极端润湿性表面研究与应用进展

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摘要 简介了极端润湿性表面相关理论,总结了极端润湿性表面的制备方法,讨论了极端润湿性表面在自清洁、防雾、抗结冰结霜、耐腐蚀、响应开关、油水分离、高负载力水上设备、液体无损转移、液体定向运输、血液相容材料等领域的应用,指出了实现极端润湿性表面真正工业化应用所需解决的问题,认为制备机械性能好、静/动压承受能力强的超双疏表面是超疏液极端润湿性表面制备方面的大趋势。

关键词 极端润湿性;超疏/亲水表面;超疏/亲油表面

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Progress on research and application of extreme wettability surfaces

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Abstract Based on the related theories of extreme wettability surface, the fabrication methods of the extreme wettability surface are reviewed, analyzed and summarized. The application of the extreme wettability surface to self-cleaning, anti-fogging, anti-icing and -frosting, corrosion resistance, response switch, oil/water separation, water equipment with high loading force, no loss transport of liquid, directional transport of liquid, and materials with blood compatibility is discussed The problems needed to be resolved for real industrial applications of the extreme wettability surface are pointed out. Fabrication of superamphiphobic surface with good mechanical property and high bearing capacity of static/dynamic pressure is the main trend.

Keywords extreme wettability; superhydrophobic/superhydrophilic surface; superoleophobic/superoleophilic surface

固体表面润湿性是固-气-液界面的一种现象,常用接触角来衡量。极端润湿性表面主要分为超亲液(接触角<10°)和超疏液(接触角>150°)两种。按照液体表面张力的不同,又常被分为超亲水、超疏水、超亲油和超疏油4种。由于油类液体的表面张力远小于水,因此通常空气中超亲水表面同时超亲油(部分超亲水表面在水下显示超疏油),而超疏水表面同时较难超疏油。

极端润湿性表面具有巨大应用前景,在过去10年,越来越多的国家和团队对这一领域进行了大量研究,ISI web of science数据库中的相关论文数量一直在增加,如图1所示,其中仅2014年发表的有关超疏水(superhydrophobic)方面的论文数量已达1449篇。目前研究人员发现极端润湿性表面在自清洁、防雾、抗结冰结霜、耐腐蚀、响应开关、油水分离、高负载力水上设备、液体无损转移、液体运输、血液相容材料等方面具有广泛的应用价值。

本文总结近年来极端润湿性表面的制备方法和应用方面的研究现状,分析当前存在的主要问题,给出解决相关问题的建议和努力方向。

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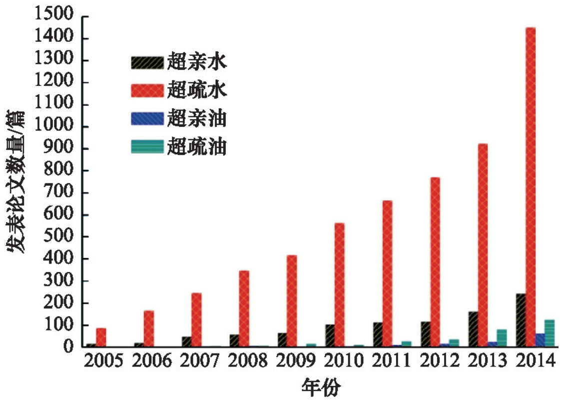

图1　在ISI web of science上检索相关主题获得的论文数量

Fig. 1　Statistics of the paper indexed in the ISI web of science by the corresponding topics

1　润湿性相关理论

润湿性研究中存在3大经典理论：Young理论[1]（式(1)、图2)、Wenzel理论[2,3]（式(2)、图3)及Casssie–Baxter理论[4]（式(3)、图4)。

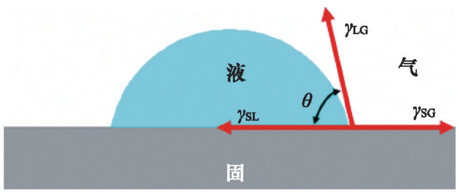

图2　水滴在固体表面上示意

Fig. 2　Schematic of a water droplet on a solid surface

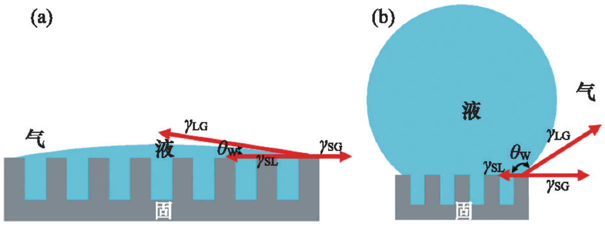

图3　水滴在粗糙固体表面上呈Wenzel状态时示意

Fig. 3　Schematic of a water droplet with Wenzel state on a rough solid surface

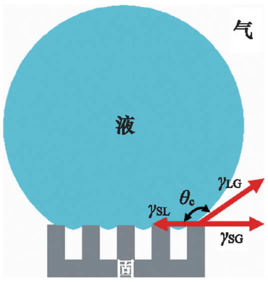

图4　水滴在粗糙固体表面上呈Cassie–Baxter状态时示意

Fig. 4　Schematic of a water droplet with Cassie–Baxter state on a rough solid surface

$$\cos\theta=(\gamma_{SG}-\gamma_{SL})/\gamma_{LG} \tag{1}$$

$$\cos\theta_w=r(\gamma_{SG}-\gamma_{SL})/\gamma_{LG}=r\cos\theta \tag{2}$$

$$\cos\theta_c=f_1(\gamma_{SG}-\gamma_{SL})/\gamma_{LG}-f_2=f_1\cos\theta-f_2 \tag{3}$$

式中，θ为液体在光滑表面的本征接触角，θ_w为液滴在粗糙表面呈Wenzel状态的表观接触角，θ_c为液滴在粗糙表面呈Cassie–Baxter状态的表观接触角，γ_{SG}、γ_{SL}和γ_{LG}分别表示固–气、固–液、液–气界面的表面张力，r为粗糙度因子，f_1、f_2分别为固–液接触面和气–液接触面在复合接触面中所占的比例，即$f_1+f_2=1$。

Young理论认为对于理想光滑的固体表面，液体在其上的接触角仅和固–气、固–液、液–气界面的表面张力有关，并满足式(1)，该公式表明尽管降低固体表面能可提高疏液性，增大接触角，但仅仅依靠降低表面能的方法无法使光滑表面获得超疏液性，已有文献表明，即使表面能最低的—CF_3基团（表面能为6.7 mJ/m^2）修饰后的光滑表面的接触角仅约119°[5]。该公式还表明光滑表面可获得超亲液性，但仅针对部分材料和部分液体。大部分材料（尤其金属）的光滑表面不显示超亲液性。

Wenzel理论认为实际表面并非理想光滑表面，存在微观几何粗糙结构，液体在其上的接触角除了和固–气、固–液、液–气界面的表面张力有关外，还和微观结构有关，并满足式(2)，该公式表明微观粗糙结构可使疏液表面变得更疏液，进而获得超疏液性，也可使亲液表面变得更亲液，进而获得超亲液性。

尽管Wenzel理论能解释为何液体在粗糙固体表面的接触角极小或极大，却无法解释为何某些表面呈现具有极小滚动角的超疏液性，即液体极易在某些表面滚落。因此，Cassie和Baxter提出了另外一种理论（即Cassie–Baxter理论）来解释Wenzel理论所无法解释的现象。Cassie–Baxter理论认为液体与具有微观结构的粗糙固体表面间的接触是复合接触，即液体的下部同时存在空气和固体，液体在其上的接触角除了和固–气、固–液、液–气界面的表面张力有关外，还和固–液接触面和气–液接触面在复合接触面中所占的比例有关，并满足式(3)，该公式表明通过减小固–液接触面积可增大接触角，且能减小液体与固体间的黏附力，形成较小的滚动角。

2　极端润湿性表面的常见制备方法

由润湿性相关理论可知，表面特殊的微观结构对极端润湿性的获得起至关重要的作用，可使疏液表面变成超疏液，使亲液表面变成超亲液。

目前制备空气中超疏液表面的方法主要有3种：1）在疏液（低表面能）材料上构造微观结构，该方法常见于在聚丙烯、聚乙烯、聚四氟乙烯、石蜡等表面的超疏液化制备[6–10]；2）先在亲液（高表面能）表面构造微观结构，再用氟硅烷、脂肪酸、聚四氟乙烯等低表面能材料修饰以降低表面能，该方法常见于在金属、陶瓷等工程材料表面的超疏液化制备[11–18]；3）同时构造微观结构并降低表面能，该方法常结合浸涂、喷

涂、刷涂等技术,对基体的原润湿性无要求[19~26]。

制备超亲液表面的方法则主要有2种:1)直接在亲液表面构造微观结构[27,28];2)光引发超亲液,常见于TiO_2、ZnO、WO_3、V_2O_5等特殊基体,该方法不具普适性[29,30],故本文不再介绍光引发超亲液的制备方法。

目前极端润湿性表面的制备方法较多,典型实例如下:

1)电火花线切割法:Bae等[31]报道了一种电火花线切割技术制备铝材料超疏水极端润湿性表面。通过程序控制丝的运行轨迹在铝合金表面获得横截面为正弦形状、波长为200~500 μm的阵列凹槽结构,凹槽结构表面还覆盖有大小约几微米的坑状结构,由此构成微纳米微观结构,水滴在其上的静态接触角达156°、滚动角仅为3°。

2)激光刻蚀法:Kam等[32]采用飞秒激光刻蚀技术在不锈钢板上加工出微米级锥状结构,通过控制扫描速度改变微米级锥状结构的形貌、尺寸、数量,进而获得不同润湿性(超亲水极端润湿性至疏水性),再经低表面能材料修饰后获得超疏水极端润湿性。

3)电化学溶解法:La等[33]以NaOH溶液作为电解液,将铜箔和铜网置于阳极进行电化学溶解,电化学溶解后的铜材料表面布满氢氧化铜纳米针结构,并显示接触角为0°的超亲水极端润湿性,最后经全氟辛基三乙氧基硅烷修饰后,转变为超疏水极端润湿性,水滴在其上的接触角达170°。

4)阳极氧化法:Tasaltin等[34]采用二步阳极氧化法来制备多孔阳极氧化铝结构,先以2°C、质量分数为1%磷酸为电解液,将铝置于194 V的电压下阳极氧化1 h,再浸泡在50°C、含6%质量分数的磷酸和2%质量分数的铬酸混合液中40 min选择性地去除部分氧化膜,再以2°C、质量分数为1%的磷酸为电解液将铝置于194 V的电压下阳极氧化5 h,最后浸泡在30°C、质量分数为5%磷酸中50 min,进而获得多孔阳极氧化铝,经气相沉积修饰六甲基二硅氮烷后获得超疏水极端润湿性,水滴在其上的接触角达153.2°。

5)电化学沉积法:Huang等[35]以含硫酸镍、氯化镍、硼酸、TiO_2纳米颗粒等的混合液为电镀液,在镍材料基体上电化学沉积了Ni-TiO_2微纳米复合镀层,该镀层具有纳米级的刺状结构,经氟硅烷修饰后,呈超疏水极端润湿性,对水的接触角达174.9°。

6)化学溶解法:Qian等[36]利用金属中缺陷优先溶解的性质,采用位错溶解剂对铝、铜、锌表面进行化学溶解,当晶面暴露在相应的位错溶解剂中时,在位错露头处将形成凹坑。他们分别使用盐酸、氢氟酸、水的混合液溶解铝材料,使用盐酸、冰醋酸、水的混合液溶解铜材料,使用盐酸溶解锌材料,均获得微纳米微观结构,经十三氟辛基三乙氧基硅烷(氟硅烷)修饰后获得超疏水极端润湿性。大连理工大学的李艳峰等[37]采用盐酸溶液对铝合金进行化学溶解,获得了由长方体状凸台和凹坑构成的深浅相间的“迷宫型”微纳米结构,并显示超亲水极端润湿性,水滴在表面上完全铺展,接触角为0°;当再经氟硅烷修饰后获得了具有超疏水性质的表面,接触角达156°。

7)化学沉积法:Jia等[38]将镁合金板浸泡在硝酸银水溶液中,表面形成由无规则排列、厚90~100 nm的纳米片构成的微米球结构(平均直径2~3 μm),再经硬脂酸修饰后获得超疏水性。

8)高温热氧化法:Xu等[39]将微米级铁粉在400°C下热处理4 h,铁颗粒表面生成与莲子微观结构相似的矛状纳米片结构,经月桂酸修饰后获得超疏水-超亲油极端润湿性。

9)涂层法:陆遥等[40]发明了一种制备超疏水-超亲油涂层的方法,将氟硅烷修饰后的TiO_2涂料通过胶水固定在各种基体上。该方法具有简单、廉价、所得涂层机械强度高等优点。邓旭等[41]通过蜡烛烟熏、化学气相沉积、高温煅烧、再次化学气相沉积等多步处理在玻璃表面获得耐磨超疏油涂层。

10)电纺法:Choi等[42]利用电纺法在铝箔上构造了含氟纤维层,由于纤维本身表面能较低,因此无需后续的低表面能材料修饰便可获得超疏油性,十六烷在其上的接触角大于150°。

3 极端润湿性表面的主要应用

极端润湿性表面的应用前景广阔,如超亲液表面可用于自清洁、防雾等领域,超疏液表面可用于自清洁、防雾、抗结冰结霜、耐腐蚀、响应开关、油水分离、高负载力水上设备、液体无损转移、防水透气、减阻等领域。

3.1 自清洁

自清洁性是最早发现的极端润湿性表面性能,不管是超疏水还是超亲水表面均具有自清洁效果。低黏附超疏水表面自清洁性的获得主要是因为水滴在其表面极易滚动,滚落时可带走泥土、灰尘等脏物,如荷叶表面的自清洁性。Fürstner等[43]使用氟化的荧光粉充当超疏水表面的污染物,发现普通人工雨可完全去除污染物。Wang等[44]使用炭黑粉末充当超疏水玻璃表面的污染物,发现污染物极易被滚落的水滴黏附并带走。自清洁效果尤其适用于高墙玻璃和汽车挡风玻璃。近几年,已有多种方法可制备出用于玻璃的透明超疏水自清洁涂层或薄膜[45~48]。

与低黏附超疏水表面的自清洁原理不同,超亲水表面具有自清洁性能是由于水滴极易在该表面铺展使超亲水表面和污染物间形成水膜,降低污染物的附着力,污染物在重力或风力的作用下极易沿着或随着水膜落下,达到自清洁效果[49]。由于TiO_2超亲水涂层还具备光催化分解有机物的能力,因此被广泛应用于自清洁玻璃。

3.2 防雾

普通玻璃在湿气或蒸汽中易发生雾化现象,表面形成微小水滴,从而影响能见度和透过率。目前主要的防雾方式分为超亲水湿式防雾和超疏水干式防雾两种。超亲水表面利用水滴铺展形成均匀水膜,使玻璃表面维持透明。利用超亲

水性实现防雾的方法已被实际应用：中科纳米技术工程中心、TOTO、Pilkington、PPG等公司均生产商业化的超亲水防雾玻璃[50]。低黏附超疏水表面由于不沾水因而在防雾领域也有一定的应用前景，但由于雾滴尺寸仅有微米级别，易进入超疏水表面的微米级粗糙结构中，导致超疏水性的消失。Cheng等[51]发现荷叶表面也易被雾气润湿，并丧失超疏水性。然而高雪峰等[52]研究发现蚊子复眼长时间处于雾气中不会被润湿，微米大小的雾滴无法停留或聚集在复眼表面。利用扫描电镜和原子力显微镜发现蚊子复眼是由数百颗直径约为26 μm的半球密堆砌组成，半球表面密集排列纳米级圆锥结构（直径约185.98 nm，高约185.19 nm）。由于微米级雾滴尺寸大于纳米锥之间的间隙，雾滴难以进入间隙中，从而获得防雾功能。高雪峰等已使用软光刻技术成功复制出类似蚊子防雾复眼的结构。

3.3　抗结冰结霜

徐文骥等[53]研究超疏水表面抗结冰结霜性能时发现，与普通表面相比，超疏水表面上的大接触角延迟了冷凝水珠的出现时间和冻结时间，减缓了其增长速度。Tourkine等[54]直接将水滴滴在过冷表面，发现超疏水表面还能有效延迟外加水滴的结冰时间。Kulinich等[55]发现固体表面冰的黏附力随接触角滞后的减小而变小，高接触角、低接触角滞后的低黏附超疏水表面具有较小的覆冰黏附力。Boreyko等[56]报告了纳米结构的超疏水表面促使霜以亚稳态Cassie状态的方式形成，霜冰融化成水后在重力的作用下沿着倾斜的超疏水表面滚落。

尽管超疏水表面不能最终抑制冰的形成，但结冰的延迟、低的覆冰黏附力及融化后易滚落等特征可节省除冰时间和能源。此外，超疏水表面用于高压输电线路上，能有效延迟电缆、绝缘子、杆塔冰层的形成，提高覆冰闪络电压，减少输电线路覆冰过载造成的短路、倒塔等事故[57]。为减少覆冰危害，2010年河南省电力公司采用匹兹堡大学Di Gao教授研发的超疏水纳米防覆冰涂料对220 kV漯薛线进行了涂刷。

3.4　耐腐蚀

由于浸入液体中的超疏液表面的微观结构中可捕获大量气体，使固体表面与液体间产生空气垫，可隔离液体与基体的大面积接触，因此超疏液表面可有效提高金属在腐蚀性溶液中的耐腐蚀性。Zang等[58]通过$FeSO_4$溶液浸泡和硬脂酸修饰在镁合金表面获得超疏水$Fe(OH)_3$涂层，极化曲线和电化学阻抗谱测量显示该超疏水涂层能有效提高镁合金基体的耐腐蚀性，普通镁合金的电化学阻抗值仅为1800 $\Omega\cdot cm^2$，而超疏水镁合金表面的阻抗值达451000 $\Omega\cdot cm^2$。此外，超疏水表面的自腐蚀电流密度（1.585×10^{-7} A/cm^2）要比普通镁合金表面（6.542×10^{-4} A/cm^2）低3个数量级。徐文骥等[59]采用电化学腐蚀和氟硅烷修饰的方法使镁合金表面获得超疏水性，并发现该表面在NaCl、Na_2SO_4、$NaClO_3$、$NaNO_3$多种溶液中的耐腐蚀性均有所提高。除金属镁以外，表面获得超疏水性同样可提高钢[60,61]、铜[62]、铝[63]、钛[64]等金属基体的耐腐蚀性。

3.5　响应开关

部分极端润湿性表面在外界能量的刺激下可发生润湿性可逆转变，如亲水可转变为疏水，而疏水又可变回亲水。这种外加能量下的润湿性可逆转变可作为智能响应开关。目前，润湿性响应开关主要有电场响应[65]、光响应[66]、pH响应[67,68]、温度响应[69]、应力响应[70]等。Accardo等[65]在超疏水硅基体上进行了润湿性电场响应试验，施加电场时，液滴在靠近固体表面附近的层界面能会减小，进而导致接触角的降低，在30 V电压的作用下，仅需179 s接触角便可从163.11°减小至49.43°。Lim等[66]用紫外光照射V_2O_5，使其由超疏水性转变为超亲水性，再将样品放入黑暗中又可恢复超疏水性。Cheng等[67,68]用$HS(CH_2)_{11}CH_3$和$HS(CH_2)_{11}NH_2$的混合液修饰的微观金结构对中性和碱性水显示超疏性，对酸性水显示超亲性；用$HS(CH_2)_{11}CH_3$、$HS(CH_2)_{11}NH_2$和$HS(CH_2)_{10}COOH$的混合液修饰后的表面仅对中性水显示超疏性，溶液酸性越强（pH值越小）或碱性越强（pH值越大）时亲水性越强；用$HS(CH_2)_9CH_3$和$HS(CH_2)_{10}COOH$混合液修饰时，对中性和酸性水显示超疏性，对碱性水显示超亲性。基于上述特征，利用$HS(CH_2)_9CH_3$和$HS(CH_2)_{10}COOH$混合液修饰的镀金泡沫镍包裹铂做成船的动力开关来控制铂与双氧水的接触与否（接触时会生成气体推动船舶前行），进而控制船舶的航行和停止。

3.6　油水分离

由于水和油表面张力的差异，已有众多方法可获得同时对油和水显示相反极端润湿性的表面。现有的油水极端润湿性表面主要有超疏水-超亲油表面和超亲水-水下超疏油表面。这种具有对油水显示不同润湿性的表面可用于油水混合物的分离，按照分离方式的不同，可分为油吸附法和油或水过滤法两种。油吸附法主要使用超疏水-超亲油织物[71~74]、聚合物海绵[75~83]、金属海绵[84,85]、纸[86]、碳纳米管[87,88]、气凝胶纳米纤维素[89,90]及大孔凝胶[91]等材料。这些材料在吸油的同时能完全排斥水，形成极高的油水分离效率和选择性吸附能力，其中Chen等[76]研发的超疏水-超亲油超轻海绵的吸油能力可达自身质量的61.8~102.6倍（具体差异取决于油的密度、黏度和表面张力）。

现有的油或水过滤法，又被称为倾倒式重力驱动法，主要使用超疏水-超亲油网和超亲水-水下超疏油网两种[92~94]。2004年，Feng等[92]报道利用超疏水-超亲油不锈钢网分离柴油/水混合物，柴油会润湿并穿过超疏水-超亲油网，而水仍留在网上，由此形成油水分离，效率高于95%。然而随着分离时间的推移，网上积水变多，密度比油大的积水会形成水桥阻止油与网的接触，中断后续分离。为解决超疏水-超亲水网在分离油水混合物的过程中易产生水桥的问题，Xue等[93]于2011年提出利用预先用水润湿的超亲水网分离油水混合物。由于此类网的粗糙结构中充满极性水相，当非极性油接触网时，油不会穿过网，而水接触网时能顺利穿过网，此外由于水的密度比油大，因此不会产生水桥问题。超亲水-水下超疏油材料的分离效率极高，超过99%。Kota等[95]按照这一

原理开发出一种水响应薄膜,该薄膜显示超亲水和水下超疏油性,用于油水分离时,分离效率超过99.9%。最近,Zhang等[96~98]和Tao等[99]又制备出可用于分离水包油乳化液或油包水乳化液的极端润湿性聚偏氟乙烯薄膜和氢氧化铜薄膜。

3.7 高负载力水上设备

2004年,高雪峰等[100]研究水黾在水上快速行走的原因时,发现单个水黾腿在超疏水性的作用下排开水的体积可达自身体积的300倍,导致单腿承载力达到水黾体重的15倍。自此以后,众多研究人员尝试使用超疏水材料提高水上设备的负载力。疏水物体在水中主要受两种向上的力,一是形成水涡排水产生的浮力,二是液体变形产生的曲率压力(该力大小约等于表面张力的垂直分力)。Feng等[101]发现水涡的深度与接触角满足一定的公式。Pan等[102]使用具有不同接触角的直径20 mm、厚50 μm的铜箔(质量仅为0.1 g)为研究对象,具体研究了润湿性对物体负载力的影响,发现负载力随着接触角的增加而增大。接触角为155.4°的铜箔负载力达到1.57 g(本身质量的15.7倍)。Lu等[103]还利用“Cheerios”效应将超疏水六边形船自组装在一起形成新的船,发现六边形船的宽度越小,自组装船的负载力越大。

3.8 液体无损转移

2002年,Autumn等[104]发现壁虎刚毛显示高黏附超疏水性,水滴在刚毛上的接触角大于160°,但即使样品翻转水滴也不会滚落。此类高黏附超疏水表面可作为机械手将水滴从低黏附超疏水表面移至亲水表面。Li等[105]通过化学浸泡和全氟癸基三乙氧基甲硅烷修饰制备高黏附超疏水ZnO纳米棒结构,并以此样品为机械手将低黏附超疏水铝表面上的水滴无损失地转移到亲水硅基体表面上。

3.9 液体运输

自然界中,水稻叶除了具有超疏水功能外还具有对水滴的各向异性滚动特性。仿水稻叶的液体定向运输表面引起了研究人员的极大兴趣。姚佳等[106]采用二次转写复制技术将水稻叶表面的结构复制到弹性聚合物材料上,垂直和平行于叶脉方向的滚动角分别为40°和25°,显示了各向异性滚动特性。Xu等[107]采用溶胶凝胶技术获得超疏水表面,再用刀片划出一条宽度为200 μm的S形曲线,水滴在重力的驱动下沿着曲线滚落,实现了液体的定向运输。Mertaniemi等[108]采用铣削、激光加工等机械加工方法在铜、锌、硅基体上加工出曲线轨迹的沟槽,再通过传统粗糙化和低表面能化处理使基体获得超疏水性后,水滴可在曲线轨迹的沟槽上快速移动。最近Kang等[109]还实现了低表面能油类液体的定向运输。除了液体的定向运输外,Ghosh等[110]还研究了液体的无泵抗重力运输,使用紫外线照射在超疏水SiO_2涂层上获得契形图案的局部超亲水表面,在半毛细力和拉普拉斯力驱动下,液体很容易从窄端向宽端移动(也可往高处运动),体积流速可达350 μL/s。

3.10 血液相容材料

血液相容材料是指该材料不易引起血液凝聚、不破坏血液成分或改变血液生理环境。部分研究显示超疏液表面可有效抗血小板黏聚,是可能的血液相容材料。Sun等[111]比较了静态血浆中的血小板在光滑的聚合物薄膜和纳米微观结构超疏水聚合物薄膜上的黏附,发现大量血小板均匀分布在光滑的聚合物表面,而黏附在超疏水表面上的血小板数量极少,显示了很好的抗血液凝聚性。

3.11 其他应用

极端润湿性表面在防水装置、流体减阻方面也存在一定的应用前景。如多孔超疏液表面由于对液体具有排斥性,且可让气、声、光波通过,可作为透气防水材料。Lee等[112]使用纳米结构化的超疏水微网包裹移动电话扬声器,即使在水下2 m时,超疏水网也能有效保护扬声器,阻止扬声器与水接触,且扬声器的声压(声音质量)在水上水下无明显差别。Shi等[113]比较了超疏水金线和疏水金线在双氧水中运行速度,发现超疏水性可提速70%。

4 结论与展望

尽管已有多种方法可制备出极端润湿性表面,且有关极端润湿性表面的应用至今在自清洁、防雾、抗结冰结霜、耐腐蚀、油水分离、高负载力水上设备、液体无损转移、液体运输等方面已获得诸多研究成果,但要实现真正的工业化应用还有以下问题亟需解决。

1) 尽管部分超亲液涂层在自清洁、防雾领域已成为商业化产品,但商业的TiO_2等超亲液涂层只有在紫外光照射的条件下才显示超亲液性,且使用寿命较短、持久性较差,具有长期稳定亲液性、耐磨性和耐候性好的超亲液涂层还有待开发。

2) 超疏液表面的低表面能涂层和高粗糙度、小尺度的微纳米结构常会因冲击或摩擦等机械作用而破坏,具有高硬度、低粗糙度的超疏液表面有待进一步研究。

3) 尽管超疏水表面在众多领域有应用价值,但因其表面极易被油污污染而丧失超疏水性,所以同时具有超疏水性和超疏油性的超双疏表面更具应用潜力,但由于油类液体的表面张力远小于水的表面张力,导致超疏油表面的制备极其困难,能制备出超疏油表面的方法较少。

4) 目前超疏液表面的液体静压和动压承受能力较低,在液下高速运动或离液面较深时,液体会进入微观结构间的空隙中,使得超疏液性消失,导致其流体减阻和防水能力失效,因此需合理设计微观结构以提高液体静压和动压承受能力。

5) 在极端润湿性表面的油水分离应用研究方面,油吸附法在每次吸油后都需挤压处理使吸附油排出,浪费大量时间和能源;倾倒式重力驱动油或水过滤法需将油水混合物预先收集后再倾倒在装置中,此方法对分离工业油水混合物可行,而对大面积海上溢油的处理则显得不足。针对大面积海上溢油,研制无需挤压、无需预先收集油水混合物的分离装置与方法十分必要。

参考文献(References)

[1] Young T. An essay on the cohesion of fluids[J]. Philosophical Transactions of the Royal Society of London, 1805, 95: 65-87.

[2] Wenzel R N. Resistance of sold surfaces to wetting by water[J]. Industrial & Engineering Chemistry, 1936, 28(8): 988-994.

[3] Wenzel R N. Surface roughness and contact angle[J]. The Journal of Physical and Colloid Chemistry, 1949, 53(9): 1466-1467.

[4] Cassie A B D, Baxter S. Wettability of porous surfaces[J]. Transactions of the Faraday Society, 1944, 40: 546-551.

[5] Nishino T, Meguro M, Nakamae K, et al. The lowest surface free energy based on $-CF_3$ alignment[J]. Langmuir, 1999, 15(13): 4321-4323.

[6] Su C H, Xu Y Q, Gong F, et al. The abrasion resistance of a superhydrophobic surface comprised of polyurethane elastomer[J]. Soft Mater, 2010, 6(24): 6068-6071.

[7] Checco A, Rahman A, Black C T. Robust superhydrophobicity in large-Area nanostructured surfaces defined by block-copolymer self assembly [J]. Advanced Materials, 2014, 26(6): 886-891.

[8] Yong J L, Chen F, Yang Q, et al. Femtosecond laser weaving superhydrophobic patterned PDMS surfaces with tunable adhesion[J]. The Journal of Physical Chemistry C, 2013, 117(47): 24907-24912.

[9] Zhang Z X, Li Y A, Ye M, et al. Fabrication of superhydrophobic surface by a laminating exfoliation method[J]. Journal of Materials Chemistry A, 2014, 2(5): 1268-1271.

[10] Jiang T, Koch J, Unger C, et al. Ultrashort picosecond laser processing of micro-molds for fabricating plastic parts with superhydrophobic surfaces[J]. Applied Physics A-Materials Science & Processing, 2012, 108(4): 863-869.

[11] Xu W J, Song J L, Sun J, et al. Fabrication of superhydrophobic surfaces on aluminum substrates using $NaNO_3$ electrolytes[J]. Journal of Materials Science, 2011, 46(18): 5925-5930.

[12] Wu W C, Wang X L, Wang D A, et al. Alumina nanowire forests via unconventional anodization and super-repellency plus low adhesion to diverse liquids[J]. Chemical Communications, 2009(9): 1043-1045.

[13] Liu Y, Yin X M, Zhang J J, et al. A electro-deposition process for fabrication of biomimetic super-hydrophobic surface and its corrosion resistance on magnesium alloy[J]. Electrochimica Acta, 2014, 125: 395-403.

[14] Liang J S, Li D, Wang D Z, et al. Preparation of stable superhydrophobic film on stainless steel substrate by a combined approach using electrodeposition and fluorinated modification[J]. Applied Surface Science, 2014, 293: 265-270.

[15] Liu L J, Feng X R, Guo M X. Eco-friendly fabrication of superhydrophobic bayerite array on Al foil via an etching and growth process[J]. The Journal of Physical Chemistry C, 2013, 117(48): 25519-25525.

[16] Ou J F, Hu W H, Liu S, et al. Superoleophobic textured copper surfaces fabricated by chemical etching/oxidation and surface fluorination[J]. ACS Applied Materials & Interfaces, 2013, 5(20): 10035-10041.

[17] Yang J, Li W. Preparation of superhydrophobic surfaces on Al substrates and the anti-icing behavior[J]. Journal of Alloys and Compounds, 2013, 576: 215-219.

[18] Zang D Y, Li F, Geng X G, et al. Tuning the wettability of an aluminum surface via a chemically deposited fractal dendrite structure [J]. The European Physical Journal E, 2013, 36(6): 1-8.

[19] Yohe S T, Grinstaff M W. A facile approach to robust superhydrophobic 3D coatings via connective-particle formation using the electrospraying process[J]. Chemical Communications, 2013, 49(8): 804-806.

[20] Xu X H, Zhang Z Z, Guo F, et al. Fabrication of bionic superhydrophobic manganese oxide/polystyrene nanocomposite coating[J]. Journal of Bionic Engineering, 2012, 9(1): 11-17.

[21] Rao A V, Latthe S S, Mahadik S A, et al. Mechanically stable and corrosion resistant superhydrophobic sol-gel coatings on copper substrate[J]. Applied Surface Science, 2011, 257(13): 5772-5776.

[22] Schutzius T M, Tiwari M K, Bayer I S, et al. High strain sustaining, nitrile rubber based, large-area, superhydrophobic, nanostructured composite coatings[J]. Composites Part A: Applied Science and Manufacturing, 2011, 42(8): 979-985.

[23] Das A, Schutzius T M, Bayer I S, et al. Superoleophobic and conductive carbon nanofiber/fluoropolymer composite films[J]. Carbon, 2012, 50 (3): 1346-1354.

[24] Tiwari M K, Bayer I S, Jursich G M, et al. Highly liquid-repellent, large-area, nanostructured poly(vinylidene fluoride)/poly(ethyl 2-cyanoacrylate) composite coatings: particle filler effects[J]. ACS Applied Materials & Interfaces, 2010, 2(4): 1114-1119.

[25] Schutzius T M, Bayer I S, Tiwari M K, et al. Novel fluoropolymer blends for the fabrication of sprayable multifunctional superhydrophobic nanostructured composites[J]. Industrial & Engineering Chemistry Research, 2011, 50(19): 11117-11123.

[26] Das A, Hayvaci H T, Tiwari M K, et al. Superhydrophobic and conductive carbon nanofiber/PTFE composite coatings for EMI shielding[J]. Journal of Colloid and Interface Science, 2011, 353(1): 311-315.

[27] Ye J M, Yin Q M, Zhou Y L. Superhydrophilicity of anodic aluminum oxide films: From "honeycomb" to "bird's nest"[J]. Thin Solid Films, 2009, 517(21): 6012-6015.

[28] Song J L, Xu W J, Liu X, et al. Electrochemical machining of super-hydrophobic Al surfaces and effect of processing parameters on wettability[J]. Applied Physics A, 2012, 108(3): 559-568.

[29] Sun R D, Nakajima A, Fujishima A, et al. Photoinduced surface wettability conversion of ZnO and TiO_2 thin films[J]. The Journal of Physical Chemistry B, 2001, 105(10): 1984-1990.

[30] Fujishima A, Zhang X T, Tryk D A. TiO_2 photocatalysis and related surface phenomena[J]. Surface Science Reports, 2008, 63(12): 515-582.

[31] Bae W G, Song K Y, Rahmawan Y, et al. One-step process for superhydrophobic metallic surfaces by wire electrical discharge machining[J]. ACS Applied Materials & Interfaces, 2012, 4(7): 3685-3691.

[32] Kam D H, Bhattacharya S, Mazumder J. Control of the wetting properties of an AISI 316L stainless steel surface by femtosecond laser-induced surface modification[J]. Journal of Micromechanics and Microengineering, 2012, 22(10): 105019.

[33] La D D, Nguyen T A, Lee S H, et al. A stable superhydrophobic and superoleophilic Cu mesh based on copper hydroxide nanoneedle arrays [J]. Applied Surface Science, 2011, 257(13): 5705-5710.

[34] Tasaltin N, Sanli D, Jonáš A, et al. Preparation and characterization of superhydrophobic surfaces based on hexamethyldisilazane-modified nanoporous alumina[J]. Nanoscale Research Letters, 2011, 6(1): 1-8.

[35] Huang S Y, Hu Y W, Pan W. Relationship between the structure and hydrophobic performance of Ni-TiO_2 nanocomposite coatings by electrodeposition[J]. Surface and Coatings Technology, 2011, 205(13/14): 3872-3876.

[36] Qian B T, Shen Z Q. Fabrication of superhydrophobic surfaces by dislocation-selective chemical etching on aluminum, copper, and zinc substrates[J]. Langmuir, 2005, 21(20): 9007-9009.

[37] 李艳峰, 于志家, 于跃飞, 等. 铝合金基体上超疏水表面的制备[J]. 高校化学工程学报, 2008(1): 6-10.
Li Yanfeng, Yu Zhijia, Yu Yuefei, et al. Fabrication of superhydrophobic surfaces on aluminum alloy[J]. Journal of Chemical Engineering of Chinese Universities, 2008(1): 6-10.

[38] Jia J, Fan J F, Xu B S, et al. Microstructure and properties of the super-hydrophobic films fabricated on magnesium alloys[J]. Journal of Alloys and Compounds, 2013, 554: 142-146.

[39] Xu L P, Wu X W, Meng J X, et al. Papilla-like magnetic particles with hierarchical structure for oil removal from water[J]. Chemical Communications, 2013, 49(78): 8752-8754.

[40] Lu Y, Sathasivam S, Song J L, et al. Robust self-cleaning surfaces that function when exposed to either air or oil[J]. Science, 2015, 347 (6226): 1132-1135.

[41] Deng X, Mammen L, Butt H J, et al. Candle soot as a template for a transparent robust superamphiphobic coating[J]. Science, 2012, 335 (6064): 67-70.

[42] Choi G R, Park J, Ha J W, et al. Superamphiphobic web of PTFEMA fibers via simple electrospinning without functionalization[J]. Macromolecular Materials and Engineering, 2010, 295(11): 995-1002.

[43] Fürstner R, Barthlott W, Neinhuis C, et al. Wetting and self-cleaning properties of artificial superhydrophobic surfaces[J]. Langmuir, 2005, 21(3): 956-961.

[44] Wang H, Tang L M, Wu X M, et al. Fabrication and anti-frosting performance of super hydrophobic coating based on modified nano-sized calcium carbonate and ordinary polyacrylate[J]. Applied Surface Science, 2007, 253(22): 8818-8824.

[45] Wang G Y, Liang W X, Wang B, et al. Conductive and transparent superhydrophobic films on various substrates by in situ deposition[J]. Applied Physics Letters, 2013, 102(20): 203703.

[46] Ebert D, Bhushan B. Transparent, Superhydrophobic, and wear-Resistant coatings on Glass and polymer substrates using SiO_2, ZnO, and ITO nanoparticles[J]. Langmuir, 2012, 28(31): 11391-11399.

[47] Chen Y, Zhang Y B, Shi L, et al. Transparent superhydrophobic/superhydrophilic coatings for self-cleaning and anti-fogging[J]. Applied Physics Letters, 2012, 101(3): 033701.

[48] Xu L B, Karunakaran R G, Guo J, et al. Transparent, superhydrophobic surfaces from one-step spin coating of hydrophobic nanoparticles[J]. ACS Applied Materials & Interfaces, 2012, 4(2): 1118-1125.

[49] 郑建勇, 钟明强, 冯杰. 基于超亲水原理的自清洁表面研究进展及产业化状况[J]. 材料导报, 2009, 27(增1): 42-44.
Zheng Jianyong, Zhong Mingqiang, Feng Jie. Research progress and industrial manufacture status of superhydrophilic self-cleaning surfaces [J]. Materials Review, 2009, 27(Suppl 1):42-44.

[50] 封玉凤, 王利新. 自清洁防雾玻璃的研究进展[J]. 玻璃与搪瓷, 2013 (1): 39-42.
Feng Yufeng, Wang Lixin. Progress on the self-cleaning and anti-fogging glass[J]. Glass & Enamel, 2013(1): 39-42.

[51] Cheng Y T, Rodak D E. Is the lotus leaf superhydrophobic?[J]. Applied Physics Letters, 2005, 86(14): 144101.

[52] Gao X F, Yan X, Yao X, et al. The dry-style antifogging properties of mosquito compound eyes and artificial analogues prepared by soft lithography[J]. Advanced Materials, 2007, 19(17): 2213-2217.

[53] 徐文骥, 宋金龙, 孙晶, 等. 铝基体超疏水表面的抗结冰结霜效果分析[J]. 低温工程, 2010(6): 11-15.
Xu Wenji, Song Jinlong, Sun Jing, et al. Research in ice and frost repellency of superhydrophobic surfaces on aluminum[J]. Cryogenics, 2010(6):11-15.

[54] Tourkine P, Le Merrer M, Quéré D. Delayed freezing on water repellent materials[J]. Langmuir, 2009, 25(13): 7214-7216.

[55] Kulinich S A, Farzaneh M. Ice adhesion on super- hydrophobic surfaces[J]. Applied Surface Science, 2009, 255(18): 8153-8157.

[56] Boreyko J B, Srijanto B R, Nguyen T D, et al. Dynamic defrosting on nanostructured superhydrophobic surfaces[J]. Langmuir, 2013, 29(30): 9516-9524.

[57] 杨洋, 李剑, 胡建林, 等. 绝缘子的超疏水涂层覆冰特性试验研究[J]. 高电压技术, 2010(3): 621-626.
Yang Yang, Li Jian, Hu Jianlin, et al. Experimental study in icing properties of superhydrophobic coatings on insulators[J]. High Voltage Engineering, 2010(3): 621-626.

[58] Zang D M, Zhu R W, Wu C X, et al. Fabrication of stable superhydrophobic surface with improved anticorrosion property on magnesium alloy[J]. Scripta Materialia, 2013, 69(8): 614-617.

[59] Xu W J, Song J L, Sun J, et al. Rapid fabrication of large-area, corrosion-resistant superhydrophobic Mg alloy surfaces[J]. ACS Applied Materials & Interfaces, 2011, 3(11): 4404-4414.

[60] Yu D Y, Tian J T, Dai J H, et al. Corrosion resistance of three-layer superhydrophobic composite coating on carbon steel in seawater[J]. Electrochimica Acta, 2013, 97: 409-419.

[61] Boinovich L B, Gnedenkov S V, Alpysbaeva D A, et al. Corrosion resistance of composite coatings on low-carbon steel containing hydrophobic and superhydrophobic layers in combination with oxide sublayers[J]. Corrosion Science, 2012, 55: 238-245.

[62] Wang P, Zhang D, Qiu R, et al. Super-hydrophobic metal-complex film fabricated electrochemically on copper as a barrier to corrosive medium[J]. Corrosion Science, 2014, 83: 317-326.

[63] Zang D M, Zhu R W, Zhang W, et al. Stearic acid modified aluminum surfaces with controlled wetting properties and corrosion resistance[J]. Corrosion Science, 2014, 83: 86-93.

[64] Ou J F, Liu M Z, Li W, et al. Corrosion behavior of superhydrophobic surfaces of Ti alloys in NaCl solutions[J]. Applied Surface Science, 2012, 258(10): 4724-4728.

[65] Accardo A, Gentile F, Coluccio M L, et al. A combined electrowetting on dielectrics superhydrophobic platform based on silicon micro-structured pillars[J]. Microelectronic Engineering, 2012, 98: 651-654.

[66] Lim H S, Kwak D, Lee D Y, et al. UV-driven reversible switching of a roselike vanadium oxide film between superhydrophobicity and superhydrophilicity[J]. Journal of the American Chemical Society, 2007, 129(14): 4128-4129.

[67] Cheng M J, Liu Q, Ju G N, et al. Bell-shaped superhydrophilic - superhydrophobic- superhydrophilic double transformation on a pH-responsive smart surface[J]. Advanced Materials, 2014, 26(2): 306-310.

[68] Xiao M, Guo X P, Cheng M J, et al. pH-responsive on-off motion of a superhydrophobic boat: towards the design of a minirobot[J]. Small, 2014, 10(5): 859-865.

[69] Chen H, Pan S J, Xiong Y Z, et al. Preparation of thermo-responsive superhydrophobic TiO_2/poly(N- isopropylacrylamide) microspheres[J]. Applied Surface Science, 2012, 258(24): 9505-9509.

[70] Zhang J L, Lu X Y, Huang W H, et al. Reversible superhydrophobicity to superhydrophilicity transition by extending and unloading an elastic polvamide film[J]. Macromolecular Rapid Communications, 2005, 26(6): 477–480.

[71] Lin J Y, Ding B, Yang J M, et al. Subtle regulation of the micro- and nanostructures of electrospun polystyrene fibers and their application in oil absorption[J]. Nanoscale, 2012, 4(1): 176–182.

[72] Lin J Y, Tian F, Shang Y W, et al. Facile control of intra-fiber porosity and inter-fiber voids in electrospun fibers for selective adsorption[J]. Nanoscale, 2012, 4(17): 5316–5320.

[73] Wu J, Wang N, Wang L, et al. Electrospun porous structure fibrous film with high oil adsorption capacity[J]. ACS Applied Materials & Interfaces, 2012, 4(6): 3207–3212.

[74] Zhu H T, Qiu S S, Jiang W, et al. Evaluation of electrospun polyvinyl chloride/polystyrene fibers as sorbent materials for oil spill cleanup[J]. Environmental Science & Technology, 2011, 45(10): 4527–4531.

[75] Calcagnile P, Fragouli D, Bayer I S, et al. Magnetically driven floating foams for the removal of oil contaminants from water[J]. ACS Nano, 2012, 6(6): 5413–5419.

[76] Chen N, Pan Q M. Versatile fabrication of ultralight magnetic foams and application for oil- water separation[J]. ACS Nano, 2013, 7(8): 6875–6883.

[77] Nagappan S, Park J J, Park S S, et al. Bio-inspired, multi-purpose and instant superhydrophobic-superoleophilic lotus leaf powder hybrid micro- nanocomposites for selective oil spill capture[J]. Journal of Materials Chemistry A, 2013, 1(23): 6761–6769.

[78] Sarkar A, Mahapatra S. Novel hydrophobic vaterite particles for oil removal and recovery[J]. Journal of Materials Chemistry A, 2014, 2(11): 3808–3818.

[79] Wang B, Li J, Wang G Y, et al. Methodology for robust superhydrophobic fabrics and sponges from in situ growth of transition metal/metal oxide nanocrystals with thiol modification and their applications in oil/water separation[J]. ACS Applied Materials & Interfaces, 2013, 5(5): 1827–1839.

[80] Zhou X Y, Zhang Z Z, Xu X H, et al. Facile fabrication of superhydrophobic sponge with selective absorption and collection of oil from water[J]. Industrial & Engineering Chemistry Research, 2013, 52(27): 9411–9416.

[81] Zhu Q, Chu Y, Wang Z K, et al. Robust superhydrophobic polyurethane sponge as a highly reusable oil- absorption material[J]. Journal of Materials Chemistry A, 2013, 1(17): 5386–5393.

[82] Zhu Q, Pan Q M. Mussel-inspired direct immobilization of nanoparticles and application for oil- water separation[J]. ACS Nano, 2014, 8(2): 1402–1409.

[83] Zhu Q, Pan Q M, Liu F T. Facile removal and collection of oils from water surfaces through superhydrophobic and superoleophilic sponges[J]. The Journal of Physical Chemistry C, 2011, 115(35): 17464–17470.

[84] Cheng M, Gao Y F, Guo X P, et al. A Functionally integrated device for effective and facile oil spill cleanup[J]. Langmuir, 2011, 27(12): 7371–7375.

[85] Cheng M J, Ju G N, Jiang C, et al. Magnetically directed clean-up of underwater oil spills through a functionally integrated device[J]. Journal of Materials Chemistry A, 2013, 1(43): 13411–13416.

[86] Wang S H, Li M, Lu Q H. Filter paper with selective absorption and aeparation of liquids that differ in surface tension[J]. ACS Applied Materials & Interfaces, 2010, 2(3): 677–683.

[87] Dong X C, Chen J, Ma Y W, et al. Superhydrophobic and superoleophilic hybrid foam of graphene and carbon nanotube for selective removal of oils or organic solvents from the surface of water[J]. Chemical Communications, 2012, 48(86): 10660–10662.

[88] Gui X C, Zeng Z P, Lin Z Q, et al. Magnetic and highly recyclable macroporous carbon nanotubes for spilled oil sorption and separation[J]. ACS Applied Materials & Interfaces, 2013, 5(12): 5845–5850.

[89] Cervin N, Aulin C, Larsson P, et al. Ultra porous nanocellulose aerogels as separation medium for mixtures of oil/water liquids[J]. Cellulose, 2012, 19(2): 401–410.

[90] Tang Y, Yeo K L, Chen Y, et al. Ultralow-density copper nanowire aerogel monoliths with tunable mechanical and electrical properties[J]. Journal of Materials Chemistry A, 2013, 1(23): 6723–6726.

[91] Hayase G, Kanamori K, Fukuchi M, et al. Facile synthesis of marshmallow-like macroporous gels usable under harsh conditions for the separation of oil and water[J]. Angewandte Chemie International Edition, 2013, 52(7): 1986–1989.

[92] Feng L, Zhang Z Y, Mai Z H, et al. A Super-hydrophobic and super-oleophilic coating mesh film for the separation of oil and water[J]. Angewandte Chemie International Edition, 2004, 43(15): 2012–2014.

[93] Xue Z X, Wang S T, Lin L, et al. A novel superhydrophilic and underwater superoleophobic hydrogel- coated mesh for oil/water separation[J]. Advanced Materials, 2011, 23(37): 4270–4273.

[94] Liang W X, Guo Z G. Stable superhydrophobic and superoleophilic soft porous materials for oil/water separation[J]. RSC Advances, 2013, 3(37): 16469–16474.

[95] Kota A K, Kwon G, Choi W, et al. Hygro-responsive membranes for effective oil- water separation[J]. Nature Communication, 2012, 3: 1025.

[96] Zhang W B, Shi Z, Zhang F, et al. Superhydrophobic and superoleophilic PVDF membranes for effective separation of water- in- oil emulsions with high flux[J]. Advanced Materials, 2013, 25(14): 2071–2076.

[97] Zhang W B, Zhu Y Z, Liu X, et al. Salt-induced fabrication of superhydrophilic and underwater superoleophobic PAA-g-PVDF membranes for effective separation of oil-in-water emulsions[J]. Angewandte Chemie International Edition, 2014, 53(3): 856–860.

[98] Zhang F, Zhang W B, Shi Z, et al. Nanowire-haired inorganic membranes with superhydrophilicity and underwater ultralow adhesive superoleophobicity for high-efficiency oil/water separation[J]. Advanced Materials, 2013, 25(30): 4192–4198.

[99] Tao M M, Xue L X, Liu F, et al. An Intelligent superwetting PVDF membrane showing switchable transport performance for oil/water separation[J]. Advanced Materials, 2014, 26(18): 2943–2948.

[100] Gao X F, Jiang L. Water-repellent legs of water striders[J]. Nature, 2004, 432(7013): 36.

[101] Feng X Q, Gao X F, Wu Z N, et al. Superior water repellency of water strider legs with hierarchical structures: Experiments and analysis[J]. Langmuir, 2007, 23(9): 4892–4896.

[102] Pan Q M, Liu J, Zhu Q. A Water strider-like model with large and stable loading capacity fabricated from superhydrophobic copper foils[J]. ACS Applied Materials & Interfaces, 2010, 2(7): 2026–2030.

[103] Lu Y, Song J L, Liu X, et al. Loading capacity of a self-assembled superhydrophobic boat array fabricated via electrochemical method[J]. Micro & Nano Letters, 2012, 7(8): 786–789.

[104] Autumn K, Sitti M, Liang Y A, et al. Evidence for van der Waals adhesion in gecko setae[J]. Proceedings of the National Academy of

Sciences, 2002, 99 (19): 12252-12256.

[105] Li J, Liu X H, Ye Y P, et al. Gecko-inspired synthesis of superhydrophobic ZnO surfaces with high water adhesion[J]. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2011, 384 (1-3): 109-114.

[106] 姚佳, 王剑楠, 于颜豪, 等. 仿生水稻叶表面制备及其润湿性研究[J]. 科学通报, 2012(15): 1362-1366.
Yao Jia, Wang Jiannan, Yu Yanhao, et al. Biomimetic fabrication and characterization of an artificial rice leaf surface with anisotropic wetting[J]. Chinese Science Bulletin, 2012, 57(15): 1362-1366.

[107] Xu Q F, Wang J N, Smith I H, et al. Directing the transportation of a water droplet on a patterned superhydrophobic surface[J]. Applied Physics Letters, 2008, 93(23):233112.

[108] Mertaniemi H, Jokinen V, Sainiemi L, et al. Superhydrophobic tracks for low- friction, guided transport of water droplets[J]. Advanced Materials, 2011, 23(26): 2911-2914.

[109] Kang S M, Lee C, Kim H N, et al. Directional oil sliding surfaces with hierarchical anisotropic groove microstructures[J]. Advanced Materials, 2013, 25(40): 5756-5761.

[110] Ghosh A, Ganguly R, Schutzius T M, et al. Wettability patterning for high-rate, pumpless fluid transport on open, non-planar microfluidic platforms[J]. Lab on a Chip, 2014, 14(9): 1538-1550.

[111] Sun T L, Tan H, Han D, et al. No platelet can adhere-largely improved blood compatibility on nanostructured superhydrophobic surfaces[J]. Small, 2005, 1(10): 959-963.

[112] Lee S M, Song J H, Jung P G, et al. Nanotextured superhydrophobic micromesh[J]. Sensors and Actuators A: Physical, 2011, 171(2): 233-240.

[113] Shi F, Niu J, Liu J, et al. Towards understanding why a superhydrophobic coating is needed by water striders[J]. Advanced Materials, 2007, 19 (17): 2257-2261.

（编辑　陈华姣）

·学术动态·

中国科学技术协会

2015青岛国际脱盐大会召开

2015年6月29日，由中国科协和青岛市人民政府联合主办、主题为“脱盐：创新驱动与绿色发展”的2015青岛国际脱盐大会在山东青岛开幕。中国科协党组副书记、副主席、书记处书记张勤，青岛市政协副主席王修林，国际水协会主席Helmut Kroiss，国际水协会执行主席Ger Bergkamp，欧洲脱盐学会秘书长Miriam Balaban，以色列驻华使馆农业、科技及国际合作参赞Eitan Neubauer，水利部副总工程师庞进武，工业和信息化部节能与综合利用司司长高云虎，中国科学院海洋研究所研究员、中国工程院院士侯保荣等出席大会开幕式。

来自美国、德国、加拿大、日本、奥地利、以色列等20多个国家（地区）和国内脱盐及水资源利用领域的专家，以及陶氏化学、懿华水处理、阿本戈、滨特尔水净化系统、苏伊士环境水务工程、以色列IDE、美国海德能、GE水处理及工艺过程处理、华电工程、东方电气、中冶海水淡化、青岛海诺等400多家国内外企业负责人700余人参加大会。

会议期间，举行了中国净水行业发展峰会、海水淡化技术的创新与发展研讨会、全国冶金节水与废水利用技术研讨会、全国印染行业水处理技术创新大会、浓盐水综合利用国际会议、全国冶金用水节水与废水综合利用技术研讨会、北京沃特尔正渗透技术发展论坛等学术研讨会，研讨了海水淡化与综合利用产业的发展战略和技术。

详见中国科协网http://www.cast.org.cn/n35081/n35473/n35518/16493919.html。