电子束表面合金化合成$(Cr, Fe)_7C_3$复合层耐磨性

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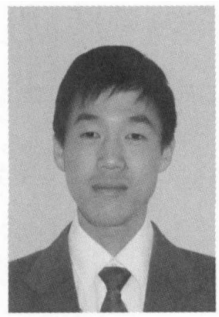

陆斌锋

摘 要：以 Fe/ Cr/ C 粉末为添加原料，采用可控电子束旋转线扫描方式对低碳钢表面进行表面改性。通过电子束加热工艺和粉末配比的优化，在表面复合层中原位合成了$(Cr, Fe)_7C_3$。对表面复合层的显微组织及室温干滑动磨损性能进行了分析。结果表明，表面复合层中主要包含两种相，即少量的初生硬化相$(Cr, Fe)_7C_3$以及奥氏体与$(Cr, Fe)_7C_3$组成的共晶相，共晶碳化物弥散分布于奥氏体基体中，呈不连续网状组织。表面复合层与基体之间为完全冶金结合。复合层与 GCr15 钢球的磨损机理为磨料磨损，在室温干滑动磨损下具有优异的耐磨损性能。

关键词：表面复合层；真空电子束扫描；碳化铬；耐磨性
中图分类号：TG115.28 文献标识码：A 文章编号：0253－360X(2008)11－0077－04

0 序 言

在众多的耐磨合金中，Fe-Cr-C 系耐磨合金由于硬度高，综合性能好，价格低廉而获得了广泛的应用。Fe-Cr-C 系合金中的初生碳化物和共晶碳化物由于硬度高和作为韧性相的奥氏体组织相互作用使其具有良好的耐磨性。$(Cr, Fe)_7C_3$中同时存在金属键和共价键，在常温和高温下都具有很高的硬度。$(Cr, Fe)_7C_3$的线膨胀系数几乎与钢的线膨胀系数相等，减少了$(Cr, Fe)_7C_3$颗粒与基体材料组织之间的机械应力，因此它能成为复合钢铁材料中极好的增强相。表面复合层的硬度和耐磨性能取决于$(Cr, Fe)_7C_3$颗粒的形状、数量和分布。一定尺寸的$(Cr, Fe)_7C_3$颗粒弥散地分布于坚韧的基体材料中能达到最佳的耐磨性能[1]。很多人研究过 Fe-Cr-C 系合金，Atamert 等人[2]研究了 Fe-Cr-C 系合金的微观组织及其稳定性，指出虽然 Fe-Cr-C 系合金在热力学上平衡相为铁素体和$(Cr, Fe)_7C_3$，实际上往往韧性相为奥氏体。在一定范围内，初生碳化物的数量随着含碳量的增加和 Cr/ C 比的减少而增加。王清宝等人[3]研究了 Fe-Cr-C 系高碳耐磨堆焊合金的组织及性能，指出对高碳 Fe-Cr-C 耐磨堆焊合金，含碳量越多，初生碳化物数量越多，碳化物的体积越大。王智慧等人[4]研究了 Fe-Cr-C 系耐磨堆焊合金初生碳化物生长方向的控制。

目前已经有很多利用不同的合成技术在材料表面制备 Fe-Cr-C 系耐磨层的研究。刘均波等人[5]以 Fe-Cr-C 为原料，利用等离子熔敷技术在 45 钢表面成功制备了耐磨性能优良的$(Cr, Fe)_7C_3/\gamma$-Fe 耐磨层。近年来，人们对利用高能粒子束（电子束，激光束等）在材料表面制备高性能的耐磨层。Yun 等人[6]用大功率电子束扫描在不锈钢表面合成了Cr_7C_3表面复合层。电子束具有能量密度大的特点，除了广泛应用于焊接和熔炼外，电子束表面改性也取得了显著的发展。

1 试验方法

采用低碳钢作为基体材料，规格为30 mm × 30 mm × 5 mm，化学成分见表 1。基体材料先经过砂纸打磨后用丙酮擦洗吹干。把上层为铁粉，下层为铬粉和碳粉的配比为 42Cr-6C-52Fe（质量分数，%）的粉末预置到基体材料，在真空条件下用电子束扫描制备表面复合层材料。

表 1 基体材料的化学成分（质量分数，%）
Table 1 Chemical composition of substrate material

C	Si	Mn	Ti	V	Fe
0.125	0.45	1.40	0.07～0.16	0.03～0.09	余量

收稿日期：2008－01－04
基金项目：上海市激光制造与材料改性重点实验室基金资助项目（08DZ2212）

采用 EBW —6C 型电子束焊机进行表面改性。电子束加速电压为 60 kV，扫描轨迹经过预先编程控制，采用十字旋转线的方式扫描样品。电子束处理过程如图 1 所示。为了减少粉末的飞溅，扫描时电子束束流缓慢增加直到粉末熔化，然后维持这个最大束流（9 mA）扫描一段时间直到反应充分进行。粉末熔化反应充分进行后停掉电子束束流，处理过程中束流随时间的变化如图 2 所示。

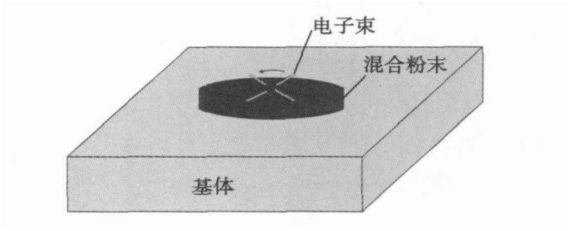

图 1 电子束表面改性示意图

Fig. 1 Schematic diagram showing the fabrication procedures of the surface composite layer

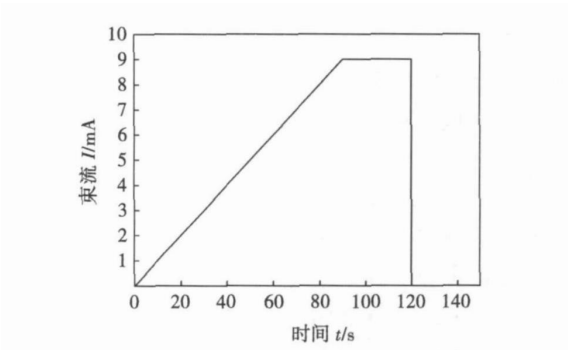

图 2 电子束扫描过程的束流与时间关系曲线

Fig. 2 Relationship of beam current and time during electron beam scanning

样品制备完成后，通过 X 射线衍射分析，金相分析及室温干滑动摩擦磨损试验对表面复合层的性质进行研究比较。首先把表面复合层用细砂纸磨平磨光后做 X 射线衍射分析，然后对样品进行室温干滑动磨损试验，在扫描电镜下观察磨损形貌。最后对样品横切面进行抛光后用氯化铁盐酸溶液腐蚀进行金相分析。

室温干滑动磨损试验在 WTM —2E 可控气氛微型摩擦磨损试验仪上进行，选取硬度为 798 HV 的 GGr15 钢球作为对磨球，对磨球直径为 3.12 mm，转速为 250 r/min，回转半径为 3 mm，载荷为 4.9 N，磨损时间为 30 min。以母材试样作为对比试样。将原位合成 $(Cr, Fe)_3C_3$ 表面复合层试样及作为对比试样的母材均用电火花切割成尺寸为 15 mm× 15 mm 的正方体，样品磨损面预先用 6 号金相砂纸磨平。用精度为 0.1 mg 的精密天平称量发生磨损前后试样及 GCr15 钢球的质量，并计算出磨损量，用绝对磨损量及相对耐磨性来评价复合层耐磨性。相对耐磨性 ε 是指采用某种材料作“标准”试样，标准材料与试验材料在相同的外部条件下磨损量的比值称为相对耐磨性，$\varepsilon = \Delta W_{标} / \Delta W_{试}$，其中 $\Delta W_{标}$ 为 GCr15 钢球磨损量，$\Delta W_{试}$ 为试样材料磨损量，ε 越大，表明耐磨性越好，图 3 为室温干滑动磨损的示意图。

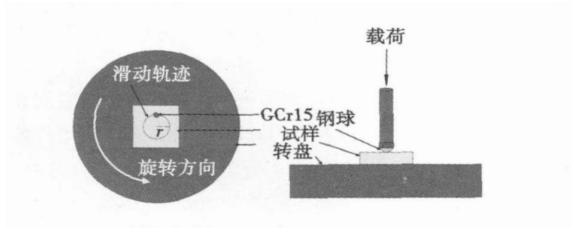

图 3 室温干滑动试验示意图

Fig. 3 Schematic diagram of tribological test

2 结果分析

粉末和低合金钢基体表层在电子束的照射下熔化后冷却形成了表面复合层，图 4 是样品的 X 射线衍射图，为了获得更好的峰值信息，采用钼靶作为 X 射线衍射仪的阳极靶。对衍射结果进行分析，可见复合层中主要存在两种相的峰，即 $(Cr, Fe)_7C_3$ 和 γ-Fe。

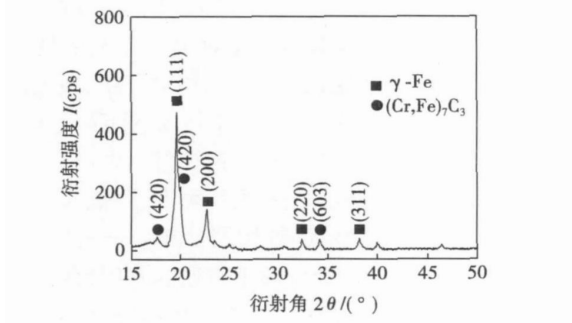

图 4 表面复合层的 X 射线衍射图

Fig. 4 X-ray diffraction data of surface composite layer

图 5 是样品表面复合层的电子扫描显微组织，黑色胞状组织为奥氏体组织，其晶界处白色组织为初生和共晶 $(Cr, Fe)_7C_3$，组织中没有六边形粗大 $(Cr, Fe)_7C_3$ 组织。由于电子束扫描时母材基体的大量熔化使得熔池中 Cr，C 元素的含量大量降低，因而初生 $(Cr, Fe)_7C_3$ 相较少，主要以共晶形式存在的 $(Cr, Fe)_7C_3$ 析出于奥氏体晶界处形成网状组织，表面复合层中没有出现气孔、裂纹等缺陷。

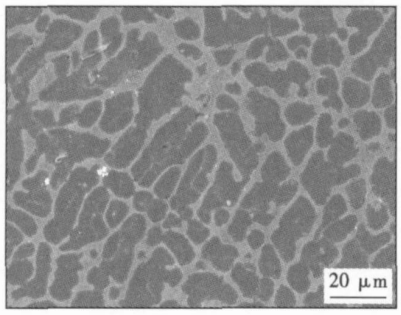

图 5　表面复合层电子扫描显微组织

Fig. 5　SEM micrograph of surface composite layer

图6a 为电子束表面熔敷层在室温干滑动磨损试验后的表面磨损SEM 形貌，可见磨损表面比较光滑，分布着较浅较细的擦划痕迹。GCr15 钢球对熔敷层的磨损主要是磨料磨损，(Cr, Fe)$_7$C$_3$ 比较细小且均匀分布在奥氏体组织晶界处，由于其极高的硬度有效地起到抗磨损的作用，大大地减少了磨损量，奥氏体组织具有优良韧性能很好的支撑(Cr, Fe)$_7$C$_3$ 硬化相，奥氏体组织还能阻碍磨损过程中裂纹和磨屑的产生，奥氏体组织产生加工硬化，提高了硬度，并使表面形成压应力，能有效阻止疲劳磨损。图 6b 为作为对比的低碳钢磨损试验后的 SEM 形貌，呈现不规则的片状和较深的犁沟。这是由于低碳钢的组织主要为铁素体单相组织，其硬度较低，而且表面主要是金属键，与 GCr15 钢的键合比较接近，因而发生了较严重的黏着磨损。

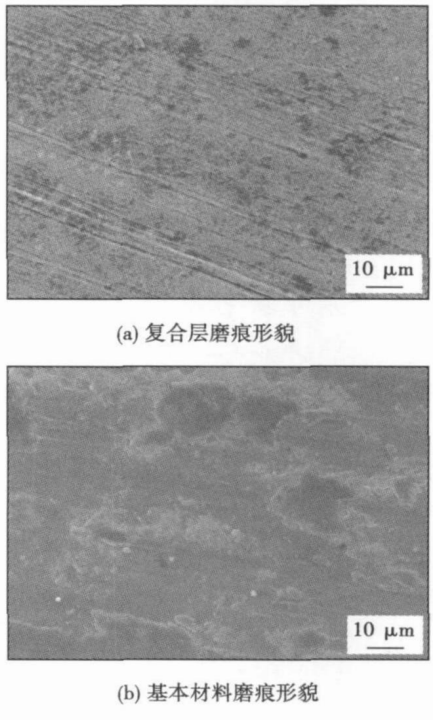

图 6　试样滑动磨损磨痕 SEM 形貌

Fig. 6　SEM micrographs of worn surface

表面复合层和基体材料的磨损失重数据见表 2。可见以 GCr15 作为标准试样，表面复合层的相对耐磨性为 1.93，而作为对比基体材料的相对耐磨性为 0.58。经电子束表面改性后的试样其相对耐磨性得到了一定的提高。考虑到大小合适的硬化相均匀弥散分布于韧性相中最有利于提高复合材料的耐磨性，而复合层中的(Cr, Fe)$_7$C$_3$ 沿奥氏体晶界析出成网状，破坏奥氏体晶粒间的联结，对于进一步提高材料的耐磨性是不利的。

表 2　磨损试验结果

Table 2　Tribological test data

试验组	材料	磨前质量 w_1/g	磨后质量 w_2/g	失重 Δw/g	相对耐磨性 ε
熔敷层组	熔敷层	8.652 6	8.651 2	0.001 4	1.93
	GCr15	0.124 6	0.121 9	0.002 7	
母材组	母材	8.486 3	8.482 7	0.003 6	0.58
	GCr15	0.125 3	0.123 2	0.002 1	

图7 为电子束原位合成表面复合层与母材在室温干滑动磨损条件下摩擦因数随时间变化的关系曲线，表面复合层的平均摩擦因数为 0.38，而母材的平均摩擦因数为 0.47。可见表面复合层中的(Cr, Fe)$_7$C$_3$ 比单相组织的母材有效地降低了和 GCr15 的粘着磨损。室温干滑动磨损表明经电子束原位合成的 (Cr, Fe)$_7$C$_3$/γ-Fe 表面复合层相比于母材其耐磨

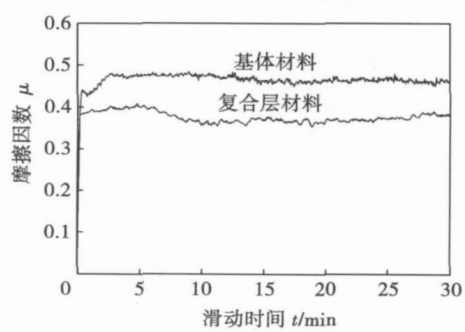

图 7　室温干滑动磨损摩擦系数随时间变化曲线

Fig. 7　Coefficient of friction vs. sliding time

性得到了较大的提高。

3 结 论

(1) 利用真空电子束扫描原位合成了耐磨复合层,通过XRD 和扫描电镜分析确定复合层中硬化相为$(Cr, Fe)_7C_3$, 韧性相为 γ-Fe。

(2) 复合层中没有发现典型六边形粗大$(Cr, Fe)_7C_3$相,以共晶形式存在的$(Cr, Fe)_7C_3$ 析出于奥氏体晶界处形成网状组织。

(3) 由于$(Cr, Fe)_7C_3$ 硬化相的存在,复合层与GCr15钢球的磨损机理为磨料磨损,相对耐磨性有比较大的提高。

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different in the second specimen. One of them is 1 mm, and the other one is 2 mm. Meanwhile, the size of bridge between two hole are different. The former is 0.4 mm, and the later is 0.2 mm. Then the numerical resultes were compared with that of the experiment to verify the validity of Gurson damage models in describing the initiation and propagation of cracks during their evolution. The results show Gurson damage model give good results to the second specimen. Because the stress triaxiality of second specimen greater than 0.4.

Key words: aluminium alloy; double-hole test; damae; finite element method

Wear resistance of chromium carbides coating alloyed by vacaum electron beam LU Binfeng, LU Fenggui, TANG Xinhua, YAO Shun (Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiaotong University, Shanghai 200240, China). p77—80

Abstract: Fe/Cr/C powder mixtures were employed to modify the surface of a low carbon steel substrate by electron beam irradiation in vacuum condition. By optimizing the electron beam parameters, chromium carbide is in situ synthesized in the surface composite layer. The surface composite layer was analyzed with optical microscope, XRD analysis and trobological test. There are two main phases in the surface composite layer: chromium carbides as hard phase and austenite as tough phase. There are little typical hexagonal primary chromium carbides in the surface composite layer. Eutectic chromium carbides dispersively distribute between the interface of austenite phase to form a net like structure. It is metallurgical combination in the surface composite layer and the substrate. The existing of carbides in the composite layer provides a notable improvement on the wear resistant property of the surface layer.

Key words: surface composite layer; vacuum electron beam irradiation; chromium carbide; wear resistance

Offline automatic programming of arc prototype system based on arc welding robot DU Naicheng[1,2], HU Shengsun[1,2], DING Wei[1] (1. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin university, Tianjin 300072, China). p81—84

Abstract: At present, methods of graphic teaching for robot are mostly adopted in offline programming system to establish the path of robotic movement. However, for this programming of the approach complex path, the workload is still a large. Moreover, the robot procedure (JOB) is hardly formed by using the position data and welding instructions, which calculated directly by path planning. The offline automatic programming was researched for arc welding robots. The relative JOB is a data exchange interface of MOTOMAN robots. With this interface, the offline automatic programming module generates robots procedures. Through ODBC interface, offline automatic programming module queries the planning instructions and data in the corresponding database in the arc prototype system. The advantages of database are conducive to the expansion of offline programming system. The experiment results show that the researched offline programming operates stably, and the robot moves coherently, and the welding path is accordant to the design.

Key words: robot; arc prototype; offline automatic programming; relative job

Quantitative analysis method of geometrical precision quality on precision welding structure KONG Liang[1], YU Hailiang[1], JIN Xin[1], WU Yixiong[1,2] (1. School of Materials Science and Engineering, Shanghai Jiatong University, Shanghai 200030, China; 2. Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiaotong University, Shanghai 200240, China). p85—88

Abstract: Based on fussy set theory, a quantitative method for welding geometrical quality control of precision welding structure (PWS) is presented. The "Quality Differentiation Coefficient" which characterizes the relation between quality difference and effective quality essentials is adopted to formulate the qualitative linguistic variables of welding quality difference properties. The welding quality analysis model which could fully utilize experts experiments and historical data for PWS is established to quantificational analysis and decision-making.

Key words: precision welding structure; welding geometrical precision; quantification; quality analysis

Misalignment production and its prediction model in tailored blank laser welding XIN Liming[1,2], ZHAO Mingyang[1], XU Zhigang[1] (1. Shenyang Institute of Automation, Chinese Academy of Science, Shenyang 110016, China; 2. Graduate School of the Chinese Academy of Sciences, Beijing 100039, China). p89—92, 96

Abstract: Misalignment is an important quality evaluation standard in tailor welded blanks. The control of misalignment, especially for thinner blanks, is a difficult problem in tailored blank laser welding process. The production and control of misalignment is studied based on a tailored blank laser welding system. The influential factors of the misalignment are obtained after numbers of experiments: the deformation of the blanks before welding, the intensity of the clamping force, the uniformity of the clamping force, deformation of the clamping beam, flatness error of the based platform and the welding process. A mathematical model is established according to the analysis of misalignment. Experimental results indicate that the model provides an effective theorical guidance in improving welding quality.

Key words: tailored blank laser welding; misalignment; finite element analysis; misalignment prediction modeling

Interfacial structure and properties of galvanized steel sheet joined by pulsed arc brazing process LI Ruifeng, YU Zhishui, HE Jianping (College of Materials Engineering, Shanghai University