

实用技术

铝表面硅烷及缓蚀剂协同改性研究

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[摘 要] 试验采用硅烷双-[3-(三乙氧基)硅丙基]四硫化物(BTESPT)和长链烷基有机酸酯缓蚀剂 A 钝化金属铝,通过先后将试样浸入 BTESPT 溶液, A 分子溶液中,取出在 100℃ 固化 12 h 制备耐腐蚀的钝化膜。析氢试验、碱浸失重试验、盐雾试验和电化学测试均证明钝化后的试样耐腐蚀性能明显高于空白样。膜中不含重金属和氟化物,通过了欧盟 ROHS 指令。利用 SEM 观察了复合膜的表面微观形貌,结合电化学试验初步探讨了复合膜的耐蚀机理。并探讨了复合膜的成膜机理。

[关键词] 铝; 硅烷; 缓蚀剂; 改性; 复合膜; 耐蚀性

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0 前 言

20 世纪 70 年代初,有机缓蚀剂开始在工业上大规模推广和应用。其化学稳定性好,不易水解和降解,缓蚀、阻垢效果好,使用剂量小。某些分子中含有长链烷基的有机酸酯缓蚀剂具有配位金属离子的能力,在一定的浓度下,可在金属铝表面自组装成有良好缓蚀效果及疏水性的保护膜^[1]。但膜层与铝合金的附着力较弱,不能在恶劣的环境下提供长效的保护。某些硅烷偶联剂(SCA)能够明显改善无机相-有机相的界面粘接性能。铝管经 SCA 预处理后,可望在金属、有机涂层之间形成结构紧密、自由体积小的界面相,从而明显提高有机涂层体系的腐蚀防护性能,目前已成为金属表面预处理领域的新技术^[2-6]。

本工作通过先后将铝浸入双-[3-(三乙氧基)硅丙基]四硫化物(BTESPT)溶液、含有长链烷基的有机酸酯缓蚀剂 A 溶液,取出吹干后在一定条件下固化形成致密疏水的复合膜。对复合膜的疏水耐蚀性能和微观形貌进行了考察,并初步探讨了其耐蚀机理。

1 试 验

1.1 试 剂

双-[3-(三乙氧基)硅丙基]四硫化物(BTESPT): 化学纯。缓蚀剂 A: 自制。

1.2 试验材料及试样制备

试样采用工业纯铝,其主要的化学成分见表 1。

表 1 工业纯铝的成分 %

元素	Cu	Fe	Si	Ti	Mn	Zn	Ni	Al
质量分数	0.002	0.130	0.050	0.016	0.007	0.010	0.004	余量

将工业纯铝片裁成 30 mm × 30 mm 的试片 400~600 号砂纸打磨光亮 丙酮中超声脱脂清洗 碱液清洗 水洗吹干置于干燥器中备用。

1.3 BTESPT 水解

BTESPT 不经过水解是不能在铝表面自组装成膜的,但如果水解太充分又容易使溶液产生絮状沉淀而失效,故对其水解程度进行监测就显得非常必要。按 (BTESPT) (蒸馏水) (乙醇) = 5 : 5 : 90 配制 BTESPT 醇水溶液,用冰醋酸调节溶液的 pH = 5.5,用 DDS-11A 型电导率仪测试溶液电导率监测 BTESPT 水解情况。监测表明,随着水解程度增大,溶液中导电离子越多,溶液电导率也越大。

1.4 成膜

把工业纯铝试片浸在达到水解平衡后的 BTESPT

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溶液中 5 s 后取出,除去表面多余溶液后用电吹风吹干。随后将其浸入 30 g/L 的长链烷基有机酸酯缓蚀剂 A 溶液中 5 s 后取出,用吸水纸轻轻擦干即获得自组装分子与缓蚀剂 A 的复合膜。

复合膜不经过固化或固化不充分时孔隙率较大,不能对基体金属铝提供足够保护。固化越彻底,膜层就越致密,其对水的接触角也越大。通过用接触角测定仪测复合膜的疏水角来考察膜层的固化程度。

1.5 复合膜耐蚀性

1.5.1 析氢试验

将试片浸入 50 mL 3 mol/L 的 HCl 中。盐酸与试片发生反应产生 H_2 ,用倒立的滴定管收集产生的气体。将收集到的 H_2 体积作为纵坐标、反应时间为横坐标作析氢图。开始析氢的时间越晚,析氢速率越慢的试片耐酸腐蚀性越好。

1.5.2 碱浸失重试验

将每种试片各 3 片精确称重后浸入 0.2 mol/L 的 NaOH 溶液中浸泡 5 h,取出后用蒸馏水浸泡超声波清除表面腐蚀产物,用压缩空气吹干再称重。用试片单位面积、单位时间的失重来考察其耐碱腐蚀性能。

1.5.3 中性盐雾 (NSS) 试验

本试验按照 GB/T 10125—1997 进行 NSS 试验。腐蚀试验后的试样评级参考 GB/T 12335—90 进行。

1.5.4 电化学极化曲线和交流阻抗谱测试

电化学试验具有快速、更贴近腐蚀实质、能反映腐蚀及保护机理等优点^[7]。在腐蚀检测方面应用最为广泛的是极化曲线、交流阻抗法。本试验用 Solarton SI 1287 型电化学综合测试仪,以铂片为辅助电极、饱和 KCl 甘汞电极为参比电极、测试铝片为工作电极组成三电极体系,先后分别进行动电位极化曲线和交流阻抗谱的测试。

1.6 安全性检测

考虑到铝合金广泛用于电气电子设备中,世界各国对其所用材料中 6 项有害组分含量有明确规定,其国际公认的有欧盟 ROHS 指令^[8],该项指令要求 2006 年 7 月 1 日以后新投放欧盟市场的电气电子产品不得含有铅、汞、镉、六价铬、多溴联苯、多溴联苯醚等 6 种有害物质。为此,本工作对缓蚀剂溶液及复合膜中这 6 种有害组分进行了测定。

1.7 复合膜的表面微观形貌

利用 SEM 分别观察单一缓蚀剂膜及复合膜的表面

微观形貌。

2 试验结果与讨论

2.1 B TESPT 水解研究

B TESPT 溶液电导率和水解时间的关系见图 1。

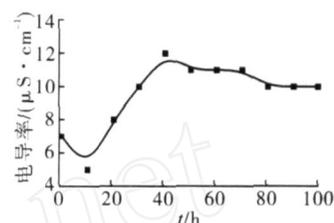
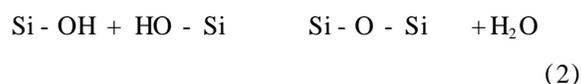


图 1 B TESPT 溶液电导率和水解时间的关系

由图 1 可知,当开始加入 B TESPT 时,由于 B TESPT 还未完全溶解,所以溶液的电导率稍有下降,B TESPT 的结构式为 $(H_5C_2O)_3Si(CH_2)_3-S-S-S-(CH_2)_3Si(OC_2H_5)_3$,随着 B TESPT 不断地发生水解反应,产生 SiOH,溶液中游离的 SiOH 不断增多,同时 SiOH 也会发生电离反应:



从而使溶液电导率在 10~40 h 之间不断增大。而 SiOH 之间易发生反应:



使游离的 SiOH 浓度减少,反应 (1) 平衡向逆反应移动,导致溶液电导率在 40 h 后缓慢下降。溶液中 Si-OH 浓度越大,B TESPT 越容易在铝表面自组装成膜。所以待 B TESPT 水解 40 h 后使用效果最佳。

2.2 复合膜固化研究

将涂覆复合膜的试片在室温下放置 12 h 后转移至电热恒温鼓风干燥箱内,在 100 °C 下分别固化 0~24 h。用接触角测定仪考察复合膜的疏水角随固化时间的变化情况。测定结果见图 2。

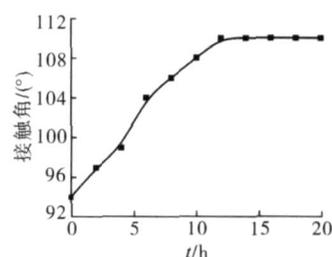


图 2 钝化膜疏水角与固化时间的关系

由图 2 可知,0~12 h 内随着固化时间的延长,复

合膜的疏水角变大,在 12 h时疏水角达到最大值,之后再增加固化时间疏水角不再增加。可见最佳固化时间为 12 h。

2.3 复合膜耐蚀性

2.3.1 析氢试验

将 3片未覆膜和 3片涂覆复合膜的铝试片,同时浸入 3 mol/L 的 HCl中做析氢试验,结果见图 3。

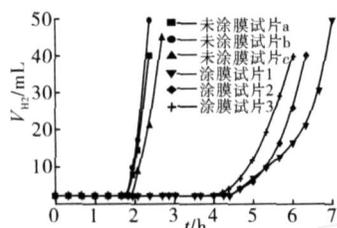


图 3 涂膜前后试样析氢试验曲线

由图 3可知,涂膜铝试片的开始析氢时间比普通铝管晚很多,析氢速率也有明显下降。析氢试验说明复合膜具有优异的耐酸蚀性能。

2.3.2 碱浸失重试验

碱浸失重试验结果见表 2。

表 2 在 0.2 mol/L NaOH中碱浸失重试验结果

	W_0/g	W_1/g	W/g	$W/(s \cdot t) / (mg \cdot cm^{-2} \cdot h^{-1})$
未涂膜试片	0.859 4	0.855 9	0.003 5	0.078
涂膜试片	0.915 2	0.913 4	0.001 8	0.040

注: W_0 为初始试片质量平均值, W_1 为碱浸后试片质量平均值, W 为碱浸后试片失重平均值, $W/(s \cdot t)$ 为试片单位面积、单位时间得平均失重。

由表 2可知,涂膜试片的失重速率较未涂膜试片有显著下降。说明复合膜具有良好的耐碱蚀性能。

2.3.3 中性盐雾试验

图 4为试片表面腐蚀面积分数随盐雾试验时间的变化情况。

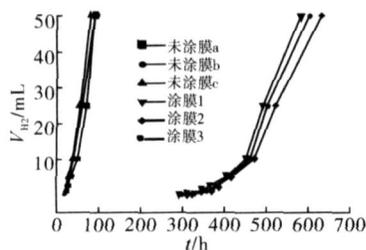


图 4 试片表面腐蚀面积分数随盐雾试验时间的变化

由图 4可知,未涂膜试片平均 23 h腐蚀面积达 1%,而涂覆复合膜的试片(在 100 下固化 12 h)平均

360 h后腐蚀面积才达 1%,说明复合膜具有良好的耐盐雾腐蚀性能。

2.3.4 电化学极化曲线和交流阻抗谱测试

(1)极化曲线测试 将未涂膜试片和涂覆复合膜的试片(在 100 下固化 12 h)分别做成有效面积为 0.9 cm^2 工作电极,在 $\text{pH} = 7$ 的 3.5% NaCl溶液中浸泡 12 h后开始测试。扫描速度为 1 mV/s 。试验结果见图 5。

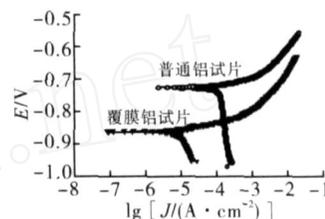


图 5 普通铝片和覆膜铝片在 3.5% NaCl中浸泡 12 h后的极化曲线

用 Cview系统软件对极化曲线数据进行拟合,获得的腐蚀电位 E_{corr} 、腐蚀电流密度 J_{corr} 、阳极和阴极表观塔菲尔斜率 b_a 和 b_c 等参数见表 3。

表 3 极化曲线拟和结果

试样	腐蚀电位 /V	$J_{\text{corr}}/(A \cdot \text{cm}^{-2})$	b_a/mV	b_c/mV
未涂膜	-0.720	1.5175×10^{-4}	64	10256
涂膜	-0.858	1.0706×10^{-5}	30	644

自腐蚀电流密度反映了电化学腐蚀速率。由表 3可知覆膜试片腐蚀电流密度降低一个数量级,说明复合膜具有良好的耐蚀性能。腐蚀电位明显降低说明复合膜主要通过抑制电化学腐蚀过程中的阴极去极化反应来保护基体金属。

(2)交流阻抗 交流阻抗(EIS)试验中同样将未涂膜试片和涂覆复合膜的试片(在 100 下固化 12 h)分别制成有效面积为 0.9 cm^2 的工作电极。在 $\text{pH} = 7$ 的 3.5% NaCl溶液中浸泡 12 h后,在开路电位下测试,振幅为 10 mV。试验结果见图 6。

用 Z-view系统软件对交流阻抗数据进行拟合,等效电路见图 7。

其中 R_1 为溶液电阻,恒相位角元件 CPE_1 代表工作电极/电解液间的双电层电容。对涂膜铝试片, R_3 为复合膜电阻, R_2 为腐蚀过程中生成的缓蚀剂膜的电阻(复合膜经 3.5% NaCl溶液 12 h浸泡后局部有破损,复合膜表面未固化完全的缓蚀剂分子在缺陷处重新成膜), L_1 为腐蚀过程中生成的缓蚀剂膜的感抗。对于普通铝

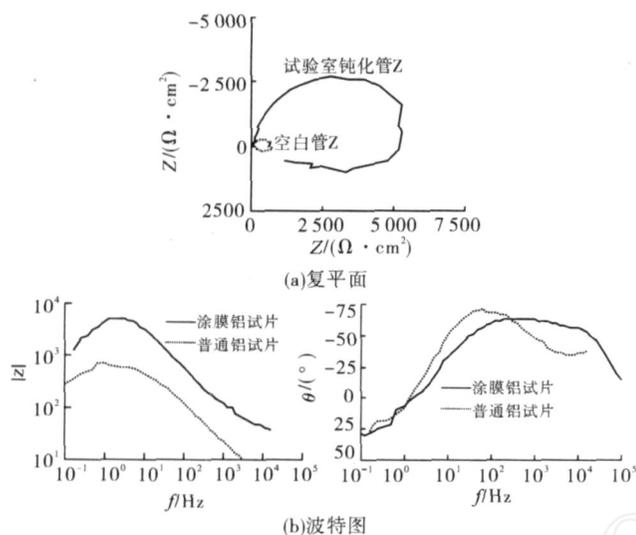


图6 交流阻抗的复平面和波特图

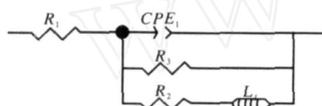


图7 交流阻抗等效电路

试样, R_3 为铝表面自然氧化膜的电阻, R_2 为腐蚀产物的电阻, L_1 为腐蚀中间产物 $Al(OH)_2Cl$ 或 $Al(OH)Cl_2$ 的感抗。利用该等效电路对图7中 Nyquist图进行数据拟合,结果见表4。

表4 交流阻抗图谱拟合结果

试样	$R_1 / (\cdot cm^2)$	$R_2 / (\cdot cm^2)$	$CPE_1 - T / (\mu F \cdot cm^{-2})$	$CPE_1 - P$	$R_3 / (\cdot cm^2)$	$L_1 / (H \cdot cm^{-2})$
未涂膜	1.20	242.8	51.730	0.77378	716.2	486.5
涂膜	31.44	2600.0	11.169	0.77376	7099.0	1228.0

R_3 值的大小定量反映了膜层的耐腐蚀性能。从表4中可以看出,覆膜试片的膜电阻比普通铝试片的膜电阻大了一个数量级,说明该复合膜具有十分优异的耐腐蚀性能。复平面图中低频感抗弧,对于普通铝试片可能与 Cl^- 穿透氧化铝膜后在金属表面生成腐蚀中间产物 $Al(OH)_2Cl$ 或 $Al(OH)Cl_2$ 的过程有关;而对于涂膜铝试片可能与复合膜表面未固化完全的缓蚀剂分子在复合膜的缺陷处重新成膜的过程有关。涂膜铝试片的 R_2 值较大,可以说明腐蚀过程中生成的缓蚀剂膜具有较好的防护能力。

2.4 安全性检测

2.4.1 缓蚀剂溶液分析检测

取缓蚀剂溶液进行测定,其中铅、镉、汞、铬采用等离子体发射光谱(ICP-AES)测定,多溴联苯、多溴二苯

醚采用气相色谱-质谱(GC-MS),测定结果见表5。

表5 缓蚀剂溶液安全性检测结果

检测项	Pb	Cd	Hg	Cr	PBB	PBDE
含量 / (mg · L ⁻¹)	1.80	0.05	0.20	0.80	0	0
检测限 / (mg · L ⁻¹)	> 0.10	> 0.05	> 0.10	> 0.10	> 2.00	> 2.00

由表5看出钝化液中6项有害组分含量很低。

2.4.2 复合膜分析检测

为进一步验证复合膜的安全性,取涂覆复合膜的试片送国家权威机构检测,测定结果(见表6)表明,复合膜中6项指标均符合欧盟ROHS标准要求。

表6 复合膜安全性检测结果 mg/kg

检测项	Pb	Cd	Hg	Cr	PBB	PBDE
涂抹试片	28	0	0	0	0	0
检测限	> 2	> 2	> 2	> 2	> 2	> 2
ROHS标准	1000	100	1000	1000	1000	1000

2.5 复合膜的表面微观形貌

利用SEM观察单一缓蚀剂膜及复合膜的表面结构,SEM形貌见图8。

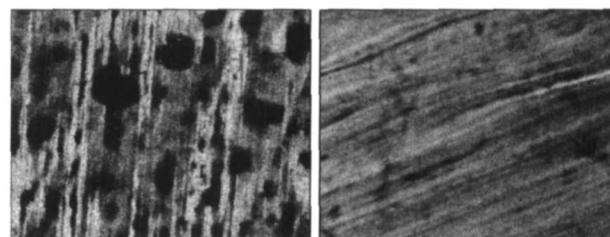


图8 单一缓蚀膜及复合膜的SEM形貌

从图8a可以看出,单一缓蚀剂膜密布针孔状孔隙,对基体覆盖度不高;复合膜(见图8b)结构致密,对基体覆盖度高。

2.6 复合膜成膜及耐蚀机理初探

BTESPT分子的两端存在丰富的可水解基团— OCH_2CH_3 ,水解后产生大量带负电荷的硅醇羟基— $SiOH$ 。BTESPT乙醇溶液的pH值为5.5,而铝板表面等电点为9.3,因此铝板表面将带正电荷,带负电荷的— $SiOH$ 将被稳定地吸附在带正电荷的铝板表面上,使BTESPT分子在铝表面排列紧密而有序,被吸附的硅醇羟基与铝表面的羟基形成氢键。未被吸附的硅醇羟基通过相互间氢键作用,使BTESPT分子交联成空间网状结构,进一步提高了BTESPT膜的致密性。

在缓蚀剂溶液中,BTESPT膜表面的— $SiOH$ 通过与缓蚀剂A分子中的羧羟基形成氢键,使A分子在其表面

紧密排列形成复合膜。同时, A 分子中的长链烷基相互交织形成致密的疏水层, 赋予复合膜更好的疏水性及耐蚀性。固化时, 羟基间氢键脱水变成键能更高的 —Zn—O—Si— 、 —Si—O—Si— 等化学键, 进一步提高了膜层与基体的附着力及膜本身的致密性、稳定性。

相对于金属铝表面, B TESPT 膜上的羟基更加丰富且分布均匀, 通过与缓蚀剂 A 分子中的羧羟基形成氢键, 使 A 分子在其表面紧密排列。同时, A 分子中的长链烷基相互交织形成致密的疏水层, 物理屏蔽了基体与腐蚀介质的直接接触, 降低了基体被腐蚀的可能性。同时, 复合膜的存在显著阻碍了 O_2 在金属界面与腐蚀溶液之间的扩散, 阻碍水分子向内部渗透和氢去极化后形成的氢气向外扩散, 即阴极还原反应被复合膜有效地抑制。而这一反应是腐蚀过程中的控制步骤, 从而大大降低了金属铝的腐蚀速率。

3 结 论

(1) B TESPT 醇水溶液经 40 h 水解后, 溶液中 SOH 浓度达到最大值。复合膜在 100 °C 下保持 12 h 后, 基本固化完全。

(2) 经析氢试验、碱浸失重试验、盐雾试验及安全检测表明, 复合膜具有良好的耐蚀性且不含重金属等有害物质, 具有工业应用价值。

(3) SEM 分析及电化学试验说明, 复合膜结构致

密, 对基体覆盖度高, 主要通过抑制电化学腐蚀过程中的阴极去极化反应来实现其对基体金属的保护。

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the plating bath composition and plating parameters as well. The results showed that the composition of the plating solution and its pH-value and temperature had complex influences on the plating rate. The plating rate was not only related to the production efficiency but also had effects on the adhesion strength and performance of the electroless Ni coating. It was feasible to prepare uniform and compact electroless Ni-P deposits without any visible defects using the optimized plating process. The resulting Ni-P alloy coating contained 8.56% P and had a hardness of 460 ~ 520 HV, while it was well adhered to the Mg alloy substrate.

Key words: magnesium alloy; electroless plating; plating rate; Ni-P alloy coating; performance

Effects of Process Parameters on the Colors of Titanium Passivation Films on Zinc Plating Coatings

DING Nan, YANG Fei, ZHU Li-qun (School of Materials Science and Engineering, University of Aeronautics and Astronautics at Beijing, Beijing 100083, China). *Cailiao Baohu* 2008, 41 (05), 45 ~ 48 (Ch). The chromate-free passivation of electroplated zinc coatings in titanate solution was investigated. The passivation films formed on the zinc coatings were investigated by means of scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS), while the possible causes leading to various colors of the passivation films in the titanate salt solution were discussed. The results showed that the passivation film on the electroplated Zn coating was mainly composed of Zn, O and Ti. It was feasible to prepare titanium-containing passivation films with various colors by adjusting the passivation parameters such as time, the temperature pH value of the passivation solution, and the temperature for drying. And the surface morphologies and elemental compositions of the passivation films were related to their colors.

Key words: zinc plating, titanate solution; passivation film; color; morphology; surface composition

The Performance of P-Free Compounding Metallic Detergent

SU Yan, JI Xue-liang, CAO Ming (School of Chemical Engineering, Kaifeng University, Kaifeng 475004, China). *Cailiao Baohu* 2008, 41 (05), 49 ~ 51 (Ch). The application of the compounded system of anionic and cationic surfactants in water-based metal detergents was investigated, while the abilities of maleic anhydride-acrylic acid copolymer sodium salt, sodium triphosphate, and 4A-type zeolite in aiding cleaning were compared. Based on a series of screening tests, the optimized formulation of the metallic detergent was determined to be fatty alcohol polyoxyethylene ether ammonium sulfate; halogenated dimethyl-dipropyl ammonium-acrylamide copolymer; nonyl phenol polyoxyethylene ether; oleamide; maleic anhydride-acrylic acid copolymer sodium salt; sodium silicate = 11.40; 2.00; 7.60; 7.60; 7.00; 3.00. Checked according to the water-based metal detergent standard of JB 4322-86. It was found that the detergent was qualified with respect to the standard and had a washing efficiency of 98.50% even at room temperature. Moreover, the detergent was found to have good stability and rust protection ability, and was simple in terms of production technology and environmentally friendly as well, making it feasible to be used in mechanized automatic washing and metalworking with promising prospect.

Key words: P-free metallic detergent; anionic-cationic surfactant; maleic anhydride-acrylic acid copolymer sodium salt; degreasing; rust protection

The Microstructures and Mechanic Properties of Wires with One- and Two-Step Hot-Dipped Zn-Al Alloy Coatings

GAO Qiu-zhi, FENG Bin, CAO Xiao-ming, WEN Ming, DU An (School of Materials Science and Engineering, Hebei Polytechnic University, Tianjin 300130, China). *Cailiao Baohu* 2008, 41 (05), 52 ~ 53 (Ch). Hot-dipped Zn-Al alloy coating has excellent corrosion resistance and is widely applied to prevent metals from corrosion. Thus galvanizing Zn-Al alloy coatings were prepared on steel substrate using one-step and two-step hot-dipping widely practiced in industry. The microstructures and elemental compositions of the resulting galvanizing Zn-Al alloy coatings were analyzed by means of scanning electron microscopy, while their mechanic properties were evaluated as well. It was found that Al was easier to react with the steel substrate and form intermetallic compound enriched with Al in the interlayer, while the galvanizing coating prepared by one-step hot-dipping had a thinner interlayer and led to minor impact to the mechanic properties

of the metallic wires.

Key words: Zn-Al alloy; one-step hot-dipping; two-step hot-dipping; interlayer; hot-dipping

Preparation and Application of Functionally Gradient Materials and Their Development Trend

XU Na, LI Chen-xi, LI Rong-de, YIN Hong-xia (School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110023, China). *Cailiao Baohu* 2008, 41 (05), 54 ~ 57 (Ch). A review is provided of the research progress about functionally gradient materials (FGM in abbreviation) at home and abroad. Thus the preparation, application and development trend of FGM are highlighted. And it was pointed out that functionally gradient materials, as novel materials with special structure and performance, have been highly focused on in the study of new multifunctional materials.

Key words: functionally gradient materials; hot-dipping; application; development trend

Research Progress for Ultrasound-Assisted Electroplating of Ni and Ni-Based Composite Coatings

FANG Xiao-hong (Faculty of Engineering, China University of Geosciences, Wuhan 430074, China). *Cailiao Baohu* 2008, 41 (05), 58 ~ 61 (Ch). A review is given of the research progress for electroplating nickel, nickel-based alloys, and nickel-based composite coatings in the presence of ultrasonic agitation. The effect and mechanism of ultrasonic agitation on the electrodeposition process are summarized. The problems concerning current research on ultrasound-assisted electroplating are discussed. Moreover, some suggestions and prospects are provided with respect to the future directions of ultrasound-assisted electroplating, in particular, of ultrasound-assisted electroplating of diamond tools.

Key words: ultrasonic; nickel electroplating; composite coating

Research Progress for Materials against Molten Zinc Corrosion

ZHAO Lei, YAN Dian-ran, HE Ji-ning, LIU Ying-kai, ZHU Lin (School of Materials Science and Engineering, Hebei Polytechnic University, Tianjin 300130, China). *Cailiao Baohu* 2008, 41 (05), 62 ~ 64 (Ch). The current research status of molten-zinc-corrosion-resistant materials was introduced, and the advantages and disadvantages of several commonly used molten-zinc-corrosion-resistant materials were compared. Moreover, the feasibility to use reactive plasma sprayed ceramic coatings for molten-zinc-corrosion-prevention was discussed. It was pointed out that the key to realize internal heating in hot-dipping galvanizing lies in that the materials to be galvanized should have good corrosion resistance to molten zinc, and plasma sprayed corrosion-resistant ceramic coatings might have tremendous prospect in the industrial production of molten-zinc-corrosion-resistant materials.

Key words: plasma spraying; ceramic coating; molten-zinc corrosion

Synergistic Surface Modification of Aluminum by Silane and Corrosion Inhibitor

XU Bin, MAN Rui-lin, HU Yu, CAO Xiao-yan, YAN Sha (School of Chemistry and Chemical Engineering, Central South University, Changsha 410083, China). *Cailiao Baohu* 2008, 41 (05), 65 ~ 69 (Ch). Bis-[3-(triethoxysilyl)propyl] tetrasulfide (a kind of silane, abbreviated as BTESPT) and an organic acid ester with long chain alkyl group (inhibitor A throughout) were used to synergistically passivate aluminum. Thus the Al samples were sequentially immersed in the silane (BTESPT) solution and inhibitor A solution, allowing the formation of compact hydrophobic complex film on the surface of the Al surfaces. The final synergistic passivation film was obtained by drying the hydrophobic complex film at 100 °C for 12 h. The corrosion resistance of the synergistic passivation film was evaluated using hydrogen evolution test, weight loss test in alkaline solution, salt-fog test, and electrochemical test. The microstructure of the passivation film was examined by means of scanning electron microscopy (SEM), and the film-formation mechanism and the corrosion resistant mechanism of the film were discussed. It was found that the complex passivation film had excellent corrosion resistance. No heavy metals and fluorides were detected in the composite passivation film, meeting the requirements of European ROHS standard.

Key words: aluminum; silane; corrosion inhibitor; modification; complex passivation film