

基于仿生的增韧环氧树脂的冲蚀磨损特性研究

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摘要: **目的** 针对钾盐输送过程中钾盐颗粒对设备造成的冲蚀磨损问题, 以及具有较好可溶性和吸湿性的钾盐易黏附于金属设备, 从而造成的腐蚀和堵塞问题, 将耐冲蚀磨损、耐腐蚀的高分子复合材料与耐冲蚀磨损仿生结构相结合对冲蚀关键零件进行设计, 以提高散料输送过程中相关部件表面的耐冲蚀磨损性能和黏附性能。**方法** 利用自备的疏水二氧化硅对环氧树脂进行增韧处理, 结合贝壳表面肋条结构及鲨鱼表皮盾鳞的特殊排列方式对冲蚀表面进行仿生设计, 再利用翻模法在增韧环氧树脂表面制备耐冲蚀仿生结构, 完成接触角的测量, 以及表面耐磨性、表面硬度、耐冲蚀磨损性能等测试, 探究疏水二氧化硅颗粒质量分数、仿生结构对环氧树脂综合性能的影响。**结果** 增加疏水二氧化硅的含量, 可以提高试样的疏水性; 相较于无仿生结构试样, 贝壳/鲨鱼复合仿生结构试样的耐磨性能更强, 其质量损失率由 0.22% 降至 0.072%。同时, 在疏水二氧化硅的质量分数为 4% 时, 冲蚀率最低, 仅为 1.4%。**结论** 疏水二氧化硅的质量分数为 4% 的增韧环氧树脂贝壳/鲨鱼仿生结构试样的综合性能最优, 其疏水性、耐磨性、耐冲蚀性能均得到提升。

关键词: 冲蚀磨损; 仿生结构; 增韧环氧树脂; 疏水二氧化硅

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Erosion Wear Characteristics of Epoxy Resin Composites Based on Texture Surface

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ABSTRACT: In the process of potassium salt transportation, due to the long-term impact of potassium salt to some transportation tanks, pipelines and other areas, it is very easy to produce erosion and wear. In the transportation process, the way of spraying saturated brine is used to remove dust, but due to the hygroscopicity of potash itself, it may cause the potash to adhere to the surface of the machine, leading to clogging easily. In addition, it will also form a microcell with the surface of the metal equipment, causing electrochemical corrosion on the surface of the transportation equipment. Although surface painting is also used to protect the surface of the transportation equipment, but this is not enough to meet the demand. At present, the special mining and transportation equipment and process of potash are still in the exploratory stage, so most of the commonly

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used potash mining and transportation equipment is inherited from coal mine machinery. Therefore, in order to obtain a wear-resistant protective layer and prevent the blockage and corrosion caused by the adhesion of potash salt, the work aims to select the corrosion-resistant and highly chemically stable epoxy resin as the surface material subject to erosion, and utilize the homemade silica particles to increase the strength, toughness, and ductility of the epoxy resin in order to overcome the hard and brittle characteristics of the epoxy resin, and at the same time, improves its hydrophobicity to avoid the adhesion of potash salt, and combine with the surface bionic technology to further improve the erosion-resistant performance of the material. The erosion resistance of the material is further improved by combining the surface bionic technology.

The hydrophobic SiO_2 particles were prepared by sol-gel method with high concentration of ammonia or polymers as catalysts through the co-hydrolysis polycondensation reaction between ethyl acetate orthosilicate and methyltriethoxysilane. A certain amount of epoxy resin was taken at $60\text{ }^\circ\text{C}$ with an electric stirrer for 5 minutes (speed of 60 r/min), then a certain amount of hydrophobic silica particles as well as an appropriate amount of antifoam agent was added for mixing, and finally an appropriate amount of curing agent was added. Next, the mixture was poured into the homemade silica gel molds with 304 stainless steel substrate for the turnover of the mold at room temperature for curing of 24 hours and the toughened epoxy resin composite coatings were obtained. The bionic morphology model combined the sediment erosion and abrasion resistance of shells and the damping characteristics of the shark skin. The shell cross-section profile and the damping curve of the shark skin were extracted to obtain the shell/shark bionic structure, and then get the bionic toughened epoxy resin coating by the over-molding method. The hydrophobic angle, hardness, abrasion resistance and erosion resistance of the bionic toughened epoxy resin coating were tested and analyzed by optical contact angle meter, Vickers hardness tester, deep microscope, and homemade erosion device.

With the increase of hydrophobic silica content, the contact angle rose and the hardness of the toughened epoxy resin showed a tendency to rise and then fall, and the increase of hydrophobic silica content led to the increase of the system concentration in the preparation process, the bubbles introduced during the mixing process were difficult to eliminate, and the phenomenon of the agglomeration of the hydrophobic silica was gradually aggravated. The wear resistance of the bionic morphology specimens was improved compared with that of the non-bionic morphology specimens. Potash media erosion wear performance test results showed that the resistance of epoxy resin coating to potash erosion effect was better, almost without weight loss in the erosion time of the coating. Regarding the erosion medium for diamond sand, the erosion wear test results under different hydrophobic silica contents showed that with the enhancement of the content of hydrophobic silica, toughened epoxy resin erosion rate was a downward trend. A single shell structure mimicry does not effectively improve the erosion and wear performance of epoxy resin composites. The shell/shark bionic structure specimen as S2W1 specimen has the best resistance to erosion and wear, and the erosion rate decreases to 1.4%.

KEY WORDS: erosion wear; bionic structure; toughened epoxy resin; hydrophobic silica

钾肥是农业三大肥料之一,世界上 95%的钾盐产品都用作肥料。目前,我国已查明钾盐资源的储量不大,难以满足农业对钾肥的需求,因此钾盐的有效开采和转运直接影响着国家粮食安全^[1-2]。目前,钾盐的开采和运输大多采用与煤矿开采和转运所用类似的带式输送及配套设备,很少有针对钾盐的开采和转运的专用配套设备^[3-6]。在工作中,由于钾盐具有可溶性和吸湿性等特殊性能,因此它极易与金属表面发生板结堵塞和电化学腐蚀。同时,转运设备(特别是落料管、冲蚀衬板等关键部件)在钾盐颗粒的长期冲击作用下,会发生冲蚀磨损,腐蚀现象的存在加剧了金属部件表面的冲蚀磨损现象^[7-10],降低了转运设备的寿命,板结造成的钾盐堵塞问题会导致转运设备停机,因此严重制约了散料的输送效率^[11-12]。

针对腐蚀和冲蚀磨损问题,目前研究者主要从

表面结构设计、耐磨材料及表面处理等多方面进行探索^[13-17]。其中,以环氧树脂为基料的复合材料具有较好的力学性能及耐腐蚀性能,在耐磨损及耐腐蚀领域得到广泛应用^[18-21]。张德虎等^[22]采用不同比例的疏水二氧化硅纳米粒子、环氧树脂和硅橡胶的甲苯溶液,通过简单的喷涂成膜法制备了具有不同疏水性的涂层,结果表明所制备超疏水涂层表现出良好的自清洁性和耐磨性。另一方面研究者发现,仿生学技术的应用对提高部件耐冲蚀磨损性能及减阻性能具有较好的效果^[23-24]。孙鸿志^[25]根据贝壳耐冲蚀磨损机理和光滑弯头冲蚀磨损出现的位置,设计了肋条方向垂直于管流方向且肋条分布在 $10^\circ\sim 90^\circ$ 区域的仿生弯头,并运用试验优化设计方法对肋条参数进行了优化。实验结果表明,试验件的耐冲蚀磨损性能提高了 5.84%。

基于相关研究成果,本文将耐腐蚀的高分子复合材料与耐冲蚀磨损的仿生结构相结合,采用自制疏水二氧化硅颗粒增韧环氧树脂为表面耐腐蚀高分子材料,以鲨鱼表皮和贝壳为原型进行仿生结构设计,并采用翻模法在增韧环氧树脂表面构建耐冲蚀磨损仿生结构,完成了相关冲蚀实验,分析了疏水二氧化硅用量对环氧树脂综合性能的影响,以及仿生形貌对环氧树脂耐冲蚀性能的影响。

1 实验

1.1 疏水二氧化硅及增韧环氧树脂的制备

利用溶胶-凝胶法制备疏水 SiO_2 颗粒,材料的配方(用物质的量之比表示): n (正硅酸乙酯, $\text{C}_8\text{H}_{20}\text{O}_4\text{Si}$): n (氨水, NH_4OH): n (无水乙醇, $\text{C}_2\text{H}_6\text{O}$): n (去离子水, H_2O): n (甲基三乙氧基硅烷, $\text{C}_7\text{H}_{18}\text{O}_3\text{Si}$)为1:3.6:30:1:0.5。制备过程:取一定量正硅酸乙酯和无水乙醇,将两者置于烧杯中,在60℃下搅拌10 min,搅拌器的转速为500 r/min,然后将氨水和去离子水同时滴入该烧杯中,氨水的滴加速度为1滴/s,每10滴氨水加1滴去离子水,并在60℃下持续搅拌1 h,往溶液中逐滴加入一定量甲基三乙氧基硅烷,在60℃下继续搅拌1 h。最后,将得到的溶液置于60℃的烘箱中干燥2 d,以获得疏水改性的二氧化硅粉末,利用研磨钵研磨后封存备用。

增韧环氧树脂材料的配方(用物质的量之比表示): n (环氧树脂): n (固化剂): n (消泡剂): n (疏水二氧化硅)为1:0.25:0.000 2: x (x 分别取0、0.025 5、0.052 1、0.079 8)。增韧环氧树脂涂层的

制备流程:取一定量环氧树脂,在60℃下使用精密增力电动搅拌器搅拌5 min(转速为60 r/min),再加入一定量的疏水二氧化硅颗粒及适量的消泡剂搅拌均匀,最后加入适量固化剂,倒入自制的硅胶模具中,利用304不锈钢基体进行翻模,在常温下固化24 h,即可得到疏水二氧化硅质量分数分别为0%、2%、4%、6%的增韧环氧树脂复合涂层。

1.2 仿生形貌设计

由于在低潮地带生存的扇贝表面存在放射性肋条结构,因此在潮汐环境中沙砾的冲击作用下它表现出良好的耐冲蚀磨损性能。其一,肋条结构在受到冲击时可扰动水流,减小冲击速度,吸收冲击能量。其二,肋条结构提高了贝壳的冲击韧性,从而提高了贝壳的冲击性能。如图1a所示,贝壳肋条截面近似于等腰梯形,本文对贝壳肋条进行仿生,贝壳仿生结构为截面为等腰梯形的肋条,如图1b所示。任何涉及水、散料等流体的运动都会遇到摩擦阻力的问题,鲨鱼皮表面存在微米级的盾鳞结构,这种微小突起以一种独特的方式进行排列,是最佳的减阻形状。使用Matlab拟合出鲨鱼表皮盾鳞的排列方式,如图1c所示,由拟合曲线得到式(1)。贝壳仿生结构按照这一曲线排列,获得了贝壳/鲨鱼仿生形貌,如图1d所示。

$$y = \frac{8}{7} \sin\left(\frac{x}{4} + \frac{3\pi}{5}\right) \quad (1)$$

钾盐颗粒的粒径为1 mm左右,其外形和粒径与海滩附近沙子具有相似之处,所以仿生结构参数参考贝壳肋条的实际大小,如图1a所示。贝壳肋条上底宽度约为1.5 mm,此肋条处于贝壳中间,宽度较大,

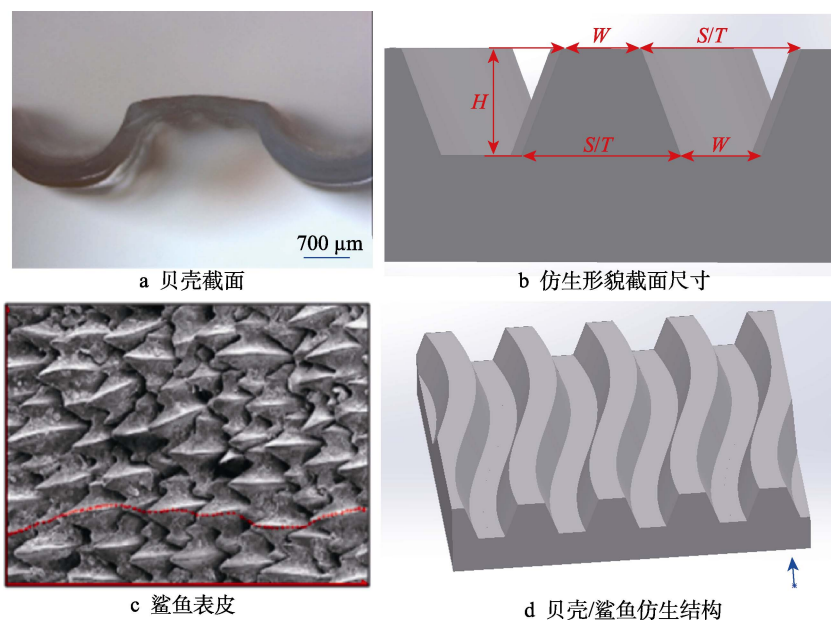


图1 仿生对象曲线耦合及尺寸

Fig.1 Schematic diagram of curve coupling and size of bionic object: a) shell section; b) bionic morphology section size; c) shark skin; d) shell/shark bionic structure

两侧分布的肋条宽度逐渐减小, 仿生试样的参数设置如表 1 所示, 其中 T 表示贝壳仿生肋条截面的下底长度, S 为贝壳/鲨鱼仿生肋条截面的下底长度, W 为肋条截面上底长度, noBionic 表示表面为平面的试样。

使用离散元颗粒仿真软件 EDEM 和力学仿真软件 Workbench 耦合仿真分析上述 7 个仿生结构。EDEM 仿真具体条件的设置: 冲蚀角度为 30° , 冲蚀距离为 10 mm, 冲蚀速度为 10 m/s, 仿真时间为 2 s, 颗粒直径为 1 mm。EDEM 离散元仿真参数如表 2 所示, 仿生模型应力结果如图 2 所示。试样 S2W1 表面在受到颗粒冲蚀后的应力最小, 为最佳的仿生结构。

1.3 增韧环氧树脂仿生结构的制备

以不锈钢为基体, 利用翻模法制备环氧树脂仿生结构。为了提高环氧树脂与 304 不锈钢基体间的结合

表 1 仿生方案
Tab.1 Bionic scheme

Specimen name	Parameter
noBionic	No bionic structure specimen
T1W0.5	Shell bionic structure specimen, $H=2$ mm, $T=1$ mm, $W=0.5$ mm
T2W1	Shell bionic structure specimen, $H=2$ mm, $T=2$ mm, $W=1$ mm
T3W1.5	Shell bionic structure specimen, $H=2$ mm, $T=3$ mm, $W=1.5$ mm
S1W0.5	Shell/shark bionic structure specimen, $H=2$ mm, $S=1$ mm, $W=0.5$ mm
S2W1	Shell/shark bionic structure specimen, $H=2$ mm, $S=2$ mm, $W=1$ mm
S3W1.5	Shell/shark bionic structure specimen, $H=2$ mm, $S=3$ mm, $W=1.5$ mm

表 2 EDEM 仿真参数
Tab.2 EDEM simulation parameters

Material	Density/($\text{kg}\cdot\text{m}^{-3}$)	Modulus of elasticity/GPa	Poisson's ratio	Coefficient of recovery	Coefficient of static friction	Coefficient of rolling friction
304 stainless steel	7 850	200	0.33	0.75	1.10	0.10
E51	1 000	1	0.38	0.75	1.05	0.11
Potassium salt	1 700	1.96	0.28	0.75	1.04	0.10

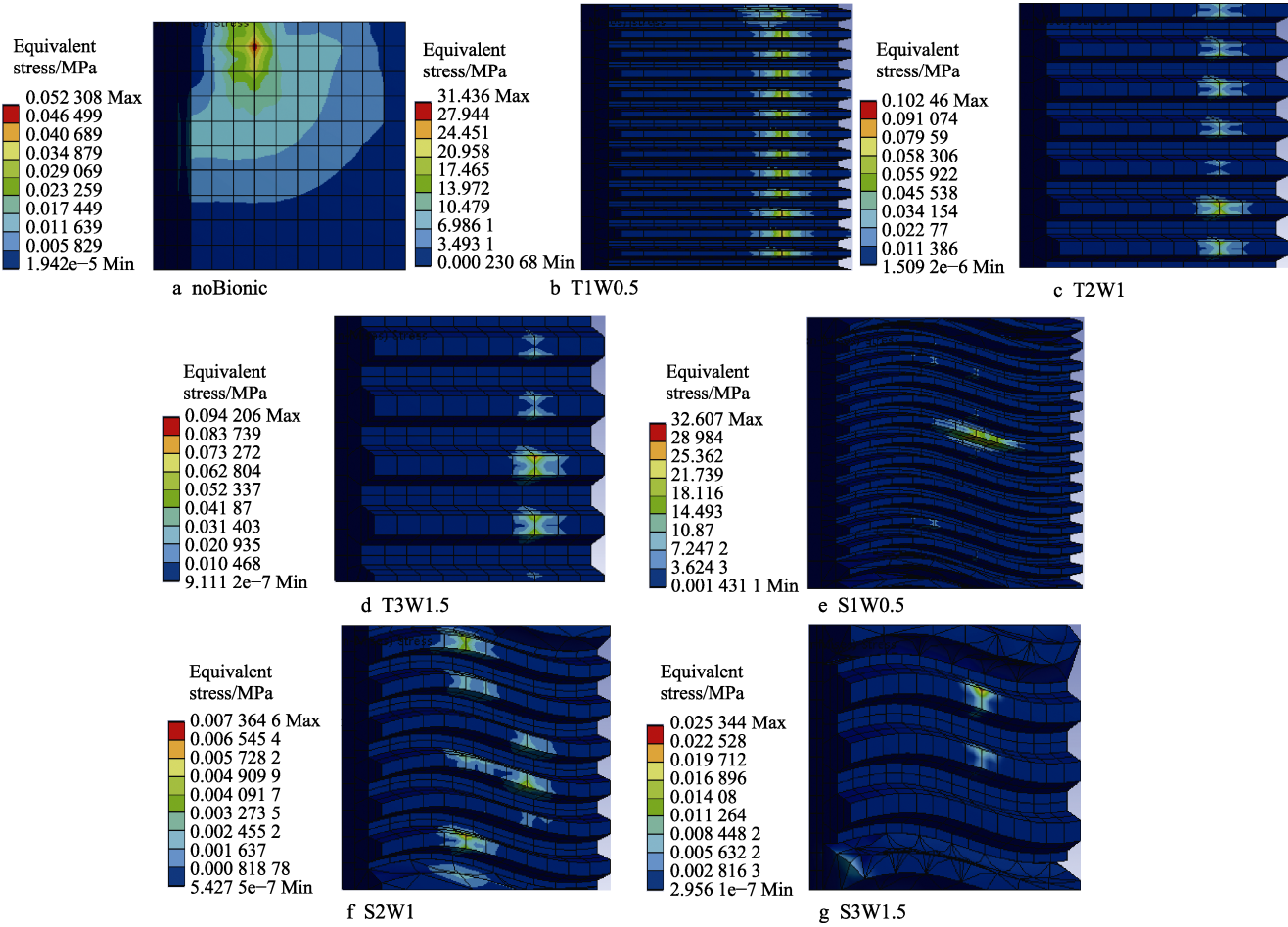


图 2 不同尺寸贝壳/鲨鱼仿生模型等效应力

Fig.2 Equivalent stress diagram of shell/shark bionic models of different sizes

强度,利用激光加工在不锈钢(30 mm×30 mm×3 mm)表面进行凹槽织构化处理,凹槽宽度和凹槽间距均为200 μm。激光加工参数:扫描速度为1 000 mm/s,功率为25 W,扫描5次。加工后的形貌如图3所示。

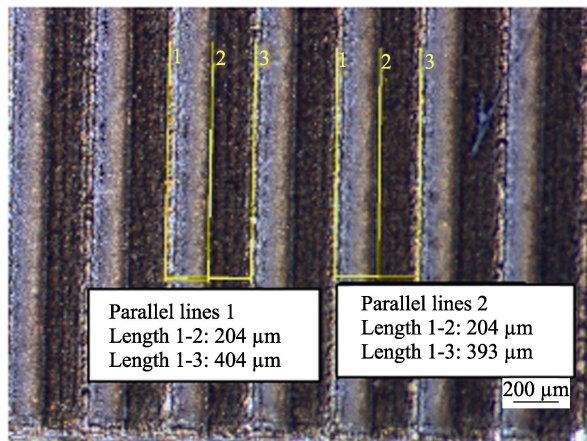


图3 沟槽织构不锈钢基体表面形貌
Fig.3 Surface morphology for stainless steel substrate of groove texture

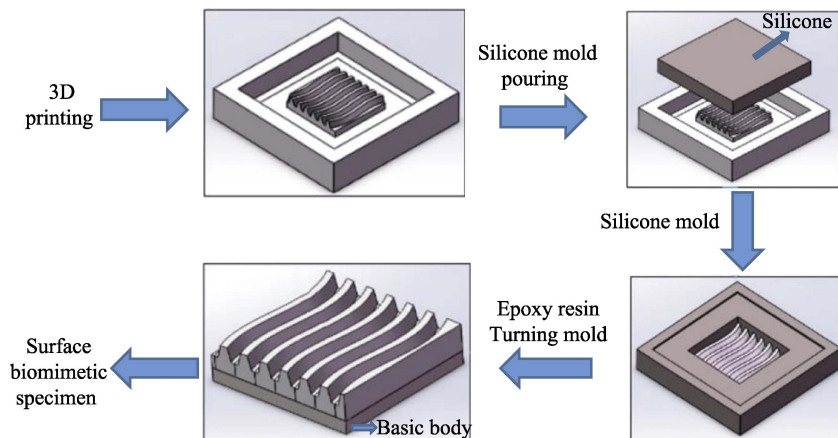


图4 环氧树脂仿生结构制备流程
Fig.4 Preparation process of epoxy resin bionic structure

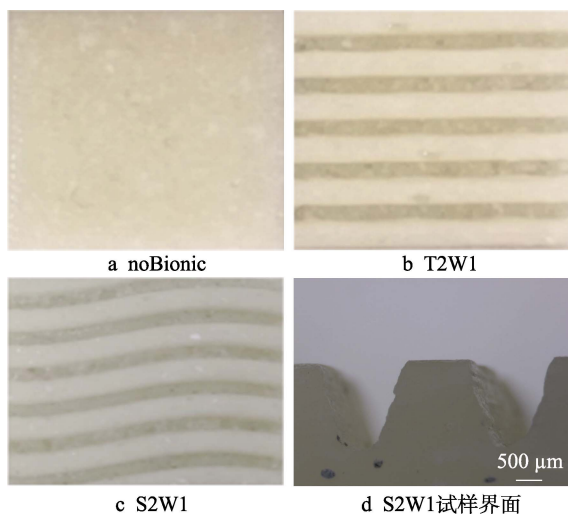


图5 不同仿生结构的环氧树脂试样
Fig.5 Epoxy resin specimens with different bionic structures

采用翻模法制备环氧树脂仿生涂层的流程如图4所示。确定仿生结构后,在三维制图软件中绘制三维模型,通过3D打印技术打印仿生模型,然后将硅胶和固化剂(质量比为100:2)混合搅拌后浇注在3D打印模型上,在常温下固化12 h后获得硅胶模具。将液态的环氧树脂浇注在硅胶模具中固化24 h,脱模后获得具有仿生形貌的环氧树脂。

仿真结果表明,T2W1试样具有最佳的仿生结构。为了比较单一贝壳仿生结构、贝壳/鲨鱼复合仿生结构对性能的影响,对3种试样(noBionic、T2W1、S2W1)进行实验。利用翻模法制备出3种试样,如图5所示。

1.4 测试与表征

相关测试如表3所示,其中noBionic试样进行接触角测试、硬度测试和冲蚀磨损性能测试,而T2W1试样、S2W1试样进行耐磨性测试和冲蚀磨损性能测试。耐磨性测试与冲蚀磨损性能测试具体操作如下。

1) 耐磨性测试。将试样置于400#砂纸上,负重 $G=400\text{ g}$ 的砝码,匀速拖行100 mm,再用吹风机吹去试样表面残留的杂质,测试增韧环氧树脂的质量损失率,耐磨性测试示意图如图6所示,计算见式(2)。

$$W = \frac{m_1 - m_2}{2a} \quad (2)$$

式中: W 为环氧树脂复合材料的质量损失率; m_1 为摩擦前的质量, g; m_2 为摩擦后的质量, g。

2) 冲蚀磨损性能测试。冲蚀实验的条件如表4所示。采用自制的冲蚀磨损箱进行冲蚀磨损性能测试,冲蚀示意图如图7所示。环氧树脂复合材料的冲蚀率计算见式(3)。

$$E = \frac{m_a - m_b}{m_a} \quad (3)$$

式中: E 为环氧树脂复合材料的冲蚀率; m_a 为冲

表 3 实验试样
Tab.3 Experimental specimens

Sample name	Hydrophobic silica mass fraction/%	Testing method
noBionic	0	Water Contact Angle Test
	2	hardness test
	4	Erosion wear performance test
	6	test
T2W1	4	Wear resistance test
		Erosion wear performance test
S2W1	0	Wear resistance test
	2	
	4	Erosion wear performance test
	6	

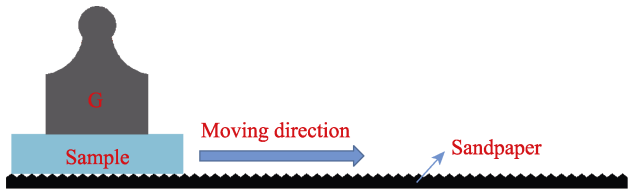


图 6 耐磨性测试示意图
Fig.6 Schematic diagram of wear resistance test

表 4 冲蚀磨损条件
Tab.4 Erosion wear condition

Erosion pressure	Particle mass	Erosion time	Erosion distance	Impact angle	Particle material
0.15 MPa	200 g	20 s	20 mm	30°	Kali salt/Emery

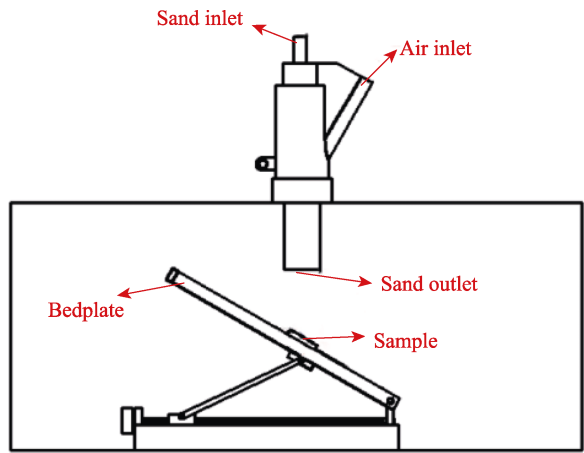


图 7 冲蚀示意图
Fig.7 Schematic diagram of erosion

蚀前的质量, g ; m_b 为冲蚀后的质量, g 。

2 结果与讨论

2.1 接触角测试

采用 400#砂纸对试样表面进行毛化处理, 利用光

学法接触角测量仪及饱和钾盐溶液对增韧环氧树脂进行接触角测试。当疏水二氧化硅的质量分数为 0% 时, 接触角达到 80°, 如图 8a 所示。当疏水二氧化硅的质量分数为 2% 时, 接触角达到 99°, 如图 8b 所示。当疏水二氧化硅的质量分数为 4% 时, 接触角达到 114°, 如图 8c 所示。当疏水二氧化硅的质量分数为 6% 时, 接触角达到 123°, 如图 8d 所示。

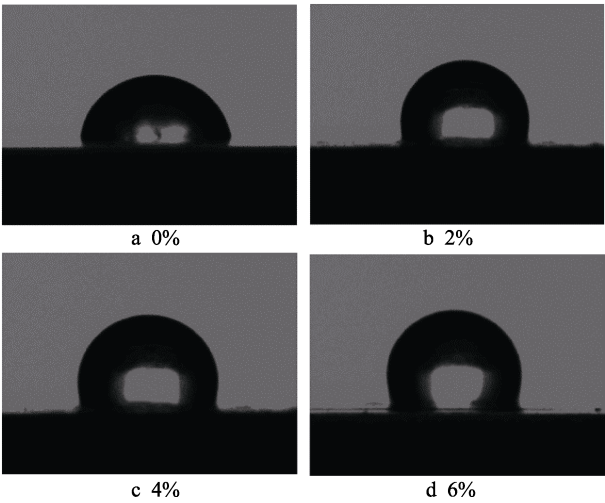


图 8 不同疏水二氧化硅质量分数增韧环氧树脂接触角测试
Fig.8 Contact angle test of toughened epoxy resin with different hydrophobic silica mass fractions

不同疏水二氧化硅质量分数对环氧树脂接触角的影响如图 9 所示。从图 9 可以看出, 加入二氧化硅后, 环氧树脂由亲水性变为疏水性; 随着疏水二氧化硅质量分数的增加, 接触角呈上升趋势。这是因为增韧环氧树脂经摩擦后, 增韧环氧树脂中的疏水二氧化硅裸露出来, 疏水二氧化硅的自身性质展现出来, 同时疏水二氧化硅裸露在增韧环氧树脂表面, 形成了微凸起 (如图 10 所示), 从而提升了增韧环氧树脂的接触角。

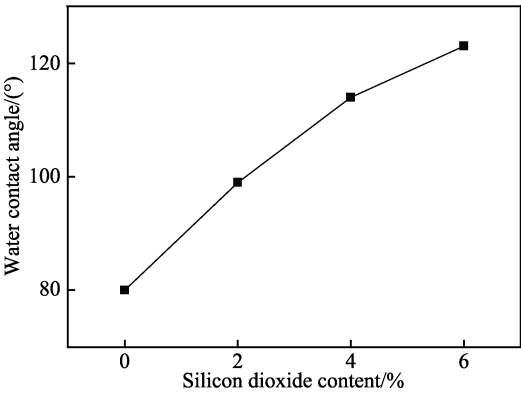


图 9 不同疏水二氧化硅质量分数对环氧树脂接触角的影响
Fig.9 Effect of different hydrophobic silica mass fractions on contact angle of epoxy resin

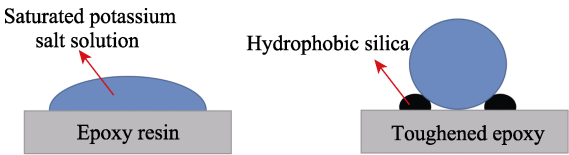


图 10 增韧环氧树脂表面疏水性原理示意图
Fig.10 Schematic diagram of hydrophobic principle of toughened epoxy resin surface

从显微组织分析及硬度分析结果可知,虽然接触角会随着疏水二氧化硅质量分数的增加而增加,但是疏水二氧化硅的质量分数过高也会严重影响增韧环氧树脂的各项性能及增韧环氧树脂的成型。当疏水二氧化硅的质量分数高于 2%时,接触角大于 90°,表明增韧环氧树脂涂层表面对钾盐溶液呈现疏水性。质量分数越高,则其疏水性能越好、防黏附性能越好,能够更加有效地防止钾盐在其表面黏附结块,避免了因钾盐吸湿性造成的堵塞问题和腐蚀问题,有效提高了转运设备的生产效率和使用寿命。在疏水二氧化硅的质量分数为 4%时,其综合性能最好。

2.2 显微形貌分析

利用 400#、600#、800#、1200#、1500#、2000#砂纸先后对试样进行打磨,利用体式显微镜(放大 20 倍)对增韧环氧树脂进行显微形貌分析。不同质量分数疏水二氧化硅增韧环氧树脂的形貌如图 11 所示。从图 11 可以看出,随着二氧化硅质量分数的增大,

疏水二氧化硅的团聚现象逐渐加重。这是因为随着二氧化硅含量的提升,制备过程中体系的浓度提高,在搅拌过程中引入的气泡难以消除,在常温固化过程中增韧环氧树脂内部形成了空穴缺陷。若疏水二氧化硅的质量分数过高,则增韧环氧树脂难以成型。在疏水二氧化硅的质量分数为 4%时,空洞缺陷较少。将材料应用于冲蚀磨损领域时,以硬度作为第一判断标准。为了保证环氧树脂的增韧效果,结合硬度测试及接触角测试分析结果可知,环氧树脂的质量分数为 4%时,材料的综合性能最好。

2.3 疏水 SiO₂ 质量分数对环氧树脂硬度的影响

利用 400#、600#、800#、1200#、1500#、2000#砂纸对试样进行打磨,利用美国威尔逊 Wilson VH1102 维氏硬度计对不同疏水二氧化硅增韧环氧树脂及 noBionic 试样进行显微硬度测试,每个试样取 3 个点进行测试,最后取显微硬度的平均值。不同疏水二氧化硅质量分数对环氧树脂硬度的影响如图 12 所示。从图 12 可以看出,随着疏水二氧化硅质量分数的增大,增韧环氧树脂的硬度呈先上升后下降的趋势。随着疏水二氧化硅质量分数的增大,由于二氧化硅颗粒的尺寸小,被嵌入环氧树脂中,提升了环氧树脂的交联密度。其中,在二氧化硅质量分数为 4%时,增韧环氧树脂的硬度达到最高值(26.57HV0.1),相较于

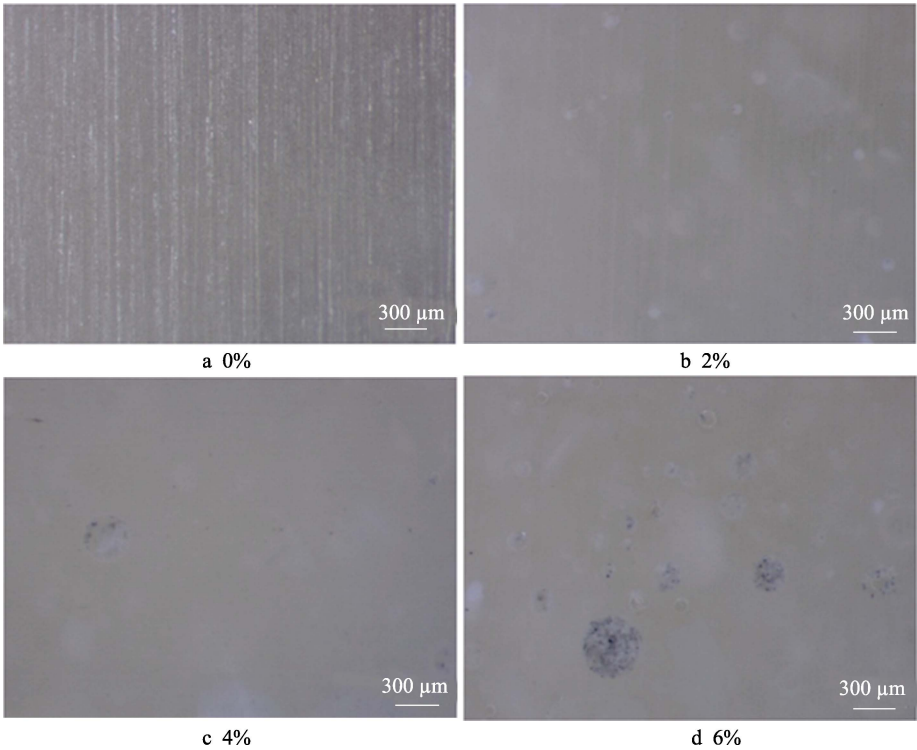


图 11 不同疏水二氧化硅质量分数增韧环氧树脂试样显微形貌
Fig.11 Morphology of epoxy resins toughened with different hydrophobic silica mass fractions:
a) 0% hydrophobic silica; b) 2% hydrophobic silica; c) 4% hydrophobic silica; d) 6% hydrophobic silica

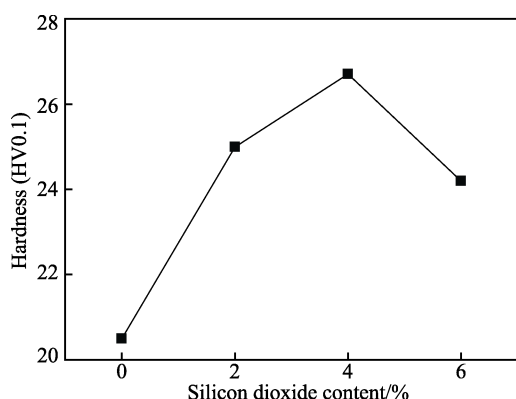


图 12 不同二氧化硅质量分数增韧环氧树脂硬度
Fig.12 Hardness of toughened epoxy resins with different silica mass fractions

纯环氧树脂的硬度, 提升了 29%。疏水二氧化硅的质量分数越高, 则环氧树脂内部形成的空穴缺陷越多, 这会严重影响环氧树脂的强度。

2.4 疏水 SiO_2 含量对仿生结构冲蚀磨损性能的影响

不同含量疏水二氧化硅 S2W1 仿生结构的冲蚀率对比如图 13 所示。可以看出, 随着疏水二氧化硅质量分数的提升, 环氧树脂的冲蚀率呈下降趋势。在疏水二氧化硅的质量分数为 4% 时, 环氧树脂仿生结构的耐冲蚀性能最好, 冲蚀率达到最低值 (1.494%)。随着二氧化硅质量分数的提升, 冲蚀率下降得不明显。这是由于在冲蚀过程中, 疏水性二氧化硅颗粒作为增强相, 也起到了抗冲击磨损的作用, 由于二氧化硅颗粒可以传递应力, 当复合材料承受外部载荷时, 外力通过界面传递并分配到整个构件, 减小了最大局部应力, 从而阻止了裂纹的扩展, 避免了碎裂、剥落和整体损伤。

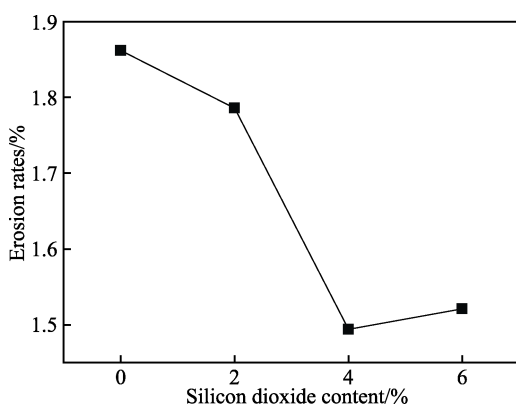


图 13 不同二氧化硅质量分数仿生环氧树脂冲蚀率对比
Fig.13 Comparison of erosion rate of bionic epoxy resins with different silica mass fractions

2.5 仿生结构形貌对环氧树脂冲蚀磨损性能的影响

由于钾盐颗粒的硬度较低, 因此增韧环氧树脂耐

钾盐的冲蚀性能较强。为了提高材料的冲蚀率, 采用金刚砂代替钾盐进行冲蚀测试。制备了不同环氧树脂仿生结构的 noBionic、T2W1、S2W1 试样, 这 3 种试样的疏水二氧化硅质量分数均为 4%。在疏水二氧化硅的质量分数为 4% 时, 不同环氧树脂仿生结构冲蚀磨损性能测试结果如图 14 所示。可以看出, T2W1 贝壳仿生结构试样相较于无仿生结构试样 (即 noBionic 试样), 其冲蚀率并未降低, 表明单一的贝壳结构仿生并不能有效改善环氧树脂的耐钾盐冲蚀磨损性能。S2W1 贝壳/鲨鱼仿生结构试样相较于无仿生结构试样, 其冲蚀率由 1.6% 降至 1.4%。由此可以看出, S2W1 试样在一定程度上能够改善环氧树脂的冲蚀磨损性能。这是因为相较于无仿生结构试样, 在冲蚀过程中仿生结构的存在能够改变颗粒流对试样的冲蚀角度, 并且对流体产生扰动作用, 吸收颗粒流对材料的冲击力, 而 T2W1 试样的结构为平行结构, 对流体的扰动效果较差, 因此耐冲蚀磨损性能相对较弱。

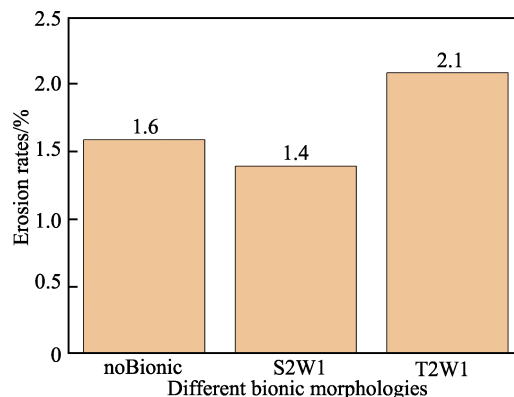


图 14 不同仿生结构环氧树脂冲蚀率的对比
Fig.14 Comparison of erosion rate of epoxy resins with different bionic structures

2.6 仿生结构形貌对环氧树脂耐磨性的影响

在疏水二氧化硅的质量分数为 4% 时, 增韧环氧树脂 noBionic、T2W1、S2W1 试样的耐磨性测试结果如图 15 所示。可以看出, 仿生结构试样相较于无

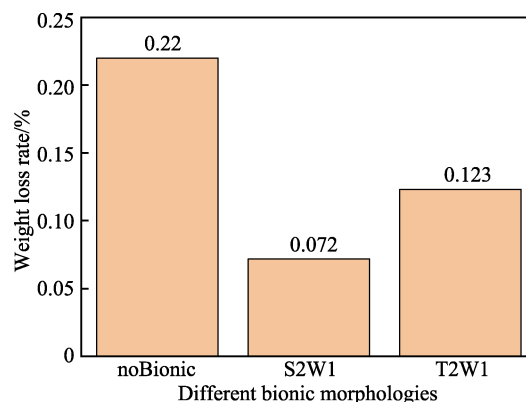


图 15 不同仿生结构环氧树脂耐磨性对比
Fig.15 Comparison of wear resistance of epoxy resins with different bionic structures

仿生结构试样 (noBionic), 其耐磨性能均有所提升。这是因为仿生结构的存在能够减小试样摩擦副的面积, 且仿生结构的存在也能够储存磨屑, 从而减少磨粒磨损。其中, S2W1 试样的耐磨性能最强, 相较于无仿生结构试样, 其质量损失率由 0.22% 降至 0.072%; 相较于 T2W1 试样 (即贝壳仿生结构试样), 其质量损失率由 0.123% 降至 0.072%。

2.7 冲蚀形貌分析

不同含量疏水二氧化硅 S2W1 仿生结构的冲蚀磨损后的形貌对比如图 16 所示。可以看出, 受到颗粒冲击后, 二氧化硅质量分数为 0% 的试样表面呈现

破碎剥离现象, 而二氧化硅质量分数分别为 2%、4%、6% 的试样表面破碎剥离得较少, 表明随着二氧化硅质量分数的提升, 由破碎剥离破坏转变为犁削损伤破坏, 环氧树脂由脆性破坏转变成韧性损伤。这是因为疏水性二氧化硅颗粒作为增强相, 提高了环氧树脂的韧性, 环氧树脂的冲击强度、拉伸强度相应提高。同时, 二氧化硅在环氧树脂内部阻碍了裂纹的延伸, 起到了抗冲击磨损作用^[26-27]; 仿生结构的存在能够改变颗粒流对增韧环氧树脂的冲蚀角度, 也能够对气固两相流产生扰动作用, 从而减缓颗粒流在增韧环氧树脂表面的冲击速度, 吸收冲击力。

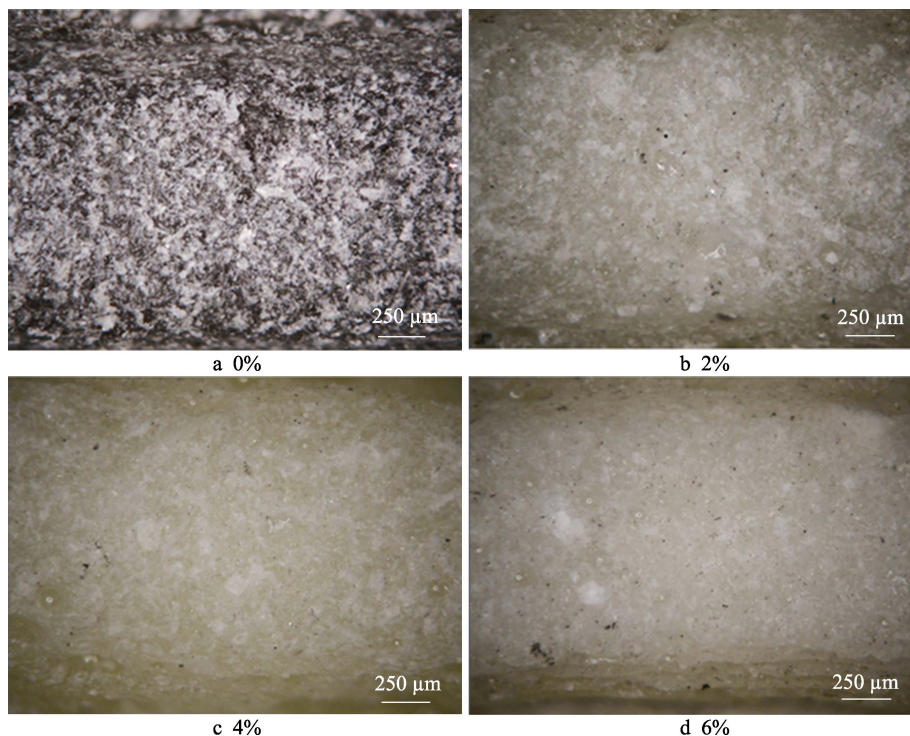


图 16 不同疏水二氧化硅质量分数 S2W1 仿生结构的冲蚀磨损后形貌对比

Fig.16 Comparison of morphology after erosive wear of S2W1 bionic structures with different hydrophobic silica mass fractions

3 结论

1) 当二氧化硅的质量分数为 0% 时, 钾盐溶液在增韧环氧树脂表面的接触角为 80° , 呈亲水性。随着疏水性二氧化硅质量分数的增加, 接触角呈上升趋势。当疏水二氧化硅的质量分数达到 2% 时, 环氧树脂呈疏水性。当疏水性二氧化硅的质量分数过高时, 增韧环氧树脂中会形成更多的孔洞缺陷, 严重影响了增韧环氧树脂的强度, 甚至影响了增韧环氧树脂的成型。由此可见, 当疏水二氧化硅的质量分数为 4% 时, 接触角达到 114° , 增韧环氧树脂的综合性能最好。

2) 随着疏水二氧化硅质量分数的提升, 增韧环氧树脂的硬度呈先上升后下降的趋势。其中, 在疏水二氧化硅的质量分数为 4% 时, 增韧环氧树脂的硬度

达到最高值 (26.57HV0.1), 相较于纯环氧树脂的硬度提升了 29%。

3) 在疏水二氧化硅的质量分数为 4% 时, 贝壳/鲨鱼仿生结构试样 S2W1 仿生结构的耐磨性能最强, 相较于无仿生结构试样, 其质量损失率由 0.22% 降至 0.072%。

4) 冲蚀磨损测试结果表明, 单一的贝壳仿生结构并不能有效改善环氧树脂复合材料的冲蚀磨损性能; 贝壳/鲨鱼仿生结构试样 (即 S2W1) 的耐冲蚀磨损性能最好, 其冲蚀率降至 1.4%。

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