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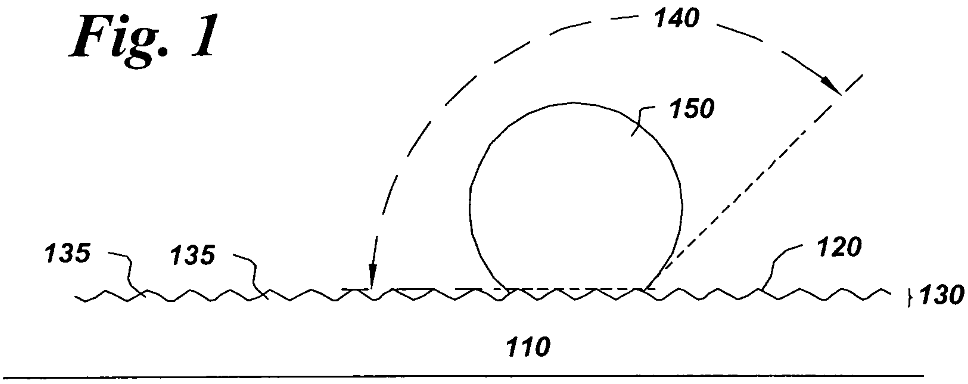
(54) Article having a surface with low wettability and its method of making

(57) An article (100) comprises a textured surface (120) disposed on a substrate (110). The surface (120) has an effective liquid wettability sufficient to generate, with a reference liquid (230), a contact angle (140) in a range from about 120° to about 180°. The surface (120) comprises a material having a nominal liquid wettability sufficient to generate, with the reference liquid (230), a nominal contact angle (240) in a range from about 60° to about 90°, the material comprising at least one material selected from the group consisting of a polymer and a ceramic. The properties of the surface (120) may include low-drag or low-friction, self-cleaning capability, and resistance to icing, fouling, and fogging, and the like. Methods of making such a surface (120) are also described.

Fig. 1



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Description

BACKGROUND OF INVENTION

[0001] The invention relates to surfaces having low liquid wettability. More particularly, the invention relates to such surfaces, where the surface is characterized by having one or more of the following properties: low-friction properties, self-cleaning capability, and resistance to icing, fouling, and fogging. Even more particularly, the invention relates to articles having such surfaces.

[0002] The "liquid wettability" of a solid surface is determined by observing the nature of the interaction occurring between the surface and a drop of a given liquid disposed on the surface. A surface having a high wettability for the liquid tends to allow the drop to spread over a relatively wide area of the surface, thereby "wetting" the surface. In the extreme case, the liquid spreads into a film over the surface. On the other hand, where the surface has a low wettability for the liquid, the liquid tends to retain a well-formed, ball-shaped drop shape. In the extreme case, the liquid forms spherical drops on the surface that easily roll off of the surface at the slightest disturbance.

[0003] The extent to which a liquid is able to wet a solid surface plays a significant role in determining how the liquid and solid will interact with each other. A high degree of wetting results in relatively large areas of liquid-solid contact, and is desirable in applications where a considerable amount of interaction between the two surfaces is beneficial, such as, for example, adhesive and coating applications. By way of example, so-called "hydrophilic" materials have relatively high wettability in the presence of water, resulting in a high degree of "sheeting" of the water over the solid surface. Conversely, for applications requiring low solid-liquid interaction, the wettability is generally kept as low as possible in order to promote the formation of liquid drops having minimal contact area with the solid surface. "Hydrophobic" materials have relatively low water wettability; so-called "superhydrophobic" materials have even lower water wettability, resulting in surfaces that in some cases may seem to repel any water impinging on the surface due to the insignificant amount of interaction between water drops and the solid surface.

[0004] Articles having tailored surface properties are used in a broad range of applications in areas such as transportation, chemical processing, health care, and textiles. Many of these applications involve the use of articles having a surface with a relatively low liquid wettability to reduce the interaction between the article surface and various liquids. In particular, the wetting properties of a material can be tailored to produce surfaces having properties that include low-drag or low-friction, self-cleaning capability, and resistance to icing, fouling, and fogging.

[0005] Different methods of reducing drag and friction have been used in different applications. To reduce friction in a pipe, for example, pipes have been made macroscopically smoother. Macroscopic structures, such as 'riblets,' have been used to create flow patterns that offer reduced resistance to flow. Similarly, 'compliant' surfaces that change adaptively based on flow characteristics have been tried as well. Such macroscopic modifications have been able to produce at best a 5-10% reduction in drag.

[0006] Hydrophobic surfaces on articles have also been formed using hydrophobic materials, such as Teflon®, polymer gels and solutions, and the like. Such materials are typically deposited as a film on a substrate or are formed into the article itself. For example, polymeric solutions are applied to racing boats to reduce drag, and polymer gels are applied to the inner surfaces of oil pipelines. Surfaces comprising such materials generally reduce drag or friction by 5-10%. Such coatings are subject to rapid wear and are not thermally or chemically stable at higher temperatures.

[0007] Current approaches to the production of articles having minimal interaction with fluids have been focused on applications of limited scope, and have produced only limited success. Therefore, there remains a need across several industries for articles having a surface with low liquid wettability. Moreover, these industries also require methods for providing such a surface on an article.

SUMMARY OF INVENTION

[0008] The present invention meets these and other needs by providing an article having a surface with a low liquid wettability.. The surface provides properties that may include, as non-limiting examples, one or more of low-drag or low-friction properties, self-cleaning capability, and resistance to icing, fouling, and fogging.

[0009] Accordingly, one aspect of the invention is to provide an article. The article comprises a surface disposed on a substrate, wherein the surface comprises

a. a material having a nominal liquid wettability sufficient to generate, with a reference liquid, a nominal contact angle in a range from about 60° to about 90°, the material comprising at least one material selected from the group consisting of a polymer and a ceramic; and

b. a texture comprising a plurality of features;

wherein the surface has an effective liquid wettability sufficient to generate, with the reference liquid, a contact angle in a range from about 120° to about 180°.

[0010] Still another aspect of the invention is to provide a method of making an article. The method comprises

a. providing a substrate and

b. forming a surface on the substrate, wherein the surface comprises a material having a nominal liquid wettability sufficient to generate, with a reference liquid, a nominal contact angle in a range from about 60° to about 90°, the material comprising at least one material selected from the group consisting of a polymer and a ceramic, and the surface further comprising a texture, wherein the texture comprises a plurality of features;

wherein the surface has an effective liquid wettability sufficient to generate, with the reference liquid, a contact angle in a range from about 120° to about 180°.

[0011] These and other aspects, advantages, and salient features of the present invention will become apparent from the following detailed description, accompanying drawings, and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012]

FIGURE 1 is a schematic cross-sectional view of a surface of an article of the present invention;

FIGURE 2 is a schematic representation of a fluid disposed on a nominally flat surface;

FIGURE 3a is a photograph of a water droplet on a superhydrophobic polycarbonate surface;

FIGURE 3b is a micrograph of the superhydrophobic polycarbonate surface shown in Figure 3a;

FIGURE 3c is a photograph of a water droplet on a nominally flat polycarbonate surface;

FIGURE 4 is a schematic representation of a cross-section of a surface of the present invention, showing the texture of the surface;

FIGURE 5 is a schematic representation of the formation of a surface of the present invention using a plurality of nanoparticles and a polymer solution;

FIGURE 6 is a schematic representation of the formation of a surface of the present invention by assembling a plurality of nanoparticles in a block copolymer matrix;

FIGURE 7 is an image of a plurality of polystyrene beads deposited onto a substrate in preparation of making a mold for replicating a surface of the present invention;

FIGURE 8 is an image of a silicone master mold having a texture on a surface of the present invention;

FIGURE 9 is an image of a polycarbonate surface having a texture that was formed by compression molding the polycarbonate with the silicone mold shown in Figure 8;

FIGURE 10 is a schematic representation of an article of the present invention, wherein the article is an airfoil; and

FIGURE 11 is a schematic representation of an aircraft turbine that incorporates at least one article having an icing resistant surface of the present invention.

DETAILED DESCRIPTION

[0013] In the following description, like reference characters designate like or corresponding parts throughout the several views shown in the figures. It is also understood that terms such as "top," "bottom," "outward," "inward," and the like are words of convenience and are not to be construed as limiting terms. Furthermore, whenever a particular feature of the invention is said to comprise or consist of at least one of a number of elements of a group and combinations thereof, it is understood that the feature may comprise or consist of any of the elements of the group, either individually or in combination with any of the other elements of that group.

[0014] Referring to the drawings in general and to Figure 1 in particular, it will be understood that the illustrations are for the purpose of describing a particular embodiment of the invention and are not intended to limit the invention thereto. Figure 1 is a schematic cross-sectional view of a surface of an article of the present invention. Article 100 comprises a surface 120 disposed on a substrate 110. As used herein, the term "surface" refers to that portion of the substrate 110 that is in direct contact with an ambient environment surrounding substrate 110. Surface 120 has a low liquid wettability. One commonly accepted measure of the liquid wettability of a surface 120 is the value of the static contact angle 140 formed between surface 120 and a tangent 145 to a surface of a droplet 150 of a reference liquid at the point of contact between surface 120 and droplet 150. High values of contact angle 140 indicate a low wettability for the reference liquid on surface 120. The reference liquid may be any liquid of interest. In many applications, the reference liquid is water; for instance, in applications focused on reducing the accretion of ice on a surface, the reference liquid is supercooled water (liquid water at a temperature below its freezing point). In other applications, the reference liquid is a liquid that contains at least one hydrocarbon, such as, for example, oil, petroleum, gasoline, an organic solvent, and the like. As described above, the term "superhydrophobic" is used to describe surfaces having very low wettability for water. As used herein, the term "superhydrophobic" will be understood to refer to a surface that generates a static contact angle with water of greater than about 120 degrees. Because wettability depends in part upon the surface tension of the reference liquid, a given surface may have a different wettability (and hence form a different contact angle) for different liquids.

[0015] Surface 120 comprises a material that has a moderately high wettability for a given reference liquid, yet surface 120 itself has a substantially lower wettability for the same reference liquid than that typically measured for the material. In particular, surface 120 comprises a material having a nominal liquid wettability sufficient to generate a nominal contact angle in a range from about 60° to about 90° with a given reference liquid. In particular embodiments, surface 120 consists essentially of the material. For the purposes of understanding the invention, a "nominal contact angle" 240 (Figure 2) means the static contact angle 240 measured where a drop of a reference liquid 230 is disposed on a flat, smooth (< 1 nm surface roughness) surface 220 consisting essentially of the material. This nominal contact angle 240 is a measurement of the "nominal wettability" of the material.

[0016] Surface 120 further comprises a texture 130 comprising a plurality of features 135. The present inventors have found that by providing a surface 120, comprising a material of moderately high nominal wettability, with a texture 130, the resulting textured surface can have remarkably lower wettability than that inherent to the material from which the surface is made. In particular, surface 120 has an effective wettability (that is, wettability of the textured surface) for the reference liquid sufficient to generate a contact angle in the range from about 120° to about 180°. Where the reference liquid is water, for example, the material would be considered to be hydrophilic based on its nominal contact angle, yet the surface 120, made of textured hydrophilic material, would be considered superhydrophobic due to its high contact angle.

[0017] An example of the behavior of a fluid drop on an article of the present invention is shown in Figures 3a and 3b. Surface 304 comprises a polycarbonate, which is hydrophilic. The contact angle formed by water droplet 302 and surface 304 is about 130° (Figure 3a). The polycarbonate surface 304 has a texture 306, which can be seen in a top view of surface 304, shown in Figure 3b. An example of the behavior of a water droplet on a flat polycarbonate surface lacking the texture of the previous example is shown in Figure 3c. The contact angle formed by fluid 308 and surface 310 is about 80°. In contrast to the textured polycarbonate surface 304 shown in Figure 3c, the flat surface 310 was substantially devoid of any texture or topographical features, such as elevated portions, depressions, and the like.

[0018] Surface 120 (Figure 1) comprises at least one material selected from the group consisting of a polymer and a ceramic. Polymer materials that may be used in surface 120 include, but are not limited to, polycarbonates, including cyclic polycarbonates; polyimides, including cyclic polyimides; polysilazanes; acrylates, including UV curable acrylates; polyurethanes; epoxies; polyether imides; polysulfones; block copolymer/copolymer mixtures; and combinations thereof. Suitable ceramic materials include inorganic oxides, carbides, nitrides, and combinations thereof. Non-limiting examples of such ceramic materials include tin oxide, titania, silicon carbide, titanium nitride, stibinite (SbS_2), zirconia, hafnia, titanium oxynitride, and combinations thereof.

[0019] Substrate 110 may comprise at least one of a metal, an alloy, a plastic, a ceramic, or any combination thereof. Substrate 110 may take the form of a film, a sheet, or a bulk shape. Substrate 110 may represent article 100 in its final form, such as a finished part; a near-net shape; or a preform that will be later made into article 100.

[0020] Surface 120 may be an integral part of substrate 110. For example, surface 120 may be formed by replicating a texture directly onto substrate 110, or by embossing the texture onto substrate, or by any other such method known in the art of forming or imparting a predetermined surface texture onto a substrate surface. Alternatively, surface 120 may comprise a layer that is disposed or deposited onto substrate 110 by any number of techniques that are known in the art.

[0021] As described above, surface 120 is not a smooth surface, but instead has a texture 130 comprising a plurality of features 135. The plurality of features 135 may be of any shape, include at least one of depressions, protrusions, nanoporous solids, foamed structures, indentations, or the like. The features may include bumps, cones, rods, wires, channels, substantially spherical features, foamed structures, substantially cylindrical features, pyramidal features, prismatic structures, combinations thereof, and the like. In certain embodiments, as depicted in Figure 4, each feature 402 has at least one dimension 404 (for example, length, width, diameter, or thickness) in a range from about 10 nm to about 50,000 nm. In some embodiments, dimension 404 is in the range from about 10 nm to about 10,000 nm, and in particular embodiments dimension 404 is in the range from about 10 nm to about 1000 nm. The features 402 are spaced from each other by a distance 406 (also referred to hereinafter as a "spacing dimension"); in some embodiments spacing dimension 406 is substantially equal to the dimensions 404 of the features. For example, spherical or sphere-like features, each having a diameter of about 100 nm, are spaced about 100 nm apart. In one embodiment, the plurality of features 402 is substantially close-packed. The plurality of features 402 may be arranged in either an ordered array on surface 408, or in a disordered or random fashion.

[0022] The plurality of features 135 (Figure 1) making up texture 130 need not be confined to the surface 120 or a region immediately proximate to the surface 120. In some embodiments, article 100 further comprises a bulk portion 110 disposed beneath surface 120, and the plurality of features 135 extends into bulk portion 110. Distributing features 135 throughout the article 100, including at the surface 120 and within the bulk portion 110, allows surface 120 to be regenerated as the top layer of surface erodes away.

[0023] Another aspect of the invention is to provide a method for making surface 120 and article 100 described hereinabove. The method comprises providing a substrate 110 and forming a surface 120 on the substrate 110. Surface 120 comprises a material having a nominal liquid wettability sufficient to generate, with a reference liquid, a nominal contact angle in a range from about 60° to about 90°, and the material comprises at least one material selected from the group consisting of a polymer and a ceramic. Surface 120 further comprises a texture 130 comprising a plurality of features 135. As previously described, the resulting surface 120 has a significantly reduced wettability compared to the nominal wettability of the material: wettability levels sufficiently low to generate, with the reference liquid, a contact angle in a range from about 120° to about 180°.

[0024] In one embodiment, shown schematically in Figure 5, a plurality of nanoparticles 540 is initially deposited on substrate 510. The plurality of nanoparticles 540 may have a liquid wettability that is high or low; may be metallic, non-metallic; or a combination of both; and may be coated or uncoated. Nanoparticles 540 may be deposited in either an ordered or disordered fashion to form an assembly 542 or array of nanoparticles on substrate 510. The coverage provided by assembly 542 may be limited to a selected area of substrate 510, or complete coverage of substrate 510. In one embodiment, the plurality of nanoparticles 540 may be secured or anchored to substrate 510 by heat treating assembly 542 at a temperature that will partially melt the particles 540 and fuse them to substrate 510. Following deposition of nanoparticles 540 on substrate 510, a polymer solution 550 is then deposited over the plurality of nanoparticles 540 to form a coating 560. Application of polymer solution to the plurality of nanoparticles 540 deposited on substrate 510 may be by spraying, spin coating, dip coating, or the like. The polymer solution comprises any of the hydrophilic polymers, such as, but not limited to, those polymers previously described herein. The resulting coating 550 is then heat treated to remove the solvent and ensure that the annealed polymer conforms to the underlying structure of the nanoparticle clusters. Additional or alternative texture may then be provided by etching means known in the art, such as, but not limited to, plasma etching, irradiation (particularly with UV light), or solvent etching. Such etching selectively removes the polymer.

[0025] In another embodiment, the plurality of nanoparticles 540 and polymer solution 550 are blended together and applied to substrate 510 in a single step using commonly used coating techniques, such as spray casting, screen printing, roll casting, drop casting, dip coating, and the like. The nanoparticles comprise from about 0.001 volume percent to about 50 volume percent of the solution. The resulting coating may then be heat treated as previously described to ensure good cohesive and adhesive strength. Additional or alternative textures may then be provided by etching processes, as previously described hereinabove.

[0026] Alternatively, the plurality of nanoparticles 540 is deposited on substrate 510 to achieve substantially complete coverage. A monomer, such as a silazane monomer, is then infiltrated into the gaps between nanoparticles 540. The monomers are then crosslinked by the use of catalysts, heat, UV radiation, thermal crosslinking, solvents, and the like, to provide a robust polymeric coating. An additional or alternative texture may then be provided by etching processes, as previously described hereinabove.

[0027] In another embodiment, a plurality of nanoparticles 640 are assembled in a block copolymer matrix 600, as shown in Figure 6. Nanoparticles 640 may be either coated or uncoated. One of the block copolymers 660 is more compatible with either nanoparticles 640 or with coatings applied to the nanoparticles, resulting in a self-assembled solution. Upon annealing, the self-assembled solution produces texture 630. An additional or alternative texture may then be provided by etching processes, as previously described hereinabove.

[0028] The methods of providing texture 130 that have been previously described above rely on the formation of at least one coating or layer on substrate 110. In other embodiments, texture 130 is provided to or formed directly on a surface of substrate 110. Texture 130 may be formed directly onto the surface 120 of substrate 110 by any one of replication, embossing, molding or extrusion. In one embodiment, a replicating means such as, but not limited to, a mold or a die, is provided with a template corresponding to the texture to be provided to a surface. A template of the replicating means is brought into contact with the surface, thereby imparting texture 130 to the surface.

[0029] The formation of texture 130 on a polycarbonate surface 120 is illustrated in Figures 7, 8, and 9. In Figure 7, a plurality of polystyrene beads 710 are deposited onto a substrate. Deposition of the polystyrene beads 710 on the substrate may be accomplished by any of the means described hereinabove. A silicone mold of the beads is then cast, and the polystyrene beads 710 are removed by dissolution, etching, or the like, to yield a silicone master mold having a texture, the face of which is shown in Figure 8. The silicone master mold is then used to compression mold polycarbonate, where face 820 creates a texture on the surface of a polycarbonate substrate that corresponds to that of face 820. The texture of the polycarbonate surface is shown in Figure 9.

[0030] In one embodiment, article 100 comprises a film or sheet that is extruded through at least one die having a face having a texture corresponding to the desired texture for article 100. Texture 130 is transferred from the die face to article 100 during extrusion. In another embodiment, texture 130 is either compression molded or injection molded onto surface 120 of article 100 to produce a textured, low-wettability surface 120 on article 100. A mold having at least one face comprisingtexture is used to impart corresponding texture 130 to surface 120 of article 100 during the molding process.

[0031] In another embodiment, a plurality of nanoparticles is combined or mixed with a ceramic precursor such as, but not limited to, polysilazane precursors to form either a slurry or suspension of nanoparticles in the ceramic precursor. The slurry (or suspension) is then applied to a surface of an article by means that are well known in the art, such as spraying, spin coating, painting, dipping, and the like. The coated article is then heated to convert the ceramic precursor into a ceramic, such as, but not limited to an oxide, carbide, nitride, silicide, or combinations thereof, thereby forming a textured, low-wettability surface comprising the plurality of nanoparticles embedded in a ceramic coating. Such heating may involve calcining the ceramic precursor or heating under a reactive atmosphere. The resultant surface may be used in applications such as icing resistant coatings for aircraft turbines, where stability at high temperature is desired.

[0032] Additionally, surface 120 may be formed by vapor-based deposition techniques such as, but not limited to, PVD, LPCVD, CVD, PECVD, and combinations thereof.

[0033] Moreover, in some embodiments, the forming step is accomplished by chemically forming the features 130 onto the substrate 110. In certain embodiments, this is accomplished by manipulating the surface chemistry of the material to form one or more discrete chemical phases on the surface, for example via such well-known techniques as molecular self-assembly, crystallization, or other processes known to induce a phase separation on the surface. In other embodiments, chemical etching may be used by applying an etchant to the substrate. The etchant may comprise an acid, a base, a solvent, or other agent with suitable properties to react with the substrate to form features on the surface.

[0034] Where the reference liquid (i.e., the liquid for which the surface of the article shows low wettability) is water, the superhydrophobic nature of surface 120 makes it suitable for a number of applications that require resistance to fogging, soiling, contamination, and icing. Article 100 having surface 120 may also be used in applications in which a surface having low-drag, self-cleaning, and heat transfer properties are desirable.

[0035] In one embodiment, the surface 120 primarily provides article with an increased resistance to "icing:" the formation and accretion of ice through deposition and freezing of supercooled water droplets on a surface. In this embodiment, article 100 is an airfoil 1000, such as, but not limited to, aircraft wings, propellers, low pressure compressor and fan components of gas turbine engines, wind turbine blades, and helicopter blades, articles that are particularly susceptible to icing under certain conditions. A schematic representation of a cross-section of an airfoil having a low-drag icing-resistant surface is shown in Figure 10. As seen in Figure 10, airfoil 1000 has an icing-resistant surface 1020, as described herein, disposed on its leading edge 1010. In another embodiment, article 100 is a component of a turbine assembly, for example, a gas turbine aircraft engine, schematically shown in Figure 11. Article 100 includes components of turbine assembly 1100, such as inlet guide vanes (IGVs) 1110, rotors, stators , struts 1120, temperature and pressure sensors located in the flow path, fan blades 1130, fan outlet guide vanes (OGVs) 1160, spinners 1170, and other surfaces that accrete ice under icing conditions. It is noted that the operating principles and general structure of turbine assemblies and airfoils are well known in the art and are not repeated herein. Incorporation of surface 120 into any of the aforementioned articles enables any accreted ice to be shed before attaining a mass that is sufficiently large to impede the function of article by, for example, flame out or stall. In many cases, such structures benefit from the low-drag properties of surface 120 as well.

[0036] Due to the high contact angle on a superhydrophobic surface, the water on surface 120 forms small droplets and rolls off instead of sheeting, and the droplets carry away dirt particles along with them, thus leaving a clean dry surface. In situations such as fogging of a surface, small droplets formed by processes such as condensation deposit on the surface and reflect the light, thus making the surface "fog." Because of the high contact angle 140 between the condensed droplets and surface 102, the droplets do not adhere to surface 120, but instead roll off. Accordingly, article 100 is resistant to such fogging. In one embodiment, article 100 is either transparent or translucent. Examples of article 100 in which surface 120 serves primarily as a self-cleaning, antifogging surface include lighting products, automotive products (such as headlamps, windows, and mirrors) building components (such as glass panes, windows, and mirrors), lenses, video displays and screens, and the like.

[0037] In one embodiment, the low-drag properties of surface 120 can be adapted to facilitate the transport of fluids, such as crude oil, water, and the like, through long pipelines. The friction within a pipeline typically leads to significant pressure drop. To overcome such a pressure drop, greater power is required to pump the fluids. Accordingly, article 100 may be a pipe, conduit, or the like, for conducting fluids and gases, having surface 120 is disposed within the pipe along the path of the fluid or gas; i.e., inside the pipe. Surface 120 with texture 130 will reduce the friction between fluid and the wall of pipe. Consequently, the power required to pump the fluid through the pipe will be significantly reduced.

[0038] Reduction of hydrodynamic drag has always been a priority for marine vessels. Increased drag not only increases the fuel consumption of the ship, but also is harmful to the environment due to larger amounts of emissions. Fouling of watercraft hulls by marine organisms is a prime source of increased drag. In yet another embodiment, the low-drag and self-cleaning properties of surface 120 can be adapted to reduce fouling and friction between water and a hydrodynamic body. Significant amounts of energy are required to overcome friction due to water. Such bodies experience significant flow friction from the water. Thus, article 100 may include various watercraft, ranging from ocean-going vessels and submarines to small sailboats and canoes. While hulls and other surfaces are shaped in such a way to reduce friction, additional reductions in skin friction may be obtained by providing the hull with surface 120 in accordance with embodiments of the present invention. Moreover, the low-wettability surface prevents marine organisms from adhering to the surface of a watercraft.

[0039] In another embodiment, the low-drag and self-cleaning properties of surface 120 can be adapted to fabrics for use in garments, furniture, hospital equipment, and the like. For example, article 100 may include clothing used in sports such as swimming, track and field, and bicycling. In another example, article 100 includes fabric upholstery and bedding having surface 120, thus utilizing the self-cleaning capability of surface 120. In such applications, at least one superhydrophobic film or coating in accordance with embodiments of the present invention may be applied to a surface of the article.

[0040] The self-cleaning properties of surface 120 are also useful in other applications. Accordingly, surface 120 may be incorporated into various household appliances, such as refrigerators, dishwashers, ovens, ranges and the like.

[0041] Surface 120 may be used in heat transfer applications, such as, but not limited to, heat exchangers, cooling towers, and other thermal-management systems, that rely on a phase change (e.g., boiling). Air bubbles on the texture of surface 120 nucleate at a higher rate than on a nominally a flat surface, facilitating heat transfer through the phase change and bubble formation and migration.

[0042] While typical embodiments have been set forth for the purpose of illustration, the foregoing description should not be deemed to be a limitation on the scope of the invention. Accordingly, various modifications, adaptations, and alternatives may occur to one skilled in the art without departing from the scope of the present invention.

Claims

1. An article (100) comprising:

a surface (120) disposed on a substrate (110), wherein the surface (120) comprises

a. a material having a nominal liquid wettability sufficient to generate, with a reference liquid (230), a nominal contact angle (240) in a range from about 60° to about 90°, the material comprising at least one material selected from the group consisting of a polymer and a ceramic; and

b. a texture (130) comprising a plurality of features (135);

wherein the surface (120) has an effective liquid wettability sufficient to generate, with the reference liquid (230), a contact angle (140) in a range from about 120° to about 180°.

2. The article (100) according to Claim 1, wherein the surface (120) consists essentially of the material.

3. The article (100) according to Claim 1, wherein the material is selected from a group consisting essentially of polycarbonates, polyimides, polysilazanes, acrylates, polyurethanes, epoxies, polyether imides, polysulfones, block copolymer/copolymer mixtures, and combinations thereof.

4. The article (100) according to Claim 1, wherein the material comprises a ceramic.

5. The article (100) according to Claim 4, wherein the ceramic comprises a ceramic selected from the group consisting of an inorganic carbide, an inorganic oxide, an inorganic nitride, and combinations thereof.

6. The article (100) according to any preceding Claim, wherein the texture (130) comprises a plurality of features (135), wherein each of the plurality of features (135) has a dimension in a range from about 10 nm to about 50,000 nm.

7. The article (100) according to claim 6, wherein the dimension is in the range from about 10 nm to about 10,000 nm.

8. The article (100) according to any preceding Claim, wherein the plurality of features (135) comprise at least one of bumps, cones, rods, wires, channels, substantially spherical features, foamed structures, substantially cylindrical features, pyramidal features, prismatic structures, and combinations thereof.

9. The article (100) according to any preceding Claim, wherein the article (100) further comprises a bulk portion disposed beneath the surface (120), and wherein the plurality of features (135) of the texture (130) of the surface (120) extends into a bulk portion of the article (100).

10. The article (100) according to any preceding Claim, wherein the article (100) is one of an airfoil (1000), a turbine component, a heat exchanger, a watercraft hull, an appliance, and a fabric.

11. An article (100) comprising:

a surface (120) disposed on a substrate (110), wherein the surface (120) comprises

a. a material having a nominal wettability sufficient to generate, with water, a nominal contact angle (240) in a range from about 60° to about 90°, the material comprising at least one material selected from the group consisting of a polymer and a ceramic; and
b. a texture (130) comprising a plurality of features (135);

wherein the surface (120) has an effective wettability sufficient to generate, with water, a contact angle (140) in a range from about 120° to about 180°.

12. A method for making an article (100), the method comprising:

a. providing a substrate (110) and
b. forming a surface (120) on the substrate (110), wherein the surface (120) comprises a material having a nominal liquid wettability sufficient to generate, with a reference liquid (230), a nominal contact angle (240) in a range from about 60° to about 90°, the material comprising at least one material selected from the group consisting of a polymer and a ceramic, and the surface (120) further comprising a texture (130), wherein the texture (130) comprises a plurality of features (135);

wherein the surface (120) has an effective liquid wettability sufficient to generate, with the reference liquid (230), a contact angle (140) in a range from about 120° to about 180°.

Fig. 1

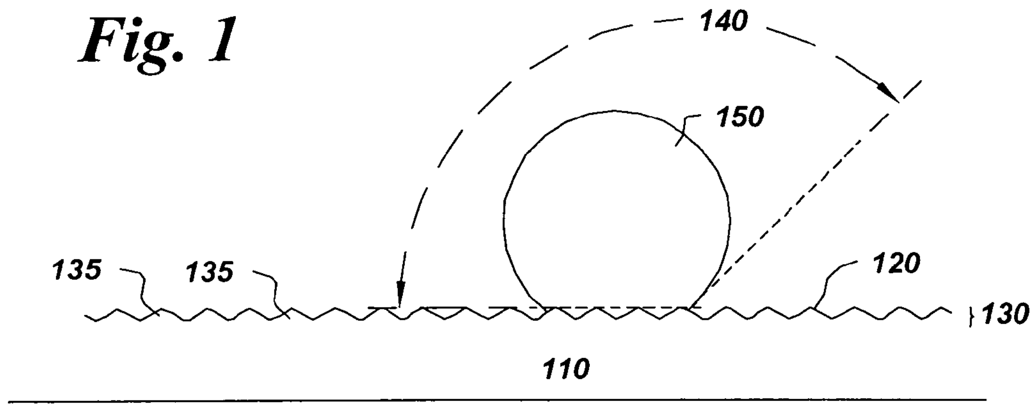


Fig. 2

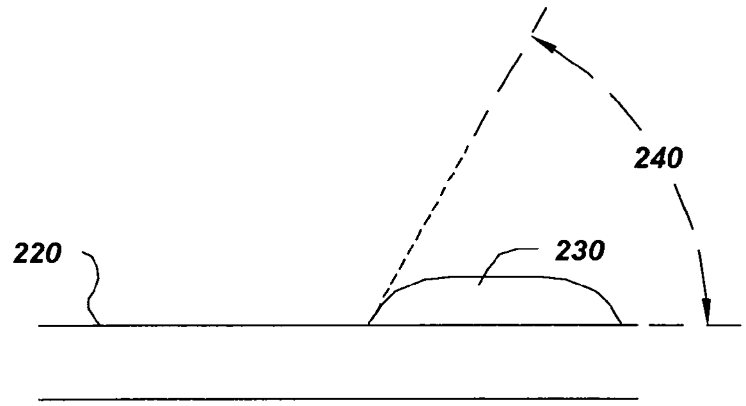


Fig. 3A

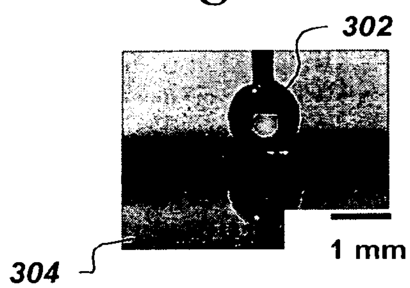


Fig. 3B

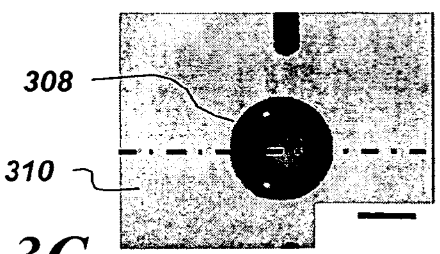
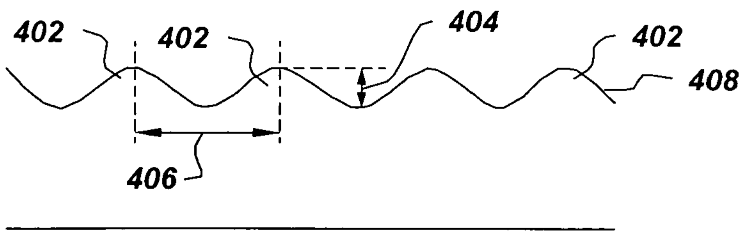


Fig. 3C

Fig. 4



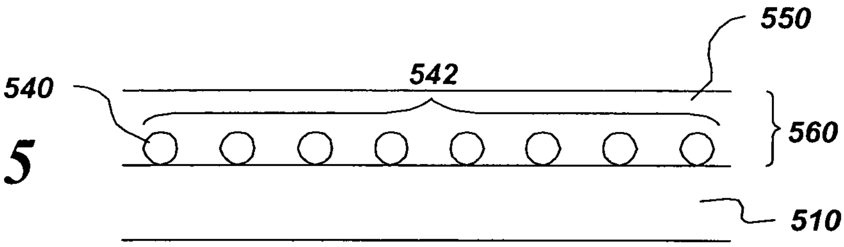


Fig. 5

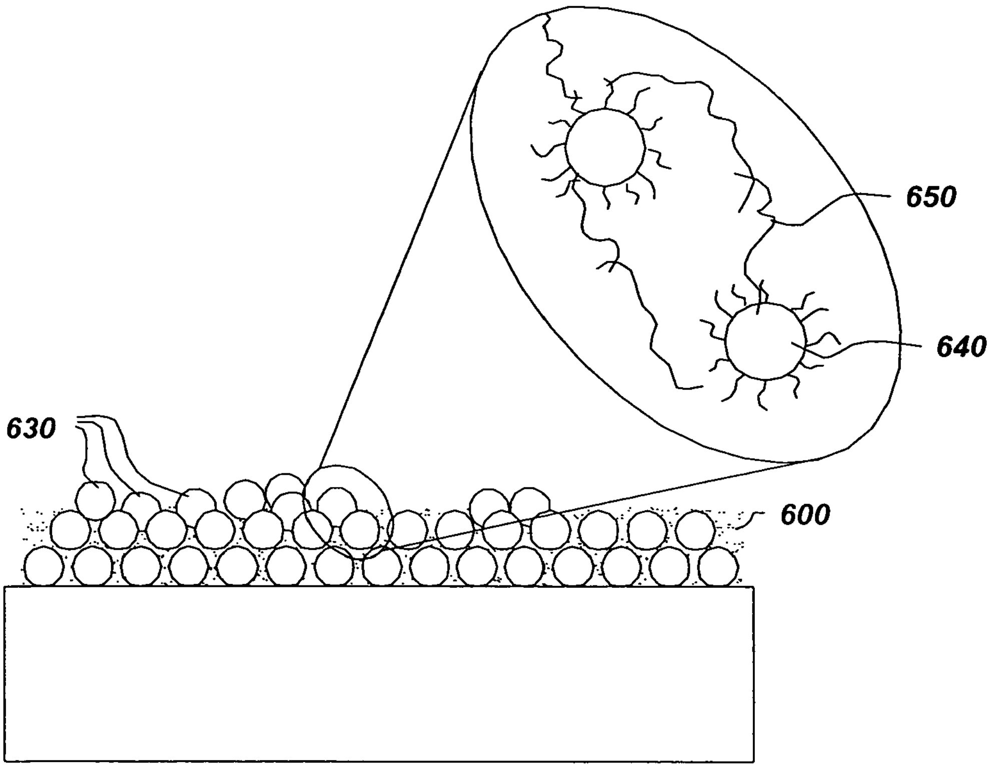


Fig. 6

Fig. 7

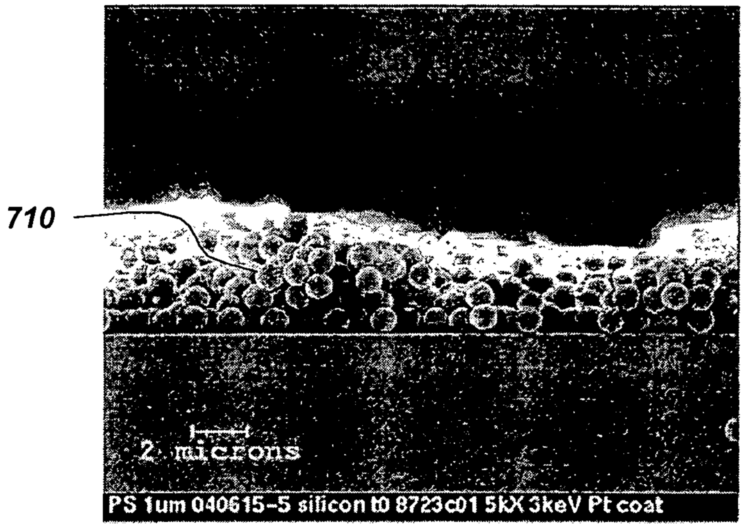


Fig. 8

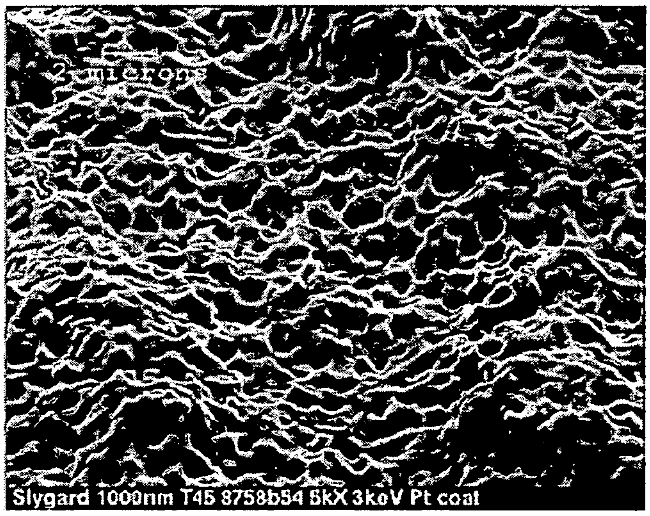
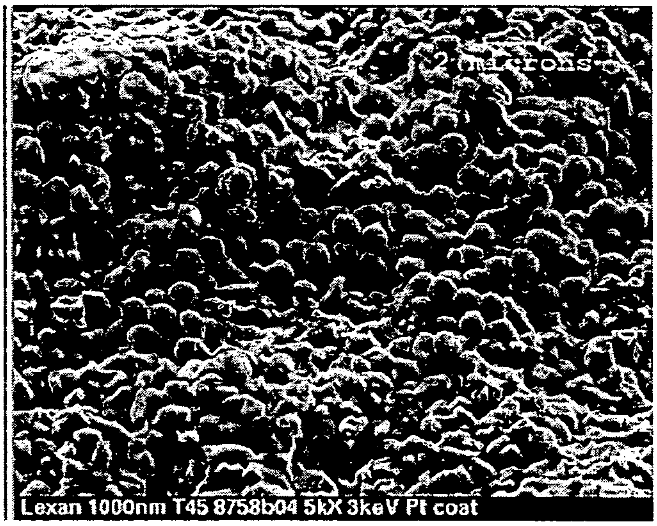


Fig. 9



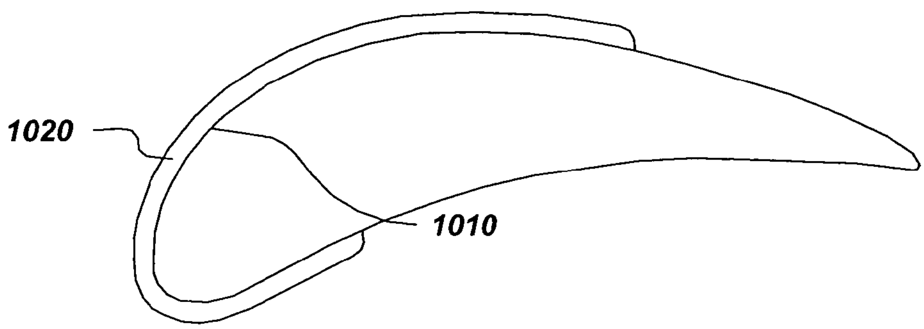


Fig. 10

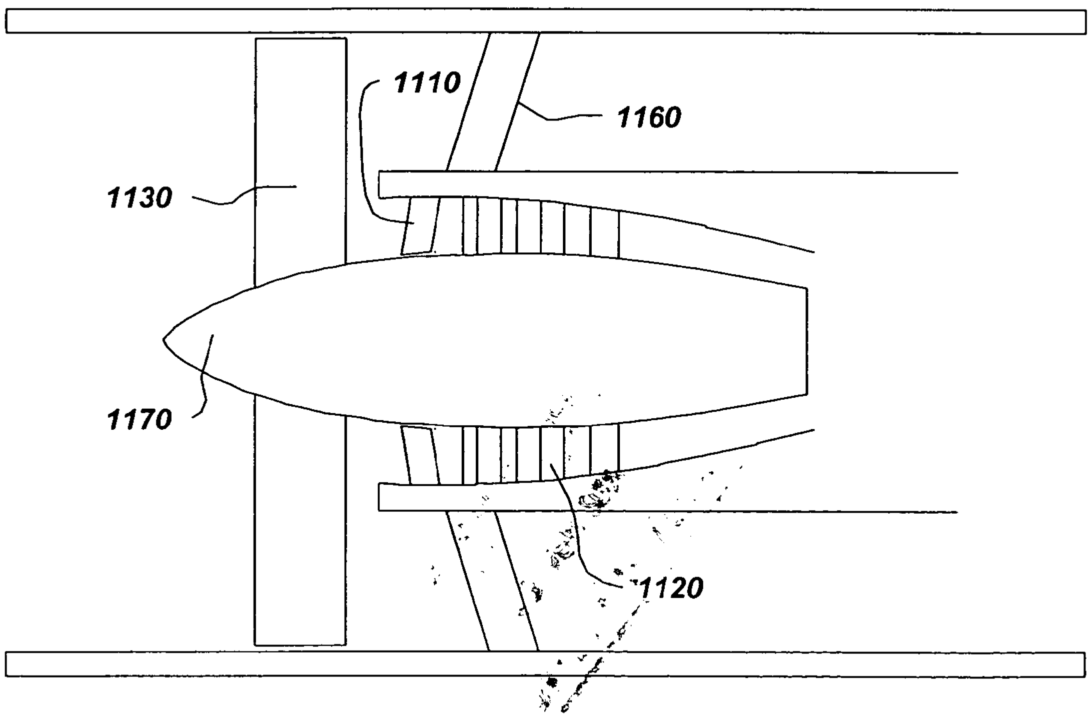


Fig. 11

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EUROPEAN SEARCH REPORT

Application Number
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	18 September 2006	Mill, Sibel

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