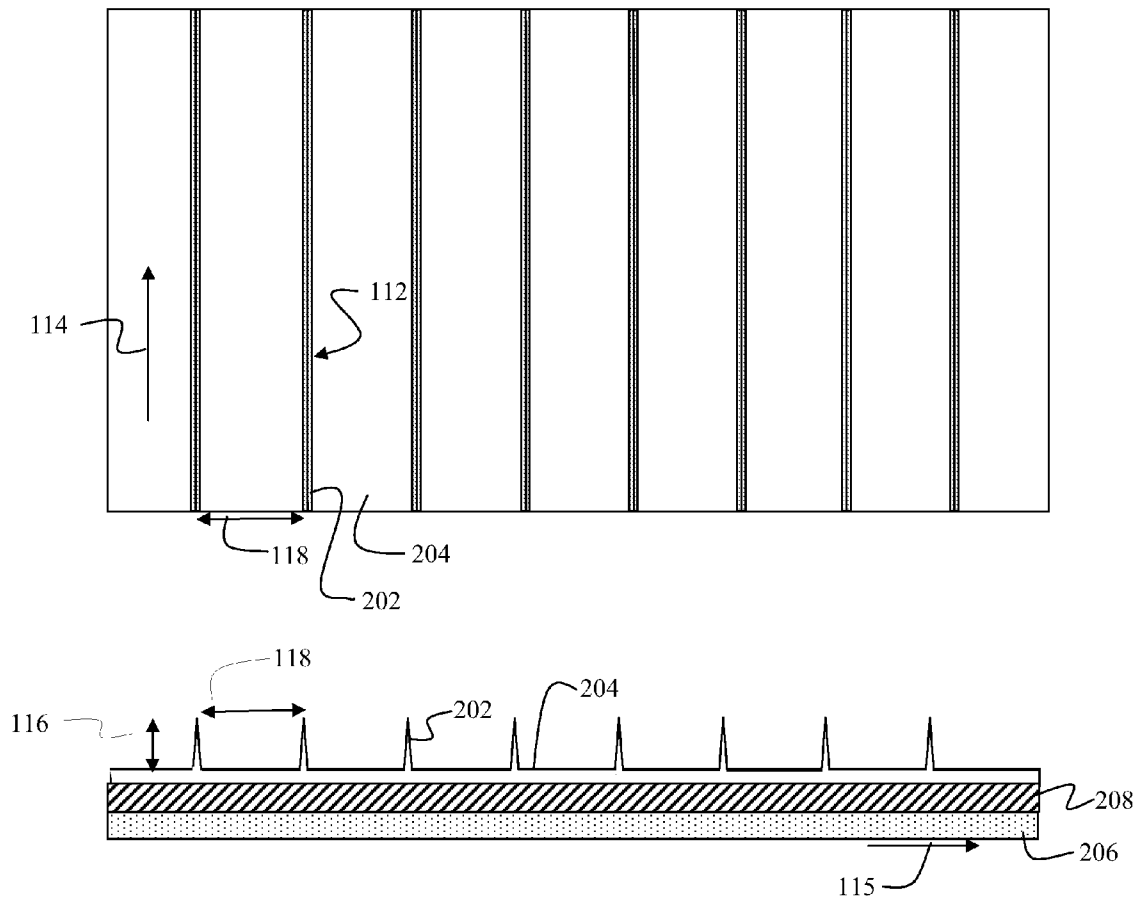




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(19) **United States**(12) **Patent Application Publication**
Rawlings et al.(10) **Pub. No.: US 2014/0174642 A1**(43) **Pub. Date: Jun. 26, 2014**(54) **ELASTOMERIC RIBLETS****Publication Classification**(71) Applicant: **The Boeing Company**, Chicago, IL
(US)(72) Inventors: **Diane C. Rawlings**, Bellevue, WA (US);
Alan G. Burg, Des Moines, WA (US)(73) Assignee: **The Boeing Company**, Chicago, IL
(US)(51) **Int. Cl.**
B64C 21/10 (2006.01)
B29C 65/48 (2006.01)(52) **U.S. Cl.**
CPC **B64C 21/10** (2013.01); **B29C 65/4855**
(2013.01)USPC **156/219**; 156/60(21) Appl. No.: **14/170,308**(22) Filed: **Jan. 31, 2014****Related U.S. Application Data**(62) Division of application No. 12/566,927, filed on Sep.
25, 2009.(57) **ABSTRACT**

An array of aerodynamic riblets incorporates a high elongation elastomeric layer having spaced tips and optionally a protective cladding. The elastomeric layer may be adhered to an aerodynamic surface directly or as an appliqué in combination with one or more of an adhesive layer, one or more supporting polymer layers and a metal foil layer.



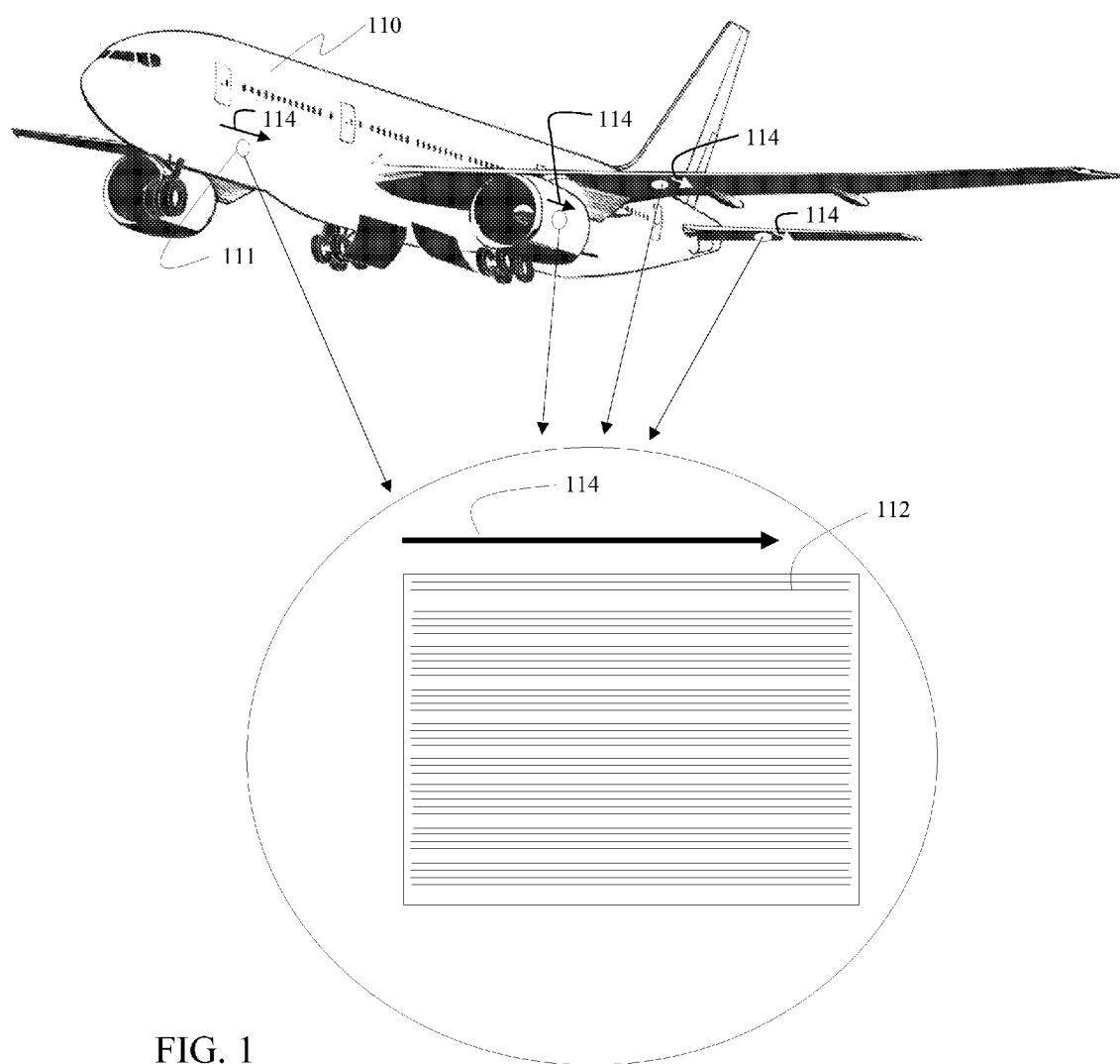


FIG. 1

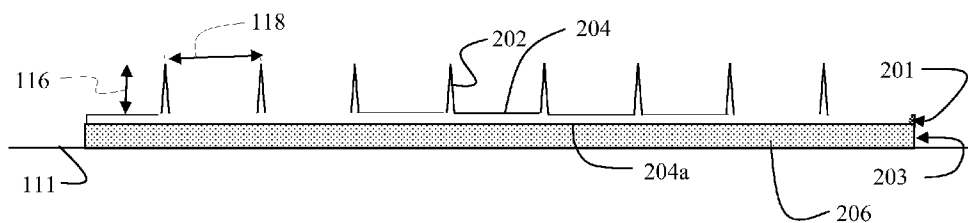


FIG. 2A

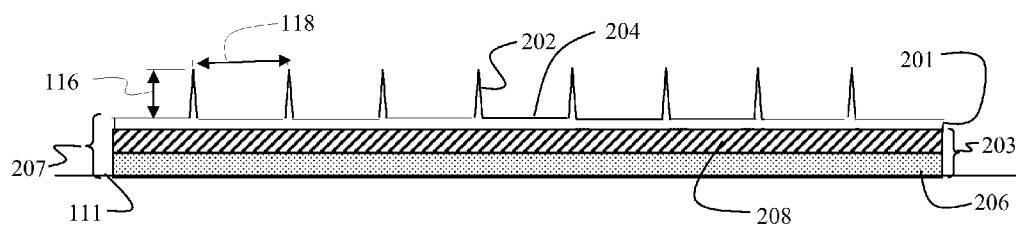


FIG. 2B

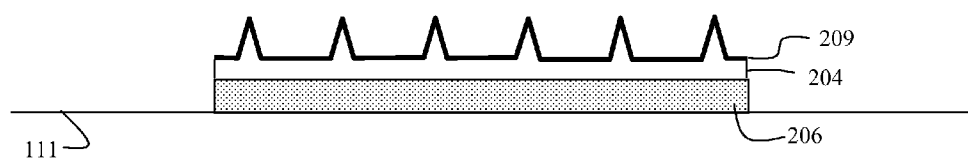


FIG. 2C

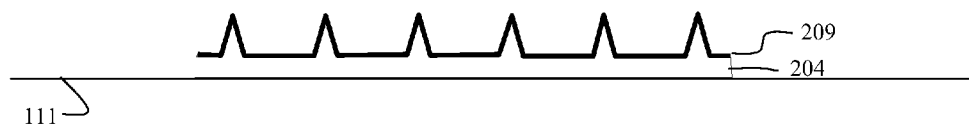


FIG. 2D

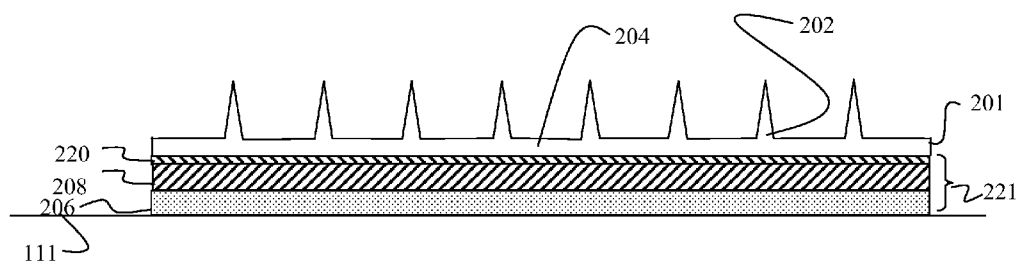


FIG. 2E

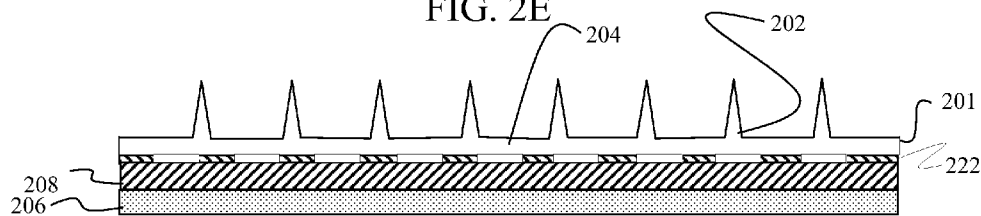


FIG. 2F

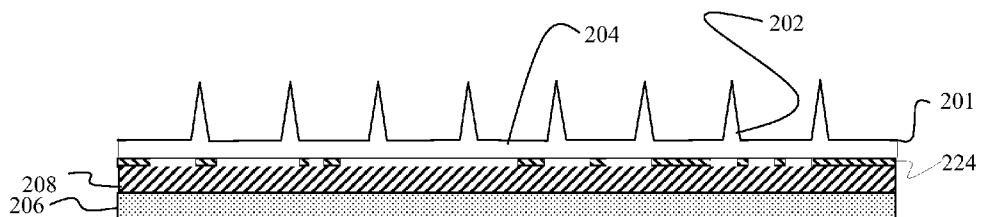


FIG. 2G

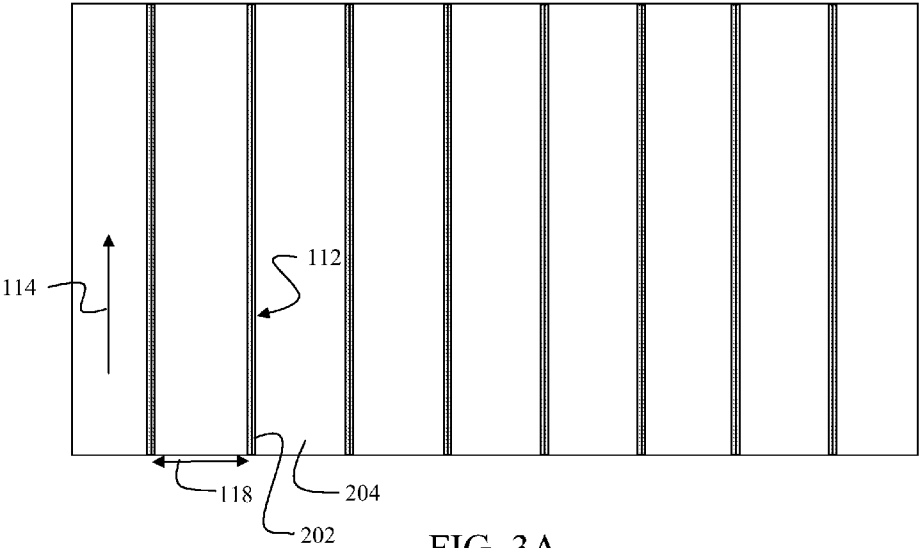


FIG. 3A

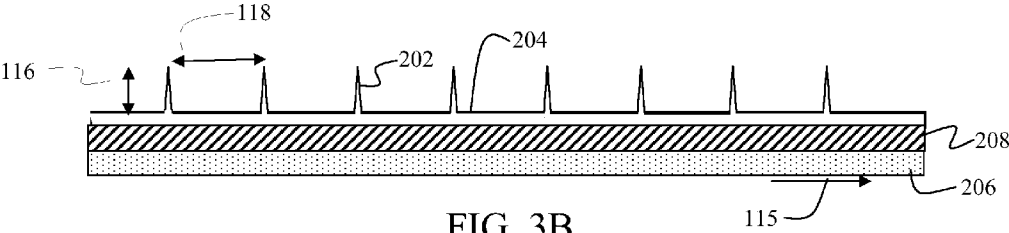


FIG. 3B

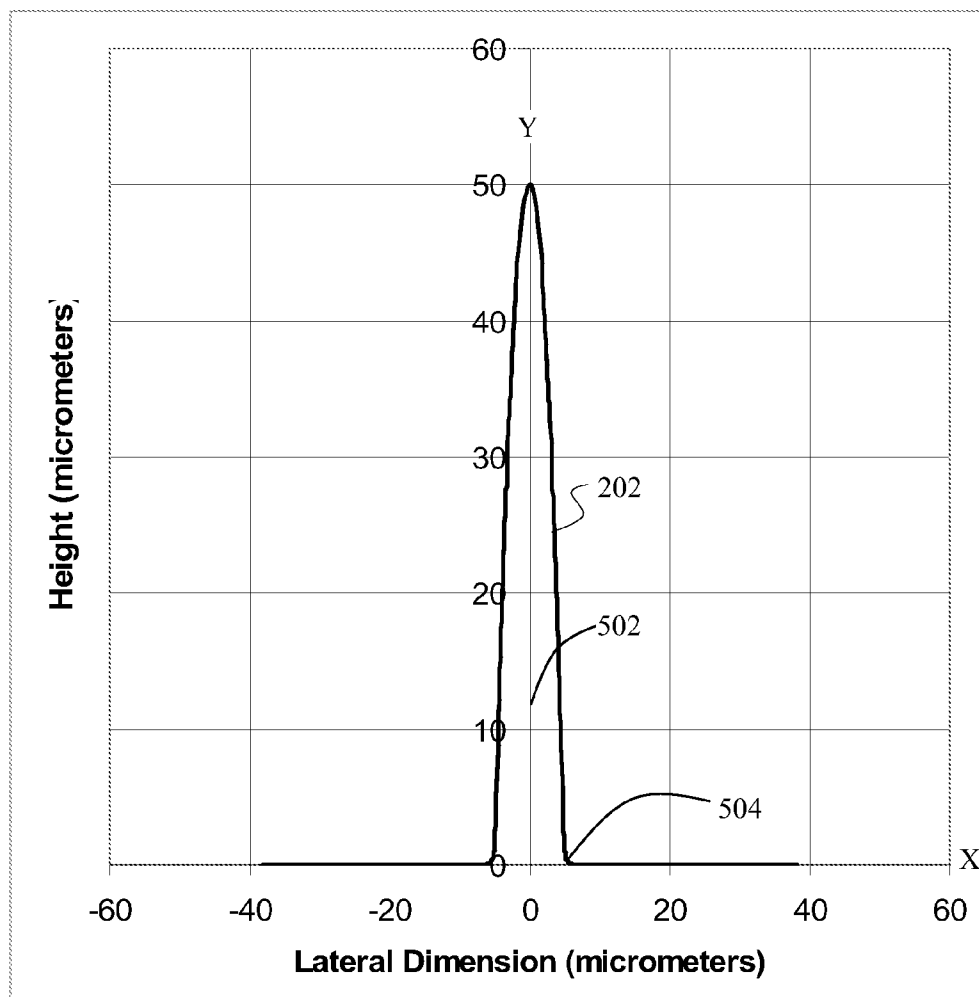


FIG. 4

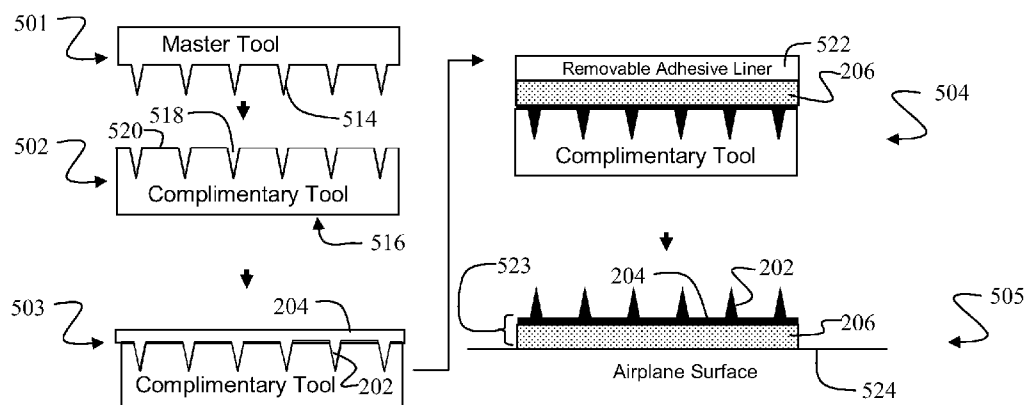


FIG. 5A

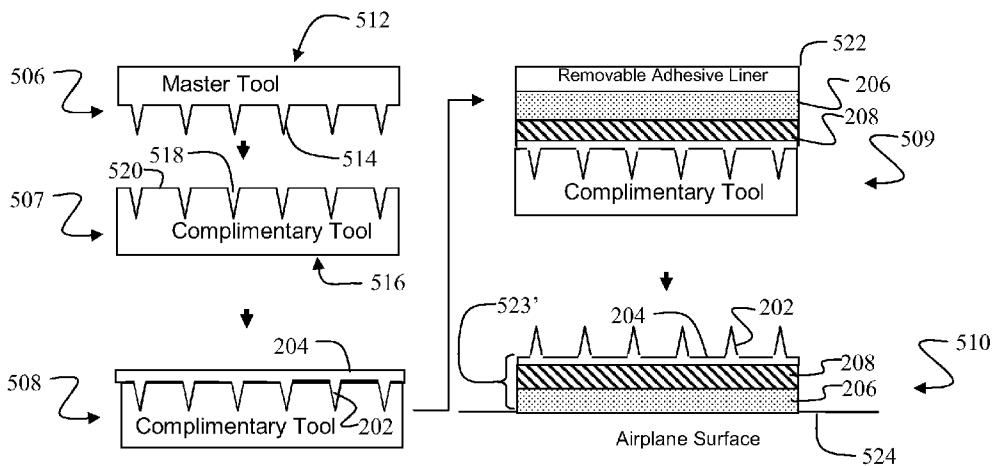


FIG. 5B

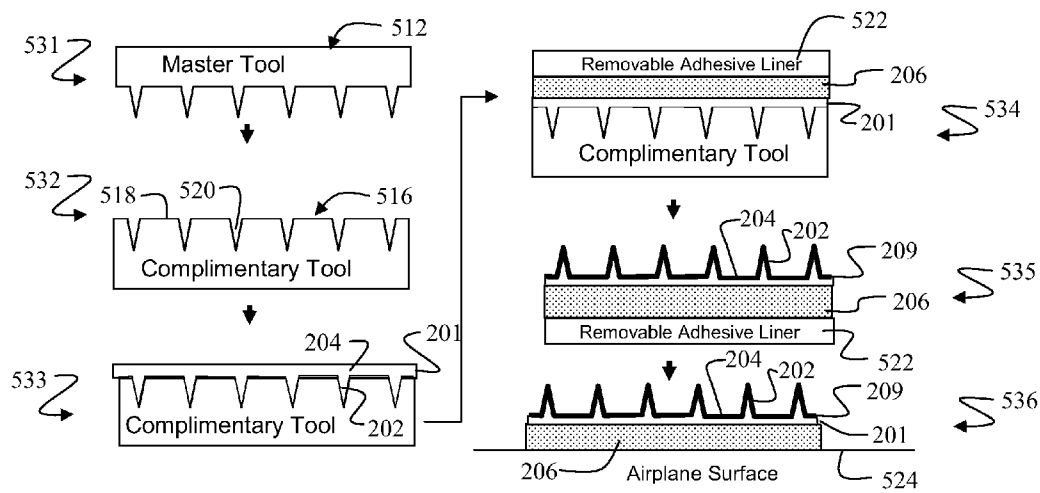


FIG. 5C

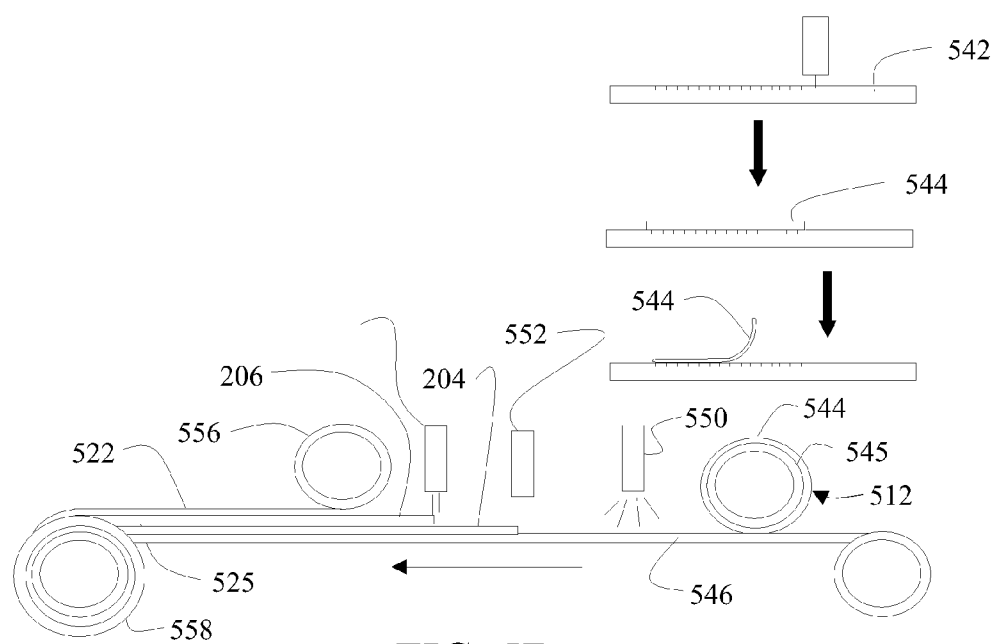


FIG. 5D

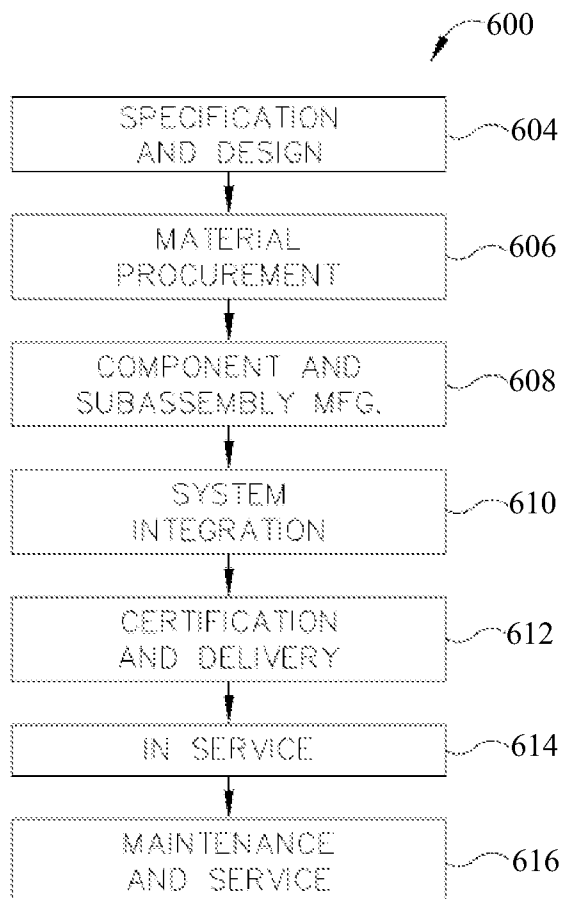


FIG. 6

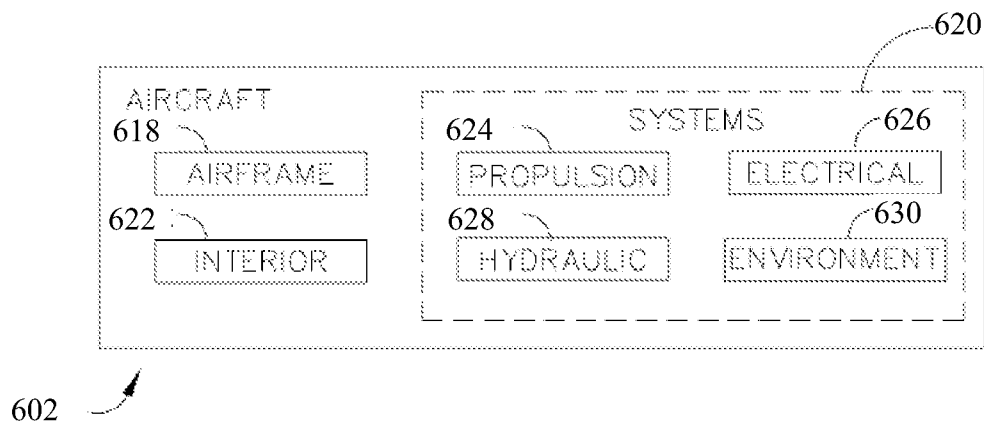


FIG. 7

ELASTOMERIC RIBLETS

REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 12/566,927 entitled Elastomeric Riblets filed on Sep. 25, 2009 by inventors Diane C. Rawlings and Alan G. Burg, the disclosure of which is incorporated herein by reference. This application is copending with U.S. patent application Ser. No. 14/051,271 entitled Rigid Tipped Riblets filed on Oct. 10, 2013, U.S. patent application Ser. No. 14/070,183 entitled Amorphous Metal Riblets filed on Nov. 1, 2013 and U.S. patent application Ser. No. 14/105,027 entitled Shape Memory Riblets filed on Dec. 12, 2013, all having a common assignee with the present application, the disclosures of which are incorporated herein by reference.

BACKGROUND INFORMATION

[0002] 1. Field

[0003] Embodiments of the disclosure relate generally to the field of surface geometries for aerodynamic improvements to aircraft or surfaces having a flow interface and more particularly to embodiments and fabrication methods for use of high elongation elastomeric materials to form aerodynamic riblets or other high-aspect-ratio surface microstructures requiring high durability.

[0004] 2. Background

[0005] Increasing fuel efficiency in modern aircraft is being accomplished through improvement in aerodynamic performance and reduction of structural weight. Recent advances in the use of microstructures such as riblets on aerodynamic surfaces have shown significant promise in reducing drag to assist in reducing fuel usage. Riblets have various forms but advantageous embodiments may be ridge-like structures that can reduce drag in areas of a surface of an aircraft exposed to a turbulent boundary layer. The riblet ridges tend to inhibit turbulent motions involving lateral velocities, thus reducing the intensity of small-scale streamwise vortices in the lower part of the boundary layer, and thus reducing skin-friction drag.

[0006] In certain tested applications riblets have been pyramidal or inverted V shaped ridges spaced on the aerodynamic surface to extend along the surface in the direction of fluid flow. Riblet structures have typically employed polymeric materials, typically thermoplastic or thermoset polymers. However in service use such as on an aircraft aerodynamic surface, polymers are relatively soft thus reducing the durability of the surface. Existing solutions with polymeric tips may readily deform hundreds of percent with fingernail pressure and may be unrecoverable since the thermoplastic polymer (fluoropolymers such as THV or FEP for example) has “yielded” or the thermoset (structural epoxy for example) has fractured at relatively low strain. Thermoplastic or low-elasticity thermosets deform readily with a fingernail cross wise to the riblet ridges/grooves, either by plastic deformation or by cavitation and cracking. Such structures may be undesirable in normal service use on an aircraft or other vehicle. Additionally certain aircraft surfaces are required to withstand interactions with various chemicals including Skydrol®, a hydraulic fluid produced by Solutia, Inc.

[0007] The practicality of riblets for commercial aircraft use would therefore be significantly enhanced with a riblet structure providing increased durability and aircraft fluids compatibility.

SUMMARY

[0008] Exemplary embodiments provide a construction for an array of riblets comprising a first layer composed of high elongation elastomeric riblets having tips and a surface layer. A second layer is provided for adherence to a surface.

[0009] In various embodiments the high elongation elastomeric material has capability for elongation of 300-3000% (including the categories of high elongation elastomers (300-500%) and elastomers with ultra high elongation defined herein to be in the range of 500% to 3000% collectively referred to herein as high elongation elastomers) and is selected from the set of polymers and copolymers (typically block copolymers) and shape memory polymers of epoxy, polyurethane, polyurea, polyolefin, ethylene propylene, silicone, polybutadiene, polychloroprene, chlorinated polyethylene and fluorosilicones, fluorinated polyurethanes, silylated polyurethanes, and other hybrid polymers that include polyhedral oligomeric silsesquioxane (POSS). The elastomeric polymer may be filled or unfilled. Fillers may include submicron pigmentation, UV-stabilizers and absorbers, tougheners, dispersion aids or flow aids including materials such as titanium dioxide, organic dyes, diamond powder, fluoropolymers or POSS. In certain embodiments, a submicron (molecular or nano-scale) “cladding” on the riblet surface or overlaying the tips and surface layer is selected from either organic and inorganic moieties or hybrids. Organic cladding is selected from the set of thin films of parylene, PTFE, polyamide (Nylon), polyimide and polyethylene. Inorganic cladding may be thin films or multilayer films including amorphous diamond like coatings (DLC), metals such as aluminum, chromium, gold, platinum, rhodium or nickel, and oxides such as silicon dioxide, aluminum oxide, indium tin oxide, tin oxide, titanium oxide, zinc oxide, and nitrides such as boron nitride and silicon nitride. Hybrid cladding might be organic-inorganic sol gels or pendant POSS or organo-metallic monolayers, or nanolayers such as metal-polymer or ceramic-metal or ceramic-polymer nanolayer. The cladding may be self-assembled or deposited via one of many different processes including sputtering, plasma deposition or dip coating. In certain embodiments, a polymer support layer selected from the set of polyurethanes, polyetheretherketone (PEEK), polyetheretherketoneketone (PEKK), polyetherketone (PEK), polyimide, polyamide, polyolefin, polyester, chloro- or fluoro-polymers such as polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP) or fluorinated polyurethane, polyethylene terephthalate (PET), silicones, epoxy, polysulfide, ethylene propylenediene, fluorosilicone, and fluoroelastomers may be deposited on the high elongation elastomeric layer. Multilayers of polymers, magnetic materials and/or metal films/foils or non-continuous metal or magnetic layers may also be deposited on the elastomeric layer to provide additional properties or functions. In yet other embodiments, an adhesive layer is deposited on the polymer support layer to form a multi layer appliqué, said adhesive layer adhering the appliqué to a surface of the aircraft.

[0010] The embodiments disclosed are fabricated in an exemplary method by forming a master tool having protuberances or depressions/indents corresponding to a desired riblet array and forming a complementary tool from the master tool. A high elongation elastomeric layer having tips and a surface layer is deposited in the complimentary tool. An adhesive layer is then deposited to from an appliqué, which is removed

from the complementary tool and the high elongation elastomeric appliqué is adhered to an aerodynamic surface.

[0011] In a further alternative methods for web processing, the complimentary tool is a roll-to-roll tool and a polymer layer, a metallic layer or a combination of polymer and metallic layers, such as an LSA, is deposited intermediate the adhesive layer and the elastomeric layer. A thin film coating or modification of the riblet exterior surface for decorative appearance and/or to provide electrical conductivity/resistance (to mitigate static charging), UV reflectivity or absorption (to improve long term durability in high solar/high altitude environments) and/or to reduce transport across the surface to improved oxidation and/or fluid resistance may be sputtered (or otherwise deposited) onto the complimentary tool prior to deposition of the high elongation elastomeric layer or deposited onto the high elongation elastomeric layer after removal from the complimentary tool. In modifications to these methods, ion implantation or chemical surface modification may be to form a layer or modified surface on the riblets.

[0012] The features, functions, and advantages that have been discussed can be achieved independently in various embodiments of the present invention or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is an isometric view of a portion of an aerodynamic surface such as a wing or fuselage skin showing exemplary riblets extending in the flow direction;

[0014] FIG. 2A is a lateral section view looking into the flow direction of a first embodiment for high elongation elastomeric riblets;

[0015] FIG. 2B is a lateral section view of a modification of the embodiment of FIG. 2A with an additional support layer;

[0016] FIG. 2C is a lateral section view of a modification of the embodiment of FIG. 2A with surface modification or cladding over the elastomer;

[0017] FIG. 2D is a lateral section view of a modification of the embodiment of FIG. 2C without an adhesive layer for direct thermoplastic bonding;

[0018] FIG. 2E is a lateral section view of an embodiment employing a multilayer Lightning Strike Appliqué LSA;

[0019] FIG. 2F is a lateral section view of an embodiment employing a multilayer structure with a Wide Area Lightning Diverter Overlay (WALDO) metallic layer;

[0020] FIG. 2G is a lateral section view of an embodiment employing a multilayer structure incorporating electrical circuits;

[0021] FIG. 3A is a top view of a portion of an aerodynamic surface employing riblets of the embodiment as shown in FIG. 2B;

[0022] FIG. 3B is a section view comparable to FIG. 2B for reference with the features of FIG. 3A;

[0023] FIG. 4 is a detailed view of one riblet tip of the embodiment of FIG. 2A with a parabolic profile;

[0024] FIG. 5A is a flow diagram of processing steps for an exemplary method of fabrication of riblets of the embodiment of FIG. 2A;

[0025] FIG. 5B is a flow diagram of processing steps for an exemplary method of fabrication of riblets of the embodiment of FIG. 2B;

[0026] FIG. 5C is a flow diagram of processing steps for an exemplary method of fabrication of riblets of an alternative embodiment of FIG. 2C with deposition of a cladding;

[0027] FIG. 5D is a schematic representation of roll processing elements and steps for use with an exemplary fabrication method as described with respect to FIG. 5B;

[0028] FIG. 6 is a flow diagram describing use of the elastomer riblet embodiments disclosed herein in the context of an aircraft manufacturing and service method; and

[0029] FIG. 7 is a block diagram representing an aircraft employing the elastomer riblets with embodiments as disclosed herein.

DETAILED DESCRIPTION

[0030] The embodiments disclosed herein provide riblets constructed with high elongation elastomeric materials that may be impacted by ground support equipment, ground support personnel or environmental hazards such as hail without permanent deformation/damage. These embodiments also allow an optimized structural design of riblets providing the capability for them to be thinner, lower weight, and more aerodynamically efficient. An exemplary embodiment of elastomeric riblets having a structure as will be described in greater detail subsequently is shown as a portion of an aerodynamic surface for an aircraft as shown in FIG. 1. The aircraft 110 employs a structure with a surface 111, shown enlarged, having multiple substantially parallel riblets 112 arranged parallel to the flow direction as represented by arrow 114. For the exemplary embodiment shown, the height dimension 116 perpendicular to the surface 111 is approximately 0.002 inch while the spacing 118 between the riblets is approximately 0.003 inch as shown for example in FIG. 2A. Spacing or distribution of the riblets in an array may vary depending on and be predetermined by the fluid dynamic properties of the air, water or other fluid for which the application of riblets is employed. While described herein with respect to an aircraft, the embodiments disclosed are equally applicable to cars, boats, windmills, rotor blades, engine nacelles, intake ducts, ventilation systems or other surfaces with associated hydrodynamic or aerodynamic flow. The aerodynamic surface is typically, without limitation, curved and may be a portion of a wing, an engine nacelle, a control surface, a fuselage or other suitable surface. Therefore flexibility and conformability of the riblets and any structure supporting and affixing the riblets to the surface may be required. While described herein with respect to an aircraft aerodynamic surface the embodiments disclosed herein are equally applicable for drag reduction on surfaces of other aerospace vehicles such as, without limitation, missiles or rockets and other vehicles such as cars, trucks, buses and trains moving in a gaseous fluid, commonly air, or on boats, submarines, hydrofoils, fluid flow conduits or other surfaces exposed to liquid fluid flow.

[0031] The embodiments disclosed herein recognize and provide the capability for riblets that may resist various impacts and/or other forces that may cause damage to the riblets affecting both aerodynamic performance and appearance and potentially ice accumulation and also affecting the riblet lifetime, i.e. the durability. Further, certain of the different advantageous embodiments provide a multi-layer structure that may have a support layer and a plurality of riblet tips located on or extending from the support layer. The tips which form the riblets may be fabricated from high elongation elastomeric materials providing recovery after deform-

ing with elongation in a range of 300% to 3000% (including the categories of high elongation elastomers (300-500%) and elastomers with ultra high elongation defined for our purposes to be in the range of 500% to 3000%).

[0032] For the exemplary usage of embodiments disclosed herein on an aircraft, a combination of shear, compression and tensile forces due to various maintenance and damage events are anticipated. Larger lateral deformations with a cross-wise gouging motion with a maintenance tool or edge of an object are anticipated. Even a fingernail will cause very high elongations for the tip of the riblet. A gouge is one of the most damaging of actions expected because of the narrowness of the object that is scraping along the surface. The stiffer the riblet, the less deformation and therefore, the more the forces will be tensile and compression. This is because the riblets are very closely spaced and any object larger than the spacing of approximately 0.003 inch will be applying load only to the tip of the riblet until it has deformed enough to either gain access to the side of the riblet or enough compression force and adhesion to create shear. Engineered elastomers that have both a high initial modulus and a high or ultra high elongation are possibly the best options for this application. The higher the modulus, the less elongation is required, and the higher the recoverable elongation, the lower the acceptable modulus. The range of % elongation as described herein is wide to accommodate varying requirements with both the tensile and compressive modulus and the temperature at which the damage event occurs. The amount of deformation is dependent on the stiffness or modulus of the elastomer, the surface frictional/adhesion forces, the thickness and the specific elastomers molecular structure (Note that the modulus is a function of temperature—stiffer when cold). The rate of deformation due to a slipped tool or gouge can be very fast, >>500 inches per minute (in exemplary cases 2,000-4,000 inches per minute). The faster the rate, the higher the modulus (because the polymers need some time to fully respond to the load), but the ultimate elongation may be the same. Initial modulus at room temperature for exemplary tested embodiments is about 5000-15000 psi and as the deformation increases the modulus changes to 300-400 psi.

[0033] A first embodiment for high elongation elastomeric riblets is shown in FIG. 2A as a multilayer construction. Individual tips **202** of the riblets protrude from a surface layer **204** to provide a first layer **201** of the multilayer construction. The protruding riblets and continuous surface layer are formed by casting or deposition, as will be described in greater detail subsequently, of the high elongation elastomer such as a urethane similar to PRC PR 1664D used in an exemplary embodiment. In various embodiments the high elongation elastomer may be selected from the set of polymers and copolymers (typically block copolymers) and shape memory polymers of epoxy, polyurethane, polyurea, polyolefin, ethylene propylene, silicone, polybutadiene, polychloroprene, chlorinated polyethylene and fluorosilicones, fluorinated polyurethanes, perfluoropolyethers, silylated polyurethanes, and other hybrid polymers that include polyhedral oligomeric silsesquioxane (POSS). The elastomeric polymer may be filled or unfilled. Fillers may include submicron pigmentation, UV-stabilizers and absorbers, tougheners, dispersion aids or flow aids including materials such as titanium dioxide, organic dyes, diamond powder, fluoropolymers or POSS. For the embodiment shown in FIG. 2A a second layer **203** created by an adhesive layer **206** is deposited on a bottom **204a** of the surface layer **204**. This adhesive

could be one of many possibilities including, without limitation, pressure sensitive acrylic adhesives, polyurethane pressure sensitive adhesives, polysulfide, epoxy, thermoplastics, thermally-reactive adhesives, silicone adhesives, or fluorosilicone adhesives.

[0034] In alternative embodiments, a supporting polymer layer **208** engages the surface layer **204** intermediate the surface layer **204** and adhesive layer **206** as shown in FIG. 2B as a portion of the second layer. The supporting polymer layer **208** may be a polymer film or other suitable material. In certain embodiments polyetheretherketone (PEEK), polyetherketoneketone (PEKK), polyetherketone (PEK), polyimide, polyamide, polyolefin, polyester, chloro- or fluoropolymers such as polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP) or fluorinated polyurethane, polyethylene terephthalate (PET), silicones, epoxy, polysulfide, ethylene propylenediene, fluorosilicone, and fluoroelastomers may be employed as the supporting polymer layer. The supporting polymer, adhesive and/or other elements in the second layer provide additional resilience (or physical support for thin metal layers or for other function such as dielectric isolation for lightning protection or for electrical circuits) and the ability to adhere to the surface and may be prepared as a prefabricated appliqué on which the high elongation elastomer of the surface layer and tips is deposited or formed.

[0035] FIG. 2C is an additional alternative embodiment wherein the high elongation elastomer is coated with a surface cladding **209**. For the embodiment shown, cladding **209** is a transparent but ultra-violet (UV) absorptive coating such as zinc oxide or indium tin oxide. The cladding may also provide alternative functionality such as UV reflectivity, electrical conductivity/resistivity to dissipate or conduct p-static charges (<500 Ohm/square) or provide coloration or other decorative effects. In various alternative embodiments to achieve the desired functionality, the cladding is selected from either organic and inorganic moieties or hybrids. Organic cladding is selected from the set of thin films of parylene, PTFE, polyamide (Nylon), polyimide and polyethylene. Inorganic cladding may be thin films or multilayer films including amorphous diamond like coatings (DLC), metals such as aluminum, chromium, gold, platinum, rhodium or nickel, and oxides such as silicon dioxide, aluminum oxide, indium tin oxide, tin oxide, titanium oxide, zinc oxide, and nitrides such as boron nitride and silicon nitride. Hybrid cladding may be organic-inorganic sol gels or pendant POSS or organo-metallic monolayers, or nanolayers such as metal-polymer produced by Modumetal 1443 N. Northlake Way, Seattle, Wash. 98103, or ceramic-metal or ceramic-polymer nanolayer. The cladding may be self-assembled or deposited via one of many different processes including sputtering, plasma deposition or dip coating. The elastomeric surface layer **204** may then be adhered to a surface using an adhesive layer **206** or directly as described with respect to FIG. 2D.

[0036] It is anticipated that many embodiments of the protective cladding **209** will not have elongation properties similar to the high elongation elastomer tips **202** and surface layer **204** and will fracture within the elastic limit of the high elongation elastomer. Cracking of the cladding (which may be on the nanoscale) under loading which is within the recoverable deflection of the high elongation elastomer is expected and upon elimination of the load and upon recovery of the elastomer to near original shape, UV protection or other

function of the cladding, which remains adhered to the elastomeric tips and surface layer even though cracked, will be substantially maintained.

[0037] If the deposition of the cladding is done to the riblet itself the riblet surface may be treated prior to deposition by plasma treatment or corona treatment. Alternatively, energetic process such as sputtering or other vacuum processes with e-beam or ion beam enhancement or by a process such as ion implantation may be employed. These energetic processes drive atoms of the cladding into the surface of the elastomer and also create very reactive surfaces for bonding/attachment. Sputtered metal films adhere well but have a relatively low cohesive strength. Sputtered films of oxides or multilayered coatings can be very well adhered and also have high internal strength as long as material compatibilities are taken into account. In certain embodiments addition of layers in the cladding may be accomplished to reduce stresses or as intermediate bonding or strain isolation layers.

[0038] In yet other embodiments, enhancing the adhesion may be accomplished by components in the elastomer either as fillers or as molecular entities that cause a reactive and/or submicron/nano textured surface. Examples are POSS fillers and pendant POSS groups incorporated into the polymer chains.

[0039] However, in further alternative embodiments, the layer(s) (composition and thickness) of the cladding may be designed to be structurally compatible and minimize the interfacial stress on elongation) using FEM, thin film and molecular design tools.

[0040] The cladding **209** may provide resistance to electromagnetic effects such as static charge dissipation which the riblet surface alone may not provide thereby substituting for or supplementing LSA foil appliques and similar materials as subsequently described for the embodiment in FIG. 2E. The cladding **209** may also be multilayer or interference film which may provide color and decorative effects.

[0041] In the form shown in FIG. 2A, 2B or 2C, the embodiment may be fabricated as a multilayer appliqué **207** as shown in FIG. 2B, including tips **202**, surface layer **204**, supporting polymer layer **208** and adhesive layer **206** which can then be adhered to the aerodynamic surface using the adhesive layer **206**.

[0042] In alternative embodiments, the surface layer **204** may be directly adhered to or deposited on the aircraft surface **111**. FIG. 2D demonstrates an embodiment similar to that described with respect to FIG. 2C however, no adhesive layer is employed. In alternative embodiments, supporting polymer layer **208** may employ a thermoplastic (or thermosetting resin such as an epoxy) in a configuration similar to that disclosed in FIG. 2B without an adhesive layer which allows direct bonding to the aircraft surface **111** with application of heat.

[0043] For the embodiment shown in FIG. 2E, a multilayer structure **221** incorporating a metal mesh/inductive grid, capacitive grid, or foil **220** such as aluminum, a supporting polymer layer **208** such as PEEK and an adhesive layer **206** supports the high elongation elastomer layer **201**. The metal foil **220** provides a conducting material for lightning strike protection in an exemplary aircraft usage of the embodiment. The foil, polymer and adhesive multilayer structure **221** may be comparable to a current Lightning Strike Appliqué (LSA) employed for composite aircraft structural surfaces such as that disclosed in U.S. patent application Ser. No. 11/611,023 to Rawlings filed on Dec. 14, 2006 entitled LIGHTNING

STRIKE PROTECTION METHOD AND APPARATUS. The metal layer in alternative embodiments may be discontinuous and may provide a structure of metallic diverter strips **222** for a Wide Area Lightning Diverter Overlay (WALDO) Ser. No. 11/229,911 to Rawlings et al. filed on Sep. 19, 2005 entitled WIDE AREA LIGHTNING DIVERTER OVERLAY as shown in FIG. 2F or integrated electronic circuits **224** within the multilayer structure as disclosed in companion application Ser. No. 112/612,576 to Rawlings filed on Dec. 19, 2006 entitled LARGE AREA CIRCUITRY USING APPLIQUES, as shown in FIG. 2G, the disclosures of which are incorporated herein by reference.

[0044] FIGS. 3A and 3B show top and side views of the embodiment as disclosed in FIG. 2B as an example of the riblet arrays resulting from the disclosed embodiments. The riblets **112** formed by the tips **202** expand longitudinally along surface layer **204** in the flow direction **114**. The thin surface layer **204** provides for flexibility in adhering to curvature having tangents substantially perpendicular to the riblets **112** as represented by arrow **115**. The properties of the high elongation elastomer used in the embodiments described allows flexibility in deformation of the appliques to match surface contours of the aircraft or other surface on which the riblet arrays are applied.

[0045] Shaping of the riblet profile for equalized stress over the height of the riblet to maximize the benefit of the high elongation elastomer is described in detail in application Ser. No. 12/566,907, attorney docket no. 09-0156 entitled Structurally Designed Aerodynamic Riblets. As shown in FIG. 4, individual riblet tips **202** for the embodiments disclosed herein may incorporate a parabolic shape cross section having an equation $y=px^2+h$ with respect to a y-axis **502** where h is the riblet height **116** and the thickness of the riblet $t=2x$ at an elevation of y. Determination of the actual shape parameter, p, may be dependent on the high elongation elastomer selected for the riblets and the desired rigidity of the riblets. For the exemplary embodiment with $h=50$ microns a value of $p=-2$ was selected for broad applicability to numerous materials with single machined tooling. A base fillet **504** is defined at the interface between riblets **202** and surface layer **204** for distribution of load to avoid plastic failure or rupture of the surface layer at maximum deflection of the riblets. For the exemplary embodiment, 1 micron was chosen as the fillet radius to maximize the extent of the parabolic shape since it distributes the stress/strain uniformly; and because it is sufficient to eliminate the discontinuity with the planar surface preventing it from becoming the cause of riblet failure under the combined loads. The transition between the fillet and the parabola must be smooth and is done by making the fillet shape tangent to the parabola (and also to the planar surface). In various embodiments, the fillet can be circular, elliptical or parabolic.

[0046] The parabolic shaping provides significant benefit because it uniformly distributes the stress and strain along the entire riblet. The higher the recoverable elongation in the material the better because the riblet tips are very fine, especially in the case of the triangular shape where the tips may be 0.1 micron. A fingernail gouge for an elastomer that is 0.1 micron thick can be stretched across more than one and maybe multiple riblets which are spaced approximately 90 microns apart which is greater than 900% if only the tip is participating. For the exemplary embodiments, the parabolic riblet folded flat to the planar surface has a maximum strain along the outside edge of only 37%.

[0047] FIGS. 5A-5D demonstrate various exemplary processes employed for the embodiments disclosed herein. In general context, an initial master tool having the desired shaping of the riblet array structure is created as either a male or female tool using, as an example without limitation, diamond machining of a copper form or other suitable material. The master tool may be a section of a flat tool, a roller or a rolled film tool or a web tool on which an acrylate, silicone or fluoropolymer is cured as a complimentary tool and then stripped to define spaced protuberances or indentations corresponding to the desired riblet dimensions. Other layers or materials may be added to make a durable tool of the appropriate flatness, stiffness and tensile strength. The high elongation elastomeric tips of the riblet array and surface layer are then created using the complimentary tool by deposition methods include casting, spray, electrophoretic or thermal forming. Most high elongation polymers can be cast from a liquid state via standard roll coating methods such as gravure, 3- or 4-reverse roll, knife over roll, slot die, spray or immersion.

[0048] For embodiments where a self adhering thermoplastic is not employed for the elastomer layer, an adhesive layer may be added using direct coating or lamination. Additional layers of supporting polymers and continuous or discontinuous metallic layers may be added for handling strength and additional functionality of the multi-layer appliqué previously described with respect to the various disclosed embodiments. As an alternative to single layer buildup, the surface of a pre-made appliqué without a topcoat (designated a TLA), as an example the exposed foil of an LSA, may be coated and then laminated in the web tool to form the riblets. Another alternative is to coat the web tool and then laminate the pre-made TLA with or without metal foil onto the coated web tool. In yet another alternative, the web tool is coated, cured and then, in a separate step, laminated to the TLA.

[0049] Cladding of the riblet tips may be accomplished by depositing the cladding onto the complimentary tool by sputtering, casting or other methods prior to creation of the elastomeric riblet tips and surface layer with the tool. Alternatively, the cladding may be applied to the elastomeric riblets tips after removal from the complimentary tool.

[0050] Similarly, the complimentary tool may be stripped from the elastomeric riblet tips and surface layer or the tool may remain attached to the elastomer layer after processing for handling purposes to protect the riblet tips through installation of the appliqué on a surface. Alternatively, a protective mask may be applied to the clad or unclad elastomer layer by deposition or casting after stripping from the complimentary tool to provide the desired handling and protective characteristics.

[0051] FIG. 5A is a flow diagram showing one exemplary manufacturing process for a riblet structure as defined in the embodiment described with respect to FIG. 2A. In step 501 a master tool or replication of a master tool 512 is created using, as an example without limitation, diamond machining of a copper form or other suitable material as the master tool on which an acrylate, silicone or fluoropolymer is cured as a replication and then stripped to define spaced protuberances 514 or indentations corresponding to the desired riblet dimensions. As previously described, other layers or materials could be added to make a durable tool of the appropriate flatness, stiffness and tensile strength.

[0052] The tool 512 as shown in FIG. 5A may be a section of a flat tool, a roller or a rolled film tool employed for

roll-to-roll web processing as will be described in greater detail with respect to FIG. 5D. A complimentary tool 516 is created in step 502 by impression on the master tool 512 which provides grooves 518 corresponding to the riblet shape. Spacing between the grooves provides a substantially flat intermediate surface 520 corresponding to the dimension 118 desired between the riblets 112 as described with respect to FIG. 3A. In step 503 high elongation elastomeric tips 202 and surface layer 204 are deposited onto the complimentary tool 516. Possible deposition methods include casting, spray, electrophoretic or thermal forming. Most high elongation polymers can be cast from a liquid state via standard roll coating methods such as gravure, 3- or 4-reverse roll, knife over roll, slot die, spray or immersion. In certain embodiments, a submicron release treatment or compound is applied to the surfaces on the complimentary tool to assist in removal of the riblet tips 202 and surface layer 204 from the tool 216. Adhesive layer 206 is then applied via direct coating or lamination in step 504 to the surface layer opposite the tips 202. A removable adhesive liner 522 for handling of the completed multilayer appliqué 523 is added as also shown in step 504. Application to the aircraft surface 524 in step 505 is accomplished by removing the multilayer appliqué 523 from the complimentary tool 516, removal of the adhesive liner 522 followed by attachment of the adhesive layer of the appliqué 523 to aircraft surface 524.

[0053] FIG. 5B is a flow diagram showing a manufacturing process for a riblet structure as defined in the embodiment described with respect to FIG. 2B. In step 505 a master tool or replication of a master tool 512 is created using, as an example without limitation, diamond machining of a copper form or other suitable material as the master tool on which an acrylate or other polymeric film is cured as a replication and then stripped to define spaced protuberances 514 corresponding to the desired riblet dimensions. As previously described with respect to FIG. 5A, the tool 512 as shown in FIG. 5B may be a section of a flat tool, a roller or a rolled film tool employed for roll-to-roll web processing as will be described in greater detail with respect to FIG. 5D. A complimentary tool 516 is created in step 507 by impression of the master tool 512 which provides grooves 518 corresponding to the riblet shape. Spacing between the grooves provides a substantially flat intermediate surface 520 corresponding to the dimension 118 desired between the riblets 112 as described with respect to FIG. 3A. In step 508 high elongation elastomeric tips 202 and surface layer 204 are deposited onto the complimentary tool 516 as previously described with respect to FIG. 5A. In certain embodiments, a release compound is applied to the surfaces on the complimentary tool to assist in removal of the riblet tips 202 and surface layer 204 from the tool 216. A polymer support layer 208 is then deposited or applied to the high elongation elastomer layer 201 and an adhesive layer 206 is applied in step 509 to the polymer support layer opposite the high elongation elastomer layer 201. A removable adhesive liner 522 for handling of the completed multilayer appliqué 523' is added as also shown in step 509. Application to the aircraft surface 524 in step 510 is accomplished by removing the multilayer appliqué 523' from the complimentary tool 516, removal of the adhesive liner 522 followed by attachment of the adhesive layer of the appliqué 523' to aircraft surface 524.

[0054] FIG. 5C is a flow diagram showing an alternative manufacturing process for a riblet structure as defined in the embodiment described with respect to FIG. 2C. In step 531 a

master tool **512** is created using, as previously described with respect to FIG. **5A**. The tool as shown in FIG. **5B** may be a section of a flat tool, roller or a rolled film tool employed for roll-to-roll web processing. A complimentary tool **516** is created in step **532** by impression on the master tool **512** which provides grooves **518** corresponding to the riblet shape. Spacing between the grooves provides a substantially flat intermediate surface **520** corresponding to the dimension **118** desired between the riblets **112**. An elastomeric layer **201** is then cast into the complimentary tool **516** to provide both elastomeric tips **202** and surface layer **204** in step **533**. In certain embodiments, a release compound is applied to the surfaces on the complimentary tool **516** to assist in removal of the elastomeric layer **201** from the tool. Adhesive layer **206** is then applied in step **534** to the high elongation elastomer layer **201** opposite the elastomeric tips **202**. A removable adhesive liner **522** for handling of the completed appliqué is added as also shown in step **534**. In step **535**, which may be conducted prior to the addition of the adhesive and liner, the core layer **201** is removed from the complimentary tool **516** and a film or cladding **209** is deposited by sputtering or alternative deposition technique onto the high elongation elastomer layer **201**. The elastomer layer may be treated prior to deposition by plasma treatment or corona treatment. Alternatively, as will be described with respect to the process of FIG. **5D**, the cladding **209** may be deposited on the complimentary tool and the elastomeric layer **201** including surface layer **204** and tips **202** then cast or deposited onto the cladding. In addition to the UV protection as described with respect to the embodiment of FIG. **2C**, the cladding **209** may provide resistance to electromagnetic effects which composite structure alone may not provide thereby substituting for or supplementing LSA foil appliqué and similar materials. The cladding **209** may also be multilayer or interference film, for example the multiple layers providing color and decorative effects (due to optical interference effects). Application to the aircraft surface **524** is accomplished as shown in step **536** by removal of the adhesive liner **522** followed by attachment of the adhesive layer **206** to aircraft surface **524**.

[0055] As shown in FIG. **5D**, an exemplary roll-to-roll web processing approach may be employed for the methods described. Master tool **512** is created using, as an example, diamond machining of a copper form **542** on which an acrylate or other polymer film **544** is cured then stripped and applied to a roller **545** to provide the master tool **512** shown in the drawing. Complimentary web tool **546** is then created by impression on master tool **512**. Sputtering of cladding **209** onto the web tool **546** is accomplished with sputtering tool **550** and high elongation elastomeric layer for tips **202** surface layer **204** is deposited onto the web tool **546** using a slot die, knife over roll, gravure or reverse roll coater **552**. The adhesive layer **206** is then deposited on the surface layer **204** with deposition tool **554** and the removable adhesive liner **522** attached by application from roll **556**. The multilayer appliqué **525** which includes the web tool **546** as a masking is collected on roll **558** and is then available for attachment to the aircraft surface **524** as described in the final steps of the methods of FIGS. **5A-5C**. The web tool **546** is then removed to expose the riblet array.

[0056] While shown in the drawings and described as a process of laminating individual layers, in certain alternative methods for fabrication of the multilayer appliqué, the surface of a pre-made appliqué such as a LSA without a topcoat (designated TLA for short) with the metallic layer as the outer

surface is laminated with a web tool to form the riblets. In another alternative, a web tool is coated with elastomer to form the riblets and then the pre-made TLA is laminated onto the coated web tool. In yet another alternative, the web tool is coated and cured, then in a separate step laminated to the TLA.

[0057] Referring more particularly to FIGS. **6** and **7**, embodiments of the high elongation elastomeric riblets disclosed herein and the methods for their fabrication may be described in the context of an aircraft manufacturing and service method **600** as shown in FIG. **6** and an aircraft **602** as shown in FIG. **7**. While described herein with respect to an aircraft, the embodiments disclosed are equally applicable to cars, boats, windmills, rotor blades, engine nacelles, intake ducts, ventilation systems or other surfaces with associated hydrodynamic or aerodynamic flow. During pre-production, exemplary method **600** may include specification and design **604** of the aircraft and material procurement **606**. During production, component and subassembly manufacturing **608** and system integration **610** of the aircraft takes place. The riblet appliqué and their manufacturing processes as described herein may be accomplished as a portion of the production, component and subassembly manufacturing step **608** and/or as a portion of the system integration **610**. Thereafter, the aircraft may go through certification and delivery **612** in order to be placed in service **614**. While in service by a customer, the aircraft **602** is scheduled for routine maintenance and service **616** (which may also include modification, reconfiguration, refurbishment, and so on). The riblet appliqué as described herein may also be fabricated and applied as a portion of routine maintenance and service **616**.

[0058] Each of the processes of method **600** may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). For the purposes of this description, a system integrator may include without limitation any number of aircraft manufacturers and major-system subcontractors; a third party may include without limitation any number of vendors, subcontractors, and suppliers; and an operator may be an airline, leasing company, military entity, service organization, and so on.

[0059] As shown in FIG. **7**, the aircraft **602** produced by exemplary method **600** may include an airframe **618** having a surface **111** as described with respect to FIG. **1** and a plurality of systems **620** and an interior **622**. Examples of high-level systems **620** include one or more of a propulsion systems **624**, an electrical and avionics system **626**, a hydraulic system **628**, and an environmental system **630**. Any number of other systems may be included. The high elongation elastomeric riblets supported by the embodiments disclosed herein may be a portion of the airframe **618**, notably the finishing of skin and exterior surfaces. Although an aerospace example is shown, the principles disclosed in the embodiments herein may be applied to other industries, such as the automotive industry and the marine/ship industry.

[0060] Apparatus and methods embodied herein may be employed during any one or more of the stages of the production and service method **600**. For example, components or subassemblies corresponding to production process **608** may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft **602** is in service. Also, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during the production stages **608** and **610**, for example, by substantially expediting assembly of or reducing the cost of an

aircraft **602**. Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof may be utilized while the aircraft **602** is in service, for example and without limitation, to maintenance and service **616**.

[0061] Having now described various embodiments in detail as required by the patent statutes, those skilled in the art will recognize modifications and substitutions to the specific embodiments disclosed herein. Such modifications are within the scope and intent of the present disclosure as defined in the following claims.

1. A method for fabricating an array of riblets comprising: forming a master tool shaped corresponding to a desired riblet array; forming at least one complementary tool from the master tool; depositing a high elongation elastomeric layer having tips and a surface layer in the complimentary tool; depositing an adhesive layer to form an appliqué; removing the high elongation elastomeric appliqué from the complementary tool; and, adhering the high elongation elastomeric appliqué to an aerodynamic surface.
2. The method of claim **1** further comprising: applying a release agent to the complementary tool for separation of the high elongation elastomeric layer from the tool.
3. The method of claim **1** further comprising depositing at least one polymer layer intermediate the adhesive layer and the elastomeric layer.
4. The method of claim **1** further comprising depositing a cladding over the high elongation elastomeric layer.
5. A method creating an array of riblets in an appliqué comprising: forming a master tool shaped corresponding to a desired riblet array; forming a web tool from the master tool; depositing a high elongation elastomeric layer to form tips and a surface layer in the web tool; depositing an adhesive layer to form an appliqué; adhering the high elongation elastomeric appliqué to an aerodynamic surface; and, removing the web tool from the high elongation elastomeric appliqué.
6. The method of claim **5** further comprising depositing a cladding on the web tool prior to depositing the high elongation elastomeric layer.
7. The method of claim **5** further comprising a step intermediate to depositing the elastomeric layer and depositing the adhesive layer of laminating a metallic layer and polymer support layer to the elastomeric layer.

8. The method of claim **5** wherein the step of depositing an adhesive layer comprises:

creating a pre-made appliqué without a topcoat (TLA); laminating the TLA onto the high elongation elastomeric layer deposited in the web tool.

9. A method of enhancing the durability of a riblet comprising:

forming an array of a plurality of riblets including a first layer composed of high elongation elastomeric riblets having tips, a surface layer, and a second layer for adherence to a surface; and adhering the array of riblets to an aerodynamic surface.

10. The method of claim **1** further comprising diamond machining of a copper form as the master tool.

11. The method of claim **5** wherein the step of forming a master tool comprises diamond machining of a copper form as the master tool.

12. The method of claim **11** further comprising: curing an polymer film on the copper form; stripping polymer film; and, applying the film to a roller.

13. The method of claim **12** wherein the step of forming a web tool comprises impressing the web tool on the roller.

14. The method of claim **5** wherein the step of depositing an elastomeric layer comprises casting the elastomeric layer from a liquid state using a roll coating method selected from the set of gravure, 3- or 4-reverse roll, knife over roll, slot die, spray or immersion.

16. The method of claim **5** further comprising adding a removable adhesive liner over the riblets for handling.

17. The method of claim **9** wherein the step of forming an array of a plurality of riblets comprises:

diamond machining of a copper form as a master tool shaped corresponding to a desired riblet array; curing an polymer film on the copper form; stripping polymer film; and, applying the film to a roller; depositing a high elongation elastomeric layer to form tips and a surface layer in the web tool; and, depositing an adhesive layer to form an appliqué.

18. The method of claim **17** further comprising depositing a cladding on the web tool prior to depositing the high elongation elastomeric layer

19. The method of claim **17** further comprising adding a removable adhesive liner over the riblets for handling.

20. The method of claim **19** further comprising removing the adhesive liner after adhering the array of riblets to the aerodynamic surface.

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