

无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层对海上管柱螺纹抗粘扣性能的影响

殷启帅¹, 杨进¹, 李振坤², 啜广山³, 沈国华³, 杨富贵⁴, 宋宇¹

(1. 中国石油大学(北京), 北京 102249; 2. 中海油能源发展股份有限公司 工程技术分公司, 天津 300452; 3. 中海油能源发展装备技术有限公司, 天津 300452; 4. 中世钛业有限公司, 辽宁 丹东 118002)

摘要: **目的** 采用无污染的无气喷涂表面处理工艺, 制备 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层, 提高海上管柱螺纹抗粘扣性能。**方法** 在 MoS_2/C 涂层中掺杂纳米级 Cu 粉末, 采用无气喷涂+高温固化+喷砂处理工艺, 制备 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层。通过显微组织、硬度测定和摩擦试验, 分别评价 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层的显微组织、显微硬度和摩擦系数, 并通过扫描电子显微镜对 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层进行形貌分析。最后, 在实物试样上进行上卸扣试验, 测试其抗粘扣性能。**结果** 无气喷涂+高温固化过程中, 半熔融粉末经过多次叠加, 沉积形成致密的结构, 未见明显孔隙。对 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层进行喷砂预处理, 可明显提高涂层的均匀度, 增加涂层的粘结强度。涂层与基体之间呈锯齿形紧密机械结合, 喷砂无气喷涂前后, 基体硬度未发生改变, 未对金属基体造成不利影响。 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层在螺纹表面结合形成光滑的保护膜, 螺纹表面摩擦系数降低, 上扣扭矩降低幅度为 19%~23%。**结论** 在 MoS_2/C 涂层中掺杂纳米级 Cu 粉末, 形成 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层, 可有效降低螺纹表面的摩擦系数, 同时不降低本体强度。采用无气喷涂+高温固化得到 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层, 可有效提高石油管螺纹的抗粘扣性能, 在海上钻井现场已取得成功应用, 该技术具有极大的借鉴意义和推广价值。

关键词: $\text{MoS}_2/\text{Cu}/\text{C}$; 复合涂层; 无气喷涂; 螺纹; 抗粘扣; 管柱; 油套管; 海上钻井

中图分类号: TG115.5+8; TE921 **文献标识码:** A **文章编号:** 1001-3660(2022)05-0024-08

DOI: 10.16490/j.cnki.issn.1001-3660.2022.05.003

收稿日期: 2022-03-07; 修订日期: 2022-04-25

Received: 2022-03-07; Revised: 2022-04-25

基金项目: “十三五”国家科技重大专项 (2017ZX05032-004); 中海油能源发展装备技术有限公司项目 (ZX2021ZCZBF5808); 国家自然科学基金青年基金项目 (52101340); 海南省科技专项资助 (ZDKJ2021026); 博士后创新人才支持计划项目 (BX2021372); 博士后科学基金面上项目 (2021M693495); 中国石油大学(北京)科研基金项目 (2462021BJRC008, 2462022YXZZ001)

Fund: The 13th Five-Year National Science and Technology Major Project of the Ministry of Science and Technology of China (2017ZX05032-004); CNOOC Science and Technology Project (ZX2021ZCZBF5808); Youth Fund Project of National Natural Science Foundation of China (52101340); Hainan Province Science and Technology Special Fund (ZDKJ2021026); China Postdoctoral Innovation Talent Support Project (BX2021372); China Postdoctoral Science Foundation (2021M693495); Science Foundation of China University of Petroleum, Beijing (2462021BJRC008, 2462022YXZZ001)

作者简介: 殷启帅 (1991—), 男, 博士, 讲师, 主要研究方向为安全工程、海洋油气工程、海上油田腐蚀与防护。

Biography: YIN Qi-shuai (1991-), Male, Doctor, Lecturer, Research focus: safety engineering, offshore oil and gas engineering, corrosion and protection of offshore oilfield.

通讯作者: 杨进 (1966—), 男, 博士, 教授, 主要研究方向为海洋钻井、海洋油气工程。

Corresponding author: YANG Jin (1966-), Male, Doctor, Professor, Research focus: drilling and completion of offshore oilfield, offshore oil and gas engineering.

引文格式: 殷启帅, 杨进, 李振坤, 等. 无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层对海上管柱螺纹抗粘扣性能的影响[J]. 表面技术, 2022, 51(5): 24-31.

YIN Qi-shuai, YANG Jin, LI Zhen-kun, et al. Effect of Airless Spray $\text{MoS}_2/\text{Cu}/\text{C}$ Composite Coating on Buckle-resistant Performance of Offshore Pipe String Threads[J]. Surface Technology, 2022, 51(5): 24-31.

Effect of Airless Spray $\text{MoS}_2/\text{Cu}/\text{C}$ Composite Coating on Buckle-resistant Performance of Offshore Pipe String Threads

YIN Qi-shuai¹, YANG Jin¹, LI Zhen-kun², CHUAI Guang-shan³,
SHEN Guo-hua³, YANG Fu-gui⁴, SONG Yu¹

(1. China University of Petroleum (Beijing), Beijing 102249, China; 2. Engineering Technology Branch of CNOOC Energy Development Co., Ltd., Tianjin 300452, China; 3. CNOOC Enertech Equipment Technology Co., Ltd., Tianjin 300452, China; 4. ZS Titanium Co., Ltd., Liaoning Dandong 118002, China)

ABSTRACT: Threaded pipes deliver offshore oil or gas under high pressure. Thus, threaded connections must be gas or liquid tight in the severe offshore environment. Uneven force or deformation on the surface of the thread tooth will cause galling and even lead to thread failure. Galling is the key that affects the safety and life of the pipe strings and restricts the quality and efficiency of offshore drilling and well completions. In addition, environmental protection has become the primary concern in recent years. This paper aims to innovatively prepare $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings using a non-polluting airless spray coating technology to improve the anti-galling performance of the threads of the offshore pipe strings. MoS_2/C coating is a well-known solid lubricant that can reduce drag. Further, nano-scale Cu powder has good thermal conductivity. The prepared $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings provide a thin layer of heterogeneous composite materials with good thermal conductivity, and excellent friction reduction on the thread surface of the offshore pipe strings. The $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings are prepared by doping MoS_2/C coating with nano-scale Cu powder and adopting airless spraying and high-temperature curing. Properties of the composite coatings, including microstructure, microhardness, and friction coefficient, are evaluated first. Then, the morphology of the prepared $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings is analyzed by scanning electron microscopy. Finally, make-up and breakout tests are conducted on the pipe string samples with the prepared $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings to test their anti-galling performance. As a result, the semi-molten powder is superimposed and deposited multiple times during airless spraying and high-temperature curing, forming a dense structure without apparent pores. Besides, sandblasting pretreatment of $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings significantly improved the uniformity and adhesive strength of the coatings. Moreover, the coatings and the metal substrate are tightly combined in a zigzag shape. The hardness of the metal substrate does not change before and after sandblasting and airless spraying. The $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings formed a smooth protective film on the thread surface and had no detrimental effect on the metal substrate. The friction coefficient of the thread surface is reduced. The make-up torque is reduced by 19% to 23%. In conclusion, doping nano-scale Cu powder in MoS_2/C coating to form $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings effectively reduce the friction coefficient of the thread surface without reducing the strength of the metal substrate. The $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings obtained by airless spraying and high-temperature curing can effectively improve the anti-galling performance of the threads of the offshore pipe strings. Pipe strings with the prepared $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings have been successfully applied to offshore drilling and well completions. The prepared $\text{MoS}_2/\text{Cu}/\text{C}$ composite coatings turn out to prolong the life of the pipe strings and enhance the efficiency of offshore drilling and well completions, saving a substantial amount of money for the oil and gas industry. Overall, the technology presented in this paper has excellent reference significance and is recommended for offshore drilling and well completions.

KEY WORDS: $\text{MoS}_2/\text{Cu}/\text{C}$; composite coatings; airless spraying; thread; anti-galling; drill string; tubing and casing; offshore drilling and completion

油套管是开采油气资源唯一、永久性的通道,是目前海上油气钻探过程的大宗关键物资^[1-2]。据统计,近年仅中海油对油套管的采购量就高达 16 万吨。“螺纹”是油套管的重要连接机构,其在工作过程中,由于螺纹牙齿面的受力和变形不均而导致局部发生粘连和撕脱,称为“粘扣”,甚至导致螺纹失效。目前,粘扣失效现象是影响管柱安全性和工作寿命的关键,

尤其对于海上钻完井过程,海上管柱螺纹粘扣直接决定上卸扣效率,影响海上钻完井作业时效,是海上钻完井“提质增效”的重要制约环节。随着目前钻探要求的不断提高,油套管螺纹齿面的受力和变形问题变得更加复杂,粘扣失效的问题也日趋突出。一旦螺纹粘连发生粘扣,即使油套管的其他部分仍然完好可用,整体套管柱的寿命就此提前终结,造成油套管资

源的极大浪费,由此导致的经济损失巨大。螺纹抗粘扣性能的影响因素众多,包括钢级、冶炼、热处理、螺纹齿形特征、配合公差、螺纹表面粗糙度、传统磷化层质量、螺纹脂性质、上卸扣速度和力矩大小等^[3]。国产的油套管螺纹目前能够实现的最高上卸扣次数为3~4次,而国外进口的油套管可高达5~6次^[4-5],高性能抗粘扣螺纹属于“卡脖子”问题,亟待攻克和国产化替代。

目前国内预防螺纹粘扣通常采用磷化、镀铜等方式对螺纹表面进行处理,来提高螺纹的抗粘扣性能。王丹净等^[6]研究指出,中温锌系磷化工艺可有效提高螺纹钢的耐蚀性。许瑾璐^[7]研究了磷化时间对磷化膜外观、微观形貌、厚度和耐腐蚀性的影响。段正勇等^[8]设计了一种全封闭式循环磷化处理装置。王少兰等^[9]通过分析对比指出,具有高熔点、低硬度的镀铜方法是防止螺纹发生粘扣的有效途径。何体财^[10]研制了一种以纳米铜为铜基的纳米复合减磨涂料AFRICO。可见磷化、镀铜等螺纹表面处理工艺得到了广泛应用,并取得了良好应用效果。但磷化废水中含有镍离子、铜离子或铅离子等重金属污染物,成分复杂,处理难度较大,而常规镀铜工艺需要硫酸铜等液体,将产生大量的工业废液,可见磷化、镀铜等传统工艺对环境产生了严重污染。随着环保要求的不断提高,2021年国家环保局发布的《限期淘汰产生严重污染环境的工业固体废物的落后生产工艺设备名录》,严格规定磷化工艺必须于2023年12月31日前被禁止使用。因此,亟须探索一种无污染的表面处理工艺来提高石油管螺纹的抗粘扣性能^[11]。

“无气喷涂”是一种绿色环保的新兴表面处理工艺,在欧美等发达国家逐步推广应用。“无气喷涂”过程,高压无气喷涂机利用高压柱塞泵将涂层增压至20.68 MPa,获得高压涂层,再通过高压软管输送到喷枪,高压涂层由特制的喷嘴小孔喷出,在大气中立刻膨胀,雾化成极细的扇形气流喷向管柱,从而在管柱表面形成致密的涂层^[12]。由于涂层雾化不需要压缩空气,故称为“无气喷涂”,其具有诸多优势:大幅提高喷涂效率,且用料损失极少,节约成本;可获得极佳的表面质量,喷涂涂层平整、光洁、致密、无刷痕、无滚痕;有效延长涂层使用寿命,高压无气喷涂能使涂层颗粒渗入空隙,增强涂层附着力,延长使用寿命^[13]。刘媛媛等^[14]简述了高压无气喷涂在工程机械行业应用的注意事项。孙禹等^[15]构建了高压无气喷涂原子灰的扇形喷嘴三维有限元模型。对于无气喷涂用于降低管柱螺纹摩擦系数,提高抗粘扣性能方面的研究尚不多见。

本文创新性地在 MoS_2/C 涂层中掺杂纳米级Cu粉末,充分利用 MoS_2/C 涂层的润滑减阻性能和纳米级Cu粉末的良好导热性能,采用无气喷涂+高温固化得到 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层,在螺纹表面制备一层附

着牢固、导热良好而又减摩性极佳的异质复合材料薄层,有效避免了基体间的直接接触,极大地提高了油套管螺纹的抗粘扣性能。通过显微组织观察、显微硬度测定、摩擦系数测试、实物上卸扣测试,评价 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层的显微硬度和抗粘扣性能,并通过扫描电子显微镜对 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层进行形貌分析。油套管实物在反复上卸扣测试过程中, $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层在外力作用下于钢铁表面形成的自修复薄层仍能完整保持,未出现破裂和剥落,可继续起到润滑减磨的作用。

1 试验

1.1 涂层制备

为研究不同表面处理工艺对螺纹表面性能的影响,采用不同表面处理工艺,以4145H合金钢为基体材料加工3组测试试样(A、B、C组)。A组试样:采用传统高温锰系磷化工艺;B组试样:不做前期表面喷砂处理,直接无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层,固化30 min;C组试样:先喷砂预处理,再无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层,固化30 min。

按照表1配比制备粉体,其中Cu粉为纳米级,加水搅拌成悬浊液,并静置30 min,无沉淀。试验前对试件表面按金相样制备方法进行研磨,抛光后表面粗糙度 R_a 小于 $1.6\text{ }\mu\text{m}$ 。将试件放置在超声波清洗器内,用丙酮清洗干净后,放在烘干箱中烘干。

表1 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层配比
Tab.1 Ratio of $\text{MoS}_2/\text{Cu}/\text{C}$ composite coating

No.	Ingredients	Mass ratio/%
1	MoS_2	30
2	Graphite carbon (C)	10
3	Nanoscale cuprum (Cu)	1
4	Binding agent	12

1.2 性能测试及组织观察

1) 采用EVO-15型扫描电子显微镜对3组试样进行微观形貌分析,观察涂层的孔隙、晶粒、均匀度和表面结构,并测量涂层厚度。

2) 采用HT-1000型高温摩擦磨损试验机进行摩擦系数检测,分别测试3组试样在不同施加力和涂抹螺纹脂下的摩擦力系数。

3) 采用R574洛氏硬度试验机,参照GB/T 6739—2006《色漆和清漆铅笔法测定漆膜硬度》测试复合涂层的洛氏硬度。

4) 参照API RP 5C5上卸扣操作流程,通过实物试样上卸扣试验系统对表面处理之后的螺纹进行上卸扣试验,测试其扭矩,并观察螺纹是否出现咬伤、

撕裂、划伤等粘扣现象^[16]。

5) 现场应用测试新型套管的下入顺畅性、螺纹抗粘扣性能, 以及是否符合作业要求和业主认可。

2 结果及分析

2.1 涂层微观形貌分析

对不同表面处理工艺下的试样表面进行扫描电镜观察, 3 种试样表面形貌结果如图 1 所示。由图 1a 可知, 经高温锰系磷化工艺处理的试样, 表面均是锰酸盐结晶, 熔滴堆叠紧密, 但有明显的孔隙存在, 晶粒粗大, 孔隙较多。由图 1b 可知, 未喷砂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样, 表面发黑, 存在孔隙较少, 裂纹明显。由图 1c 可知, 喷砂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样, 表面发黑, 存在孔隙最少, 覆盖均匀、完全, 孔隙率小。喷砂预处理可大幅增加涂层的表面粗糙度, 从而增加涂层与基体的接触面积, 提高粘结强度和附着力。因此, 在石油管螺纹表面采用无气喷涂+高温固化得到的 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层, 经喷砂预处理, 可以明显提高涂层的均匀度, 增加粘结强度^[17-20]。喷砂处理的 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层是本文研究的重点。

对喷砂预处理的 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层截面进行微观分析, 如图 2 所示。涂层厚度为 $176.2\ \mu\text{m}$, 涂层截面呈致密的层状结构, 说明在无气喷涂+高温固化过程中, 半熔融粉末经过多次叠加, 每次都是以极高的速度 ($\geq 700\ \text{m/s}$) 沉积形成致密的结构。同时, 通过半熔融粉末的高速沉积以及基材表面的喷砂处理, 使得涂层与基体之间呈锯齿形紧密结合, 如图 3 所示。涂层与基体为机械结合, 涂层致密, 未见明显孔隙^[21]。

2.2 试样摩擦系数检测

首先, 使用 HT-1000 型高温摩擦磨损实验机对 A、B、C 试样进行摩擦系数检测^[22]。在室内 $25\ ^\circ\text{C}$, 施加 $5\ \text{N}$ 的力, 得到 3 种试样的摩擦系数曲线, 如图 4 所示, 平均摩擦系数见表 2。由图 4 和表 2 可知, A 试样的摩擦系数最大, B 试样次之, C 试样的摩擦系数最小。下文将着重针对 C 试样开展研究和分析。

使用 HT-1000 型高温摩擦磨损实验机对喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层 C 试样在有/无螺纹脂的情况下进行摩擦系数检测, 在室内 $25\ ^\circ\text{C}$, 分别施加 3 、 6 、 $10\ \text{N}$ 的力, 得到的摩擦系数曲线如图 5 所示。平均摩擦系数见表 3。

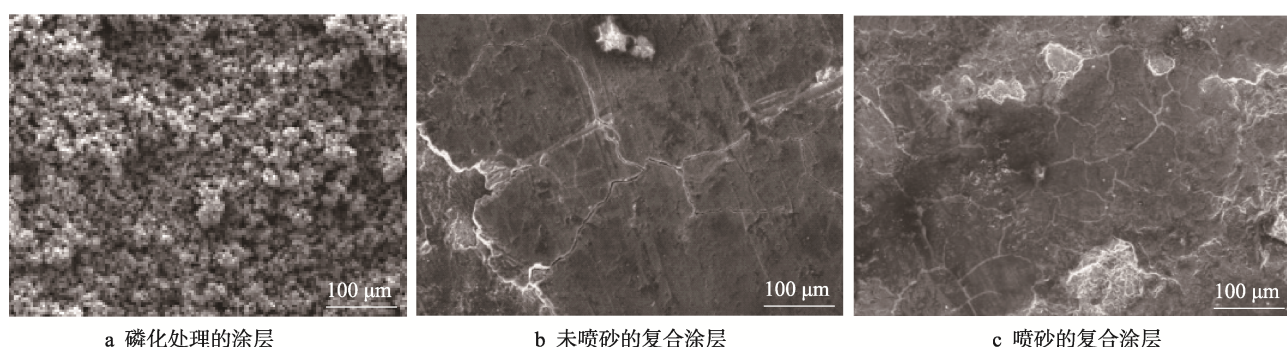


图 1 不同表面处理工艺涂层的 SEM 表面形貌

Fig.1 SEM surface morphologies of coatings under different surface treatments techniques: a) phosphating coating; b) unsandblasted composite coating; c) sandblasted composite coating

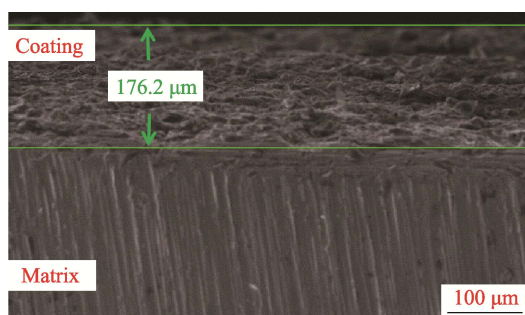


图 2 喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层的表面 SEM 形貌

Fig.2 SEM surface morphologies of sandblasted airless sprayed $\text{MoS}_2/\text{Cu}/\text{C}$ composite

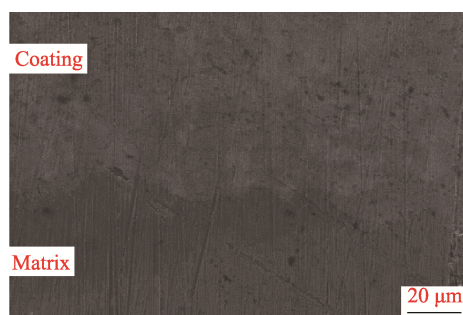


图 3 喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层结合部位的表面 SEM 形貌

Fig.3 SEM surface morphologies of bonding site of sandblasted airless sprayed $\text{MoS}_2/\text{Cu}/\text{C}$ composite

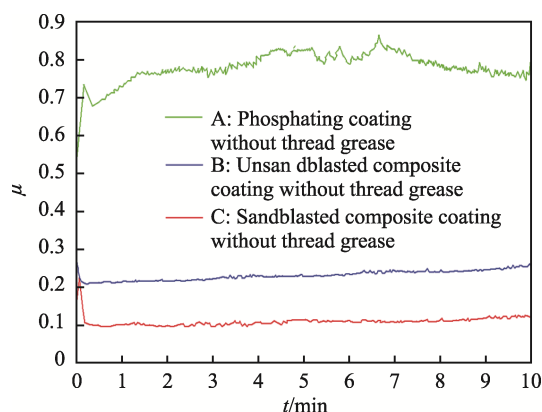


图4 A/B/C试样在5 N下的摩擦系数检测曲线
Fig.4 Friction coefficient testing curve of A/B/C specimen under 5 N force

表2 A/B/C试样在5 N力下的平均摩擦系数
Tab.2 Average friction coefficient of A/B/C specimen under 5 N force

Specimen	Force/N	Average friction coefficient μ
A	5	0.766
B	5	0.239
C	5	0.108

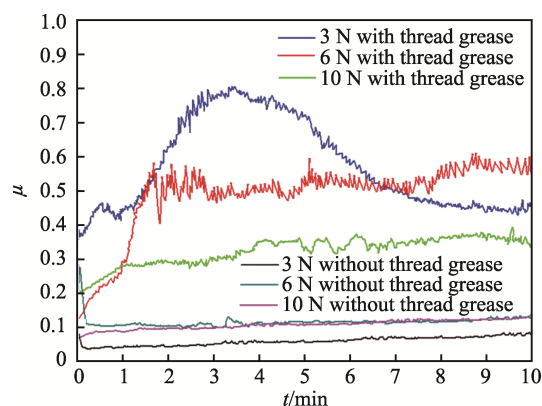


图5 喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样摩擦系数检测曲线
Fig.5 Friction coefficient testing curve of sandblasted airless sprayed $\text{MoS}_2/\text{Cu}/\text{C}$ composite

表3 喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样平均摩擦系数

Tab.3 Average friction coefficient of sandblasted airless sprayed $\text{MoS}_2/\text{Cu}/\text{C}$ composite

Force/N	Specimen coated with thread grease	Specimen coated without thread grease
3	0.612	0.059
6	0.491	0.112
10	0.316	0.097

由图5和表3可知, 喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样在进行摩擦系数测试时, 未涂抹螺纹脂的试样, 摩擦系数较小, 而涂抹螺纹脂的试样, 摩擦

系数相对较大。这是因为目前在石油管柱螺纹连接时, 常用的抗粘扣螺纹脂是添加铜颗粒的, 由于铜颗粒较大, 增加了接触面的粗糙度, 因而相对摩擦系数较大。对于施加3 N力且涂抹螺纹脂的试样, 螺纹脂中的铜颗粒先破坏了复合涂层, 使摩擦系数增大, 但随后复合涂层进行了自修复, 摩擦系数减小, 但一直大于未涂抹螺纹脂的试样。因此, 综合考虑螺纹粘扣机理等因素, 在实物试样上卸扣试验时, 可以不涂抹螺纹脂^[23-27], 旨在降低螺纹表面粗糙度, 减少上卸扣时的摩擦热量, 从而降低粘扣风险。下文将针对未涂抹螺纹脂但喷砂处理的 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层开展研究和分析。

2.3 复合涂层硬度测试

使用 R574 洛氏硬度实验机对无气喷涂+高温固化前油管环形试样基体、喷砂无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样基体分别进行硬度测试, 检测位置见图6, 试验结果见表4。结果显示, 喷砂无气喷涂前后, 基体的硬度值未发生明显改变, 说明该工艺对金属基体未造成不利影响。

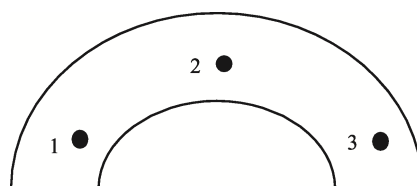


图6 硬度检测位置
Fig.6 Diagram of hardness detection positions

表4 洛氏硬度试验结果 (HRC)
Tab.4 Rockwell hardness testing results (HRC)

Specimens	Testing location 1	Testing location 2	Testing location 3
Before sandblasting airless spraying	21.2	21.7	22.1
After sandblasting airless spraying	21.9	21.3	21.8

2.4 实物试样上卸扣试验

2.4.1 套管上卸扣试验

以 $\phi 177.8 \text{ mm} \times 9.19 \text{ mm}$ P110 BTC 套管为例, 准备2组试样, 其中1#试样进行常规磷化处理^[28], 2#试样内外螺纹喷砂后无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层。设置扭矩为10 914、14 800、18 507 N·m, 试验步骤及方法按照 API RP 5C5 上卸扣试验过程^[29-30], 上卸扣3次, 均未发生粘扣现象, 试验结果如图7所示。

由图7可知, 磷化和无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层后的 P110 LTC 套管上扣时, 起始扭矩圈数基本相同, 但无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层试样提前0.305圈 (折合0.97 mm) 达到15 000 N·m。对应相等J值

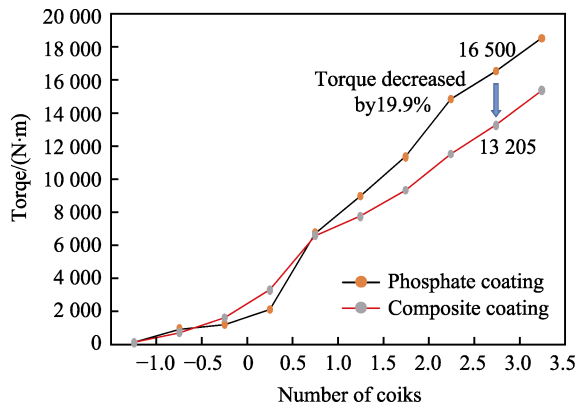


图 7 $\phi 177.8\text{ mm}\times 9.19\text{ mm}$ P110 BTC
套管扭矩/圈数对比
Fig.7 $\phi 177.8\text{ mm}\times 9.19\text{ mm}$ P110 BTC
casing torque/coil comparison

(拧接后管端到接箍中心的理论长度) 条件下, 扭矩下降约 19.9%。

2.4.2 钻杆上卸扣试验

以 3-1/2"NC38 G105 钻杆为例进行试验, 内外螺纹喷砂, 再无气喷涂 MoS₂/Cu/C 复合涂层, 进行 100 次上卸扣试验, 试验数据见表 5, 试验结果如图 8 所

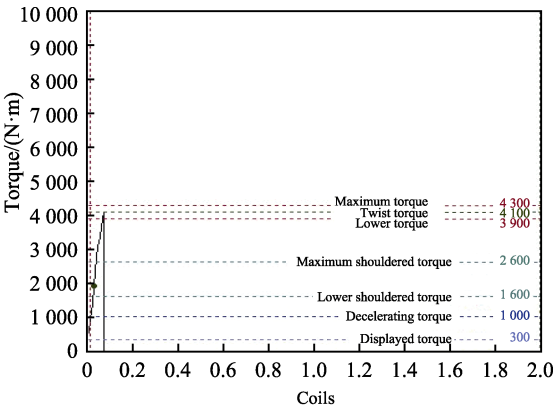
示。由表 5 和图 8 可知, 3-1/2"NC38 G105 钻杆经 100 次上卸扣试验后, 内外螺纹表面完好, 未出现咬伤、撕裂、划伤等粘扣现象, 而且肩负扭矩未发生明显变化, 满足现场钻杆多次循环作业的使用要求。

表 5 4.3-1/2"NC38 G105 钻杆上卸扣参数
Tab.5 3-1/2"NC38 G105 Drill pipe make-up
and screw off parameters

Number of testings	Number of screwed coils	Screwed torque /(N·m)	Should-ered coils	Should-ered torque/%	Quality assess-ment
1	0.07	4 102	0.05	46	Qualified
2	0.06	4 132	0.04	47	Qualified
3	0.08	4 102	0.06	47	Qualified
4	0.06	4 115	0.03	50	Qualified
5	0.06	4 118	0.03	47	Qualified
6	0.06	4 124	0.04	46	Qualified
7	0.06	4 110	0.04	49	Qualified
...	Qualified
99	0.04	4 129	0.02	44	Qualified
100	0.04	4 154	0.02	48	Qualified



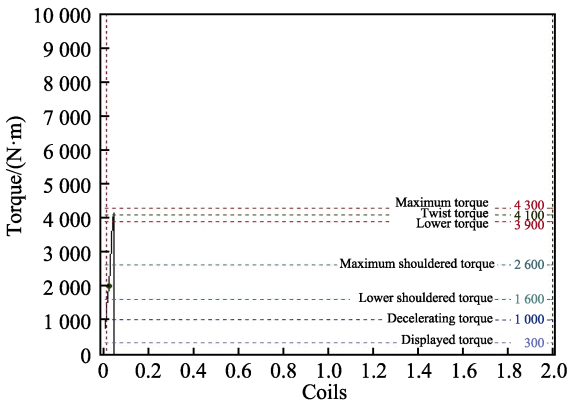
a 第1次卸扣



b 第1次上扣曲线



c 第100次卸扣



d 第100次上扣曲线

图 8 3-1/2"NC38 G105 钻杆首次和末次上卸扣曲线和实物
Fig.8 3-1/2"NC38 G105 Drill pipe first and last make-up and break-up curves and objects:
a) 1st break-out; b) 1st make-up curve; c) 100th break-out; d) 100th make-up curve

3 现场应用

基于无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层 $\phi 177.8 \text{ mm} \times 9.19 \text{ mm}$ 、钢级 N80Q BTC 套管, 先后在海上油气田应用 10 余井次, 其中 X1 井均为难度较大的水平井, 设计井深达 3 350.78 m, 水平段长 950 m, 最大井斜 90° , 套管顺利下入无遇阻现象, 并被送至目的层位。整个下入过程扭矩曲线平滑, 未发现粘扣现象, 螺纹参数良好, 受到了业主及现场监督的认可和好评。

4 结论

1) 对螺纹表面喷砂处理, 无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层, 可有效增强复合涂层的粘结强度, 且摩擦系数较小, 大幅降低上卸扣摩阻。实物上卸扣试验过程中, 内外螺纹表面完好, 未出现粘扣, 且上扣过程扭矩曲线平滑, 螺纹参数良好。

2) 新型无污染的无气喷涂表面处理工艺可用于制备 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层, 能显著提高海上油套管螺纹的抗粘扣性能。该方法具有操作简便、成本低、环保等优点, 可为海上油气安全、高效、环保开采提供技术保障。

3) 无气喷涂 $\text{MoS}_2/\text{Cu}/\text{C}$ 复合涂层用于提高海上管柱抗粘扣性能是无气喷涂表面处理工艺在海上油气田的一次成功应用与实践, 对于其他领域具有极大的借鉴意义和应用推广价值。

参考文献:

- [1] 殷启帅, 杨进, 施山山, 等. 南海东部某油田隔水导管腐蚀失效分析[J]. 表面技术, 2018, 47(11): 134-141.
YIN Qi-shuai, YANG Jin, SHI Shan-shan, et al. Corrosion Failure Analysis of Conductor in Eastern Oilfield in the South China Sea[J]. Surface Technology, 2018, 47(11): 134-141.
- [2] 殷启帅, 杨进, 杨宇平, 等. 海上油田注水开采中 H_2S 成因及油管腐蚀分析[J]. 表面技术, 2017, 46(9): 171-178.
YIN Qi-shuai, YANG Jin, YANG Yu-ping, et al. Origin of H_2S and Corrosion Analysis of Tubing in Offshore Oil-field Flooding[J]. Surface Technology, 2017, 46(9): 171-178.
- [3] 苏文瑛, 武振鹏, 朱绘丽, 等. 钻铤螺纹加工工艺的研究[J]. 煤矿机械, 2021, 42(2): 100-103.
SU Wen-ying, WU Zhen-peng, ZHU Hui-li, et al. Research on Processing Technology of Drill Collar Thread[J]. Coal Mine Machinery, 2021, 42(2): 100-103.
- [4] 张毅, 陈建初, 陈甦. 使用液压钳对油管粘扣的影响分析[J]. 石油机械, 2002, 30(11): 4-7.
ZHANG Yi, CHEN Jian-chu, CHEN Su. Influence of Using Hydraulic Tongs on Thread Gluing of Tubing[J]. China Petroleum Machinery, 2002, 30(11): 4-7.
- [5] 黄志潜, 李平全, 刘天民, 等. 石油工业发展对油套管和管线管的要求与对策[J]. 石油专用管, 1998(4): 1-10.
HUANG Zhi-qian, LI Ping-quan, LIU Tian-min, et al. Requirements and Countermeasures for Oil Casing and Line Pipe in the Development of Petroleum Industry[J]. Petroleum Special Pipe, 1998(4): 1-10.
- [6] 王丹净, 李景魁, 孙伟. 框架结构用螺纹钢磷化处理及耐蚀性研究[J]. 电镀与精饰, 2021, 43(6): 15-19.
WANG Dan-jing, LI Jing-kui, SUN Wei. Study on Phosphating Treatment and Corrosion Resistance of Screw-Thread Steel Used in Frame Structure[J]. Plating and Finishing, 2021, 43(6): 15-19.
- [7] 许瑾璐. 框架结构用螺纹钢中温锌锰系磷化及封闭处理[J]. 兵器材料科学与工程, 2021, 44(6): 15-20.
XU Jin-lu. Medium-Temperature Zinc-Manganese Phosphating of Screw-Thread Steel for Frame Structure and Sealing Treatment[J]. Ordnance Material Science and Engineering, 2021, 44(6): 15-20.
- [8] 段正勇, 彭勇, 王辉锋. 石油钻铤接头螺纹磷化处理装置研究[J]. 石油矿场机械, 2014, 43(7): 62-66.
DUAN Zheng-yong, PENG Yong, WANG Hui-feng. Study on Phosphating Device Applied to Oil Drill Collar Coupling Screw Thread[J]. Oil Field Equipment, 2014, 43(7): 62-66.
- [9] 王少兰, 费敬银, 骆立立, 等. 石油钻具螺纹防粘扣技术及应用[J]. 电镀与精饰, 2014, 36(1): 18-22.
WANG Shao-lan, FEI Jing-yin, LUO Li-li, et al. Anti-Galling Brush Plating Technology for Oil Drill Thread and Its Application[J]. Plating & Finishing, 2014, 36(1): 18-22.
- [10] 何体财. 石油钻具螺纹应力分析与减摩涂料的开发[D]. 西安: 西安科技大学, 2019.
HE Ti-cai. Analysis of Thread Stress of Oil Drill and Development of Thread Reduction Coating[D]. Xi'an: Xi'an University of Science and Technology, 2019.
- [11] 刘强, 范晓东, 宋生印, 等. 钛合金油管表面抗粘扣处理工艺研究[J]. 石油管材与仪器, 2017, 3(4): 26-31.
LIU Qiang, FAN Xiao-dong, SONG Sheng-yin, et al. Research on Process of Thread Gluing Resistance for Titanium Alloy Tubing Surface[J]. Petroleum Tubular Goods & Instruments, 2017, 3(4): 26-31.
- [12] 杨云, 史彬, 赵世龙, 等. 特殊螺纹套管接头纳米铜干式涂层的制备及性能研究[J]. 润滑与密封, 2015, 40(12): 90-94.
YANG Yun, SHI Bin, ZHAO Shi-long, et al. Preparation and Properties of Nano-Copper Dry Lubrication Coating of Premium Connection for Casing[J]. Lubrication Engineering, 2015, 40(12): 90-94.
- [13] 孟昭, 杨云, 赵世龙, 等. 纳米铜/PTFE 复合纳米减摩涂料在石油专用管材上的应用[J]. 润滑与密封, 2014, 39(7): 93-97.
MENG Zhao, YANG Yun, ZHAO Shi-long, et al. Application of Composite Nano-Copper/PTFE Friction Redu-

- cing Coating in Oil Country Tubular Goods[J]. Lubrication Engineering, 2014, 39(7): 93-97.
- [14] 刘媛媛, 王萌, 姜立勇, 等. 高压无气喷涂在工程机械制造业中的应用探讨[J]. 现代涂料与涂装, 2013, 16(7): 52-53.
- LIU Yuan-yuan, WANG Meng, JIANG Li-yong, et al. Discussion on Application of High Pressure Airless Spraying Used in Construction Machinery Manufacturing Industry[J]. Modern Paint & Finishing, 2013, 16(7): 52-53.
- [15] 孙禹, 赵民, 夏海渤, 等. 用于高压无气喷涂原子灰的扇形喷嘴内部流场的数值仿真[J]. 大连交通大学学报, 2018, 39(4): 42-46.
- SUN Yu, ZHAO Min, XIA Hai-bo, et al. Numerical Simulation of Internal Flow Field of Fan-Shaped Nozzle Used for High-Pressure Airless Spraying Putty[J]. Journal of Dalian Jiaotong University, 2018, 39(4): 42-46.
- [16] 朱禄发, 龙剑平, 刘二勇, 等. 等离子喷涂 Al_2O_3 -13% TiO_2 涂层的海水腐蚀磨损性能[J]. 中国表面工程, 2015, 28(6): 96-103.
- ZHU Lu-fa, LONG Jian-ping, LIU Er-yong, et al. Tribocorrosion Behavior of Plasma Sprayed Al_2O_3 -13% TiO_2 Coatings in Seawater[J]. China Surface Engineering, 2015, 28(6): 96-103.
- [17] 张继豪, 宋凯强, 张敏, 等. 高性能陶瓷涂层及其制备工艺发展趋势[J]. 表面技术, 2017, 46(12): 96-103.
- ZHANG Ji-hao, SONG Kai-qiang, ZHANG Min, et al. Development Trend of High Performance Ceramic Coatings and Preparation Technologies[J]. Surface Technology, 2017, 46(12): 96-103.
- [18] 杨宏波, 刘朝辉, 丁逸栋, 等. 热化学反应法制备 Al_2O_3 -13% TiO_2 陶瓷涂层及其性能研究[J]. 表面技术, 2017, 46(9): 215-222.
- YANG Hong-bo, LIU Zhao-hui, DING Yi-dong, et al. Preparation of Al_2O_3 -13% TiO_2 Ceramic Coating in the Method of Thermo-Chemical Reaction and Its Properties[J]. Surface Technology, 2017, 46(9): 215-222.
- [19] 石绪忠, 许康威, 武笑宇, 等. 等离子喷涂纳米氧化铝钛涂层机械性能研究[J]. 表面技术, 2018, 47(4): 96-101.
- SHI Xu-zhong, XU Kang-wei, WU Xiao-yu. Mechanical Behavior of Plasma Sprayed Nano- $\text{Al}_2\text{O}_3/\text{TiO}_2$ Coatings[J]. Surface Technology, 2018, 47(4): 96-101.
- [20] 刘美淋, 孙宏飞, 于惠博, 等. 降低热喷涂涂层孔隙率的方法[J]. 腐蚀与防护, 2007, 28(4): 171-173.
- LIU Mei-lin, SUN Hong-fei, YU Hui-bo, et al. A Method to Decrease the Porosity of Thermal Spray Coating[J]. Corrosion & Protection, 2007, 28(4): 171-173.
- [21] 李水清, 糜亮, 丁毅, 等. Ni 对 Cr_2O_3 涂层孔隙率及耐蚀性的影响[J]. 表面技术, 2011, 40(3): 8-10.
- LI Shui-qing, MI Liang, DING Yi, et al. The Effect of Nickel on Porosity and Corrosion Resistance of Chromium Oxide Coating[J]. Surface Technology, 2011, 40(3): 8-10.
- [22] 杨云, 孟昭, 王晰, 等. 复合纳米抗粘扣涂层在油管上的应用[J]. 材料保护, 2016, 49(9): 64-68.
- YANG Yun, MENG Zhao, WANG Xi, et al. Application of Nano-Composite Anti-Galling Coating on Tubing[J]. Materials Protection, 2016, 49(9): 64-68.
- [23] 贾碧, 潘复生, 陈春江, 等. Al_2O_3 对等离子喷涂 $\text{Cr}_2\text{O}_3/\text{TiO}_2/\text{Al}_2\text{O}_3/\text{SiO}_2$ 复合陶瓷涂层性能影响研究[J]. 表面技术, 2020, 49(8): 55-62.
- JIA Bi, PAN Fu-sheng, CHEN Chun-jiang, et al. Effect of Al_2O_3 on Properties of Plasma Sprayed $\text{Cr}_2\text{O}_3/\text{TiO}_2/\text{Al}_2\text{O}_3/\text{SiO}_2$ Composite Ceramic Coating[J]. Surface Technology, 2020, 49(8): 55-62.
- [24] 郑志刚, 刘敏, 邓春明. 等离子喷涂 Al_2O_3 涂层/GCr15 干摩擦磨损性能研究[J]. 材料研究与应用, 2009, 3(1): 55-59.
- ZHENG Zhi-gang, LIU Min, DENG Chun-ming. Dry Wear Behavior of Plasma Sprayed Alumina Coating Against GCr15[J]. Materials Research and Application, 2009, 3(1): 55-59.
- [25] 杨媛, 王婷婷, 朱定一, 等. Au-30%Si 合金熔体与石墨的润湿性及铺展动力学[J]. 中国有色金属学报, 2016, 26(6): 1175-1181.
- YANG Yuan, WANG Ting-ting, ZHU Ding-yi, et al. Wettability and Spreading Dynamics of Melting Au-30%Si Alloys with Graphite[J]. The Chinese Journal of Nonferrous Metals, 2016, 26(6): 1175-1181.
- [26] 吕玥, 殷勇高. 填料表面参数对 LiCl 溶液降膜润湿性的影响[J]. 东南大学学报(自然科学版), 2020, 50(5): 889-895.
- LÜ Yue, YIN Yong-gao. Effects of Filler Surface Conditions on Falling-Film Plate Wettability Using LiCl- H_2O [J]. Journal of Southeast University (Natural Science Edition), 2020, 50(5): 889-895.
- [27] 李振铎, 吴朝军, 曾克里, 等. 等离子喷涂纳米结构 $\text{Cr}_2\text{O}_3/5\text{SiO}_2/3\text{TiO}_2$ 涂层性能研究[J]. 有色金属, 2007(1): 72-74.
- LI Zhen-duo, WU Chao-jun, ZENG Ke-li, et al. Study on Properties of Plasma Sprayed Nanostructured $\text{Cr}_2\text{O}_3/5\text{SiO}_2/3\text{TiO}_2$ Coating[J]. Nonferrous Metals, 2007(1): 72-74.
- [28] 赵世龙, 孟昭, 杨丁门, 等. 纳米铜/PTFE 复合纳米减摩涂料在 P110 套管上的应用[J]. 润滑与密封, 2016, 41(8): 92-96.
- ZHAO Shi-long, MENG Zhao, YANG Ding-men, et al. Application of Composite Nano-Copper/PTFE Friction Reducing Coating on P110 Casing[J]. Lubrication Engineering, 2016, 41(8): 92-96.
- [29] 李振坤, 殷启帅, 李铁, 等. 中短半径侧钻井新型套管螺纹设计及应用[J]. 石油机械, 2019, 47(8): 140-144.
- LI Zhen-kun, YIN Qi-shuai, LI Tie, et al. Design and Application of a New Type of Casing Thread for Medium and Short Radius Sidetracking Well[J]. China Petroleum Machinery, 2019, 47(8): 140-144.
- [30] YIN Qi-shuai, YANG Jin, XIU Hai-mei, et al. Material Qualification of a 13Cr-L80 Casing for Sour Conditions[J]. Materials Testing, 2019, 61(9): 833-841.

责任编辑: 刘世忠