

H13 钢表面激光熔覆 NbC/Ni60 复合涂层 组织及高温耐磨损性能

常倾城¹, 任利兵¹, 刘英^{1,2*}, 谢咏馨¹, 李卫¹

(1.暨南大学 先进耐磨蚀及功能材料研究院, 广州 510632;

2.暨南大学 韶关研究院, 广东 韶关 512027)

摘要: **目的** 研究 NbC 颗粒的加入量对 H13 钢表面激光熔覆 NbC/Ni60 复合涂层的组织、硬度和耐磨性的影响。**方法** 将 Ni60 合金粉末与 NbC 碳化物粉末球磨混合, 采用激光熔覆技术, 在 H13 钢基体表面制备不同 NbC 含量 (质量分数分别为 0%、10%、20%、30%) 增强的 NbC/Ni60 合金复合涂层。采用电子扫描显微镜 (SEM)、X 射线衍射仪对复合涂层的微观组织和物相进行分析。借助显微硬度计, 研究复合涂层的截面显微硬度分布规律。采用高温摩擦磨损试验机测试复合涂层在真空 400 °C 下的摩擦磨损性能。**结果** 在激光熔覆 NbC/Ni60 复合涂层中, 物相主要由 γ -(Ni, Fe) 固溶体、Ni₂Si、CrB、Cr₂₃C₆、NbC 组成; 熔覆层以胞晶和枝晶为主, NbC 含量对复合熔覆层组织及形态具有显著影响, 加入少量 NbC 可使熔覆层组织细化; 在 NbC 的质量分数为 20% 时, 大量弥散的 NbC 颗粒在枝晶间呈聚集趋势; 在 NbC 的质量分数为 30% 时, 熔覆层中 NbC 相呈现块状、花瓣状形貌。NbC/Ni60 复合涂层的硬度显著高于 H13 钢基体, 随着 NbC 含量的增加, NbC/Ni60 复合熔覆层的显微硬度逐渐升高, NbC 的质量分数为 30% 的 NbC/Ni60 复合熔覆层的平均硬度高达 848HV。在真空 400 °C、压力 100 N、转速 100 r/min、时间 7 200 s 磨损工况下, NbC 质量分数为 20% 的 NbC/Ni60 复合涂层的磨损量最小, 因此其高温耐磨性最好。NbC 质量分数为 10% 的 NbC/Ni60 复合涂层的摩擦因数最小。随着 NbC 含量的增加, 复合涂层的摩擦因数反而升高。**结论** NbC/Ni60 复合涂层与 H13 钢基体具有很好的冶金结合, 显著提高了高温耐磨性能; NbC 颗粒硬质相具有较好的增强作用, 能够明显提高 NbC/Ni60 复合涂层的硬度和耐磨性; 粗大 NbC 相不利于复合涂层耐磨性的进一步提高。NbC/Ni60 复合涂层的磨损机制主要为磨粒磨损、疲劳剥落磨损。

关键词: 激光熔覆; NbC/Ni60 复合涂层; 微观组织; 显微硬度; 高温耐磨性能

中图分类号: TG146.4 **文献标志码:** A **文章编号:** 1001-3660(2024)05-0108-07

DOI: 10.16490/j.cnki.issn.1001-3660.2024.05.011

Microstructure and High Temperature Wear Resistance of Laser Cladding NbC/Ni60 Composite Coating on H13 Die Steel

CHANG Qingcheng¹, REN Libing¹, LIU Ying^{1,2*}, XIE Yongxin¹, LI Wei¹

(1. Institute of Advanced Wear & Corrosion Resistant and Functional Materials, Jinan University, Guangzhou 510632, China;

收稿日期: 2023-03-01; 修订日期: 2023-10-09

Received: 2023-03-01; **Revised:** 2023-10-09

基金项目: 广东省自然科学基金 (2023A1515010269)

Fund: Natural Science Foundation of Guangdong Province (2023A1515010269)

引文格式: 常倾城, 任利兵, 刘英, 等. H13 钢表面激光熔覆 NbC/Ni60 复合涂层组织及高温耐磨损性能[J]. 表面技术, 2024, 53(5): 108-114.

CHANG Qingcheng, REN Libing, LIU Ying, et al. Microstructure and High Temperature Wear Resistance of Laser Cladding NbC/Ni60 Composite Coating on H13 Die Steel[J]. Surface Technology, 2024, 53(5): 108-114.

*通信作者 (Corresponding author)

2. Research Institute of Shaoguan, Jinan University, Guangdong Shaoguan 512027, China)

ABSTRACT: Composite coatings on H13 steel are fabricated with NbC and Ni60 mixture powders by laser cladding to improve the wear resistance of matrix materials. In this study, the effect of NbC content on microstructure, hardness and high temperature tribological behavior of the coatings was investigated. The NbC particles reinforced Ni60 alloy composite coating with different NbC contents (0%, 10%, 20%, 30%) was fabricated by laser cladding with a pulsed Nd-YAG laser of a wavelength of 1 064 nm and a beam diameter of 1 mm under argon shielding gas, and with the Ni60 and NbC mixed powders by ball-milling method and H13 die steel as the substrate. The microstructure and phases were analyzed with a scanning electron microscope (SEM) and X-ray diffraction (XRD). The section micro-hardness distribution of composite coatings were studied with a micro-hardness tester. The friction and wear properties of the composite coatings were carried out on a high temperature friction wear tester at 400 °C in a vacuum environment. The Ni60 laser cladding layer was mainly composed of γ -(Ni,Fe) solid solution, Ni₂Si, Fe₃C, CrB and Cr₂₃C₆. With the addition of NbC, a new hard-phase NbC was introduced in NbC/Ni60 laser cladding coatings and the microstructure was modified. The cladding layer was dominated by columnar crystals and dendritic structure, in which the dendrite spacing became smaller and the grain size was refined. During laser processing, the added NbC melts, and decomposes, and subsequently, a number of fine NbC precipitates formed and grew up during the solidification. NbC phases evolved and existed as particles, flakes, blocks or snowflakes distributed some uniformly in the coating. The amount of NbC addition had a strong influence on the morphology and size of NbC particles. When the mass fraction of NbC was above 20%, the dispersed NbC particles became aggregated between the dendrites. When the mass fraction of NbC was 30%, much grown and bigger block-shaped NbC, snowflake-shaped NbC was generated in the cladding layer. It was observed that the microhardness of NbC/Ni60 composite coatings were significantly higher than that of the H13 matrix, which increased with the increase of NbC content from 635HV to 848HV when 30% NbC was added. The NbC/Ni60 coating containing 20% NbC had the smallest wear mass loss, namely the the best wear resistance under the wear conditions of load 100 N, speed 100 r/min and time 7 200 s at 400 °C in vacuum. The NbC/Ni60 coating containing 10% NbC had the lowest friction coefficient and the more NbC addition reversedly improved friction coefficient. The NbC/Ni60 coating can be metallurgically bonded to the substrate and increase its wear resistance greatly. The NbC works as a hard enhanced phase and increases the hardness and wear resistance of the composite coatings, but the coarse NbC phase is not conducive to further improvement of wear resistance. The main wear mechanisms of H13 steel are adhesive wear and abrasion wear. Moreover, the dominant wear mechanisms of the NbC/Ni60 composite coatings are abrasion wear and fatigue spalling wear.

KEY WORDS: laser cladding; NbC/Ni60 composite coating; microstructure; microhardness; high temperature wear resistance

H13 钢 (4Cr5MoSiV1) 是一种具有高淬透性、高韧性、较高高温强度、较高热硬度的热作模具钢, 其服役温度可接近 600 °C, 常用于热锻模、热挤压模和压铸模等^[1]。在中高温下, 热作模具型腔表面易发生磨损和热疲劳等现象, 还会受到冲蚀、应力腐蚀的影响, 从而降低模具寿命, 或导致模具失效。通过表面工程技术可改变模具钢的表面化学成分、相组成和微观组织, 可以提高模具的表面硬度、强度等, 增加模具抵抗磨损、变形和热疲劳的能力, 从而有效提高模具的使用寿命^[2]。相较于碳氮共渗 (化学热处理)、感应加热淬火 (表面热处理)、热喷涂等传统的表面改性技术, 激光熔覆技术利用高能激光束快速熔化表层合金及粉末, 凝固时的冷却速度快 ($10^2 \sim 10^6$ °C/s), 制备的涂层具有过饱和固溶体、超细晶组织及亚稳定相组织, 以及高强度、高硬度、优良的耐磨耐腐蚀性能, 而且与基体之间为冶金结合, 具有厚度较大、组织致密、变形小、加工灵活性好等特点^[3-5], 因此在汽车

模具、航空、电子机械等领域得到广泛应用^[6-7]。模具钢的表面强化激光熔覆涂层常采用硬度高、耐磨性好和抗高温氧化性好的 Ni 基自熔性合金^[8-11], 通过在 Ni 基合金粉末中加入 WC^[12-14]、TiC^[15-16]、NbC^[17-19] 等高硬度陶瓷粉, 获得复合粉末, 再制备金属基陶瓷复合熔覆涂层, 进一步提高其硬度、耐磨性等, 这已成为模具表面强化研究的热点之一。通过 Nb 合金化可以细化晶粒, 改善金属组织, 从而提高其性能^[17-18]。NbC 具有高熔点 (3 600 °C)、高硬度 (2 400HV)、良好化学稳定性、良好的耐磨损性等, 其密度 (7.79 g/cm^3) 与激光熔覆用镍基、铁基合金及其基体的密度非常接近, 是一种很好的增强相^[19-24]。文中采用 YGA 脉冲激光器, 以不同 NbC 含量的 Ni60+NbC 复合粉末为激光熔覆粉末, 在 H13 热作模具钢表面制备高硬度的 NbC/Ni 基合金复合涂层, 研究 NbC/Ni60 复合材料熔覆层的微观组织、显微硬度及高温耐磨损性能。

1 实验

基材为 H13 钢 (4Gr5MoSiV1), 其线切割尺寸为 50 mm×40 mm×20 mm, 化学成分如表 1 所示, 组织为回火托氏体及碳化物。采用 400~1200 号砂纸依次打磨、清洗、烘干基材表面。熔覆层粉末采用 NbC+Ni60 的混合粉末。其中, NbC 粉末的粒径为 1~3 μm。Ni60 粉末的主要化学成分见表 1, 其粒径为 50~150 μm。在实验时, 将 NbC 粉末分别以质量分数 0%、10%、20%、30%的配比掺入 Ni60 合金粉末中, 采用球磨机进行球磨混粉, 转速为 200 r/min, 球料比为 5 : 1, 球磨时间为 6 h, 经球磨后得到了相对均匀、形状不规则的混合粉末。在激光熔覆前, 在 H13 钢基体表面用有机黏合剂混涂预置混合粉末, 预置层厚度约为 300~400 μm, 经预热处理 (在 200 °C 下烘干) 后备用。通过对激光熔覆样品进行加热 (保温) 处理, 以减少可能因急冷、急热产生的裂纹。

激光熔覆采用 JHM-1GXY-700B 型 Nd:YAG 固体工业激光设备, 数控系统为 PA8000NT CNC, YAG 激光器激光波长为 1.06 μm, 激光熔覆原理和涂层样品示意图如图 1 所示。激光熔覆工艺的参数: 激光电流为 250 A, 频率为 20 Hz, 脉宽为 2.5 ms, 光斑直径为 1 mm, 扫描速度为 100 mm/min。在实验过程中, 保护气体使用氩气, 流速为 10 L/min。采用 Phenom XL 台式扫描电镜观察分析熔覆层的组织及表面形貌, 采用 MiniFlex 600 型 X 射线物相衍射仪 (Cu 靶, 管电压为 40 kV, 管电流为 15 mA, 扫描范围为 25°~100°, 扫描速度为 4 (°)/min) 分析物相。采用 HXD-1000TM 型显微硬度计 (加载载荷为 0.49 N, 加载时间为 20 s) 测试显微硬度。采用 MG-2000 型高速高温摩擦磨损试验机, 在高温 400 °C 下对不同试样进行磨损特性测试, 摩擦磨损示意图如图 2 所示。设置磨损工况: 真空度低于 1 mPa, 加载压力为 100 N, 转速为 100 r/min, 时间为 7 200 s, 磨损行程为 138 m; 磨损试样尺寸为 φ4 mm×15 mm, 对磨片为淬火回火 45[#]钢。

表 1 基材 H13 钢和 Ni60 粉末的化学成分
Tab.1 Chemical composition of H13 steel matrix and Ni60 powder

Chemical composition	Mass fraction/%									
	C	Si	Mn	Cr	V	Mo	Fe	Cu	B	Ni
H13	0.41	1.10	0.31	4.95	1.15	1.21	Bal.			
Ni60	0.5-1.0	3.5-5.0		14-19		2-4	8.0	2-4	3.0-4.5	Bal.

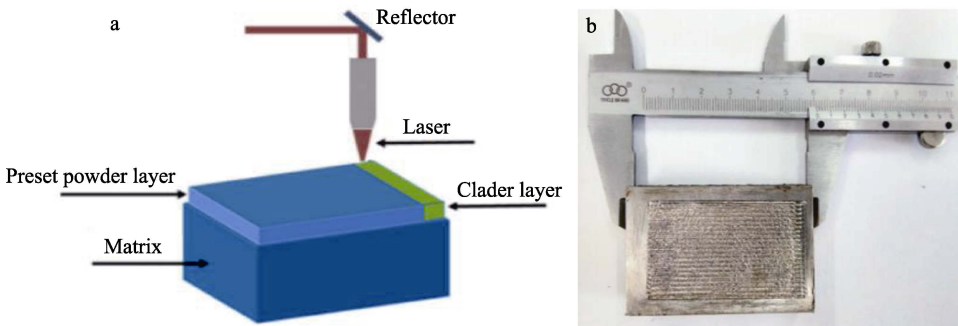


图 1 激光熔覆原理 (a) 及涂层样品 (b)
Fig.1 Schematic diagram of laser cladding principle (a) and coating sample (b)

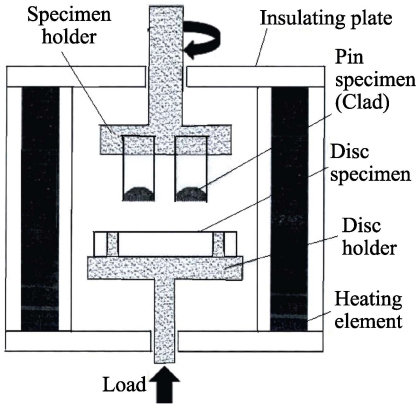


图 2 摩擦磨损示意图
Fig.2 Schematic diagram of friction and wear

2 结果与分析

2.1 激光熔覆层的物相分析

将 NbC 质量分数分别为 10%、20%、30%的 NbC/Ni60 复合熔覆层分别记为 10%NbC/Ni60、20%NbC/Ni60、30%NbC/Ni60, 其 X 射线衍射图谱如图 3 所示。由图 3 可知, Ni60 熔覆层主要含有 γ-(Ni, Fe)固溶体、Ni₂Si、Fe₃C、Cr₂₃C₆、CrB; 加入 NbC 后, 熔覆层中增加了 NbC 相, NbC/Ni60 复合熔覆层的物相主要由 γ-(Ni, Fe)固溶体、Ni₂Si、Fe₃C、Cr₂₃C₆、CrB、NbC 组成; 在熔覆层中, Ni 与 Fe 形成了 γ-(Ni, Fe)固

溶体, 在激光作用下涂层元素间发生了冶金化学反应, 形成了 Ni_2Si 、 Fe_3C 、 Cr_7C_3 为快速凝固后的介稳相, NbC 为外加的硬质相。在激光熔覆后, 涂层表面多种硬质相 (如碳化物) 的均匀分布将有益于提高复合熔覆层的硬度和耐磨性。

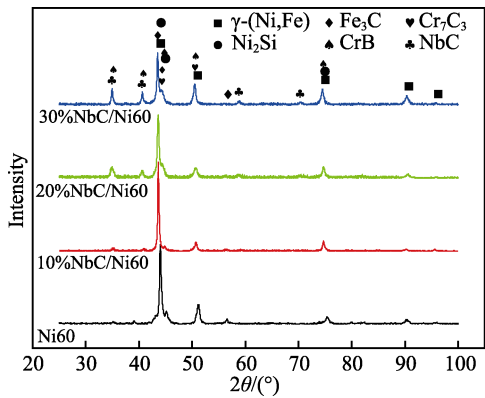


图 3 激光熔覆涂层的 X 射线衍射图谱
Fig.3 X-ray diffraction patterns of laser cladding layers

2.2 激光熔覆层的显微组织

不同 NbC 含量的 NbC/Ni60 复合熔覆层 2 种区域的截面组织形貌如图 4 所示。由图 4 可知, NbC/Ni60 复合熔覆层的厚度约为 250~300 μm , 与基体具有良好的冶金结合界面。Ni60 熔覆层主要为快速凝固形成的细小枝晶组织, 枝晶间距为 2~5 μm 。加入少量 NbC (10%) 后, NbC/Ni60 复合熔覆层组织细化, 枝晶间距为 1~3 μm 。在 10%NbC/Ni60 复合熔覆层中, NbC 颗粒粒径为 0.5~3 μm 。随着 NbC 含量的增加,

NbC 的质量分数为 20%、30% 时, 复合熔覆层主要呈块片状、颗粒状、花瓣状、星状等形貌。NbC 颗粒逐渐出现聚集长大的现象, 有的片状尺寸长达 6 μm 。由区域能谱分析 (见表 2) 结果可知, 枝晶含有大量 Ni、Fe、Cr 元素, 属于 γ -(Ni,Fe) 型固溶体, 枝晶间 Ni、Fe 的含量下降, 且 Cr、Si 等元素含量显著增加, 发生了 Ni_2Si 、 Fe_3C 、 Cr_{23}C_6 等相的聚集。在加入 NbC 后, 枝晶内 (C 点) 存在 Nb 元素。在 NbC 相中也存在其他元素 (如 Ni、Si、Cr、Fe、B 等), 原因是凝固时部分 NbC 相长大, Ni_2Si 、 Cr_{23}C_6 等相在 NbC 表面析出或聚集。分析 NbC/Ni60 激光熔覆层的组织细化原因, 一方面在激光熔覆过程中部分 NbC 在熔池中发生溶解、分解, 释放出 Nb、C 元素, 出现成分波动或成分过冷等现象, 可抑制晶核的长大; 另一方面, NbC 作为异质结晶核心, 起到了细化作用。随着 NbC 含量的增加, 大量未熔化的 NbC 弥散白色小颗粒也阻碍了枝晶的长大。

2.3 激光熔覆层的显微硬度

不同 NbC 含量对 NbC/Ni60 熔覆层截面显微硬度的影响如图 5 所示。由图 5 可知, 熔覆层的显微硬度远大于淬火回火 H13 钢的显微硬度; 在加入 NbC 后, 熔覆层表面的显微硬度随着 NbC 含量的增加而提高, NbC 的质量分数为 0%、10%、20%、30% 时 NbC/Ni60 复合熔覆层的平均硬度分别为 635HV、690HV、753HV、848HV。激光熔覆层经过快速熔化和凝固, 枝晶组织得到显著细化。NbC 的加入使得复合熔覆层的硬度提升, 一方面是因 NbC 的加入导致枝晶晶粒

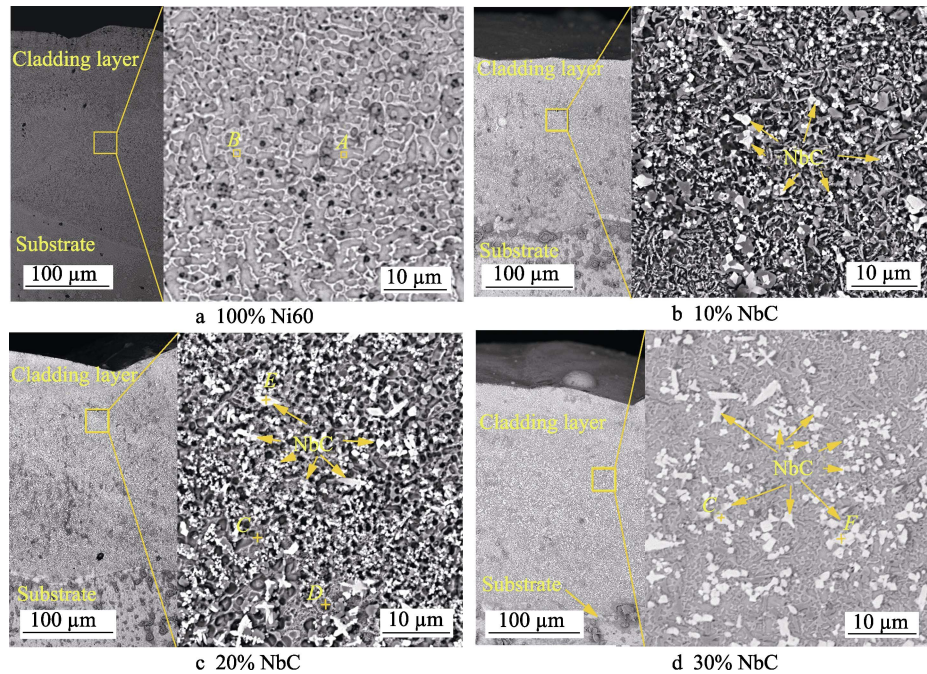


图 4 NbC/Ni60 熔覆层微观组织
Fig.4 Microstructure of NbC/Ni60 cladding layers

表 2 熔覆层部分区域组织能谱分析
Tab.2 EDS results of different regions in cladding layers

EDS	Atomic percentage/%						
	Ni	Fe	Cr	Si	Nb	C	B
A (area)	50.36	32.05	10.32	4.27		3.00	
B (area)	33.82	37.75	11.56	4.92		10.01	1.94
C (point)	41.92	36.35	11.61	3.55		6.57	
D (point)	24.98	35.27	19.49	1.85	1.76	11.41	5.24
E (point)	2.99	6.75	1.84		51.22	37.16	2.04
F (point)	4.24	1.77	7.33	2.09	52.59	31.98	
G (point)	0.89	9.38	1.39	2.73	50.48	35.13	

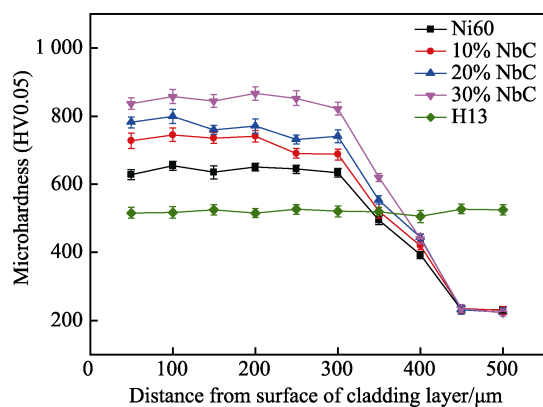


图 5 熔覆层横截面显微硬度分布
Fig.5 Cross-sectional microhardness distribution of cladding layers

变得细小,其他金属间化合物(如碳化物等)得到细化,发挥了细化晶粒的作用;NbC在熔池中发生分解,部分Nb、C元素固溶到基体组织中,起到了固溶强化的作用;NbC颗粒的硬度(2400HV)极高,在激光熔覆时熔化后重新析出或长大,具有较高的第二相强化作用,NbC弥散分布在熔覆层内部,产生了较好的增强效果。熔覆层的显微硬度随着与表面距离的增加而逐渐减小,熔覆层的硬度在通过熔覆层与基体界面的结合区(距离表面300~400 μm)后明显降低。

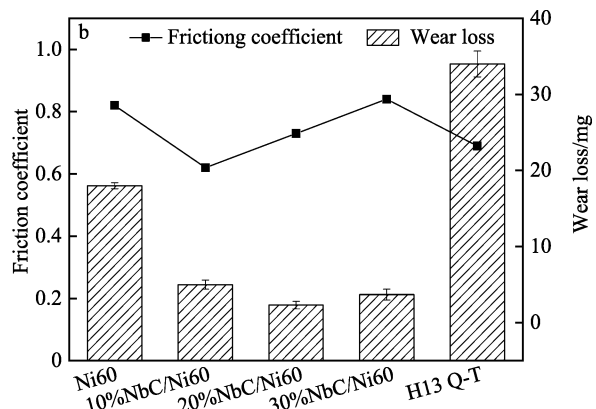
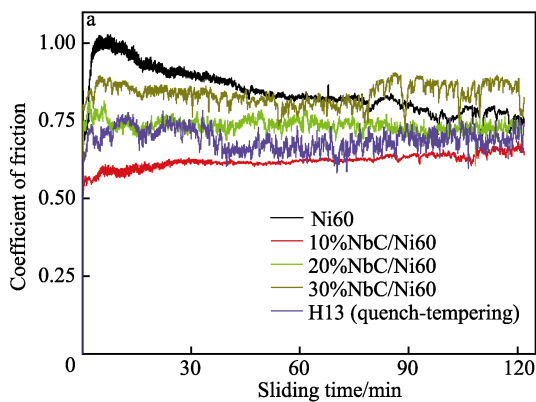


图 6 在温度 400 °C 下不同成分熔覆层的摩擦因数 (a) 及平均摩擦因数、磨损量 (b)

Fig.6 Friction coefficient (a), average friction coefficient and wear loss (b) of cladding layers of different components at 400 °C

2.4 激光熔覆层的摩擦磨损性能

不同NbC含量的NbC/Ni60复合熔覆层在400 °C下实验时,其摩擦因数-时间曲线及磨损量结果如图6所示。由图6a可见,在磨损实验过程中,熔覆层的摩擦因数随着时间的延长有所波动,但总体较稳定;Ni60熔覆层的摩擦因数较高,平均摩擦因数为0.82;10%NbC/Ni60复合熔覆层的摩擦因数最小,平均摩擦因数为0.69;初始时加入NbC具有降低摩擦因数的效果,随着NbC含量的增加,摩擦因数有所增加。由图6b可知,Ni60熔覆层的磨损量仅为18 mg,显著低于基体热处理(淬火回火)硬化的H13钢的磨损量(34 mg);当加入质量分数为10%、20%、30%的NbC时,熔覆层的平均磨损量分别为5、2.3、3.7 mg。通过激光熔覆显著提高了H13钢的耐磨性能,在熔覆层Ni60中加入NbC明显降低了其磨损量,提高了耐磨性。随着NbC含量的增加,熔覆层的磨损量呈先减小后增大的趋势;当NbC的质量分数为20%时,磨损量最小,耐磨性较佳。NbC的加入有利于细晶强化、固溶强化、第二相强化,从而进一步提高了硬度、耐磨性。当NbC的质量分数为30%时,熔覆层的平均硬度最高,不过其磨损量反而升高,耐磨性下降,原因是在熔覆层中NbC颗粒粗大容易产生大的内应力,导致表面脆性过高。

在400 °C下进行摩擦磨损实验,不同NbC含量(0%、10%、20%、30%)的NbC/Ni60熔覆层的磨损表面形貌如图7所示,磨损表面局部区域的能谱分析如表3所示。由图7可知,对磨片淬火回火45#钢表面磨损严重,有大量剥层脱落,并出现凹坑区域。由于硬度较低,容易出现塑性变形和黏着磨损,黏着部分被撕裂,其磨损机制主要为黏着磨损。热处理(淬火回火)H13钢试样表面有较深的磨损犁沟,出现明显的剥层脱落凹坑区域,耐磨性能较差,其磨损机制主要为磨粒磨损和黏着磨损。Ni60熔覆层表面磨损程度较低,出现较浅的划痕痕迹和少量剥层脱落。NbC/Ni60熔覆层表面划痕变得更浅、更细,NbC/Ni60

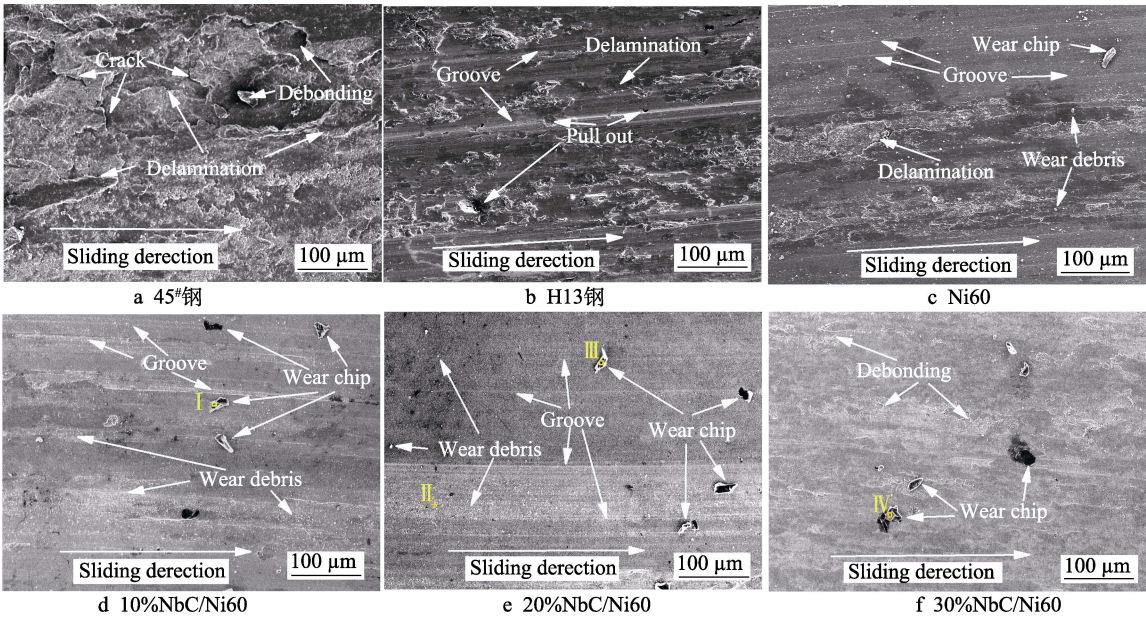


图 7 400 °C 下熔覆层的磨损形貌
Fig.7 Worn surface morphology of cladding layers at 400 °C: a) 45# steel; b) H13 steel;
c) Ni60; d) 10%NbC/Ni60; e) 20% NbC/Ni60; f) 30%NbC/Ni60

表 3 磨损表面局部区域能谱分析
Tab.3 EDS results of different worn surface regions

EDS	Atomic percentage/%								
	O	Fe	Cr	Ni	Si	Nb	C	Mo	B
I (area)	58.53	39.30	2.17						
II (point)	10.11	5.24	8.25	2.07	35.41	19.81	4.96	14.14	
III (area)	50.47	41.56	3.19	3.02	1.23	0.53			
IV (area)	46.42	41.71	3.02	2.22	1.51	1.67	2.92	0.53	

熔覆层表面有片状磨屑（Ⅰ、Ⅲ、Ⅳ），其主要成分为 O、Fe、Cr，主要是对磨片的黏着磨损脱离产物。由于 NbC 的硬度较高，通过添加 NbC 提高了熔覆层的抗变形能力，磨损表面微切削作用减弱，仅留下磨粒磨损产生的犁沟，且随着 NbC 含量的增加，犁沟形划痕越来越少、越来越浅，表面趋于光滑。20%NbC/Ni60 熔覆层表面存在细小磨粒，从能谱分析（Ⅱ）可见，富含 Nb、C，表明在磨损过程中有 NbC 脱落。该磨损机制主要为磨粒磨损，也呈从二体模式转变为三体磨损的趋势，添加 NbC 在一定程度上避免了熔覆层受到更严重的磨损，起到了一定的减磨、抗磨作用。在 NbC 的质量分数为 30%时，熔覆层表面出现一些剥层剥落痕迹。这主要是因 30%NbC/Ni60 熔覆层表面的 NbC 颗粒粗化，容易变脆，在周期反复切应力的作用下易发生应力集中，从而萌生裂纹，发生了表面剥落疲劳磨损。

3 结论

1) 激光熔覆 NbC/Ni60 复合涂层的物相主要由 γ -(Ni, Fe)固溶体、 Ni_2Si 、 Fe_3C 、 Cr_{23}C_6 、CrB、NbC

组成。NbC 的加入明显细化了熔覆层的显微组织，在 NbC 的含量较高时，NbC 逐渐出现聚集长大现象，主要表现为块片状、颗粒状、花瓣状、星状等形貌。

2) 激光熔覆 NbC/Ni60 复合涂层的硬度显著高于 H13 钢基材的硬度。熔覆层的显微硬度随着 NbC 含量的增加而提高，30%NbC/Ni60 复合熔覆层的平均硬度最高。

3) 在真空 400 °C、压力 100 N、转速 100 r/min、时间 7 200 s 的摩擦磨损工况下，适量加入 NbC 具有降低摩擦因数的效果，10%NbC/Ni60 复合熔覆层的摩擦因数最小；20%NbC/Ni60 复合涂层的高温耐磨性最佳。NbC/Ni60 复合涂层具有优良的耐磨性，加入 NbC 可明显降低熔覆层的磨损率，尽管过多及粗大的 NbC 颗粒使其硬度增加，但其磨损率反而有所降低。H13 钢的主要磨损机制为磨粒磨损和黏着磨损，NbC/Ni60 复合熔覆层的主要磨损机制表现为磨粒磨损、疲劳剥落。

参考文献:

[1] KHEIRANDISH S, NOORIAN A. Effect of Niobium on Microstructure of Cast AISI H13 Hot Work Tool Steel[J]. Journal of Iron and Steel Research, International, 2008, 15(4): 61-66.

[2] RODRÍGUEZ-BARACALDO R, BENITO J A, PUCHI-CABRERA E S, et al. High Temperature Wear Resistance of (TiAl)N PVD Coating on Untreated and Gas Nitrided AISI H13 Steel with Different Heat Treatments[J]. Wear, 2007, 262(3/4): 380-389.

[3] LU J Z, XUE K N, LU H F, et al. Laser Shock Wave-

- Induced Wear Property Improvement and Formation Mechanism of Laser Cladding Ni25 Coating on H13 Tool Steel[J]. *Journal of Materials Processing Technology*, 2021, 296: 117202.
- [4] FARNIA A, MALEK GHAINI F, OCELÍK V, et al. Microstructural Characterization of Co-Based Coating Deposited by Low Power Pulse Laser Cladding[J]. *Journal of Materials Science*, 2013, 48(6): 2714-2723.
- [5] DINDA G P, DASGUPTA A K, MAZUMDER J. Laser Aided Direct Metal Deposition of Inconel 625 Superalloy: Microstructural Evolution and Thermal Stability[J]. *Materials Science and Engineering: A*, 2009, 509(1/2): 98-104.
- [6] WANG K M, CHANG B H, CHEN J S, et al. Effect of Molybdenum on the Microstructures and Properties of Stainless Steel Coatings by Laser Cladding[J]. *Applied Sciences*, 2017, 7(10): 1065.
- [7] DUTTA MAJUMDAR J, PINKERTON A, LIU Z, et al. Mechanical and Electrochemical Properties of Multiple-Layer Diode Laser Cladding of 316L Stainless Steel[J]. *Applied Surface Science*, 2005, 247(1/2/3/4): 373-377.
- [8] HEMMATI I, OCELÍK V, DE HOSSON J T M. Effects of the Alloy Composition on Phase Constitution and Properties of Laser Deposited Ni-Cr-B-Si Coatings[J]. *Physics Procedia*, 2013, 41: 302-311.
- [9] 孙荣禄, 牛伟, 雷贻文, 等. 钛合金表面激光熔覆 TiB₂-TiC/Ni 复合涂层的真空摩擦磨损性能[J]. *材料热处理学报*, 2012, 33(5): 131-135.
- SUN R L, NIU W, LEI Y W, et al. Tribological Properties in Vacuum of TiB₂-TiC/Ni Laser Clad Layer on Titanium Alloy Substrate[J]. *Transactions of Materials and Heat Treatment*, 2012, 33(5): 131-135.
- [10] HE X M, LIU X B, WANG M D, et al. Elevated Temperature Dry Sliding Wear Behavior of Nickel-Based Composite Coating on Austenitic Stainless Steel Deposited by a Novel Central Hollow Laser Cladding[J]. *Applied Surface Science*, 2011, 258(1): 535-541.
- [11] WANG L Q, ZHOU J S, YU Y J, et al. Effect of Powders Refinement on the Tribological Behavior of Ni-Based Composite Coatings by Laser Cladding[J]. *Applied Surface Science*, 2012, 258(17): 6697-6704.
- [12] DESCHUYTENEER D, PETIT F, GONON M, et al. Processing and Characterization of Laser Clad NiCrBSi/WC Composite Coatings-Influence of Microstructure on Hardness and Wear[J]. *Surface and Coatings Technology*, 2015, 283: 162-171.
- [13] BARTKOWSKI D, KINAL G. Microstructure and Wear Resistance of Stellite-6/WC MMC Coatings Produced by Laser Cladding Using Yb:YAG Disk Laser[J]. *International Journal of Refractory Metals and Hard Materials*, 2016, 58: 157-164.
- [14] MA Q S, LI Y J, WANG J, et al. Investigation on Cored-Eutectic Structure in Ni60/WC Composite Coatings Fabricated by Wide-Band Laser Cladding[J]. *Journal of Alloys and Compounds*, 2015, 645: 151-157.
- [15] 赵雪阳, 刘英, 夏一龙, 等. H13 钢激光熔覆 TiC/Ni 合金复合涂层的组织与耐磨性[J]. *材料热处理学报*, 2016, 37(4): 190-196.
- ZHAO X Y, LIU Y, XIA Y L, et al. Microstructure and Wear Resistance of TiC/Ni Based Alloy Composite Coatings on H13 Steel by Laser Cladding[J]. *Transactions of Materials and Heat Treatment*, 2016, 37(4): 190-196.
- [16] CHEN L Y, YU T B, CHEN X, et al. Process Optimization, Microstructure and Microhardness of Coaxial Laser Cladding TiC Reinforced Ni-Based Composite Coatings[J]. *Optics & Laser Technology*, 2022, 152: 108129.
- [17] HU H J, XU G, WANG L, et al. The Effects of Nb and Mo Addition on Transformation and Properties in Low Carbon Bainitic Steels[J]. *Materials & Design*, 2015, 84: 95-99.
- [18] SUN S T, FU H G, PING X L, et al. Reinforcing Behavior and Microstructure Evolution of NbC in Laser Cladded Ni45 Coating[J]. *Applied Surface Science*, 2018, 455: 160-170.
- [19] FERNANDES M R P, MARTINELLI A E, KLEIN A N, et al. Production of Nickel Matrix Composites Reinforced with Carbide Particles by Granulation of Fine Powders and Mechanical Pressing[J]. *Powder Technology*, 2017, 305: 673-678.
- [20] ZHONG L S, XU Y H, YE F X. In Situ NbC Particulate-Reinforced Iron Matrix Composite: Microstructure and Abrasive Wear Characteristics[J]. *Tribology Letters*, 2012, 47(2): 253-259.
- [21] HUANG S G, LIU R L, LI L, et al. NbC as Grain Growth Inhibitor and Carbide in WC-Co Hardmetals[J]. *International Journal of Refractory Metals and Hard Materials*, 2008, 26(5): 389-395.
- [22] LI Q T, LEI Y P, FU H G. Laser Cladding In-Situ NbC Particle Reinforced Fe-Based Composite Coatings with Rare Earth Oxide Addition[J]. *Surface and Coatings Technology*, 2014, 239: 102-107.
- [23] CAO Y B, REN H T, HU C S, et al. In-Situ Formation Behavior of NBC-Reinforced Fe-Based Laser Cladding Coatings[J]. *Materials Letters*, 2015, 147: 61-63.
- [24] GAO W L, LENG Y, FU D F, et al. Effects of Niobium and Heat Treatment on Microstructure and Mechanical Properties of Low Carbon Cast Steels[J]. *Materials & Design*, 2016, 105: 114-123.