material characterisation and hexagonal cellular structure optimisation

The response of a honeycomb material is critical if used for energy absorbing applications as it can be subjected to various impact speeds and temperature conditions. An investigation was undertaken to understand the strain rate and temperature dependence across different Laser Sintered processing conditions. The material investigated was Polyamide 12 and all tests were in compression.

	ED1	**ED2**	**ED3**	**ED4**
Laser Power (*W*)	19	21	23	21
Scan Spacing (*mm*)	0.25	0.25	0.25	0.25
Scan Speed (*mm/s*)	2500	2500	2500	1500
ED (J/mm^2)	0.03	0.034	0.037	0.056

Four energy densities (ED) (J/mm^2) were investigated, as outlined in the table above. The processing ED was controlled by the EPSRC Centre for Innovative Manufacturing at Nottingham University using an EOS P100 machine. ED was altered through laser power and scanning speed. To obtain consistency in parts, the orientation and position of each build was uniform. Initially compressive characterisation was performed over a range of strain rates to investigate the relationship to energy density in axial compression. One of the materials, ED2 was then subjected to quasi-static compression tests at temperatures from -60°C to 60°C. All experiments were repeated three times and the mean specimen response is presented. The mass and volume of each material produced at each energy density was measured five times to calculate the respective mean physical density. The mass was found using an analytical balance with a readability of 0.01 mg, the volume was measured from a micrometer of readability 0.001 mm.

Low rate compressions (0.001, 0.01 and 0.1 s^{-1}) was undertaken using an Instron testing machine. For these low strength materials machine compliance is not an issue, and true strain control from the cross head is used; however, an extensometer was also attached to the loading anvils close to the specimen to verify the specimen extension. The total resisting force on the specimen as a function of time was obtained from a 100 kN load cell with a stated precision of ± 0.05 N. Medium strain rate (1 and 10 s^{-1}) was obtained through a custom built hydraulic load frame that was used to access strain rates between 1 and 50 s^{-1}. A linear Variable Differential Transformer (LVDT) measured the displacement of the sample; the signal suffered no significant distortion from load cell ringing and other machine noise. High strain rate (>1000 s^{-1}) compression experiments were performed using a Split Hopkinson Pressure Bar (SHPB). For the SHPB system, the input and output bars were made of silver steel. The input bar is 1 m long, and gauged halfway along its length; the output bar was 500 mm long and gauged 50 mm from the bar-specimen interface. Reflected and transmitted gauge signals were used to derive the stress-strain relationship using the standard analysis. Petroleum jelly was used as the lubricant. For non-ambient quasi-static experiments, nitrogen gas and heated filaments were used to obtain the necessary chamber temperature. Each sample was pre heated/cooled for between 5-10 minutes at the testing temperature to ensure thermal equilibrium.

The high energy density samples were found to have a coarse surface area, showing large surface porosity. This porosity is likely to weaken the material since there is a lower volume fraction of solid.

Appendix E - Mechanics of Stretch-dominated Structures

An example of a stretch-dominated structure is a micro-truss lattice or out-of-plane honeycomb, where the mechanism of deformation involves ‘hard’ modes such as compression and tension rather than bending . The graph below shows a stress-strain curve of a stretch dominated structure with an elastic-plastic material. Yield stress occurs due to localised plastic buckling and brittle collapse of the struts. This is also known as the bifurcation point because the structure becomes unstable and a post yield softening regime ensues.

The stress rises steeply at the densification strain, which can be calculated from the following equation.

$$\varepsilon_d = 1 - \left(\frac{\rho}{\rho_s}\right) \Big/ \left(\frac{\rho_{crit}}{\rho_s}\right)$$

The post-yield softening counteracts the area increase of the oval shaped helmet dissipating energy at a more uniform plateau force. For example line x in the graph below is the post yield softening seen in the experimental results, whereas line y shows the area increase of a particular head shape. By multiplying the stress decrease and area increase one attains a constant plateau force, which is beneficial in reducing peak force and thickness required to absorb the energy.

Because stretch dominated structures rely on hard modes of deformation, the stress at yield is much higher compared to foams (bending dominated structures). This can be seen in the diagram below, where relative modulus is the ratio between bulk material strength and structural strength at a particular relative density.

Therefore for a given yield stress, the relative density of a stretch-dominated structure can be much lower. According to the equation below, the densification strain is inversely proportional relative density

$$\varepsilon_d = 1 - \left(\frac{\rho}{\rho_s}\right) \Big/ \left(\frac{\rho_{crit}}{\rho_s}\right)$$

Where ρ is the density of the structure and ρ_s that of the bulk material, and where ρ_{crit}/ρ_s is the relative density (or volume fraction solid) at which the structure locks up, which is typically 0.71. The graph below describes experimental results confirming the relationship above.

Therefore for a required yield stress, stretch dominated structures require a lower relative density, and according to the equation above attain a greater densification strain. Because the amount of energy absorbed is the product of stress and strain, increasing strain would mean increasing the amount of energy absorbed (essentially stretch dominated structures require less material and so have longer displacement before the cell walls densify increasing potential energy absorbed.)

1. An impact absorbing structure, comprising a unitary material formed as a stretch-dominated hollow cell structure wherein at least a plurality of cells are configured to tessellate with a cell axis normal to the surface or out-of-plane and the unitary material has a relative density substantially between 0.05 and 0.15.

2. An impact absorbing structure as claimed in claim **1** wherein substantially all the cells of the hollow cell structure are 2D hollow-cells.

3. An impact absorbing structure as claimed in claim **2** wherein substantially all the cells are aligned substantially out of plane.

4. An impact absorbing structure as claimed in claim **1** wherein the cells are formed as a micro-truss lattice.

5. An impact absorbing structure as claimed in claim **1** wherein the cells are formed as a crystal lattice structure.

6. (canceled)

7. (canceled)

8. An impact absorbing structure as claimed in claim **1** wherein at least a plurality of the cells are hexagonal.

9. An impact absorbing structure as claimed in claim **1** wherein at least a plurality of the cells are triangular.

10. An impact absorbing structure as claimed in claim **1** wherein at least a plurality of the cells are square.

11. An impact absorbing structure as claimed in claim **1** wherein at least a plurality of the cells are a combination of octagons and squares co-located in a tessellating pattern.

12. (canceled)

13. (canceled)

14. An impact absorbing structure as claimed in claim **1** wherein the ratio of cell wall thickness to cell length is significantly small.

15. An impact absorbing structure as claimed in claim **14** wherein the wall has a maximum thickness of substantially 1 mm.

16. An impact absorbing structure as claimed in claim **1** wherein the unitary material is a polymer material.

17. An impact absorbing structure as claimed in claim **16** wherein the unitary material is an elastomer.

18. An impact absorbing structure as claimed in claim **16** wherein the unitary material is elastic-plastic and elastic-brittle.

19. An impact absorbing structure as claimed in claim **16** wherein the unitary material is selected from the group consisting of Nylon 11 and ST Elastomer.

20. (canceled)

21. (canceled)

22. A helmet, comprising an inner impact resistant liner at least partly formed from an impact absorbing structure as claimed in claim **1**.

23. A helmet as claimed in claim **22** further comprising an outer shell formed to substantially cover the inner impact resistant liner.

24. A helmet as claimed in claim **22** further comprising an outer shell formed to substantially cover the inner impact resistant liner wherein the outer shell is at least partly formed from a composite material.

25. A helmet as claimed in claim **22** further comprising an outer shell formed to substantially cover the inner impact resistant liner wherein the outer shell is at least partly formed from a thermoplastic material.

26. A helmet as claimed in claim **22** further comprising an outer shell formed to substantially cover the inner impact resistant liner wherein at least one vent slot is formed in the outer shell.

27-50. (canceled)

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