南京航空航天大學

论 文 集

（二〇〇六年）第25册

材料科学与技术学院

（第1分册）

南京航空航天大學科技部編

二〇〇七年三月

材料科学与技术学院

上

材料科学与技术学院

061 系

062 系

063 系

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
1	徐 江 刘文今 钟敏霖	副教授 教 授 教 授	061 外单位 外单位	Microstructure and dry sliding wear behavior of MoS2/TiC/Ni composite coatings prepared by laser cladding	Surface & Coatings Technology	2006.200 4227-4232	
2	徐 江 刘文今	副教授 教 授	061 外单位	Wear characteristic of in situ synthetic TiB2 particulate-reinforced Al matrix composite formed by laser cladding	Wear	2006.260 -486-492	
3	徐 江 刘文今 阚义德 钟敏霖	副教授 教 授 博 士 教 授	061 外单位 外单位 外单位	Microstructure and wear properties of laser cladding Ti–Al–Fe–B coatings on AA2024 aluminum alloy	Materials and Design	2006.27. 405-410	
4	徐 江 李正阳 朱文慧 刘子利 刘文今	副教授 博士后 硕 士 副教授 教 授	061 外单位 061 061 外单位	The comparative study of thermal fatigue behavior of laser deep penetration spot cladding coating and brush plating Ni–W–Co coating	Applied Surface Science	2006.253 2618-2624	
5	刘子利, 潘青林 陈照峰 刘希琴 陶 杰	副教授 教 授 副教授 副教授 教 授	061 外单位 061 061 061	Heat transfer characteristics of lost foam casting process of magnesium alloy	TRANSACTIONS OFNONFERROUS METALS OCIETY OF CHINA	2006.2.28	
6	刘子利, 潘青林 陈照峰 刘希琴 陶 杰	副教授 教 授 副教授 副教授 教 授	061 外单位 061 061 061	INVESTIGATION OF FOAM-METAL INTERFACE BEHAVIORS DURING MOLD FILLING OF MAGNESIUM ALLOY LFC PROCESS	Transactions of Nanjing University of Aeronautics & Astronautics	2006.3.22	
7	刘子利, 潘青林 陶 杰 崔益华	副教授 教 授 副 授 副教授	061 外单位 061 062	消失模铸造技术的现状与发展	铸造工程	2006.10.22	
8	刘子利	副教授	061	消失模铸造技术新进展-第七届中国消失模铸造学术年会概述	铸造	2006.11.11	

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
9	刘子利	副教授	061	Recent Development of Lost Foam Casting Technology	China Foundry	2006.11.11	
10	刘子利, 陈照峰 刘希琴 陶 杰	副教授 副教授 副教授 教 授	061 061 061 061	Sb 合金化对 AE41 镁合金耐热性能的影响	材料科研究学报	2006.3.22	
11	郭华明 刘子利 刘新波	研究生 副教授 研究生	061 061 061	Y 含量对 Mg-Zn-Y 合金组织和性能的影响	特种铸造及有色合金	2006.10.15	
12	徐 杰 刘子利 沈以赴 刘仕福	研究生 副教授 副教授 研究生	061 061 061 061	镁合金焊接的研究与发展	宇航材料工艺	2006.1.18	
13	徐 杰 刘子利 沈以赴	研究生 副教授 副教授	061 061 061	AZ31 镁合金扩散焊接实验	金陵科技学院学报	2006.22.1	
14	刘子利 温建萍 孔垂谦 张平则	副教授 副教授 副教授 副教授	061 061 061	基于工程创新能力的“工程材料及机械制造基础”课程体系平台的建设与实践	南京航空航天大学学报（高教研究版）	2006.8.2	
15	向定汉 单昆仑	教 授 硕 士	061 061	Friction and wear behaviour of self-lubricating and heavily loaded metal-PTFE composites	Wear	2006.5.	
16	向定汉 顾传锦	教 授 硕 士	061 061	A study on the friction and wear behavior of PTFE filled with ultra-fine kaolin particulates	Materials Letters	2006.3.	
17	向定汉 陶克梅	教 授 硕 士	061 061	The mechanical and tribological properties of PTFE filled with PTFE waste powders	Journal of Applied Polymer Science	2007.1.	
18	陶克梅 向定汉	硕 士 教 授	061 061	PTFE、石墨与玻纤填充聚甲醛的摩擦磨损特性	润滑与密封	2006.9.	
19	单昆仑 向定汉	硕 士 教 授	061 061	短玻璃纤维和石墨填充 PTFE 的摩擦磨损特性研究	润滑与密封	2006.5.	
20	曾 敏 向定汉	硕 士 教 授	061 061	再生 PTFE 粉末填充聚甲醛复合材料的摩擦磨损特性研究	润滑与密封	2006.1.	
21	吴光英 王 蕾	副 高 副 高	061	等温淬火球铁等温转变过程及连续生产线	第四届全国等温淬火球铁技术研讨会论文集	2006．12	
22	王 蕾 吴光英	副 高 副 高	061 外单位	脉冲工艺参数对气体氮碳共渗层深的影响	金属热处理	2006.31.3	

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
23	李玉芳 郭建亭 沈以赴	讲 师 研究员 副教授	061 外单位 061	Infleence of recrystallization and environment on tensile behavior of cold-rolled Ni3Al (Zr) alloys	TRANSACTIONS OF NONFERROUS METALS OCIETY OF CHINA	2006. 16.2	
24	冯晓梅 刘广耀 黄清镇 饶光辉	副教授 研究员 研究员 研究员	061 外单位 外单位 外单位	Influence of annealing treatment on structural and magnetic properties of double perovskite Sr2FeMoO6	TRANSACTIONS OF NONFERROUS METALS OCIETY OF CHINA	2006. 16	
25	冯晓梅 刘广耀	副教授 研究员	061 外单位	双层钙钛矿(Sr2-xBax)FeMoO6 的结构和电磁性能研究	南京航空航天大学学报	2005.37.5	
26	傅仁利 陈克新 S.Agathopoulos J. Ferreira	正 高 正 高 正 高 正 高	061 外单位 外单位 外单位	Factors which affect the morphology of AlN particles made by self-propagating high-temperature synthesis (SHS)	Journal of Crystal Growth	2006.296:97-103	
27	傅仁利	正 高	061	陶瓷颗粒(纤维)增强聚合物复合电子封装与基板材料	世界科技研究与发展	2006.28.1:	
28	韩艳春 傅仁利 何 洪 沈 源 宋秀峰	硕 士 正 高 硕 士 硕 士 硕 士	061 061 061 061 061	一类新型高导热环氧模塑料的制备	电子元件与材料	2006.25.12:	
29	韩艳春 杨克涛 何 洪 宋秀峰 沈 源 傅仁利	硕 士 硕 士 硕 士 硕 士 硕 士 正 高	061 061 061 061 061 061	金属铝基板表面微弧氧化绝缘化处理与介电性能	2006 年 第九届江苏省热处理年会会议	2006.5 357-360	
30	宋秀峰 韩艳春 何 洪 沈 源	硕 士 硕 士 硕 士 硕 士	061 061 061 061	磁控溅射法制备 AlN 薄膜的研究进展	山东陶瓷	2006.29.6:	
31	杨克涛 傅仁利	硕 士 正 高	061 061	绝缘金属铝基板的制备及介电性能研究	山东陶瓷	2006.29.6:	

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
32	王月勤 秦 亮 陶 杰	硕 士 硕 士 教 授	061 061 061	二氧化钛纳米管的制备方法	2006中国江苏国际先进复合材料技术发展研讨会	2006 71-75	
33	潘 峰 陶 杰 张炎炎	硕 士 教 授 硕 士	061 061 061	RDP接枝NP及阻燃消烟ABS制备	2006中国江苏国际先进复合材料技术发展研讨会	2006 177-180	
34	周叶青 鲍天民 崔益华 陶 杰	硕 士 学 士 副教授 教 授	061 061 061 061	再生胶粉及玻璃纤维改性WPC的研究	2006中国江苏国际先进复合材料技术发展研讨会	2006 238-244	
35	董 祥 陶 杰 崔益华 汪 涛	博 士 教 授 副教授 教 授	061 061 061 061	原位聚合纳米ZnO/PET复合材料的结晶行为研究	2006中国江苏国际先进复合材料技术发展研讨会	2006 355-358	
36	周叶青 刘洪博 崔益华 陶 杰	硕 士 学 士 副教授 教 授	061 061 061 061	再生型木塑复合材料的界面设计	2006中国江苏国际先进复合材料技术发展研讨会	2006 245-250	
37	李之琦 石求斌 崔益华 陶 杰	硕 士 学 士 副教授 教 授	061 061 061 061	纳米ZnO/玻璃纤维/PP复合材料制备及性能研究	2006中国江苏国际先进复合材料技术发展研讨会	2006 210-215	
38	张新烨 崔益华 郭 萍	硕 士 副教授 学 士	061 061 061	纳米ZnO/环氧复合材料的制备及性能研究	2006中国江苏国际先进复合材料技术发展研讨会	2006 216-220	
39	曾志海 崔益华 朱晓婷 周叶青	硕 士 副教授 学 士 硕 士	061 061 061 061	纳米ZnO增强再生型木塑复合材料的研究	2006中国江苏国际先进复合材料技术发展研讨会	2006 221-225	
40	张 凤 陶 杰 崔益华	硕 士 教 授 副教授	061 061 061	聚合物/纳米复合材料进展及前景展望	2006中国江苏国际先进复合材料技术发展研讨会	2006 59-64	
41	张炎炎 陶 杰 潘 峰	硕 士 教 授 硕 士	061 061 061	无卤阻燃ABS的研究进展	2006中国江苏国际先进复合材料技术发展研讨会	2006 38-41	
42	陶 杰 季学来	教 授 硕 士	061 061	聚合物纳米复合材料的研究进展	机械制造与自动化	2006. 13-17.-22	

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
43	耿 妍 陶 杰 崔益华	硕 士 教 授 副教授	061 061 061	聚磷酸铵微胶囊化的工艺研究	玻璃钢/复合材料	2006.3 39-41	
44	章媛媛 陶 杰 庞迎春 王 玲 王 炜	硕 士 教 授 硕 士 高 工 硕 士	061 061 061 061 061	钛基材上用电化学沉积法制备 HA 涂层的研究	稀有金属材料与工程	2006.35.3	
45	汤育新 陶 杰 陶海军	硕 士 教 授 博 士	061 061 061	一种磁载光催化剂的制备及光催化活性的研究	南京航空航天大学学报	2006.38.2	
46	章媛媛 陶 杰 庞迎春 王 炜 汪 涛	硕 士 教 授 硕 士 硕 士 教 授	061 061 061 061 061	Electrochemical deposition of hydroxyapatite coatings on titanium	Transanctions of non ferrous metals Society of china	2006.16 633-637	
47	刘红兵 陶 杰 张平则 徐 江	硕 士 教 授 副教授 副教授	061 061 061 061	防氚渗透涂层制备技术的研究进展	材料导报	2006.20.9	
48	王月勤 陶 杰	硕 士 教 授	061 061	钛基材上电化学沉积羟基磷灰石	中国表面工程	2006.19.6	
49	倪晓燕 陶 杰 钱惠慧.	硕 士 教 授 学 士	061 061 061	玻璃纤维增强聚丙烯制品翘曲变形的研究	工程塑料应用	.2006. 34.10	
50	陶 杰 汪 涛 董 祥 单晓茜	教 授 教 授 博 士 硕 士	061 061 061 061	Mechanical properties and crystallization behavior of nanostructured ZnO/PET in-situ composites	Journal of nanoscience and nano technology	2006. 6.12	
51	苏宏华 徐鸿钧 肖 冰 傅玉灿 徐九华	副教授 教 授 副教授 教 授 教 授	061 052 052 052 052	Microstructure and Performance of Porous Ni-Cr Alloy Bonded Diamond Grinding Wheel	Material Science Forum	2006. 532~533	
52	王俭辛 薛松柏 方典松 鞠金龙 韩宗杰 姚立华	博 士 教 授 本 科 本 科 博 士 硕 士	061 061 外单位 外单位 061 061	Effect of diode-laser parameters on shear strength of micro-joints soldered with Sn-Ag-Cu lead-free solder on Au/Ni/Cu pad	Transactions of Nonferrous Metals Society of China	2006.16.6	

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
53	薛松柏 吴玉秀 韩宗杰 张 玲	教 授 硕 士 博 士 硕 士	061 061 061 061	Effects of lead widths and pitches on reliability of soldered joints and optimum simulation for QFP devices	The 2006 World Congress in Computer Science Computer Engineering, and Applied Computing	2006	
54	韩宗杰 薛松柏 刘 琳 王俭辛 吴玉秀 黄 翔 王 慧	博 士 教 授 硕 士 博 士 硕 士 硕 士 硕 士	061 061 061 061 061 061 061	Effects of Micro-amount of Ce on Microstructures of Sn-Ag-Cu Solder and Soldered Joint	Journal of Rare Earths	2006.24.S	
55	薛松柏 胡永芳 禹胜林 吴玉秀	教 授 硕 士 博 士 硕 士	061 061 061 061	热循环对 CBGA 封装焊点组织和抗剪强度的影响	焊接学报	2006.27.6	
56	薛松柏 韩宗杰 王 慧 王俭辛	教 授 博 士 硕 士 博 士	061 061 061 061	矩形片状元件无铅焊点断裂机制	焊接学报	2006.27.8	
57	张 玲 薛松柏 韩宗杰 黄 翔	硕 士 教 授 博 士 硕 士	061 061 061 061	高强铝锂合金炉中钎焊及接头组织分析	焊接学报	2006.27.8	
58	吴玉秀 薛松柏 张 玲 黄 翔	硕 士 教 授 硕 士 硕 士	061 061 061 061	QFP 组件的优化模拟及焊点热疲劳寿命的预测	焊接学报	2006.27.8	
59	王俭辛 薛松柏 韩宗杰 汪 宁 禹胜林	博士生 教 授 博 士 本 科 博 士	061 061 061 外单位 061	温度与镀层对 Sn-Cu-Ni 无铅钎料润湿性能的影响	焊接学报	2006.27.10	
60	韩宗杰 薛松柏 王俭辛 陈 旭	博 士 教 授 博 士 本 科	061 061 061 外单位	QFP 器件半导体激光钎焊焊点力学性能和显微组织	焊接学报	2006.27.10	

序号	姓 名	职 称	单 位	论 文 题 目	刊物.会议名称	年、卷、期	类别
61	张 玲 薛松柏 师怀江 吴玉秀	硕 士 教 授 本 科 硕 士	061 061 外单位 061	铝锂合金钎焊接头断口组织与性能	焊接学报	2006.27.10	
62	薛松柏 吴玉秀 崔国平 张 玲	教 授 硕 士 本 科 硕 士	061 061 外单位 061	热循环对 QFP 焊点强度及其微观组织影响规律的数值拟	焊接学报	2006.27.11	
63	黄 翔 薛松柏 张 玲 王俭辛	硕 士 教 授 硕 士 博 士	061 061 061 061	半导体激光加热时间对焊膏在铜基板上润湿铺展性能的影响	焊接学报	2006.27.11	
64	韩宗杰 鞠金龙 薛松柏 方典松 王俭辛 姚立华	博 士 本 科 教 授 本 科 博 士 硕 士	061 外单位 061 外单位 061 061	半导体激光软钎焊 Sn-Ag-Cu 焊点微观组织	中南大学学报	2006.37.2	
65	黄 翔 薛松柏 韩宗杰	硕 士 教 授 硕 士	061 061 061	激光软钎焊的研究现状及发展趋势	焊接	2006. .8	
66	沈以赴 顾冬冬 潘琰峰	副教授 助 教 硕 士	061 061 061	Balling Process in Selective Laser Sintering 316 Stainless Steel Powder	Key Engineering Materials	2006, 315-316: 357-360	
67	沈以赴 顾冬冬 赵剑峰 黄因慧 杨家林 王 洋	副教授 助 教 副教授 教 授 工程师 研究员	061 061 052 052 外单位 外单位	多组分铜基合金粉末选区激光烧结的组织形成机制	机械工程学报	2006. 42.7 114-118	
68	顾冬冬 沈以赴	助 教 副教授	061 061	Influence of Phosphorus Element on Direct Laser Sintering of Multicomponent Cu-Based Metal Powder	Metallurgical and Materials Transactions B	2006.37 967-977	
69	顾冬冬 沈以赴	助 教 副教授	061 061	WC-Co particulate reinforcing Cu matrix composites produced by direct laser sintering	Materials Letters	2006.60 3664-3668	
70	顾冬冬 沈以赴	助 教 副教授	061 061	Processing and microstructure of submicron WC-Co particulate reinforced Cu matrix composites prepared by direct laser sintering	Materials Science and Engineering A	2006.435-436: 54-61	

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Surface & Coatings Technology 200 (2006) 4227–4232

ELSEVIER

SURFACE & COATINGS TECHNOLOGY

www.elsevier.com/locate/surfcoat

Microstructure and dry sliding wear behavior of MoS_2/TiC/Ni composite coatings prepared by laser cladding

Jiang Xu [a,b,*], Wenjin Liu [b], Minlin Zhong [b]

[a] *Department of Material Science and Engineering, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing 210016, PR China*
[b] *Laser Processing Research Center, Mechanical Engineering Department, Tsinghua University, Beijing 10084, PR China*

Received 22 October 2004; accepted in revised form 10 January 2005
Available online 28 September 2005

Abstract

A PRC-3 kW continuous wave CO_2 laser was used to clad a MoS_2/TiC/Ni coatings on the surface of a 1045 low carbon steel substrate. The microstructure and phase composition of the composite coating were studied. The typical microstructure of the composite coating is composed of multi-sulfide phases including binary element sulfides, ternary element sulfides, Ni, TiC and Mo_2C. Wear tests were carried out using a FALEX-6 type pin-on-disc machine. The results showed that the MoS_2/Ni coating (as a contrasted sample) exhibited the lowest friction coefficient and the largest weight loss in comparison to other investigated specimens. The friction coefficient of the MoS_2/TiC/Ni coating is lower than that of quenched 45 steel and weight loss is only one-sixth of that of 45 steel. The worn surface of MoS_2/TiC/Ni laser cladding coating is so clean and smooth (no noticeable groove and scratches visible) that the microstructure of coating is identified after dry wear test of 40 min.

Keywords: Laser cladding; MoS_2/TiC/Ni; Wear resistance and anti-friction; Wear behavior

1. Introduction

With development of the aerospace and vacuum industries, the components in an engine or in general machinery are required to meet with severe environment, such as high temperature, high loading, strong radiant etc. Under these conditions, the presence of liquid is not possible or may be forbidden to avoid contamination (food industry). In particular, dry machining could have a detrimental effect on the tool performance (high tool wear or damage). The risk of this can be drastically reduced or eliminated by using solid lubricant. In special occasion, the use of a solid lubricant deposited where a traditional lubricant cannot perform, will increase the performance of tools and components [1–3]. As restriction imposed by environmental legislation tighten, solid lubrication provides a viable solution. Laser is a powerful tool for surface modification of metal in improving their corrosion and tribological properties. Laser cladding is a novel surface treatment technology which takes possession of advanced features, such as the integrity of fusion bond between the cladding coating and substrate, high process flexibility, high working speeds and no requirement for post process treatment.

Cladding of a composite coatings containing ceramic particles (such as WC, TiC, SiC, ZrO_2 or Al_2O_3 ceramics) involves a direct injection of powders into melt pool generated at the substrate surface employing a laser beam [4–9]. However, such coatings are not good option for some applications. From the viewpoint of tribology, the hardness of the surface coating is not the only factor which determines the wear behavior of metal materials. These coatings do not always efficiently improve the intensity of friction and do not provide any protection for the opposing surface. During wear process, if hard and rough particles peel off, serious abrasive wear will occur. In order to provide optimum wear protection for easily worn components, it is necessary to adopt a solid lubricant coating

* Corresponding author. Department of Material Science and Engineering, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing 210016, PR China.
E-mail address: xujiang73@sina.com.cn (J. Xu).

0257-8972/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.surfcoat.2005.01.036

reducing friction and protecting the opposing surface. The metal base composites containing sulfides have a low friction coefficient and a low wear rate from room temperature up to 600 °C and can be used as solid lubricant coating materials [10,11].

In present study, a new hard lubricant composite coating with amount of Ni coated MoS_2 powder has been prepared by laser cladding technology. The purpose of this work aims at the composite coating which is characteristic of high hardness combined with low friction and low wear rate combined with the good adhesion lead to very high load-bearing capacity.

2. Experimental

The 1045 low carbon steel samples were machined into rectangular blocks on size 10 mm×10 mm×50 mm. Before laser cladding, the surface was ground to a surface finish of Ra=0.2 μm, and rinsed with ethanol followed by acetone. A mixture of 70 wt.% Ni coated MoS_2, 20 wt.% TiC and 10 wt.% Ni powder was used as the coating materials for MoS_2/TiC/Ni coating. The MoS_2/Ni coating was selected for comparing the wear behavior. The ratio of Ni coated MoS_2 powder to Ni powder was 3:1 in weight. The particle size of Ni coated MoS_2 powder was less than 10 μm and the ratio of Ni to MoS_2 is 4:6 in weight. The particle size of the TiC powder was less than 15 μm and the grains had a polygonal shape. The powders were mixed by hand using a spoon in a glass and were pasted on the surface of low carbon steel. The paste was 1 mm thick. The laser cladding was carried out with a defocused laser beam of 3-mm diameter using PRC-3 kW continuous wave CO_2 laser processing system in an argon shielding atmosphere. The laser cladding parameter was laser power 1.25 kW, scan speed 12 mm/s.

Metallographic cross-sections of clad samples were prepared in the plane perpendicular to the scan direction. The chemical composition and microstructure were analyzed by a LEO-1450 scanning electron microscopy (SEM), and worn surfaces of coatings were observed by a CSM-950 SEM using also X-ray energy dispersive spectroscopy (X-EDS). The phase composition was investigated by X-ray diffraction (XRD) with a D/Max-RB diffractometer. The radiation source was Cu Kα, the voltage was 40 kV and the scan rate was 5 min^{-1}. The microhardness measurement were done on a HX-200 micro-Vickers machine with a 0.2 kg load.

Dry sliding friction and wear tests without lubricant were performed in a pin-on-ring mode on a Falex-6 friction and wear testing machine (Falex, Sugar Grove, Illinois, USA). The pin specimens were machined in the form of cylinders with 4.8-mm diameter and 12.7-mm length. The counterpart discs were made of a quenched and tempered GCr15 bearing steel with a nominal chemical composition (mass percent): 1.0 C, 1.5 Cr, 0.25 Si, 0.30 Mn, 0.20 Ni, 0.05 Mo, 0.15 V, surface hardness of 60 HRC and surface roughness of Ra=0.2 μm. The quenched 1045 low carbon steel with surface hardness of 50 HRC was selected as reference test material for all wear tests in order to rank the wear resistance of the MoS_2/TiC/Ni coating in comparison to other test materials. The applied load was 17.8 N and the sliding speed was kept constant at 0.24 m/s. The friction coefficient μ was calculated using the expression $\mu = T/RP$, where T is the friction moment, R is the ring radius and P is the normal load on the pin specimen. The specimens were thoroughly cleaned with acetone in an ultrasonic cleaner before and after the wear test. After the wear test, the weight loss was measured using a photoelectric balance 1712MP8 with the resolution of ±0.01 mg.

3. Results and discussion

3.1. Microstructure characterization and microhardness

Fig. 1 presents a typical X-ray diffraction (XRD) pattern of a coating produced from a MoS_2/TiC/Ni powder blend. The results of XRD indicate that the major phases constituents of composite coatings are multi-element sulfide phases including binary element sulfides (TiS, NiS Ni_3S_2, Ni_3S_4, NiS_2), ternary element sulfides ($Ni_{2.5}Mo_6S_{6.}$, $Ni_{0.33}TiS_2$, $Ni_3Ti_4S_8$, $Ti_3Mo_{0.75}S_5$), Ni, TiC and Mo_2C. Owing to irradiation of laser beam, the MoS_2 particle is heated to reach the temperature higher than the melting point of the particle, then dissociation of MoS_2 to Mo and S occurs swiftly.

Fig. 2(a) shows the SEM of the longitudinal section of the MoS_2/TiC/Ni coating. It can be found that the coating is about 0.3 mm thick and free from pores and cracks. There exists an excellent metallurgical bond between the coating and the substrate. TiC particles dissolve partially into the melt pool during cladding and their density gradually increases with distance from the bottom of the coating. Because the density of TiC is about 4.25 g cm^{-3} and is lighter than nickel-based alloy, the TiC particles have a

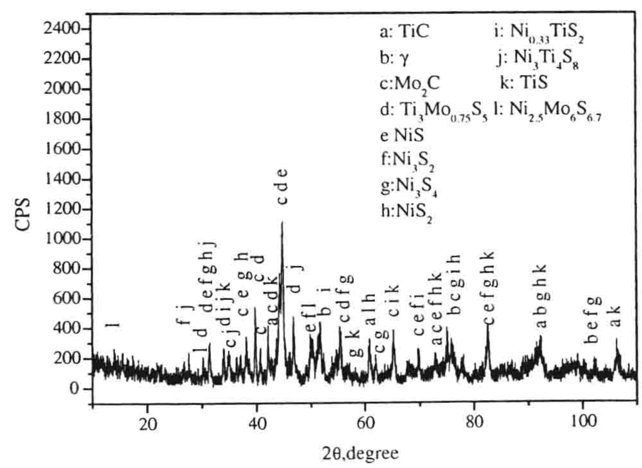


Fig. 1. XRD pattern MoS_2/TiC/Ni composite coatings.

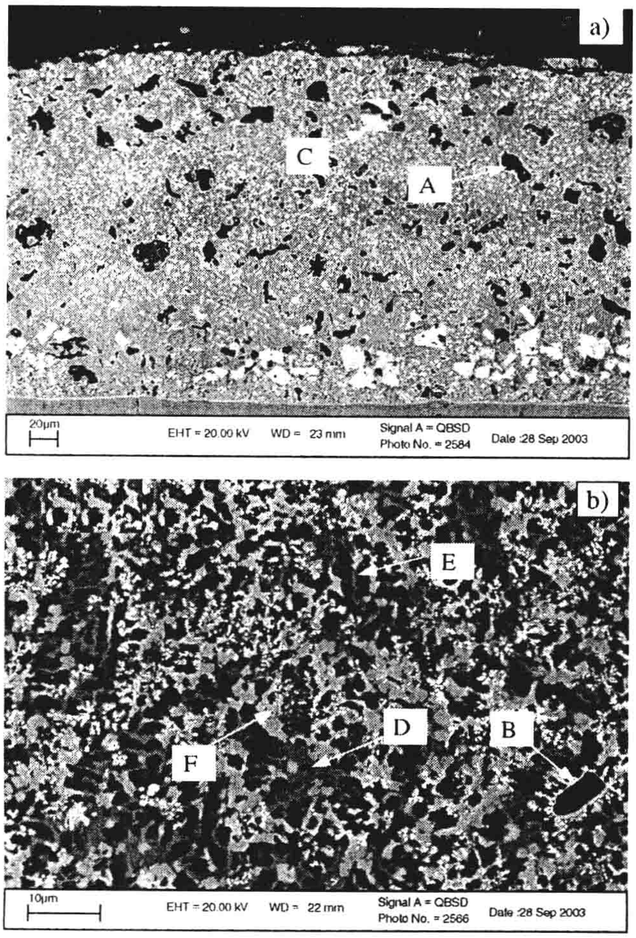


Fig. 2. SEM micrographs showing the microstructure of the MoS_2/TiC/Ni composite coatings: (a) overview cross-section, (b) high magnification.

tendency to concentrate at the top of the coating. The typical microstructure in the middle of the coating has been shown in Fig. 2(b). SEM observation reveals that the microstructure of the coating is very complicated, consisting of different constituent phases. The composition of phases analyzed using X-EDS are shown in Table 1. Combining the XRD results and composition of phases in coating, it can indicate that the Black particle (marked A in Fig. 2(a)) is partially dissolve TiC ceramic particle, which is embraced by Mo_2C carbide (marked B in Fig. 2(b)). The White block phase (marked C in Fig. 2(a)), which mainly consist of Mo, S and Ni element, is identified $Ni_{2.5}Mo_6S_{6.7}$ ternary sulfide. During the laser cladding process, there are the convective

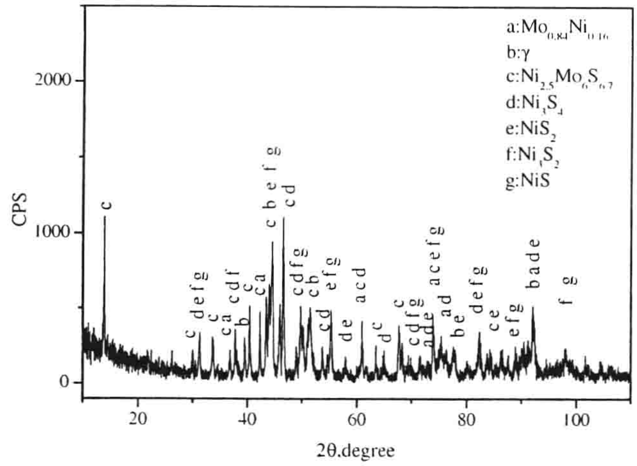


Fig. 3. XRD patterns of laser cladding MoS_2/Ni composite coating.

flow of the molten metal, which results in the reaction of Mo, S, Ti and Ni to form ternary or binary element sulfide such as $Ni_{0.33}TiS_2$, $Ni_3Ti_4S_8$, $Ti_3Mo_{0.75}S_5$ (marked D in Fig. 2(b)) and Nickelous sulfide (marked E in Fig. 2(b)). The TiC particle was decomposed into Ti and C, and partially dissolved in the melt pool. The dissociated C combines with the dissolution of Mo to form Mo_2C carbide. It is noted that there are two kinds of distribution feature of Mo_2C, namely, surrounding structure of the exterior of TiC particle and in shape of particle homogeneous distribution in clad coating. The surrounding structure contained a little of Ni and Ti and can be confirmed as composite carbide of Mo_2C type, and which plays an important role in bonding the TiC particle with matrix of clad coating. Owing to the supersaturation of Mo and C in the matrix, the Mo_2C precipitates from the matrix in particle-like during solidification. Under condition of rapid heating and cooling during the laser treatment, Ni reacts with decomposed MoS_2 to form $Ni_{2.5}Mo_6S_{6.7}$ in the place of Ni coated MoS_2 powder of preplaced coating due to diffusing insufficiency. The dissociation of MoS_2 to Mo and S reacts with Ni and Ti to form multi-element sulfide phase.

Fig. 3 shows the XRD pattern of the MoS_2/Ni coating. The result of XRD indicates that main phase constituents of the coating are Ni, $Ni_{2.5}Mo_6S_{6.7}$, intermetallic $Mo_{0.84}Ni_{0.16}$ and binary element sulfides (Ni_3S_4, NiS_2, Ni_3S_2, NiS). The microstructure of the cladding coating is shown in Fig. 4. The results of energy dispersive X-ray (X-EDS) analysis of different marked microzone, as shown in the Table 2, the large grey block (marked A), white particle-like (marked B),

Table 1
X-EDS analyses result of MoS_2/TiC/Ni coating (at.%)

Phase label	Phase	Ni	Mo	S	Ti	Fe	C
A	TiC	–	–	–	94.0794	–	5.9236
B	Mo_2C	10.2393	86.765	1.6194	1.3757	–	–
C	$Ni_{2.5}Mo_6S_{6.7}$	14.5537	24.7327	60.4144	–	0.2992	–
D	$Ni_{0.33}TiS_2$,$Ni_3Ti_4S_8$,$Ti_3Mo_{0.75}S_5$, TiS	22.4454	21.9407	49.8493	5.7646	–	–
E	NiS, Ni_3S_4, Ni_3S_2, NiS_2	60.5509	1.4560	36.7667	0.4858	0.7406	–
F	Ni	83.9130	0.9374	12.4436	0.5606	2.1453	–

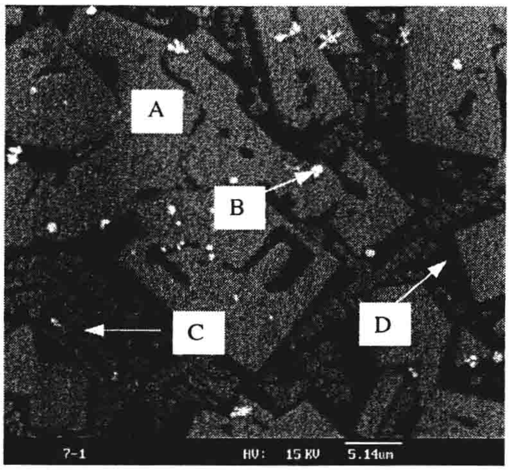


Fig. 4. SEM micrographs of cross-section of MoS_2/Ni coating.

small cluster block (marked C) and black grey structure in the middle of the large grey block are determined as $Ni_{2.5}Mo_6S_{6.7}$, intermetallic $Mo_{0.84}Ni_{0.16}$, Ni and binary nickelous sulfide, respectively.

The hardness profiles of a MoS_2/TiC/Ni coating and a MoS_2/Ni coating along the depth direction are depicted in Fig. 5(a),(b). It can be seen that the hardness of the MoS_2/TiC/Ni coating decreases gradually as the distance from the surface increases. The gradient microstructure leads to a gradual hardness distribution of the coating from $HV_{0.2}$743 down to $HV_{0.2}$ 160. The microhardness of the MoS_2/Ni coating is ranging between $HV_{0.2}$250 and $HV_{0.2}$440 and is thus lower than that of the MoS_2/TiC/Ni coating. It is noted that there is no sudden transition from the coating to the substrate in the hardness, which indicates an absence of a sharp demarcation in materials properties across the interface.

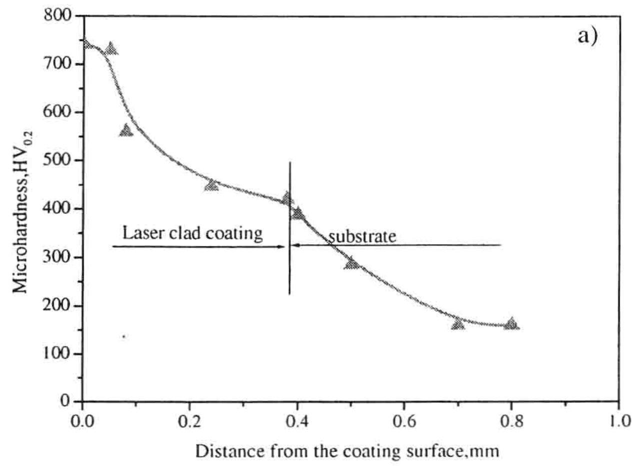
3.2. Sliding friction and wear behaviors

Fig. 6 shows the friction coefficients of the MoS_2/TiC/Ni composite coating, MoS_2/Ni coating and hardened 1045 low carbon steel at given normal load (17.8 N) and wear time of 10 min. The friction coefficient of the MoS_2/Ni coating is the lowest of the tested materials; hence it possesses good lubricant behavior. The friction coefficient of MoS_2/TiC/Ni coating is higher than that of the MoS_2/Ni coating but considerably lower than that of hardened AISI 1045 steel.

The wear weight loss of MoS_2/Ni coating is 2.1 mg after a wear time of 10 min and the clad coating has been worn

Table 2
The EDAX analyses result of laser cladding Ni coated MoS_2/Ni composite coating (at.%)

Phase label	Phase	Ni	Mo	S
A	$Ni_{2.5}Mo_6S_{6.7}$	18.3751	27.7205	53.9044
B	$Mo_{0.84}Ni_{0.16}$	18.1051	81.8949	–
C	Ni	89.3453	9.5974	–
D	Ni_3S_4,NiS_2,Ni_3S_2,NiS	75.5753	1.5028	22.9219



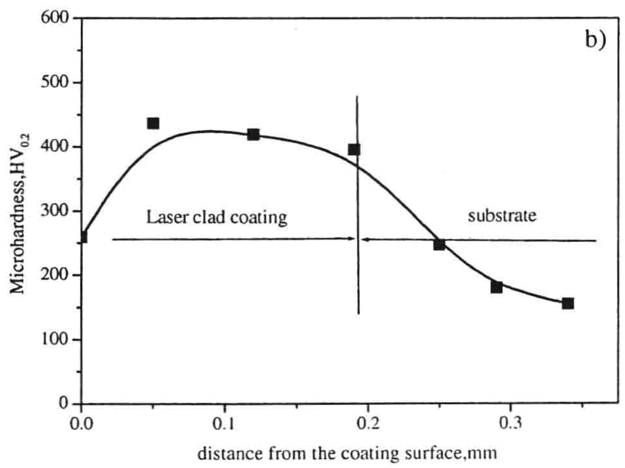


Fig. 5. Microhardness profile of the laser clad: (a) MoS_2/TiC/Ni coating; (b) MoS_2/Ni coating.

out. The wear weight losses of the MoS_2/TiC/Ni coating and AISI 1045 steel as function of wear time at given normal load (17.8 N) are compared and shown in Fig. 7. An approximately linear relationship between wear weight loss and wear time occurs and the slope of 1045 steel is

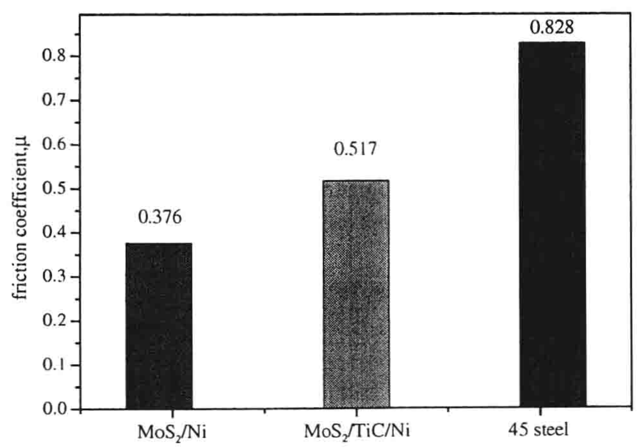


Fig. 6. Friction coefficients of clad coatings and 1045 steel at a given normal load (17.8 N) and wear time of 10 min.

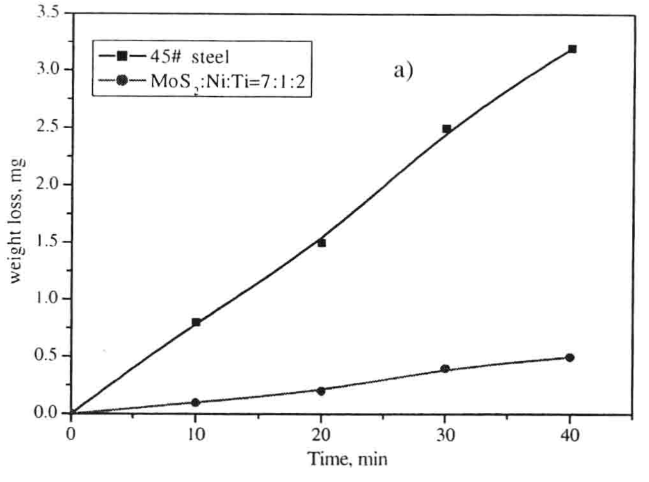


Fig. 7. Wear weight loss of coating and AISI1045 steel as function of wear time at a given normal load of 17.8 N.

obviously larger than that of the MoS_2/TiC/Ni coating. Thus, the MS_2/TiC/Ni coating has excellent wear resistance and friction properties.

Fig. 8(a) shows the worn surface of MoS_2/Ni coating. Delamination occurs, and the materials are removed from the surface due to adhesive wear. The removed materials are transferred to the surface of the counterpart disc, can act as a solid lubricant film, help to reduce the friction force and protect the surface of counterpart disc. But the low hardness and load-bearing capacity limit its application. The morphology of worn surface of low carbon steel (Fig. 8(b)) is very rough and deep plowing grooves and adhesive flake debris can be observed. Because of the low capability of plastically deformation and the low hardness, the abrasive particle is able to plough deeply into the surface of 1045 steel and is able to cause microcutting and grooving. Fig. 8(c),(d) shows that the surface morphologies of the worn surfaces of the MoS_2/TiC/Ni coating after a dry sliding wear test of 40 min are so clean and smooth (no noticeable grooves and scratches visible) that the microstructure of the coating can be clearly revealed. The undissolved TiC particle plays an important role in increasing the hardness and resisting plastic deformation. It is well known that the microhardness is closely related to the wear resistance of materials. The higher the hardness, the higher the wear resistance and the lower the weight loss. The wear properties of the MoS_2/TiC/Ni coating differ completely from those of the single constituents and depend on the microstructure configuration. The excellent wear resistance of MoS_2/TiC/Ni coating is due to the presence of the hard phase of TiC particles and friction-reducing properties of sulfides. Moreover, the increased bonding strength between

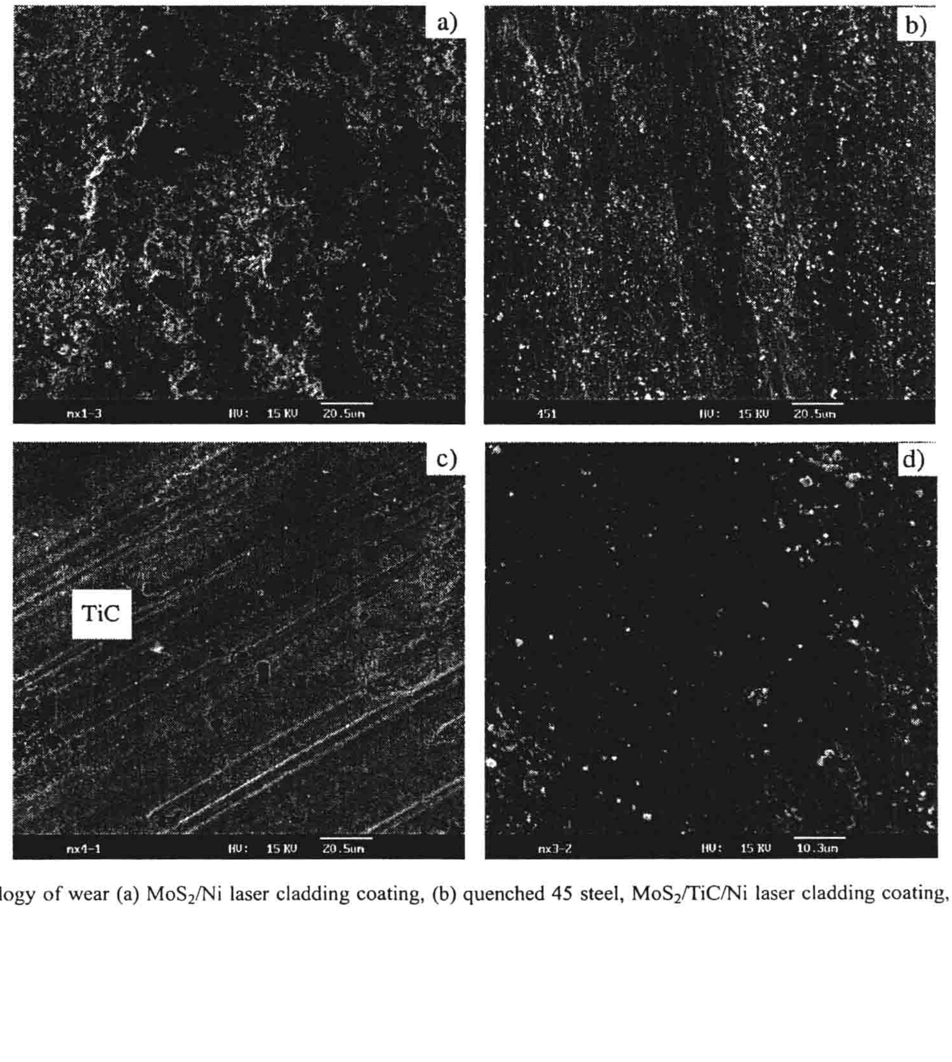


Fig. 8. Surface morphology of wear (a) MoS_2/Ni laser cladding coating, (b) quenched 45 steel, MoS_2/TiC/Ni laser cladding coating, (c) at low and (d) high magnification.

the TiC particle and the matrix due to the surrounding structure of Mo_2C, helps to prevent the delamination of the TiC particle during the wear. Compared with MoS_2/Ni coating, the MoS_2/TiC/Ni coating has a notably better load-bearing and wear lifetime under dry sliding wear conditions. A great amount of sulfide in the MoS_2/TiC/Ni coating is provided with the friction reducing during sliding wear and can protect both its own surface and the surface of counterpart discs.

4. Conclusion

1. Laser clad MoS_2/TiC/Ni composite coatings offer advantages over laser clad MoS_2/Ni coatings and hardened AISI 1045 steel because of their hardness, wear resistance, low friction and good load-bearing capacity.
2. The typical microstructure of MoS_2/TiC/Ni composite coatings is composed of multi-sulfides phases including binary element sulfides and ternary element sulfides, Ni, TiC and Mo_2C. The microstructure of MoS_2/Ni coating consists of Ni, $Ni_{2.5}Mo_6S_{6.7}$, intermetallic $Mo_{0.84}Ni_{0.16}$, Ni_3S_4, NiS_2, Ni_3S_2, NiS.
3. After dry sliding wear of 40 min, weight loss of MoS_2/TiC/Ni composite coatings is only one-sixth that of hardened AISI 45 steel, and the friction coefficient of clad MoS_2/TiC/Ni composite coating is higher than that of Ni coated MoS_2/Ni coating but considerably lower than that of hardened AISI 1045 steel. The morphology of the worn surface of the MoS_2/TiC/Ni composite coating is so clean and smooth that the microstructure of the clad Ni coated MoS_2/TiC/Ni composite coating can be clearly revealed.

References

[1] V. Fox, A. Jones, N.M. Renevier, D.G. Teer, Surf. Coat. Technol. 125 (2000) 347.
[2] N.M. Renevier, V.C. Fox, D.G. Teer, J. Hampshire, Mater. Des. 21 (2000) 337.
[3] N.M. Renevier, V.C. Fox, D.G. Teer, J. Hampshire, Surf. Coat. Technol. 127 (2000) 24.
[4] Yongqiang Yang, H.C. Man, Surf. Coat. Technol. 132 (2000) 130.
[5] A. Hidouci, J.M. Pelletier, F. Ducoin, D. Dezert, R. El Guerjouma, Surf. Coat. Technol. 123 (2000) 17.
[6] P.H. Chong, H.C. Man, T.M. Yue, Surf. Coat. Technol. 154 (2002) 268.
[7] Y. Herrera, I.C. Grigorescu, J. Ramirez, C. Di Rauso, M.H. Staia, Surf. Coat. Technol. 108–109 (1998) 308.
[8] A. Mchimann, S.F. Dirnfeld, I. Minkoff, Surf. Coat. Technol. 42 (1990) 275.
[9] T.C. Lei, J.H. Quyang, Y.T. Pei, J. Harbin Inst. Technol. 1 (1995) 90.
[10] Wu Yun Xin, Cheng Yinqian, Wang Fuxing, Mater. Mech. Eng. 4 (1998) 22 (in Chinese).
[11] Liu Rutie, Li Xibin, Zhao Caiqin, J. Mater. Sci. Eng. 21 (2003) 393.

Available online at www.sciencedirect.com
SCIENCE DIRECT
Wear 260 (2006) 486–492
ELSEVIER
WEAR
www.elsevier.com/locate/wear

Wear characteristic of in situ synthetic TiB_2 particulate-reinforced Al matrix composite formed by laser cladding

Jiang Xu *, Wenjin Liu

Laser Processing Research Center, Mechanical Engineering Department, Tsinghua University, Beijing 10084, PR China

Received 24 August 2004; received in revised form 18 February 2005; accepted 8 March 2005
Available online 22 June 2005

Abstract

In order to improve the wear resistance of an aluminum alloy, an in situ synthesized TiB_2 particulate-reinforced metal matrix composite coating was formed on a 2024 aluminum alloy by laser cladding with a powder mixture of Fe-coated boron, Ti and Al was successfully achieved using a 3-kW CW CO_2 laser. The chemical composition, microstructure and phase structure of the composite clad coating were analyzed by energy dispersive X-ray spectroscopy (EDX), SEM, TEM and XRD. The nanohardness and the elastic modulus of the phases of the coating have been examined. The dry sliding wear behaviour of the coating was investigated using a pin-on-ring machine under four loads, namely 8.9, 17.8, 26.7, and 35.6 N. It has been found that the wear characteristics of cladding were completely dependent on the content and morphology of the TiB_2 particulate and intermetallic in the microstructure and the applied load. At the lowest load (8.9 N), with increasing content of TiB_2 particulate and intermetallic, the wear weight loss of the laser cladding was decreased. At higher loads (17.8, 26.7, and 35.5 N), the 2024 Al alloy exhibited superior wear resistance to the particle-reinforced metal matrix composite cladding.

Keywords: Laser cladding; Particle-reinforced composites; Microstructure; Wear resistance

1. Introduction

Aluminum alloys are the most widely used non-ferrous metals in engineering owing to their attractive properties, such as high strength-to-weight ratio, good ductility, good corrosion resistance, availability and low cost [1]. However, their applications have often been restricted because conventional Al alloys are soft and notorious for their poor wear resistance.

Laser cladding is an attractive surface treatment technology which takes possession of advanced features, such as the integrity of fusion bond between the cladding coating and substrate, high process flexibility, high working speeds and no requirement for post-process treatment. There has been a growing interest in fabrication of a surface layer of particulate-reinforced metal matrix composites on metallic materials. This process involves a massive introduction of hard particle into the wear resisting surface clad layer, such as WC, TiC, SiC, ZrO_2 or Al_2O_3 ceramics, which are directly injected into the high temperature molten pool created in the surface of substrate by laser beam [2–7]. There is a major drawback to adding the reinforced phase directly into laser cladding coating because of poor wetting behavior between ceramic phase and metal matrix and a large different thermal expansion coefficient between them. In order to solve this problem, the in situ synthesized particles particulate-reinforced metal matrix composites have been extensively investigated [8,9].

Titanium diboride is an attractive material for a range of application [10,11] including wear components mechanical seals, aerospace parts and cutting tools because of its hardness, high melting point and low specific weight. TiB_2 also has potential uses as a surface coating to steels and aluminum alloys to improve wear resistance in components like cylinder heads, liners, engine blocks, pistons, brake rotors and drums.

The present work is aimed at the investigation of the effect of in situ synthesized particulate and intermetallic

* Corresponding author.
E-mail address: xujiang73@sina.com.cn (J. Xu).

0043-1648/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2005.03.032