《全国高技术重点图书》

出版指导委员会

《全国高技术重点图书·激光技术领域》

编审委员会

前　言

激光在各个领域的应用近几年得到了迅速的发展，材料激光加工是激光应用的重要组成部分，它在我国的发展更是迅猛，已经在电子、汽车制造和其他机械行业得到了很多的应用。材料激光加工所使用的设备类型主要是CO_2和YAG激光器，加工对象主要是碳钢、合金钢、铸铁以及有色合金等金属材料，采用的加工方法有激光相变硬化、激光重熔、激光熔覆、激光焊接和激光烧结等。激光对材料的辐射会引发作用区金属发生强烈的传热、传质和液体流动等物理现象，经过激光加工以后的金属组织结构较常规组织有明显的变化，与被加工材料的性能密切相关。了解和控制加工材料的组织是获得理想加工效果的关键。

本书列为“十五”国家重点图书出版规划项目，旨在为从事激光加工的工程技术与教学人员了解和研究控制金属材料经激光加工后的金相组织，探索最佳激光加工工艺提供帮助。中科院长春光机所关振中研究员提出撰写本书的构想及编写大纲，并对全书进行了审校。全书共分为7章，第1章由关振中编写，第2章至第7章由胡建东、郭作兴编写。长春一汽姚远高级工程师为本书无私提供激光焊接样品，在此深表感谢。由于编者水平所限，书中不妥之处在所难免，敬请读者予以批评指正。

编　者

2005年9月

目　　录

第1章 绪 论

1.1 概 述

激光被誉为“万能加工工具”和“未来制造系统的共同加工手段”。激光加工技术是20世纪70年代初随着工业用大功率激光器的不断问世而发展起来的高新技术。它是一种理想的、高效的先进制造技术，在工业发达国家已经形成了一个高技术新兴产业，在我国这个新兴产业正在形成[1.1]。

激光加工是一种无接触加工，因而在其加工过程无“切削力”作用于工件上，可以实现非常精密的加工；激光加工是一种能量密度高、加工速度快且是表面局部加工，因此其热影响区小、工件变形小，后续加工量可以很小；由于激光束的能量、聚焦、导向及其移动速度均可方便地进行调控，因此可以实现一机多能、对复杂零件进行加工。激光加工技术的应用是一个系统工程。它涉及的学科多，可变因素多，需要研究、探讨和解决的问题多。

激光加工技术应用面广，其内容极为丰富，其内涵亦极为深刻。

1.2 激光加工的丰富内容

激光加工工艺的内容可以粗略归纳为：激光去除，如激光打孔等；激光连接；如激光焊接等；激光表面改性，如激光热处理（激光相变硬化、激光重熔和激光熔覆）等；激光制造新材料，如激光烧结和激光制备纳米材料等；激光零件加工，如激光零件快速成型加工等。具体如图1－1所示[1.2]。其中，激光连接、激光表面改性、激光制备新材料及激光零件加工等涉及金属材料的内部组织结构变化，本书在后面分别给出其金相图谱300余幅。

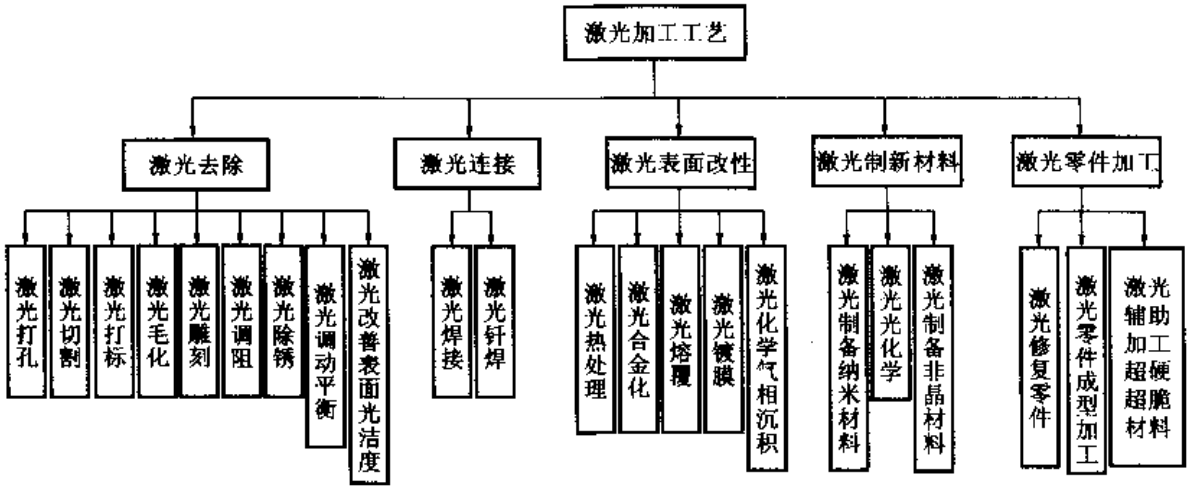

图1－1 激光加工的丰富内容

应当指出，有些工艺方法既属于表面改性，又在向激光快速制造金属零件迈进。比如激光熔覆就是如此。另外有些工艺属于激光制备新材料，同时又具有表面改性的作用等。

1.3 激光加工系统

对于一个已被确定的具体零件而言，首先要根据其对性能的要求，优选正确的工艺参数，必须有针对性的合理的采用何种激光器、外光路以及相应的加工机床。所有这些就构成一个激光加工系统，如图 1－2 所示 [1.2]。

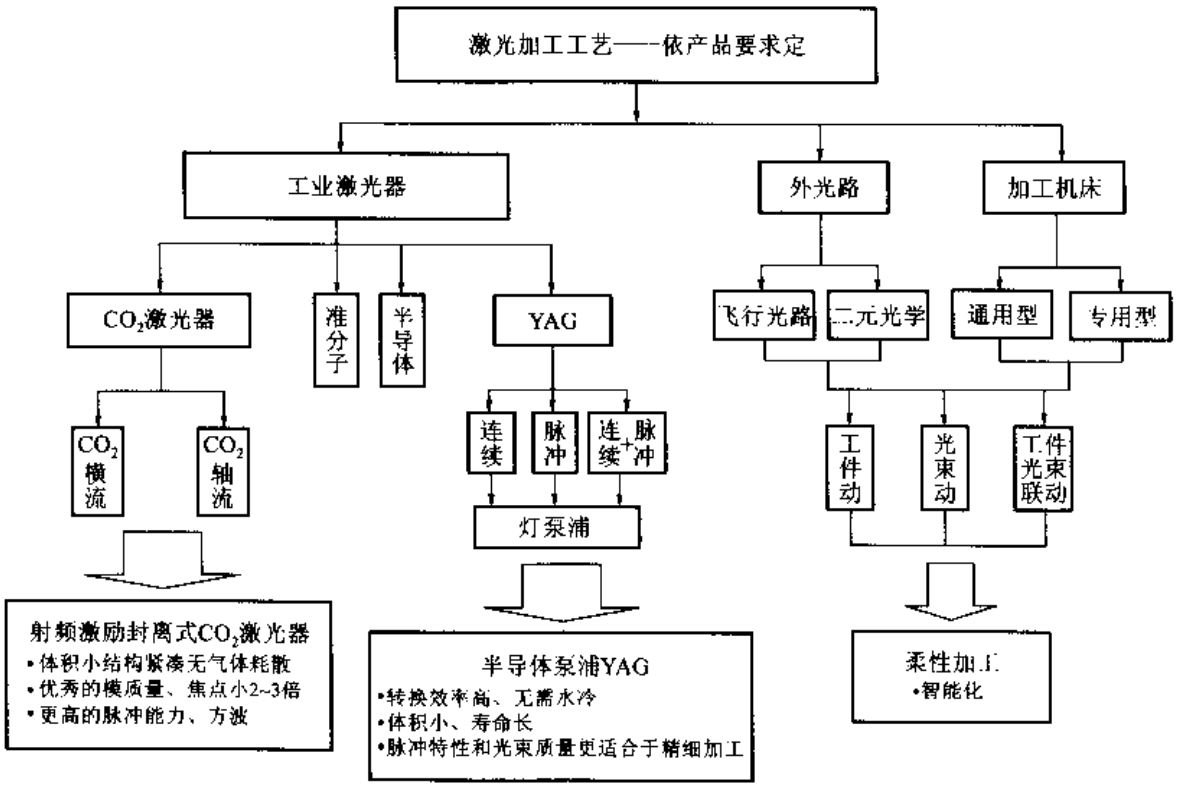

图 1 2 激光加工系统

目前，工业激光器种类繁多，其中 CO_2 激光器和 YAG 激光器是主导产品。由于射频激励封离式 CO_2 激光器具有体积小、结构紧凑、无气体耗散、模质量好等优点，备受各方关注。由于半导体泵浦 YAG 激光器具有转换效率高、寿命长、特别适合于精细加工等优点而备受各方重视。准分子激光器和半导体激光器有着广阔的应用前景。

外光路亦称导光系统是确保激光加工工艺实施的重要环节，飞行光路和二元光学的应用使其质量更高，效果更好。由外光路与加工机床组合实现工件动或光束动或工件与光束联动，实现智能柔性加工。

激光加工系统中每个环节或单元技术的进步都会推动或改善整个加工系统性能提高 [1.3]。凡从事这方面工作的都要时刻关注各个环节的技术进步与发展，一旦成熟就应适时采用。

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[1.3] 关振中. 我国激光加工实现产业化的若干问题探讨. 激光集锦 Vol.5 No.2 1995：23～26

第2章　激光相变硬化

激光相变硬化(Transformation hardening，Laser beam quenching or Laser heat treatment)是用高能激光束对工件进行扫描，使材料表面获得淬火组织的一种表面热处理方法。激光辐射可以使铁碳合金表面的温度升高到奥氏体化温度以上，依靠自身冷却，获得马氏体淬火组织。激光相变处理的主要对象是加热时有相变发生的钢铁材料，如各种钢和铸铁等。用于激光相变硬化材料的原始组织多为退火或回火组织。

激光相变硬化有以下一些特点：(1)加热及冷却速度快，处理周期短，自身淬火，不需冷却介质；(2)相变硬化层组织细，经常含有一些非平衡相，其硬度高于常规淬火，耐磨性和耐腐蚀性有明显改善；(3)可以对筒壁、盲孔和深孔等隐藏部位和大型零部件局部表面进行淬火；(4)零件的变形小，节省了淬火介质，减轻环境污染。激光相变硬化研究成果的主要应用是发动机缸体表面热处理等。

激光相变硬化的加热和冷却是在极短的周期内完成的，其特性可以用热循环曲线来描述。热循环曲线表示在材料某特定深度处温度随时间的变化情况，热循环曲线的特点和激光处理工艺参数、金属表面的吸收率以及材料的热物理参数有关。温度随加热层深度和时间的变化可以用热传导方程来描述，通常可以求出它的解析解[2.1]。

激光对材料加热时，表层温度远高于奥氏体化温度，从表层到次表层依次可以分为奥氏体相变区和热影响区。在激光功率足够的情况下，材料的冷却速度足以保证奥氏体转变成马氏体。一般可以把激光处理区分成三个层：第一层的组织是马氏体；在第二层中包括马氏体、贝氏体和珠光体，是混合组织；第三层是热影响区，是非相变组织[2.2]。激光处理后材料表层的硬度最高，具有良好的耐磨性和耐腐蚀性。

淬硬层深度一般小于1mm，硬度可以达到55HRC甚至更高，取决于钢的含碳量。激光相变硬化时被加热材料的成分经常是不均匀的，存在成分偏析现象，转变产物往往偏离合金的平衡相图，产生一些特殊组织，(后面提到的激光重熔、激光熔覆和激光焊接也有此特点)，如铸铁激光处理区的大量残余奥氏体等[2.3]，从本章给出的照片中，可以看到电子显微镜下淬火马氏体和残余奥氏体以及热影响区的组织形貌。

2.1　20# 钢激光相变硬化

图 2－1　激光相变硬化，Fe－0.2C 合金(20# 钢)，CO_2 激光，TEM 照片，显示激光硬化区板条马氏体

Laser hardening, Fe－0.2C alloy(20# steel), CO_2 laser, TEM micrograph, showing lath martensite in the laser hardened zone.

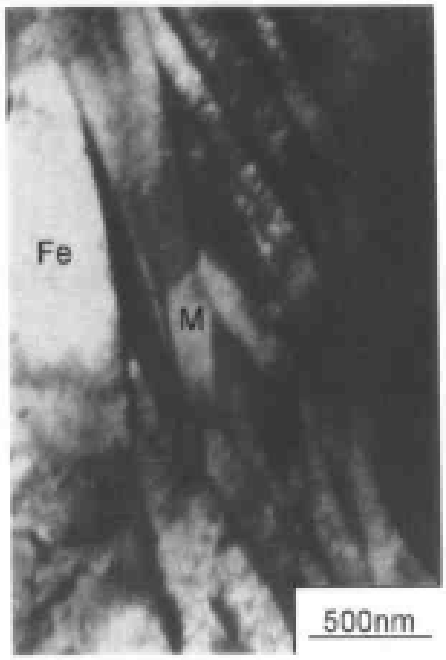

图 2－2　激光相变硬化，Fe－0.2C 合金(20# 钢)，CO_2 激光，TEM 照片，显示激光硬化区板条马氏体(M)和未发生相变的铁素体(Fe)

Laser hardening, Fe－0.2C alloy(20# steel), CO_2 laser, TEM micrograph, showing lath martensite (M) and ferrite(Fe) without transformation in the laser hardened zone.

图 2－3　激光相变硬化，Fe－0.2C 合金(20# 钢)，CO_2 激光，TEM 照片(明场)，显示激光硬化区板条马氏体中间的残余奥氏体组织

Laser hardening, Fe－0.2 C alloy(20# steel), CO_2 laser, TEM micrograph (BF), showing retained austenite between lath martensite in the laser hardened zone.

图 2－4　激光相变硬化，Fe－0.2C 合金(20# 钢)，CO_2 激光，TEM 照片(暗场)，显示激光硬化区板条马氏体中间的残余奥氏体组织

Laser hardening, Fe－0.2C alloy(20# steel), CO_2 laser, TEM micrograph (DF), showing retained austenite between lath martensite in the laser hardened zone.

图 2－5　激光相变硬化，Fe－0.2C 合金(20# 钢)，CO_2 激光，TEM 照片，显示激光硬化区中的贝氏体组织

Laser hardening, Fe－0.2C alloy(20# steel), CO_2 laser, TEM micrograph, showing bainite in the laser hardened zone.

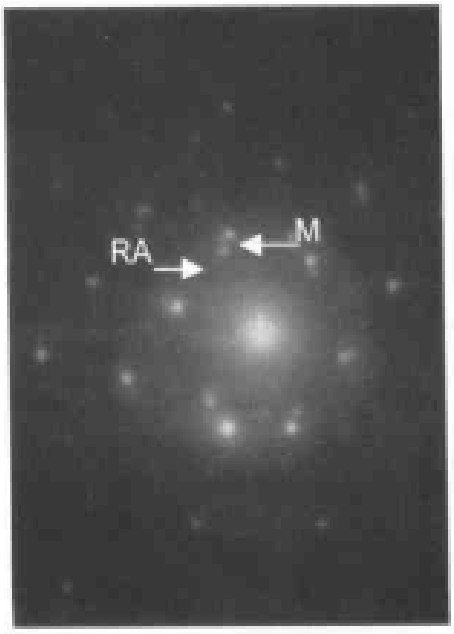

图 2－6　激光相变硬化，Fe－0.2C 合金(20# 钢)，CO_2 激光，图 2－3 的电子衍射图，显示激光硬化区马氏体(M)和残余奥氏体(RA)的衍射斑点

Laser hardening, Fe－0.2C alloy(20# steel), CO_2 laser, showing diffraction pattern of No. 2－3 from martensite (M) and retained austenite (RA) between lath martensite in the laser hardened zone.

2.2　35# 钢激光相变硬化

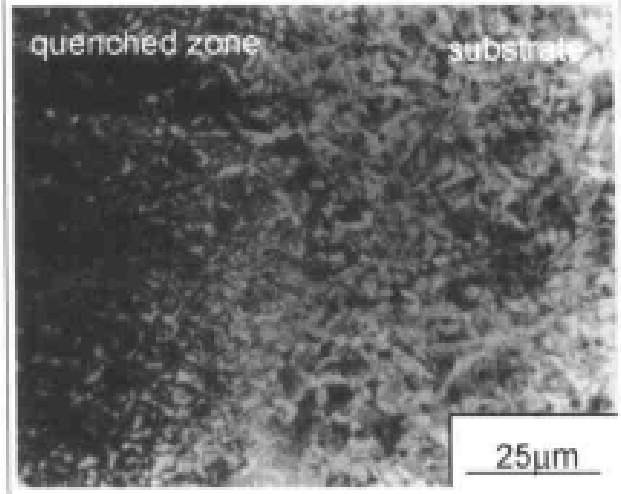

图 2－7　激光相变硬化，Fe－0.35C 合金（35# 钢），CO_2 激光，光学照片，显示激光相变硬化区及基体形貌

Laser transformation hardening, Fe－0.35C alloy (35# steel), CO_2 laser, optical micrograph, showing the morphology of laser transformation hardening zone and substrate.

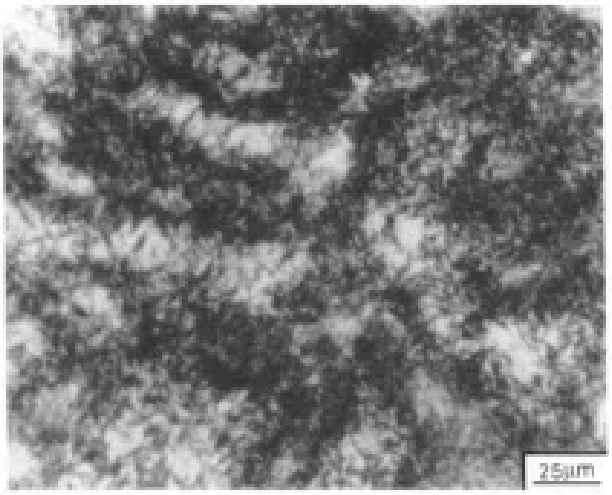

图 2－8　激光相变硬化，Fe－0.35C 合金（35# 钢），CO_2 激光，光学照片，显示激光相变硬化区形貌

Laser transformation hardening, Fe－0.35C alloy (35# steel), CO_2 laser, optical micrograph, showing the morphology in laser transformation hardening zone.

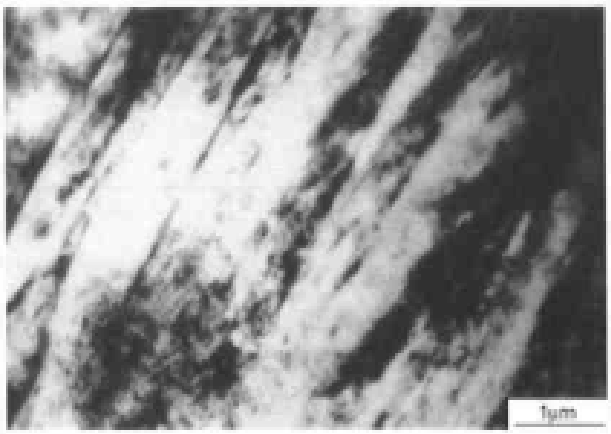

图 2－9　激光相变硬化，Fe－0.35C 合金（35# 钢），CO_2 激光，TEM 照片，显示马氏体

Laser transformation hardening, Fe－0.35C alloy (35# steel), CO_2 laser, TEM micrograph, showing the morphology of martensite.

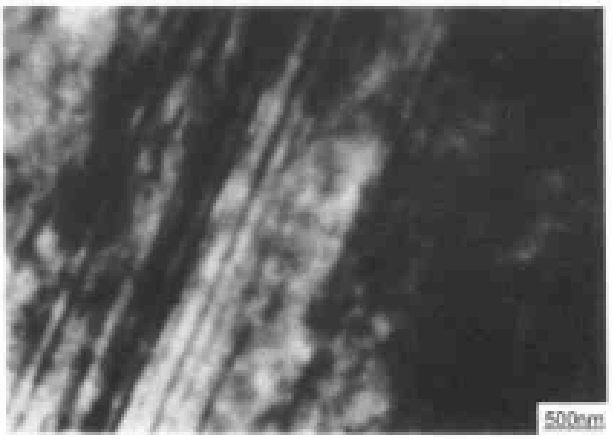

图 2－10　激光相变硬化，Fe－0.35C 合金（35# 钢），CO_2 激光，TEM 照片，显示马氏体

Laser transformation hardening, Fe－0.35C alloy (35# steel), CO_2 laser, TEM micrograph, showing the morphology of martensite.

2.3 T10钢激光相变硬化

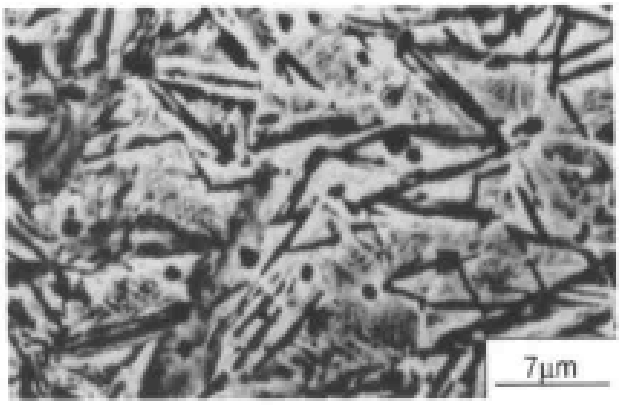

图2－11 激光相变硬化，Fe－1.0C合金(T10钢)，CO_2激光，SEM照片，液氮处理24小时，显示激光硬化区马氏体和残余奥氏体组织

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, SEM micrograph, treated with liquid nitrogen for 24 hours, showing martensite and retained austenite structure in the laser hardened zone.

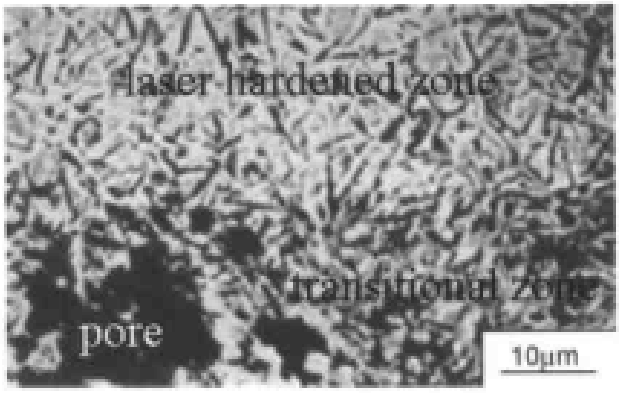

图2－12 激光相变硬化，Fe－1.0C合金(T10钢)，CO_2激光，SEM照片，显示激光硬化区和过渡区孔洞

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, SEM micrograph, showing pores in transitional zone.

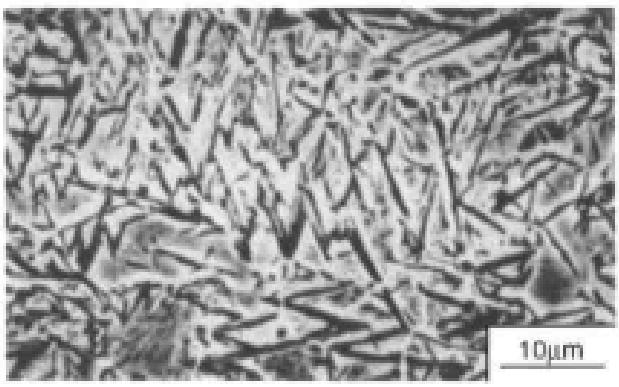

图2－13 激光相变硬化，Fe－1.0C合金(T10钢)，CO_2激光，SEM照片，显示激光硬化区马氏体

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, SEM micrograph, showing martensite structure in the laser hardened zone.

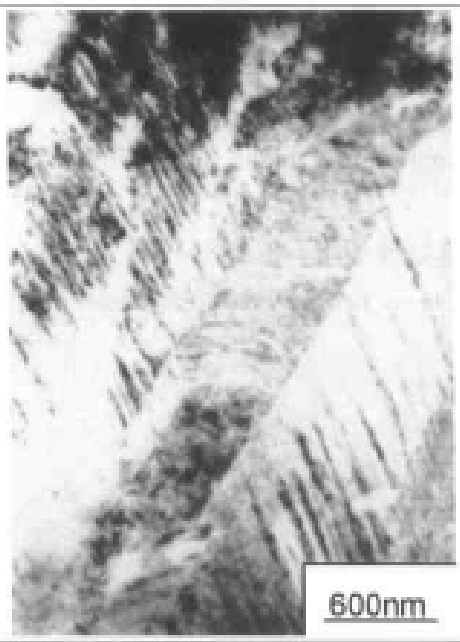

图 2－14　激光相变硬化，Fe－1.0C 合金（T10 钢），CO_2 激光，TEM 照片，显示激光硬化区孪晶组织

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, TEM micrograph, showing twinning structure in the laser hardened zone.

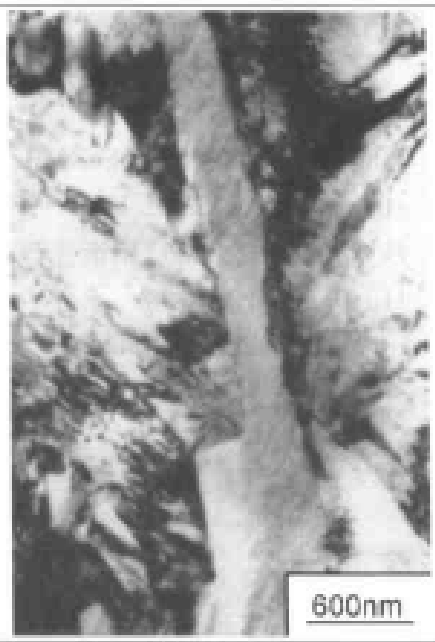

图 2－15　激光相变硬化，Fe－1.0C 合金（T10 钢），CO_2 激光，TEM 照片，显示激光硬化区组织

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, TEM micrograph, showing structure in the laser hardened zone.

图 2－16　激光相变硬化，Fe－1.0C 合金（T10 钢），CO_2 激光，TEM 照片，显示热影响区珠光体

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, TEM micrograph, showing pearlite structure in the heat affected zone.

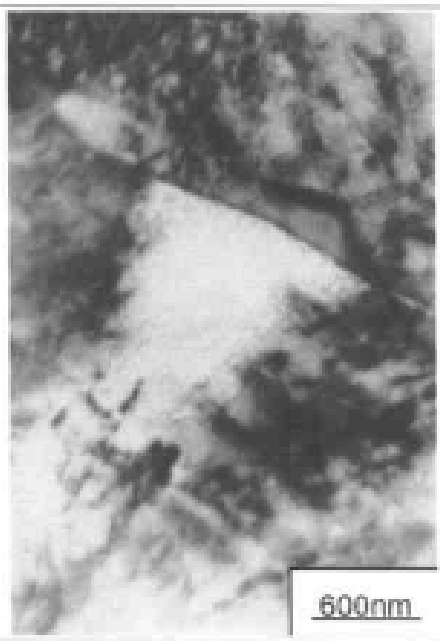

图 2－17　激光相变硬化，Fe－1.0C 合金（T10 钢），CO_2 激光，TEM 照片，显示激光硬化区细晶粒奥氏体

Laser hardening, Fe－1.0C alloy(T10 steel), CO_2 laser, TEM micrograph, showing fine austenite structure in the laser hardened zone.

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[2.3] Hu Jiandong, Li Zhang. Wear resistance of laser processed 1.0%C tool steel. Materials Science Technology, 8(1992)796

第3章　激光重熔

激光重熔（laser remelting）或者称熔凝，是指用高能激光束对金属材料表面进行快速熔化处理的一种激光加工技术，主要处理对象有铸铁、高碳钢和铝合金等。进行激光重熔时表层材料在短时间内发生熔化和快速凝固。激光重熔区可以依次分为熔化区、固态相变区和热影响区；熔化区是细小的枝晶组织，次表层包含马氏体和其他固态相变组织。经激光重熔处理的铸铁的改性层的最外层是莱氏体，硬度很高，能到 HRC54[3.1]，与其紧相连接的区域是马氏体相变硬化层。激光重熔特殊组织有铸造重熔区直径 200Å* 的超细奥氏体[3.2]和 T10 钢中的微晶及非晶组织[3.3]，激光对 Al－Si 合金的重熔处理仅有重熔层，无相变硬化层，但重熔层的枝晶组织非常细，硬度也高，这类合金中重熔区中的特殊组织有珠光体型层片状铝硅共晶[3.4]，层错[3.5]及孪晶[3.6]。

3.1　镁合金激光重熔

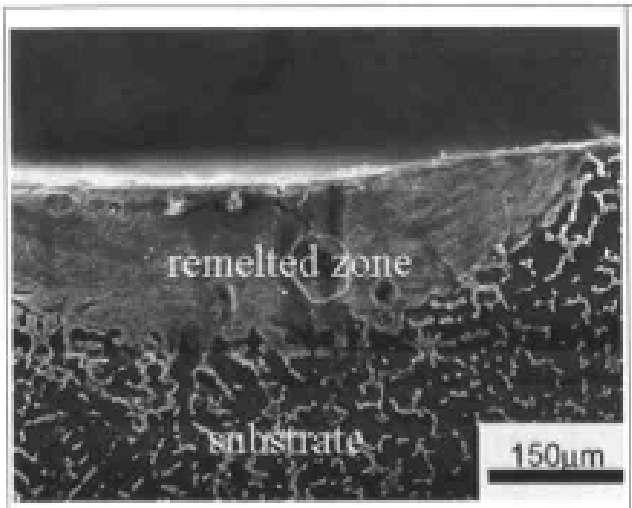

图 3－1　镁合金，激光重熔，YAG 激光，扫描速度 1.5mm/s，脉宽 4ms，频率 10Hz，能量 1.15J，显示重熔区和基体，重熔区有裂纹

Laser remelted magnesium alloy, YAG laser, showing laser melted region with cracks and substrate, scanning speed 1.5mm/s, pulse width 4ms, frequency 10Hz, power 1.15J.

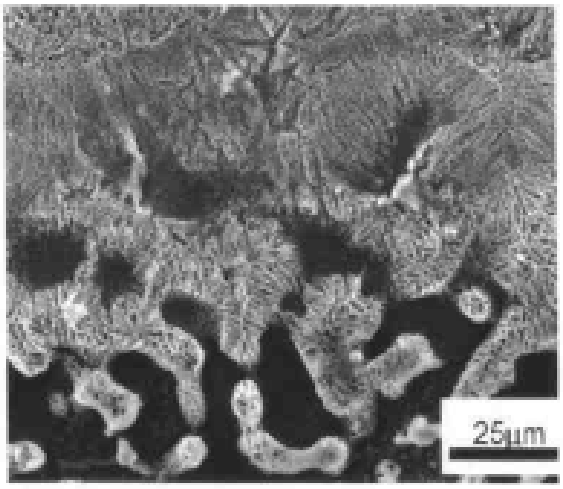

图 3－2　镁合金，激光重熔，YAG 激光，扫描速度 1.5mm/s，脉宽 4ms，频率 10Hz，能量 1.15J，显示过渡区

Laser remelted magnesium alloy, YAG laser, showing transit zone, scanning speed 1.5mm/s, pulse width 4ms, frequency 10Hz, power 1.15J.

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*：1Å＝0.1nm

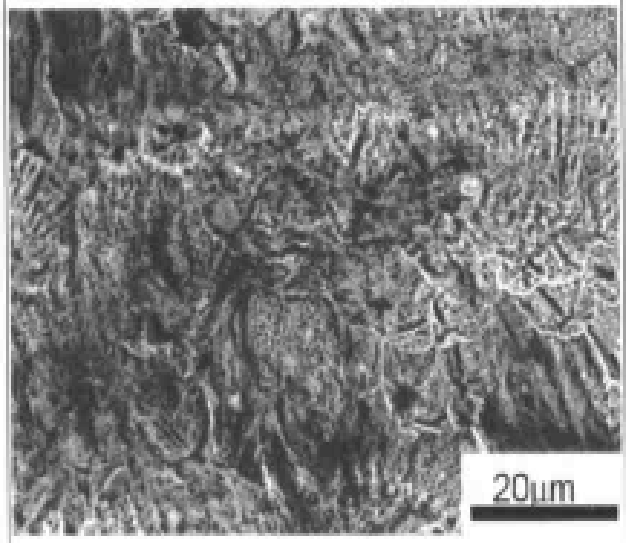

图 3－3　镁合金，激光重熔，YAG 激光，扫描速度 1.5mm/s，脉宽 4ms，频率 10Hz，能量 1.15J，显示过渡区(高倍)

Laser remelted magnesium alloy, YAG laser, showing transit zone with high magnification, scanning speed 1.5mm/s, pulse width 4ms, frequency 10Hz, power 1.15J.

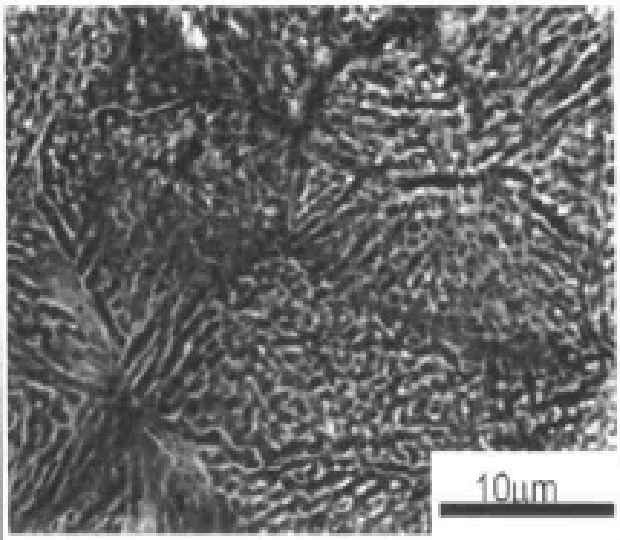

图 3－4　镁合金，激光重熔，YAG 激光，扫描速度 1.5mm/s，脉宽 4ms，频率 10Hz，能量 1.15J，显示重熔区(高倍)

Laser remelted magnesium alloy, YAG laser, showing laser melted zone with high magnification, scanning speed 1.5mm/s, pulse width 4ms, frequency 10Hz, power.

3.2　铝合金激光重熔

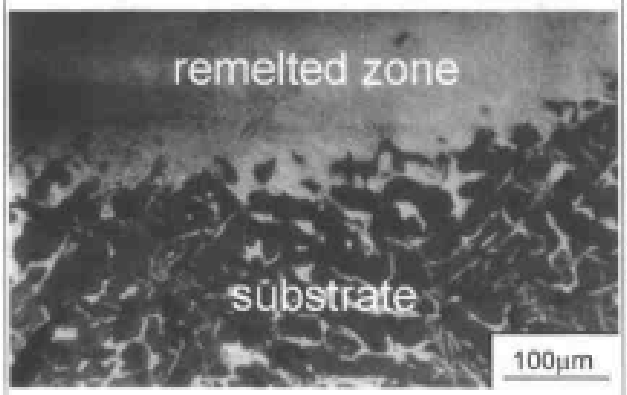

图 3－5　激光重熔，Al－12Si 合金，CO_2 激光，SEM 照片，显示重熔区(上部)和基体组织(下部)

Laser remelting, Al－12Si alloy, CO_2 laser, SEM micrograph, showing microstructure of the remelting zone (the top)and the substrate (the bottom).

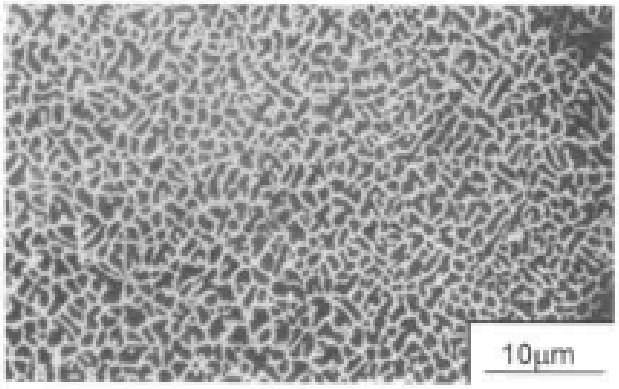

图 3－6　激光重熔，Al－12Si 合金，CO_2 激光，SEM 照片，显示重熔区枝晶结构

Laser remelting, Al－12Si alloy, CO_2 laser, SEM micrograph, showing microstructure of the dendritic in the remelting zone.

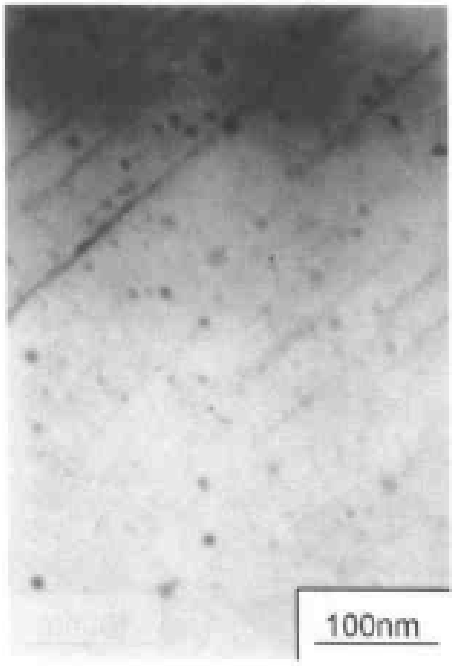

图 3－7 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，TEM 照片(明场)，显示重熔区中的 CuAl 相(条状)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (bright field), showing CuAl in laser remelted region(strip shape).

图 3－8 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，TEM 照片(暗场)，显示重熔区中的 CuAl 相(条状)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (dark field), showing CuAl in laser remelted region (strip shape).

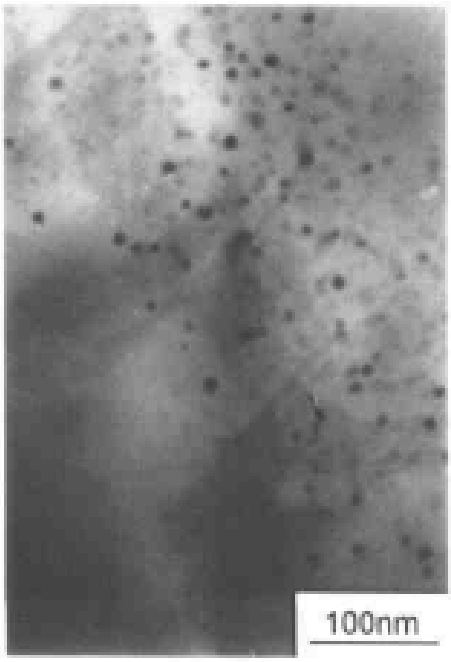

图 3－9 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，重熔区 TEM 照片(明场)，显示重熔区中的 Mg_2Si 相(球状)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (bright field), showing Mg_2Si in laser remelted region(spherical shape).

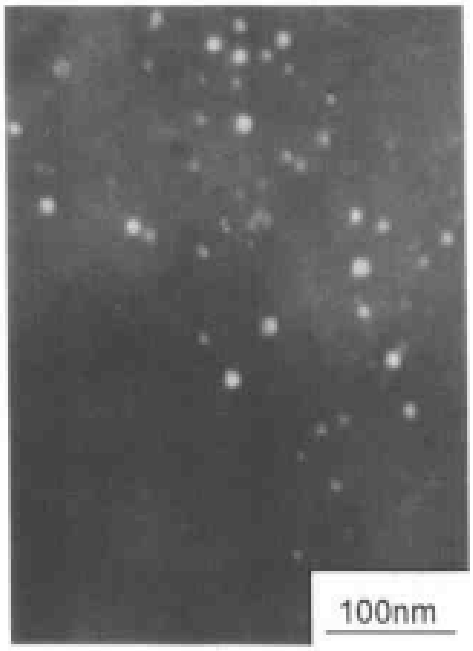

图 3－10 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re 合金，CO_2 激光，200℃时效 6 小时，TEM 照片(暗场)，显示重熔区中的Mg_2Si相(球状)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (dark field), showing Mg_2Si in laser remelted region(spherical shape).

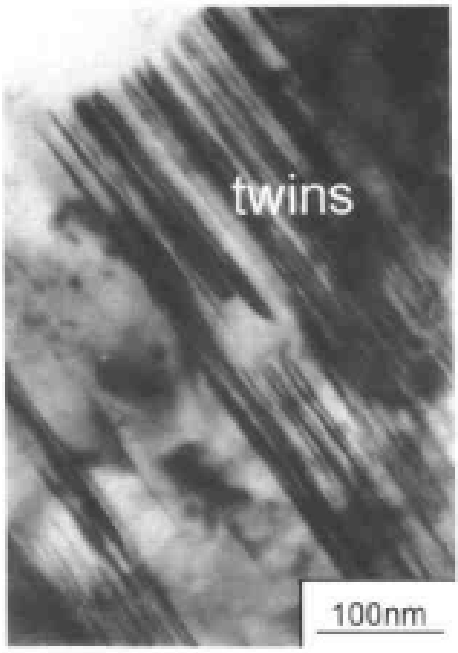

图 3－11 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，重熔区 TEM 照片(明场)，显示重熔区中的孪晶

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (bright field), showing twins in laser remelted region.

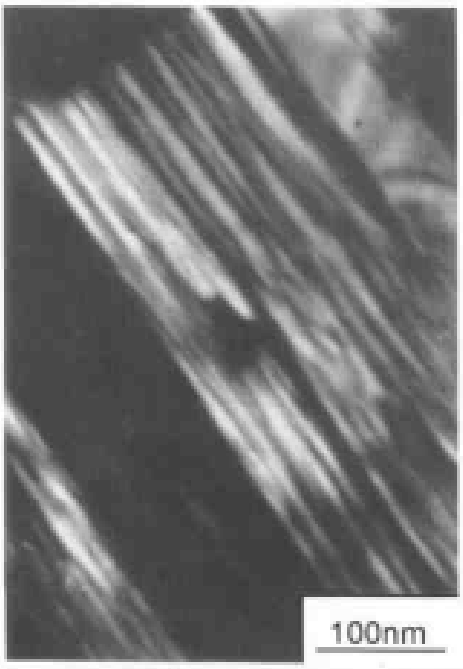

图 3－12 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，重熔区 TEM 照片(暗场)，显示重熔区中的孪晶

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (dark field), showing twins in laser remelted region.

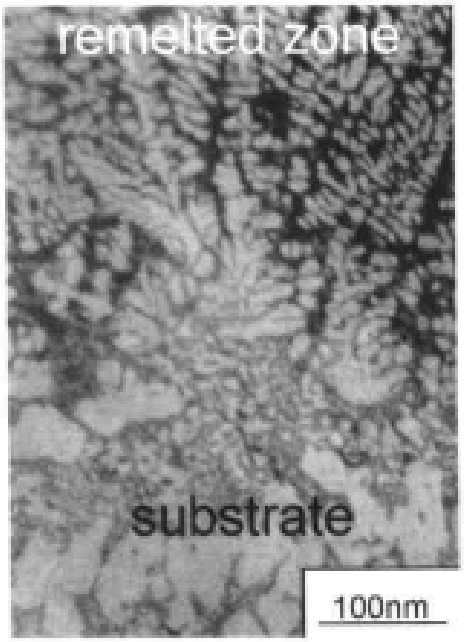

图3－13 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效6小时，重熔区照片，显示重熔区(上部)和基体(下部)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, showing the laser remelted region (the top) and the substrate (the bottom).

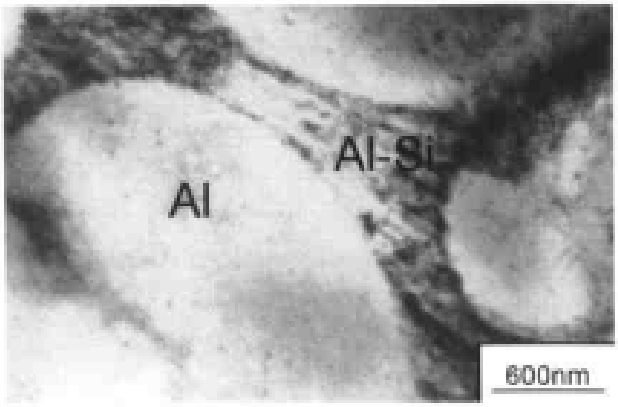

图3－14 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效6小时，重熔区 TEM 照片(箭头)，主要显示重熔区中的铝枝晶(Al)和铝硅共晶(Al－Si)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph, showing Al dendritic and Al－Si eutectic in laser remelted region.

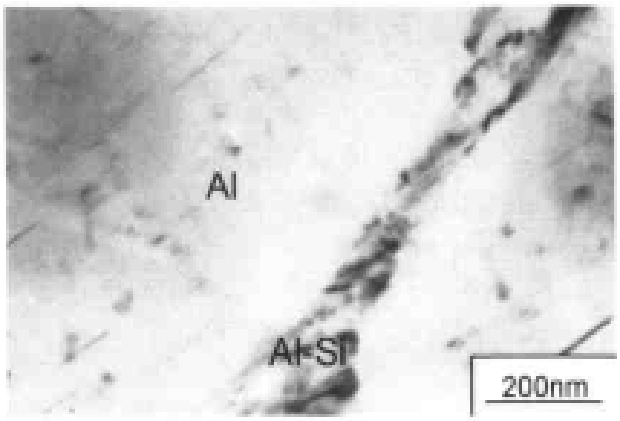

图3－15 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效6小时，重熔区 TEM 照片(高倍)，主要显示重熔区中的铝枝晶(Al)和铝硅共晶(Al－Si)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph (high modification), showing Al dendritic and Al－Si eutectic in laser remelted region.

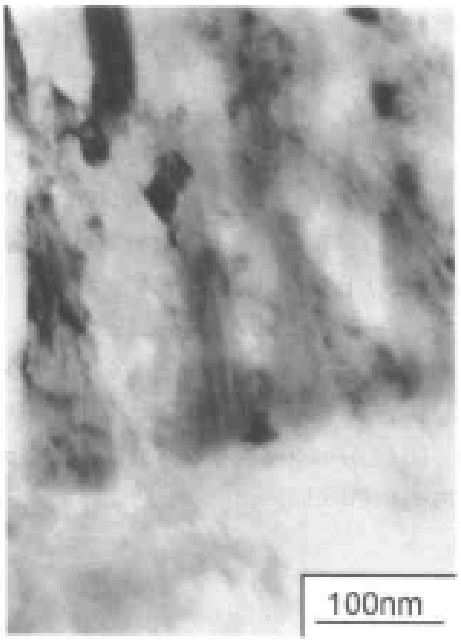

图 3－16 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，重熔区 TEM 照片，显示重熔区中的铝(下部)和铝硅共晶(上部)

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph, showing Al dendritic (the bottom) and Al－Si eutectic (the top) in laser remelted region.

图 3－17 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，重熔区 TEM 照片，显示重熔区中的层错

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph, showing stacking faults in laser remelted region.

图 3－18 激光重熔，合金成分 Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re，CO_2 激光，200℃时效 6 小时，TEM 照片，显示重熔区铝中的位错

Laser remelting, alloy composition Al－12Si－1.23Cu－1.0Fe－0.5Mn－0.93Mg－0.1Re, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph, showing dislocations in laser remelted region.

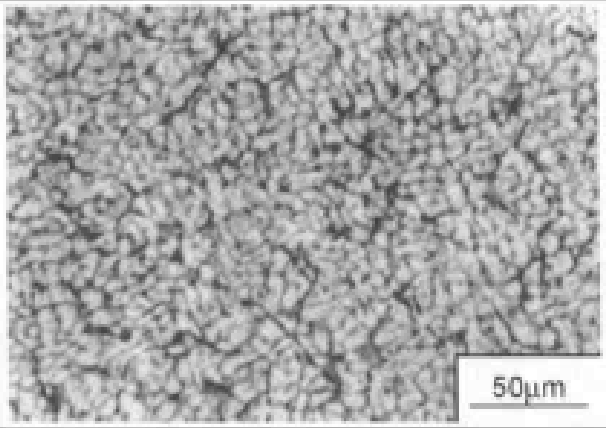

图3－19 激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C，CO_2 激光，200℃时效6小时，重熔区照片，显示重熔区组织

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C, CO_2 laser, aging at 200℃ for 6 hours, optical micrograph, showing microstructure in laser remelted region.

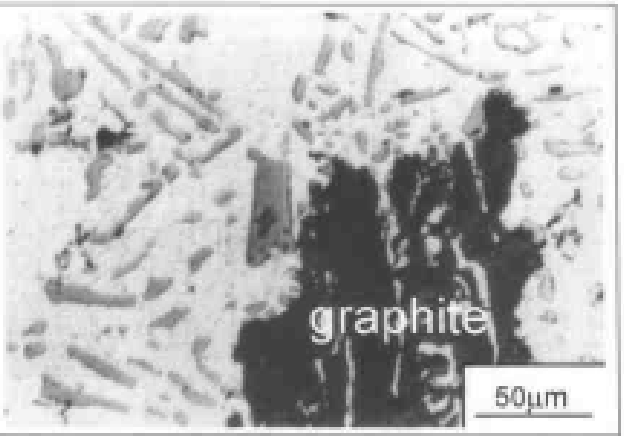

图3－20 激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C，原始组织照片

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C, optical micrograph showing substrate.

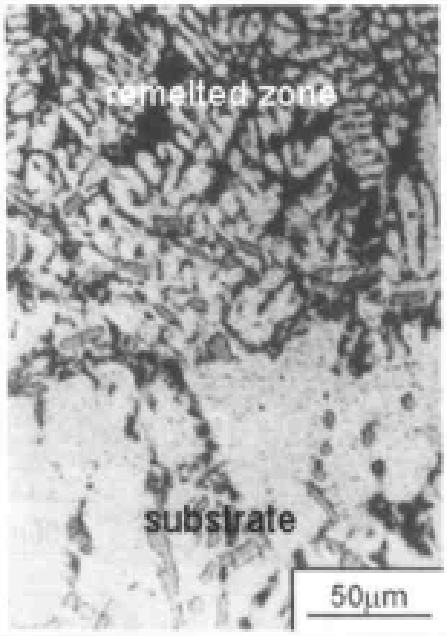

图3－21 激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C，CO_2 激光，200℃时效6小时，光学照片，显示重熔区（上部）和基体（下部）

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C, CO_2 laser, aging at 200℃ for 6 hours, optical micrograph showing the laser remelted region (the top), and the substrate (the bottom).

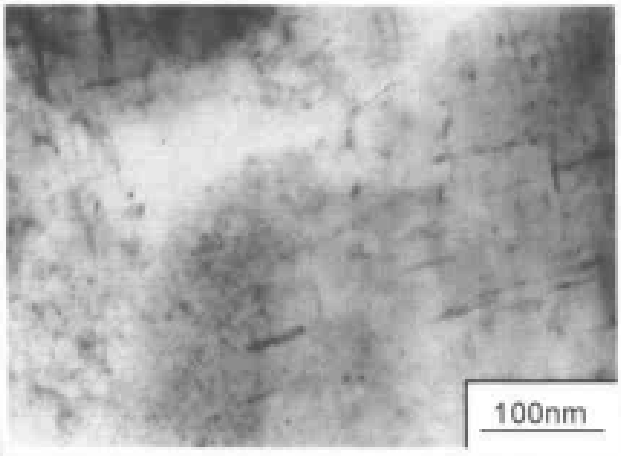

图3－22 激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C合金，CO_2 激光，200℃时效6小时，重熔区TEM照片，显示CuAl相

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C alloy, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph, showing CuAl in laser remelted region.

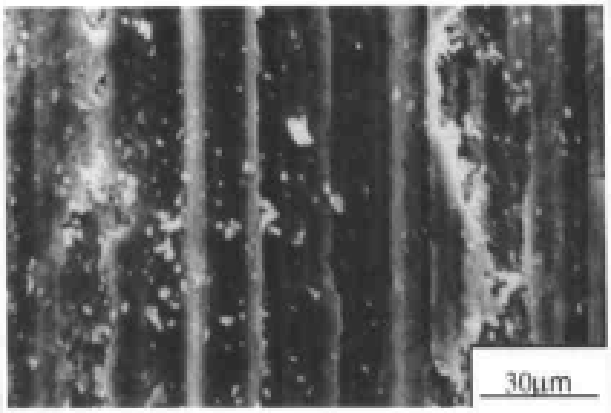

图 3－23　激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C 合金，CO_2 激光，200℃时效 6 小时，磨痕形貌，SEM 照片，磨损载荷 90N

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C alloy, CO_2 laser, aging at 200℃ for 6 hours, worn surface morphology, SEM micrograph, load 90N.

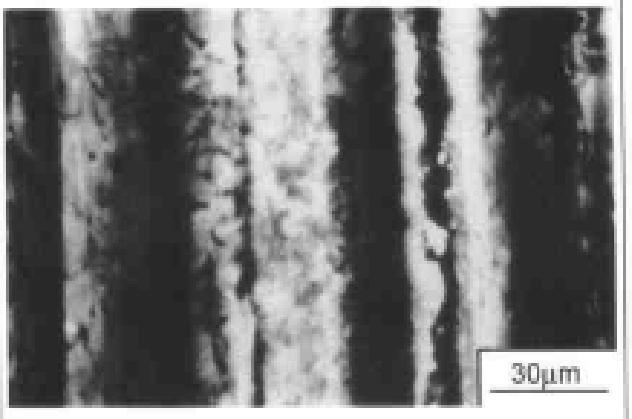

图 3－24　激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C 合金，CO_2 激光，200℃时效 6 小时，磨痕形貌，SEM 照片，磨损载荷 120N

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C alloy, CO_2 laser, aging at 200℃ for 6 hours, worn surface morphology, SEM micrograph, load 120N.

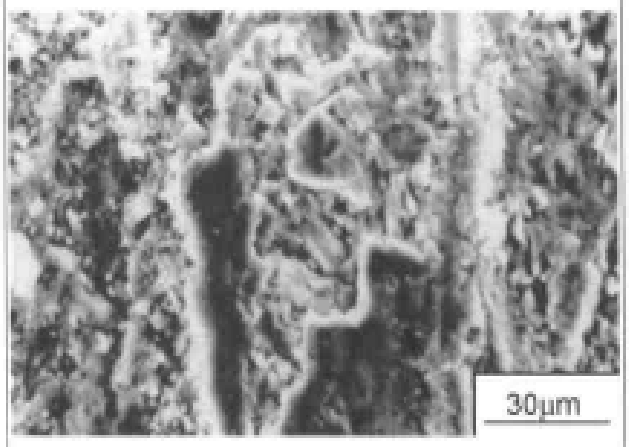

图 3－25　激光重熔，合金成分 Al－13％Si－0.88％Cu－1.0％Fe－0.5％Mn－1.13％Mg－0.85％Ni－0.07％Ti－1.55Graphite 合金，CO_2 激光，200℃时效 6 小时，磨痕形貌，SEM 照片，磨损载荷 150N

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C alloy, CO_2 laser, aging at 200℃ for 6 hours, worn surface morphology, SEM micrograph, load 150N.

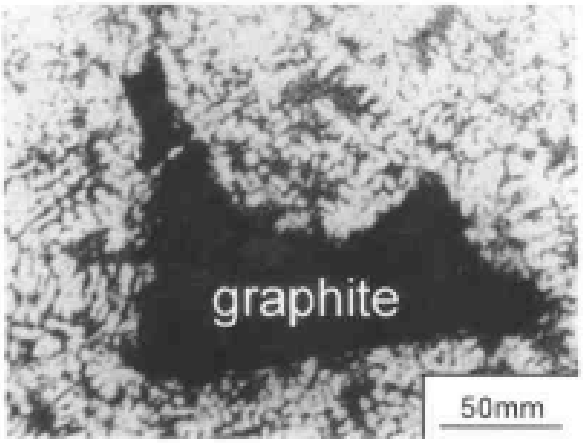

图 3－26　激光重熔，合金成分 Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C，CO_2 激光，200℃时效 6 小时，重熔区照片，显示重熔区中的枝晶和石墨

Laser remelting, alloy composition Al－13Si－0.88Cu－1.0Fe－0.5Mn－1.13Mg－0.85Ni－0.07Ti－1.55C, CO_2 laser, aging at 200℃ for 6 hours, TEM micrograph, showing dentrities and graphite in laser remelted region.

3.3　铸铁激光重熔

3.3.1　灰铸铁激光重熔

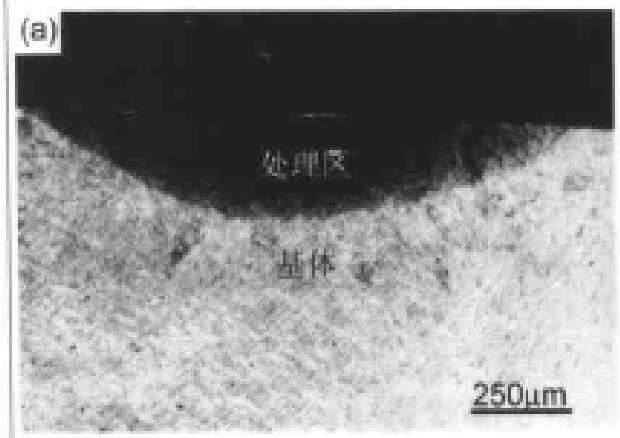

图 3－27　激光重熔，灰铸铁，CO_2 激光，功率 1200W，扫描速度 40mm/s

Laser remolting，grey cast iron，CO_2 laser，power 1200W，scanning speed 40mm/s.

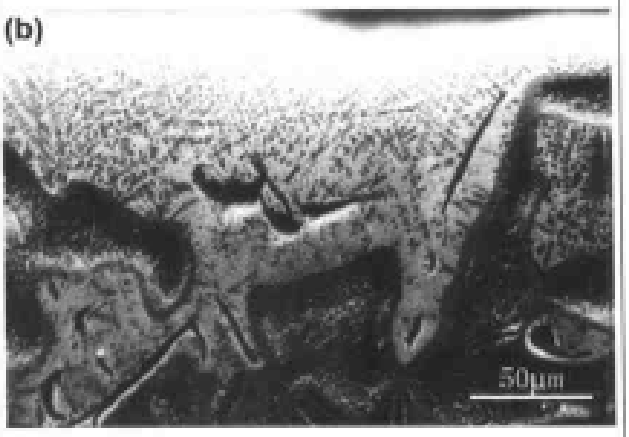

图 3－28　激光重熔，灰铸铁，CO_2 激光，功率 1400W，扫描速度 35mm/s

Laser remolting，grey cast iron，CO_2 laser，power 1400W，scanning speed 35mm/s.

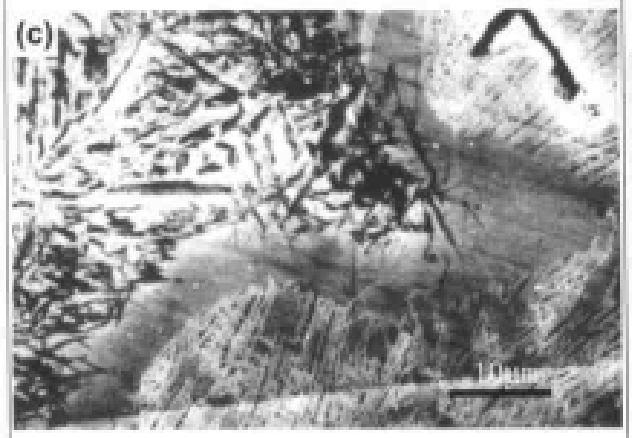

图 3－29　激光重熔，灰铸铁，CO_2 激光，功率 1300W，扫描速度 40mm/s

Laser remolting，grey cast iron，CO_2 laser，power 1300W，scanning speed 40mm/s.

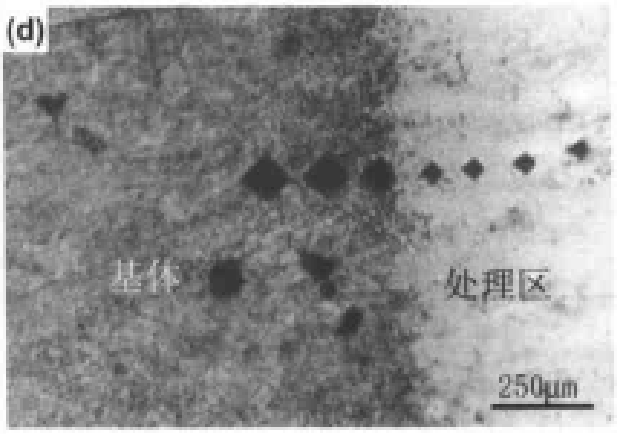

图 3－30　激光重熔，灰铸铁，CO_2 激光，功率 1300W，扫描速度 40mm/s

Laser remolting，grey cast iron，CO_2 laser，power 1300W，scanning speed 40mm/s.

3.3.2 可锻铸铁激光重熔

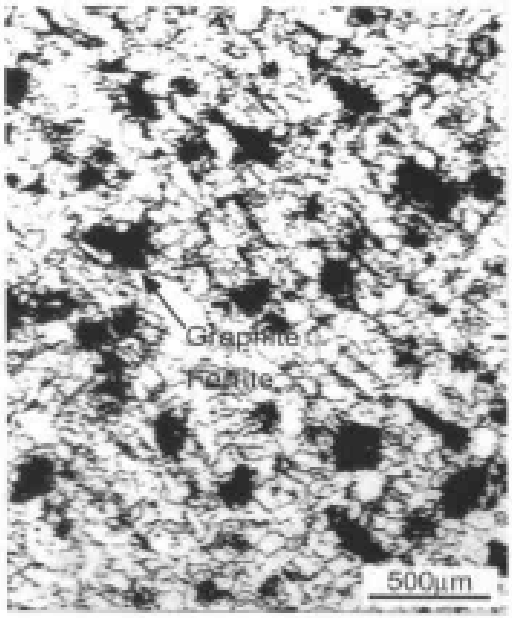

图 3－31 激光重熔，可锻铸铁(KT35－10)，显示原始组织

Laser remelting, ductile cast iron (KT35－10), substrate used for laser melting treatment (optical micrograph).

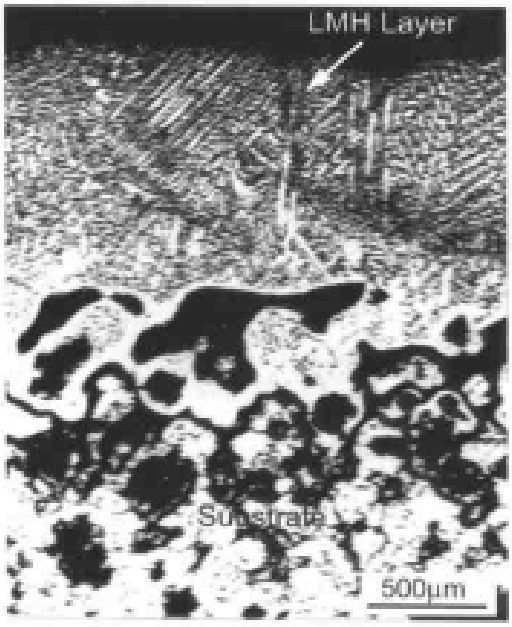

图 3－32 激光重熔，可锻铸铁(KT35－10)，CO_2 激光，激光功率 1500W，焦距 400mm，扫描速度 9mm/s，光学照片，显示重熔区和基体

Laser remelting, ductile cast iron (KT35－10), CO_2 laser, power 1500W, focus distance 400mm, scanning speed 9mm/s, optical micrograph, showing laser melting hardening zone (LMH) and substrate.

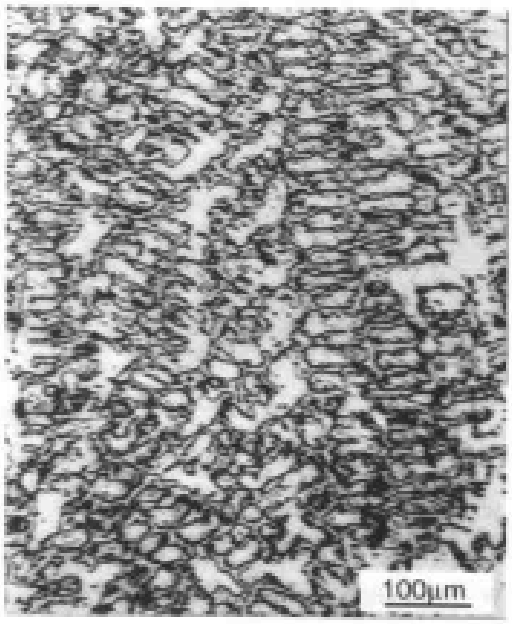

图 3－33 激光重熔，可锻铸铁(KT35－10)，CO_2 激光，激光功率 1500W，焦距 400mm，扫描速度 9mm/s，光学照片，显示重熔区组织(高倍)

Laser remelting, ductile cast iron (KT35－10), CO_2 laser, power 1500W, focus distance 400mm, scanning speed 9mm/s, optical micrograph, showing laser melting hardening zone (LMH) in high magnification.

3.3.3 球墨铸铁激光重熔

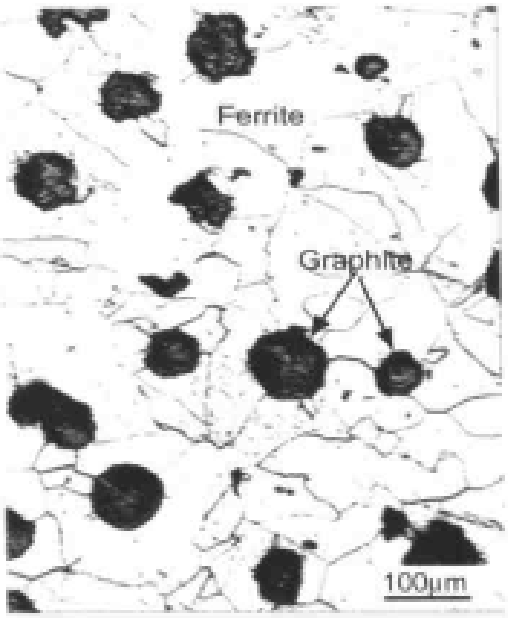

图3－34 激光重熔，球墨铸铁(QT400－15)，CO_2 激光，激光功率1500W，焦距400mm，扫描速度9mm/s，光学照片，显示原始组织

Laser remelting, ductile cast iron (QT400－15), substrate used for laser melting treatment (optical micrograph).

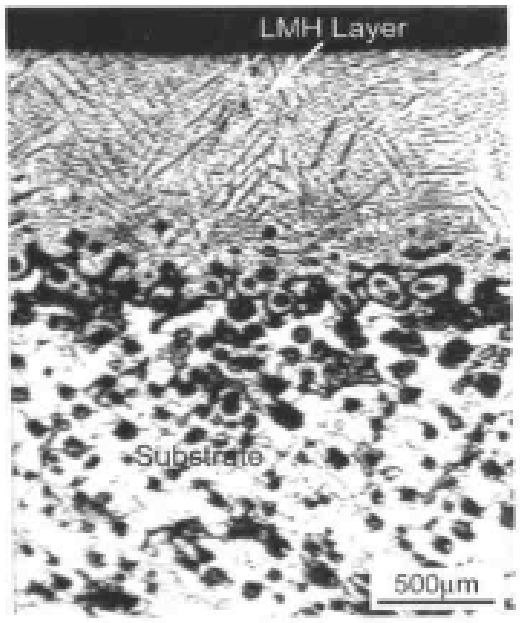

图3－35 激光重熔，球墨铸铁(QT400－15)，CO_2 激光，激光功率1500W，焦距400mm，扫描速度9mm/s，光学照片，显示重熔区和基体

Laser remelting, ductile cast iron (QT400－15), CO_2 laser, power 1500W, focus distance 400mm, scanning speed 9mm/s, optical micrograph, showing laser melting hardening zone (LMH) and substrate.

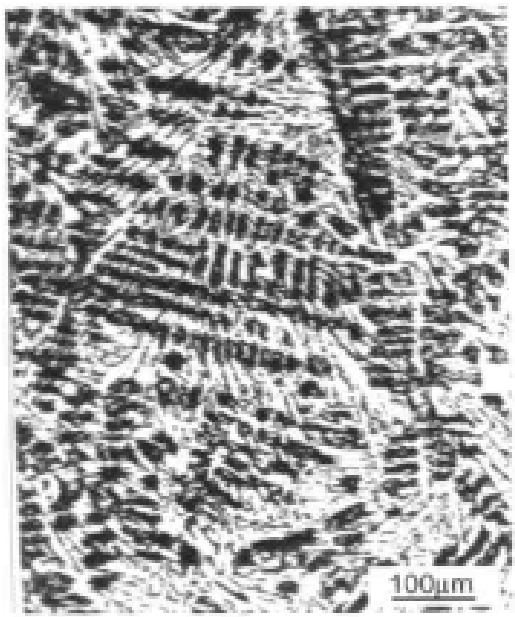

图3－36 激光重熔，球墨铸铁(QT400－15)，CO_2 激光，激光功率1500W，焦距400mm，扫描速度9mm/s，光学照片，显示重熔区组织(高倍)

Laser remelting, ductile cast iron (QT400－15), CO_2 laser, power 1500W, focus distance 400mm, scanning speed 9mm/s, optical micrograph, showing laser melting hardening zone (LMH) in high magnification.

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[3.4] Hu Jiandong, Li Yongbing, Li Zhang. Pearlite—eutectic of Zl 108 aluminium—silicon alloy containing rare—earth elements rapidly solidified by laser. Journal of Materials Science Letters, 1990(9): 587

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第4章　激光熔覆

激光熔覆(laser coating/cladding)是用高能量激光束对材料表面进行合金化的一种激光加工工艺，其特点是被加热材料在发生熔化的同时也发生化学成分变化。在激光熔覆时发生传热、原子传输、液体金属的流动及结晶等复杂化学和物理现象。激光熔覆的工艺参数有：激光功率、扫描速度（标志激光材料的作用时间）和涂层成分等。激光熔覆是通过熔化把熔覆材料和基体材料结合起来[4.1]，常用的熔覆材料如表4—1所示。

表4—1　常用熔覆材料成分及用途

材料名称	粒度范围（目）	化学成分（%）	硬度（HRC）	用　途
镍基合金粉末 Ni60	−140/+250	Cr13−15，B23，Si2.83，Ni余量	55～65	用于机械，易损件、耐磨性好
镍基合金粉末 Ni35	−140/+250	Cr1011，B23，Si2.83，Ni余量	30～40	用于硬质合金刀具、各种模具
镍包铝覆合粉末	−140/+250	Al1720.0，Ni余量 杂质（1.0）		与基体形成微扩散、微焊接
钴基合金粉末	−100/+325	Cr30，W12.5，Ni3.0 C2.5，Co余量	40～48	用于高温阀门、阀座及链锯导板
镍基合金粉末	−140/+320	Cr30，W6.0，Ni3.0 Fe5，C1，Co余量	30～38	用于各种热锻模具表面涂敷

可以采用自动送粉或是在待处理材料表面预先敷设涂覆材料的方式实现激光熔覆。前者称为自动送粉激光熔覆；后者为预置法激光熔覆。采用预置法进行激光熔覆时，需要粘结剂，它的选择直接影响到材料的熔覆效果。常用的粘结剂有松香丙酮溶液、水玻璃、醋酸纤维素等，激光辐照水玻璃时产生大量烟气，对激光器镜头危害较大，尽量不采用。用松香丙酮溶液作粘结剂时，熔敷层中没有残留物且辐照时烟气较小。

激光熔覆要求的功率较高，一般在2kW以上为宜。激光光斑形状和尺寸是影响激光熔覆效果的重要工艺参数，大尺寸光斑可以获得大面积熔覆区，具有高能量密度的宽带矩形光斑最适合激光熔覆。过高的功率密度和缓慢的扫描速度会导致熔覆材料烧损或飞溅，无法形成优良的熔覆层。

金属材料经过激光熔覆以后，组织结构较常规组织有明显变化，组织应力和热应力也非常大，容易产生组织缺陷。下面的图片涉及激光熔覆区的组织形貌。

注：本章中的大部分图片是由栾景飞、姚远和杨悦的博士论文提供的，在此对他们表示感谢。

4.1 铝合金激光熔覆

4.1.1 铝合金/镁激光熔覆

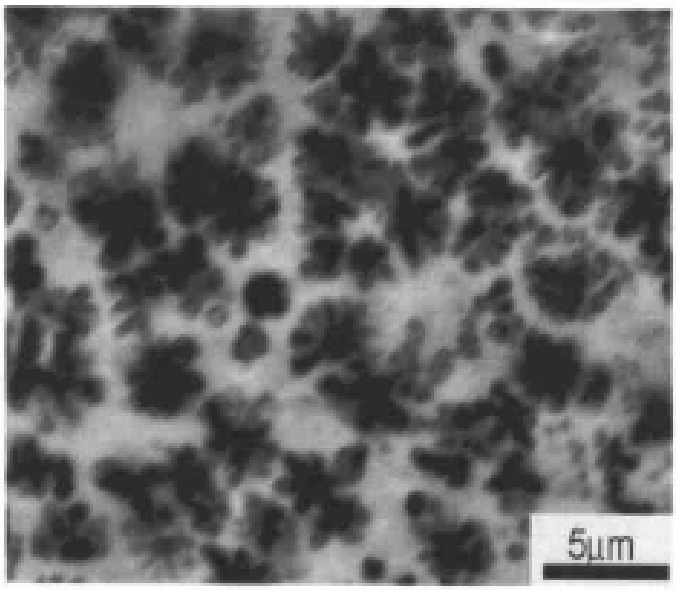

图 4－1 激光熔覆，Al－Mg 熔覆材料，Mg 合金基体，YAG 激光，显示熔覆区，扫描速度 2.5mm/s，脉宽 3ms，10Hz，能量 0.61J

Laser cladding of Al－Mg on Mg alloy，YAG laser，scanning speed 2.5mm/s，pulse width 3ms，10Hz，power 0.61J.

4.1.2 铝合金/钛-碳-铝激光熔覆

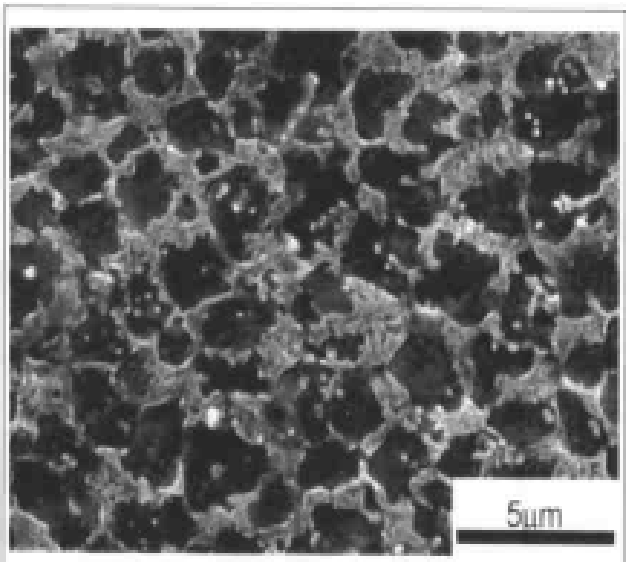

图 4－2 激光熔覆，Ti－C－Al 熔覆材料，铝合金基体，YAG 激光

Laser cladding of Ti－C－Al on aluminum，YAG laser.

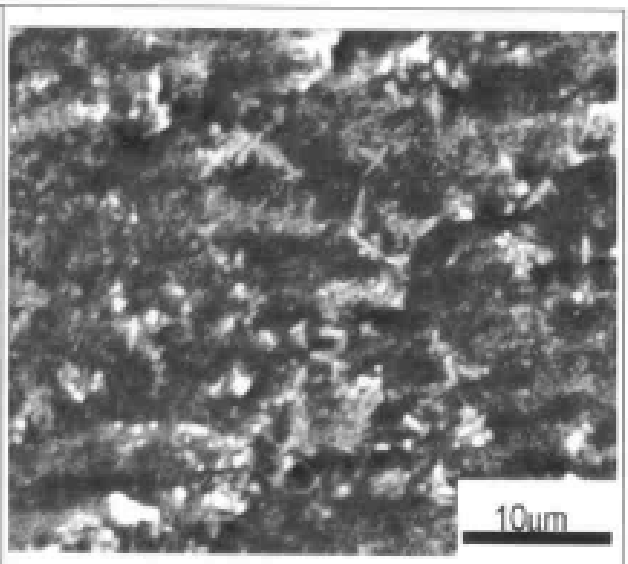

图 4－3 激光熔覆，Ti－C－Al 熔覆材料，铝合金基体，YAG 激光

Laser cladding of Ti－C－Al on aluminum，YAG laser.

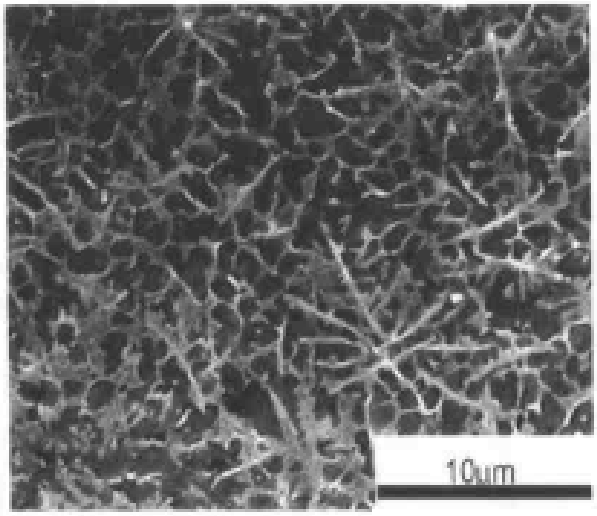

图 4－4　激光熔覆，Ti－C－Al 熔覆材料，铝合金基体，YAG 激光
Laser cladding of Ti－C－Al on aluminum，YAG laser.

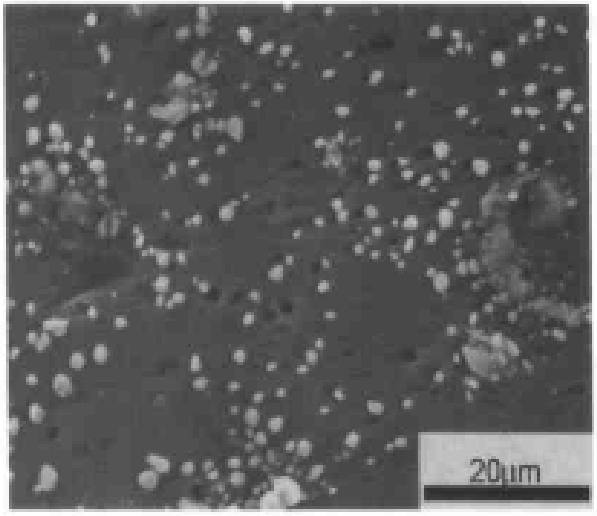

图 4－5　激光熔覆，Ti－C－Al 熔覆材料，铝合金基体，YAG 激光
Laser cladding of Ti－C－Al on aluminum，YAG laser.

4.1.3　铝合金/镍激光熔覆

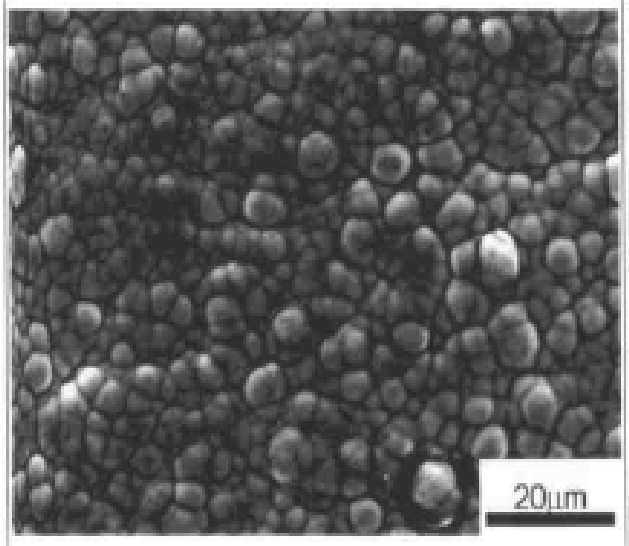

图 4－6　激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示表面形貌，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，能量 8.43J
Laser alloying of Ni on Al alloy，YAG laser，SEM micrograph，showing treated surface，scanning speed 2.5mm/s，pulse width 4ms，frequency 8Hz，power 8.43J.

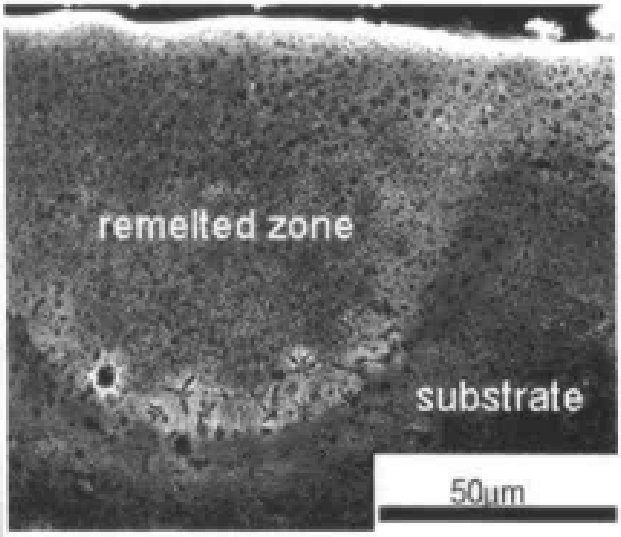

图 4－7　激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示熔覆形貌，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，能量 8.43J
Laser alloying of Ni on Al alloy，YAG laser，SEM micrograph，showing the coated region in cross section，scanning speed 2.5mm/s，pulse width 4ms，frequency 8Hz，power 8.43J.

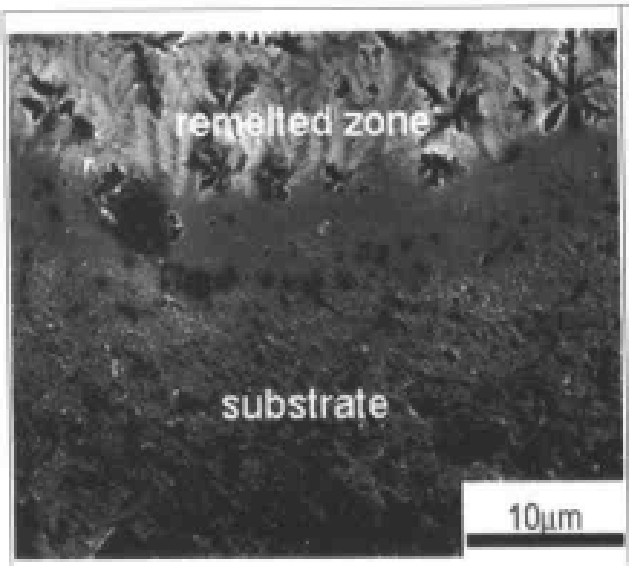

图 4－8 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示熔覆形貌，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，能量 8.43J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing the coated region in cross section, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power 8.43J.

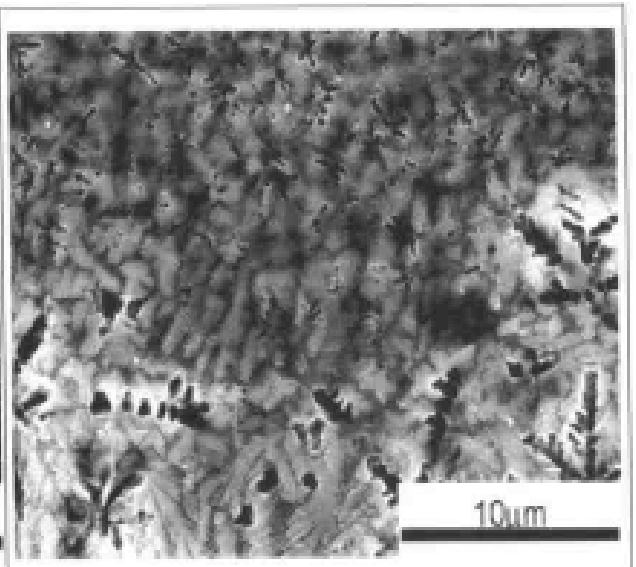

图 4－9 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示熔覆形貌，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，能量 8.43J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing the coated region in cross section, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power 8.43J.

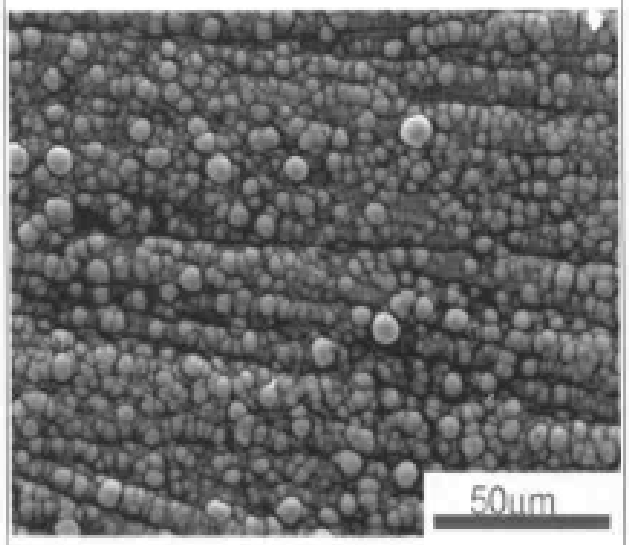

图 4－10 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示表面形貌，扫描速度 0.5mm/s，脉宽 1ms，频率 5Hz，能量 0.34J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing treated surface, scanning speed 0.5mm/s, pulse width 1ms, frequency 5Hz, power 0.34J.

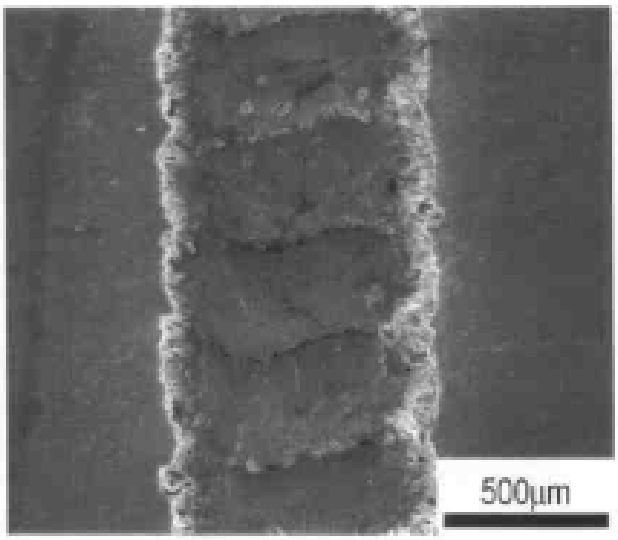

图 4－11 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示连续多脉冲形貌，扫描速度 2.0mm/s，脉宽 4ms，频率 8Hz，能量 7.18J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for continual multi pulses, scanning speed 2.0mm/s, pulse width 4ms, frequency 8Hz, power 7.18J.

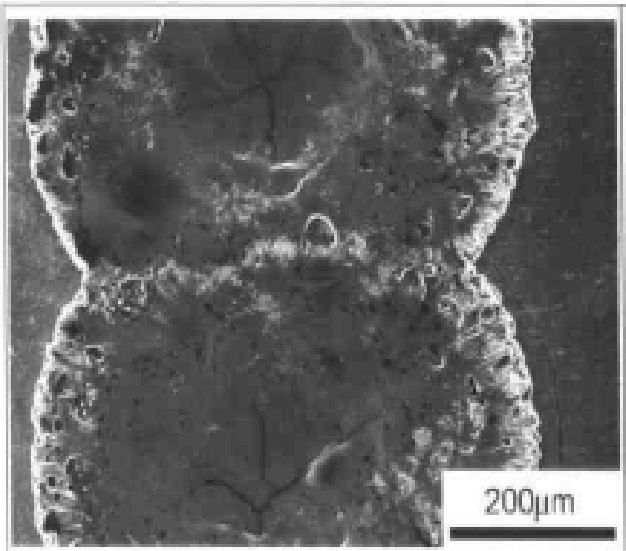

图 4－12　激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示连续多脉冲形貌，中心部有裂纹，扫描速度 3.5mm/s，脉宽 4ms，频率 8Hz，能量 6.03J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for continual multi pulses, cracks in center, canning speed 3.5mm/s, pulse width 4ms, frequency 8Hz, power 6.03J.

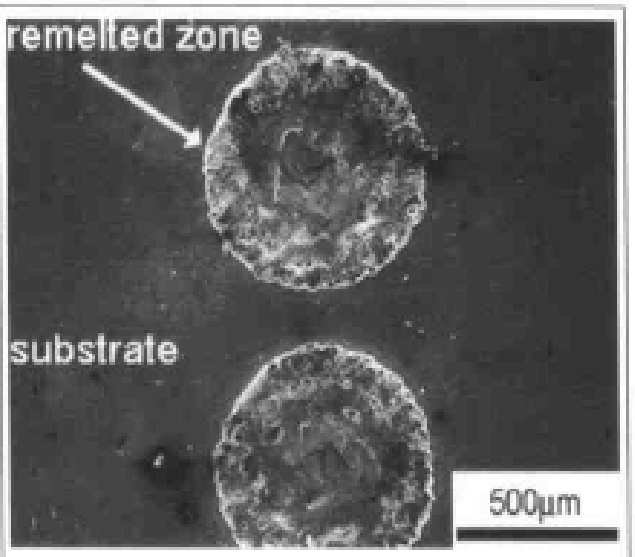

图 4－13　激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示单脉冲形貌，扫描速度 4.5mm/s，脉宽 4ms，频率 8Hz，能量 5.14J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for single pulses, scanning speed 4.5mm/s, pulse width 4ms, frequency 8Hz, power 5.14J.

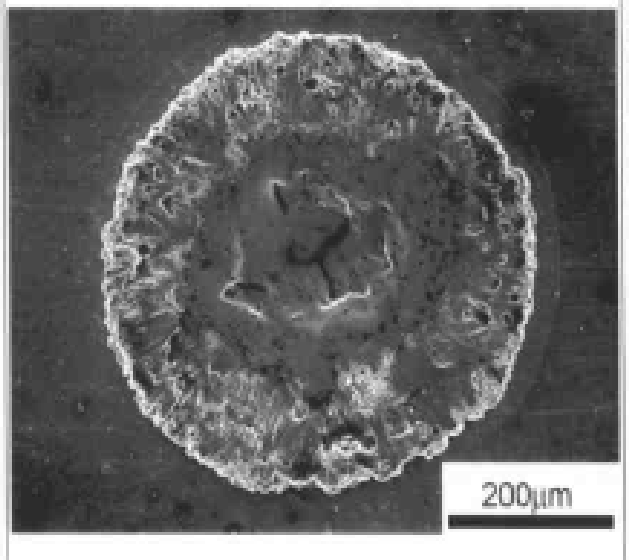

图 4－14　激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示单脉冲形貌，扫描速度 6.0mm/s，脉宽 4ms，频率 8Hz，能量 3.90J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for single pulse, scanning speed 6.0mm/s, pulse width 4ms, frequency 8Hz, power 3.90J.

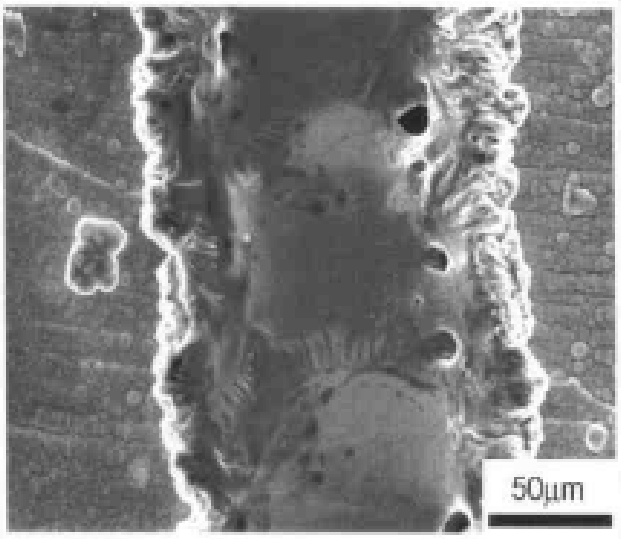

图 4－15　激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示连续多脉冲形貌，扫描速度 4.0mm/s，脉宽 4ms，频率 8Hz，能量 7.18J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for continual multi pulses, scanning speed 4.0mm/s, pulse width 4ms, frequency 8Hz, power 7.18J.

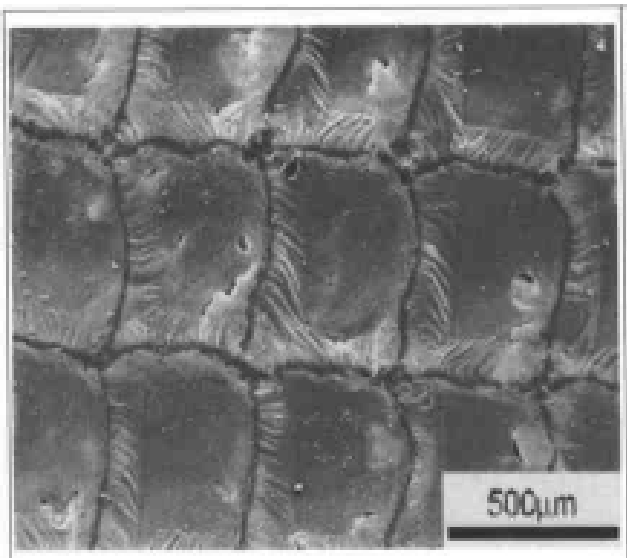

图 4－16 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示连续多脉冲形貌，扫描速度 4.0mm/s，脉宽 4ms，频率 5Hz，能量 0.742J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for continual multi pulses, scanning speed 4.0mm/s, pulse width 4ms, frequency 5Hz, power 0.742J.

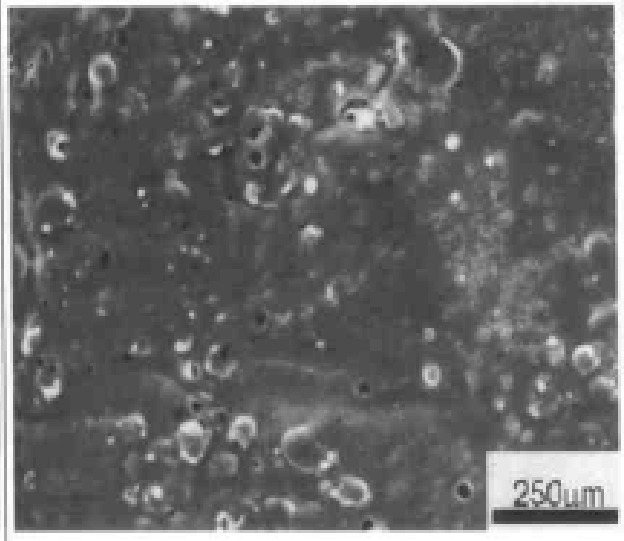

图 4－17 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示表面形貌，扫描速度 0.25mm/s，脉宽 1ms，频率 5Hz，能量 0.685J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing treated surface, scanning speed 0.25mm/s, pulse width 1ms, frequency 5Hz, power 0.685J.

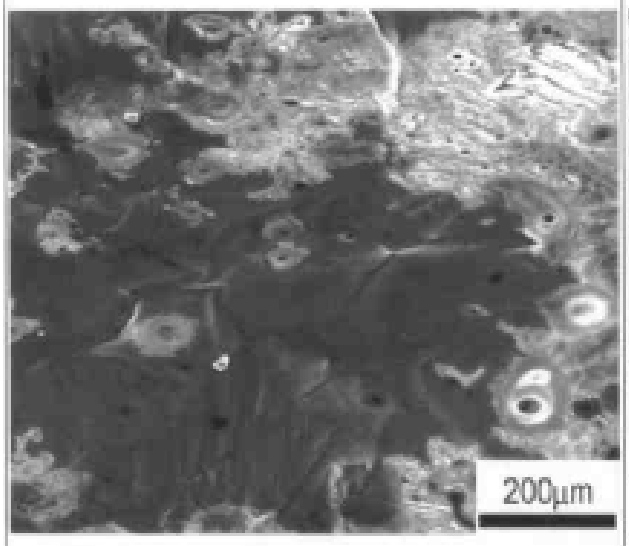

图 4－18 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示表面形貌，中心部有裂纹和气孔，扫描速度 4.0mm/s，脉宽 4ms，频率 8Hz，能量 8.43J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing treated surface, cracks and pores in center, scanning speed 4.0mm/s, pulse width 4ms, frequency 8Hz, power 8.43J.

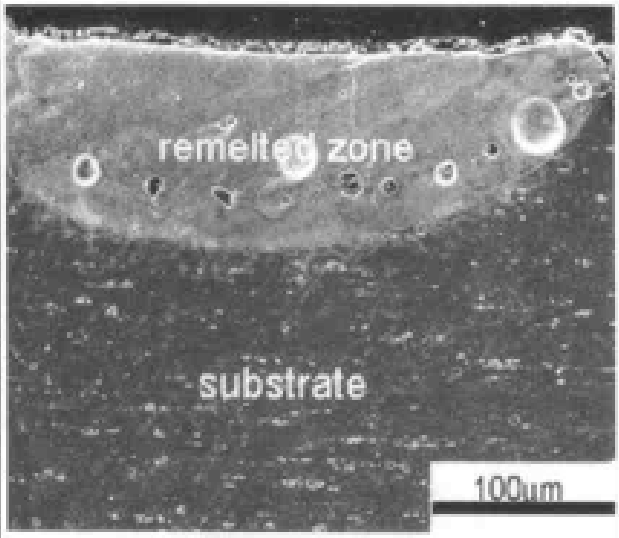

图 4－19 激光熔覆，铝基体，镍熔覆材料，YAG 激光，SEM 照片，显示熔覆形貌，有裂纹和气孔，扫描速度 0.5mm/s，脉宽 1ms，频率 5Hz，能量 0.148J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing the coated region in cross section, cracks and pores, scanning speed 0.5mm/s, pulse width 1ms, frequency 5Hz, power 0.148J.

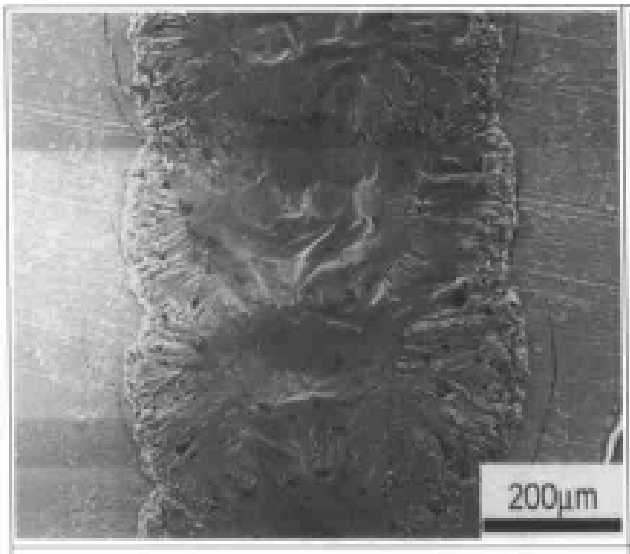

图4—20 激光熔覆,铝基体,镍熔覆材料,YAG激光,SEM照片,显示连续多脉冲形貌,热影响区有裂纹,扫描速度4.0mm/s,脉宽4ms,频率8Hz,能量8.43J

Laser alloying of Ni on Al alloy, YAG laser, SEM micrograph, showing morphology for continual multi pulses with cracks in HAZ, scanning speed 4.0mm/s, pulse width 4ms, frequency 8Hz, power 8.43J.

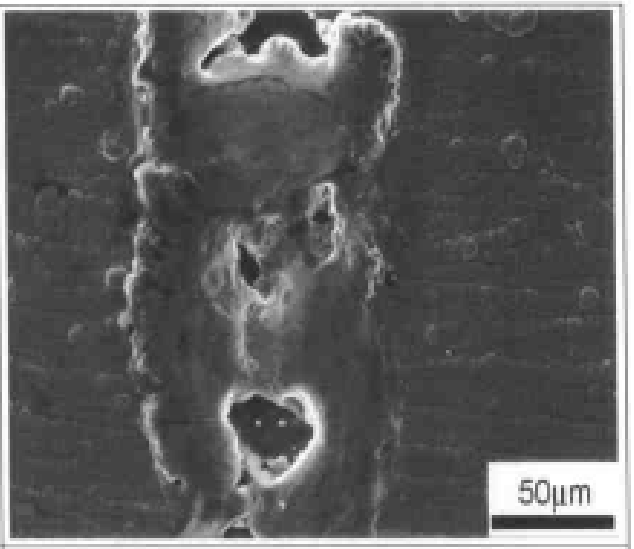

图4—21 激光熔覆,铝基体,镍熔覆材料,YAG激光,SEM照片,显示熔覆表面形貌层和孔洞,多脉冲,搭接,扫描速度4.0mm/s,脉宽4ms,频率8Hz,能量3.9J

Laser coated Al with Ni, SEM microphotograph, showing, surface morphology and holes, scanning speed 4.0mm/s, pulse width 4ms, frequency 8Hz, power 3.9J.

4.1.4 铝合金/镍激光熔覆透射电镜

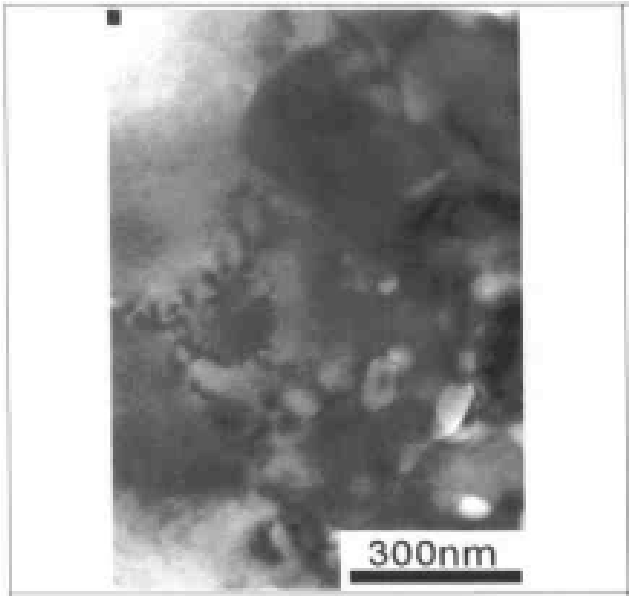

图4—22 激光熔覆,铝基体,镍熔覆材料,YAG激光,TEM照片,显示析出相,扫描速度2.5mm/s,脉宽4ms,频率8Hz,功率密度6.46×10^9 W/m²

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power 6.46×10^9 W/m².

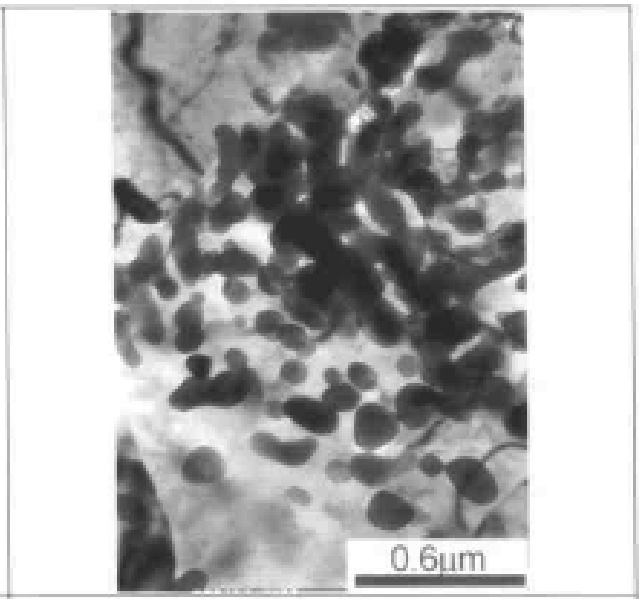

图4—23 激光熔覆,铝基体,镍熔覆材料,YAG激光,TEM照片,显示析出相,扫描速度2.5mm/s,脉宽4ms,频率8Hz,功率密度5.36×10^9 W/m²

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power 5.36×10^9 W/m².

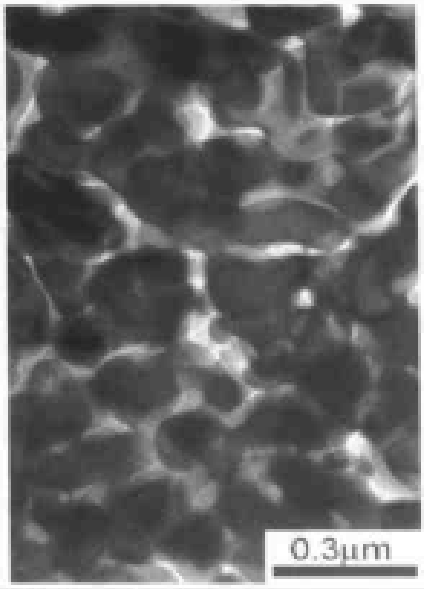

图 4－24 激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

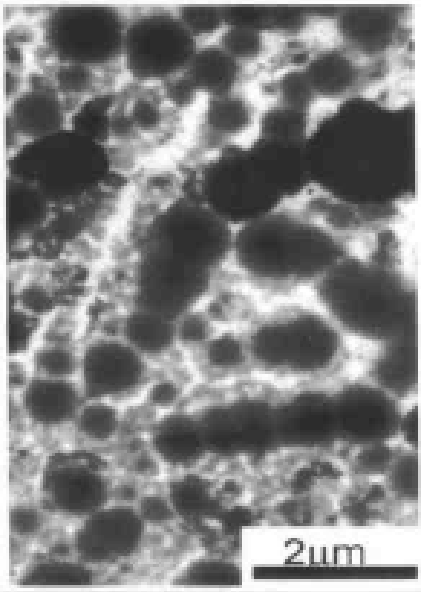

图 4－25 激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $6.46\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $6.46\times10^{9}\ W/m^{2}$.

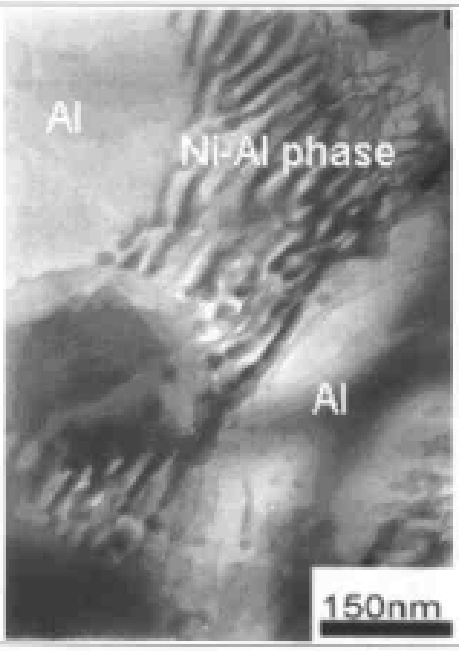

图 4－26 激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

图 4－27 激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

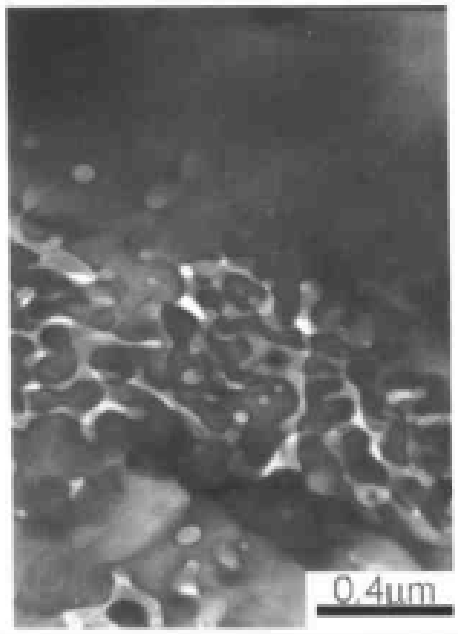

图 4－28　激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

图 4－29　激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示铝中的位错，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing dislocations in laser coated Al, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

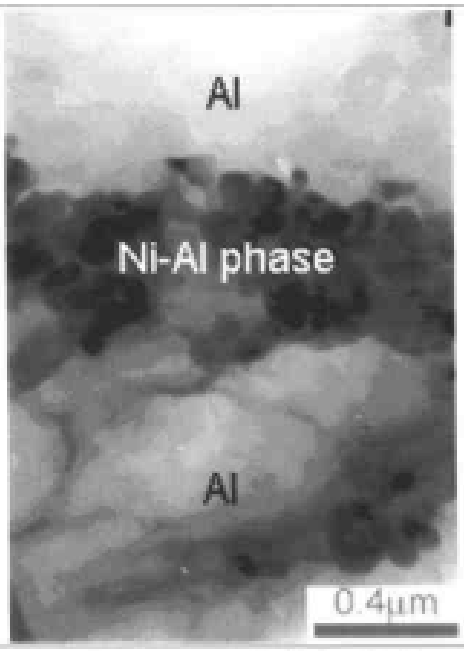

图 4－30　激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s 脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

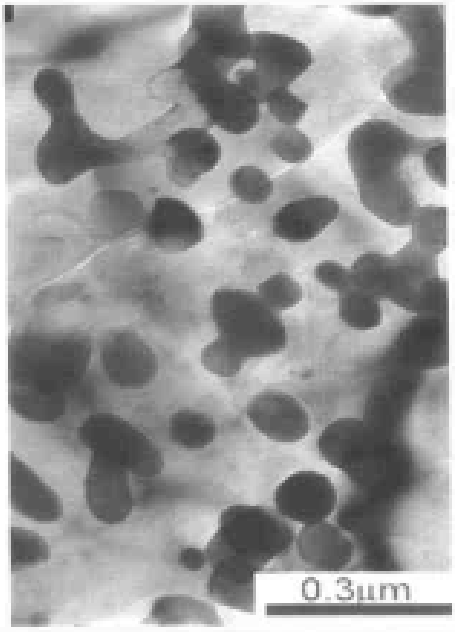

图 4－31　激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s 脉宽 4ms，频率 8Hz，功率密度 $5.36\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $5.36\times10^{9}\ W/m^{2}$.

图 4－32 激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $6.46\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $6.46\times10^{9}\ W/m^{2}$.

图 4－33 激光熔覆，铝基体，镍熔覆材料，YAG 激光，TEM 照片，显示析出相和位错，扫描速度 2.5mm/s，脉宽 4ms，频率 8Hz，功率密度 $6.46\times10^{9}\ W/m^{2}$

Laser coated Al with Ni, TEM micrograph, showing precipitates and dislocations in laser coated region, scanning speed 2.5mm/s, pulse width 4ms, frequency 8Hz, power $6.46\times10^{9}\ W/m^{2}$.

4.2 镁合金激光熔覆

4.2.1 镁合金/铝激光熔覆

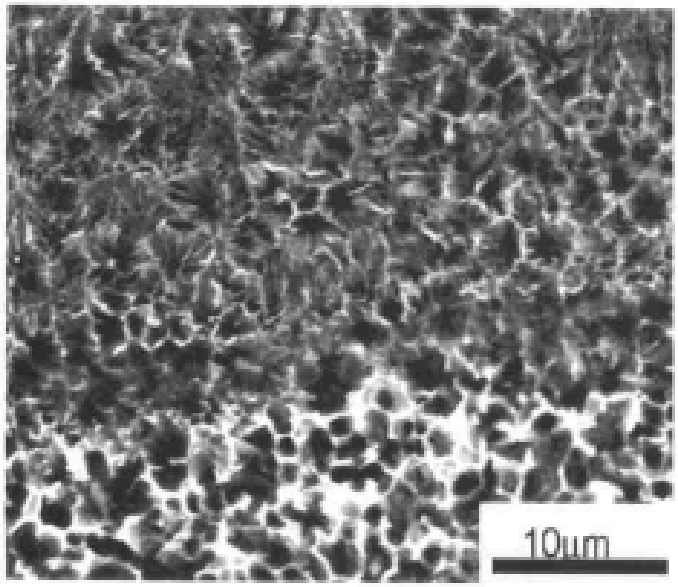

图 4－34 激光熔覆，铝熔覆材料，镁合金基体，YAG 激光，扫描速度 2.5mm/s，脉宽 3ms，频率 10Hz，能量 0.34J。

Laser coated magnesium alloy with Al, YAG laser, scanning speed 2.5mm/s, pulse width 3ms, 10Hz, power 0.34J.

4.2.2 镁合金/三氧化二铝激光熔覆

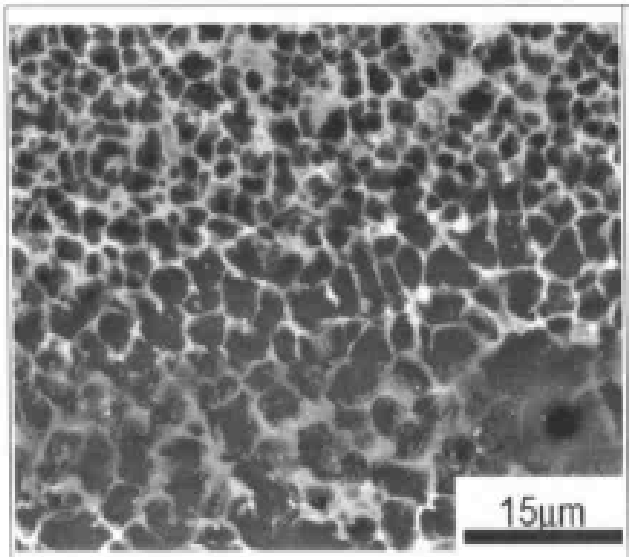

图4-35 激光熔覆，铝和三氧化二铝(1∶3)熔覆材料，镁合金基体，YAG激光，扫描速度0.75mm/s，脉宽3ms，频率17Hz，能量1.0265J
Laser cladding of Al－AlO_3(1∶3) powder on Mg, YAG laser, scanning speed 0.75mm/s, pulse width 3ms, frequency 17Hz, power 1.0265J.

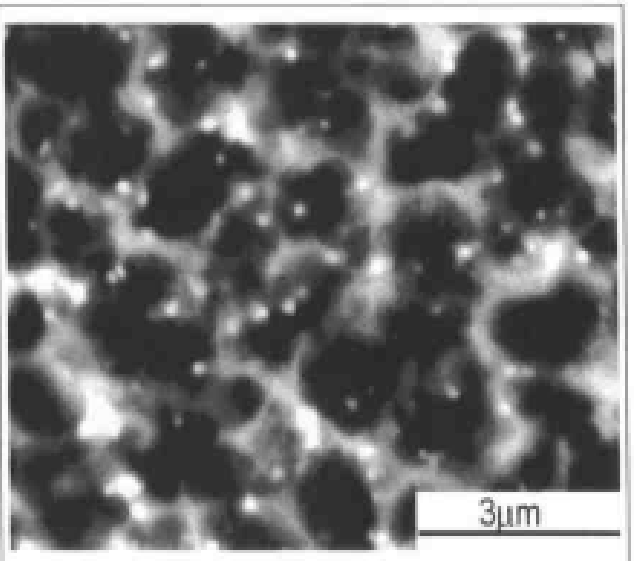

图4-36 激光熔覆，铝和三氧化二铝(1∶3)熔覆材料，镁合金基体，YAG激光，扫描速度0.5mm/s，脉宽5ms，频率17Hz，能量0.26J
Laser cladding of Al－AlO(1∶3) powder on Mg, YAG laser, scanning speed 0.5mm/s, pulse width 5ms, frequency 17Hz, power 0.26J.

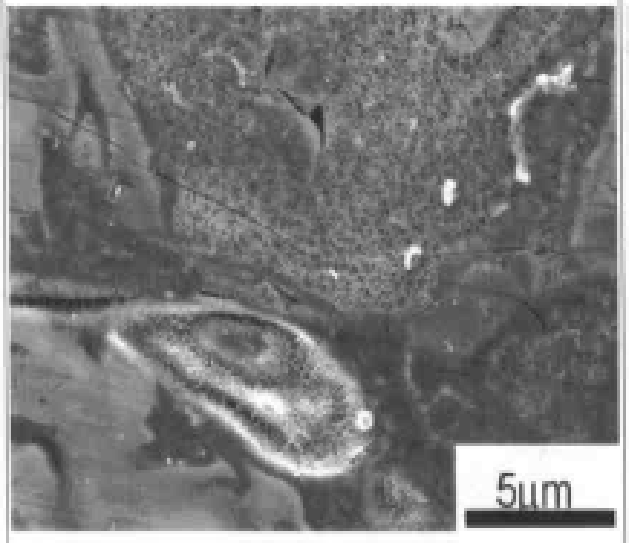

图4-37 激光熔覆，铝和三氧化二铝(1∶3)熔覆材料，镁合金基体，YAG激光，扫描速度0.5mm/s，脉宽3ms，频率10Hz，能量0.45J
Laser cladding of Al－AlO(1∶3) powder on Mg, YAG laser, scanning speed 0.5mm/s, pulse width 3ms, frequency 10Hz, power 0.45J.

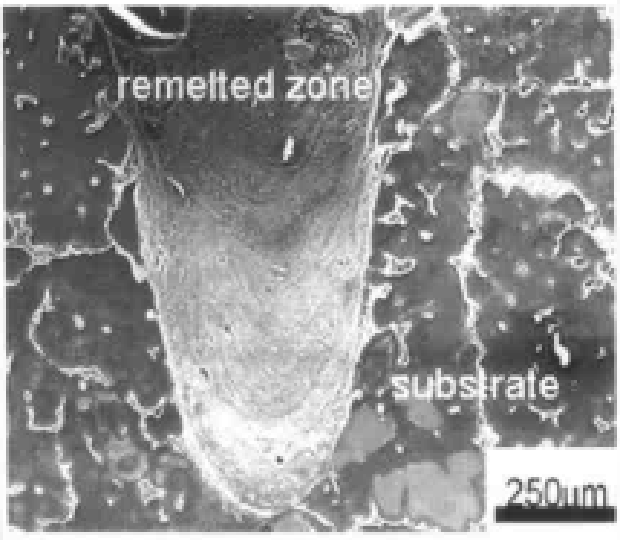

图4-38 激光熔覆，铝和三氧化二铝(1∶3)熔覆材料，镁合金基体，YAG激光，扫描速度2mm/s，脉宽3ms，频率10Hz，能量0.45J
Laser cladding of Al－AlO(1∶3) powder on Mg, YAG laser, scanning speed 2mm/s, pulse width 3ms, frequency 10Hz, power 0.45J.

4.2.3 镁合金/铝－硅激光熔覆

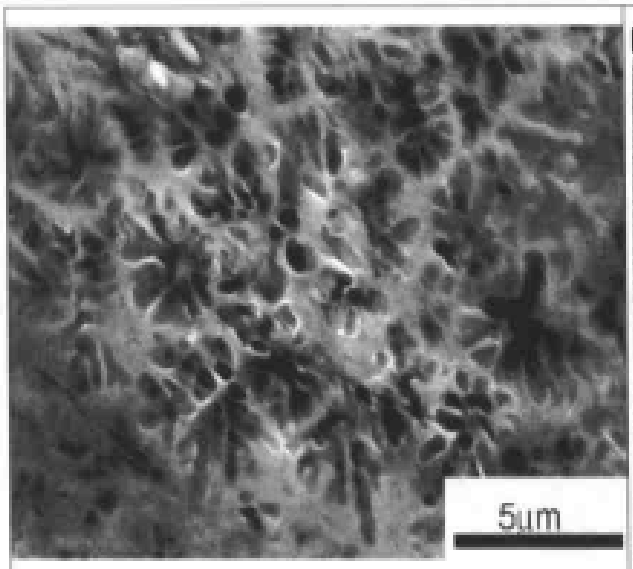

图 4－39 激光熔覆，YAG 激光，基体 Mg 合金，熔覆材料 Al－12.5 Si，SEM 显微组织，扫描速度 5mm/s，脉宽 3ms，频率 10Hz，能量 0.783J

Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，scanning speed 5mm/s，pulse width 3ms，10Hz，power 0.783J.

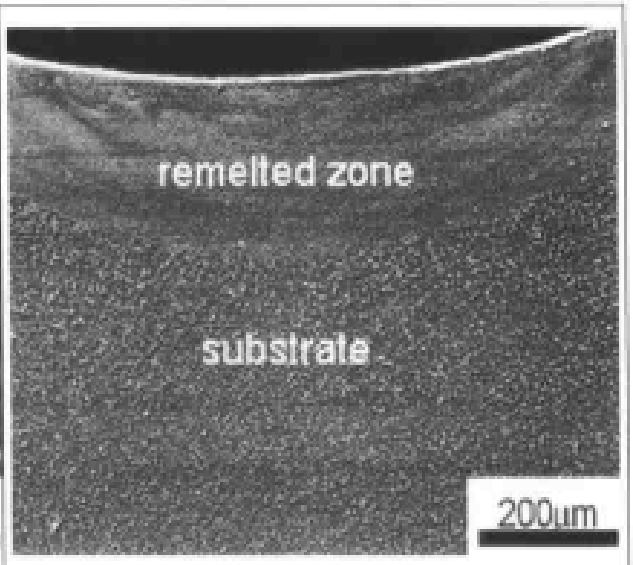

图 4－40 激光熔覆，YAG 激光，基体 Mg 合金，熔覆材料 Al－12.5 Si，SEM 显微组织，显示熔覆区（上部）和基体（下部），扫描速度 0.75mm/s，脉宽 3ms，频率 15Hz，能量 1.0265J

Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph showing laser melted zone（up part）and substrate（low part），scanning speed 0.75mm/s，pulse width 3ms，15Hz，power 1.0265J.

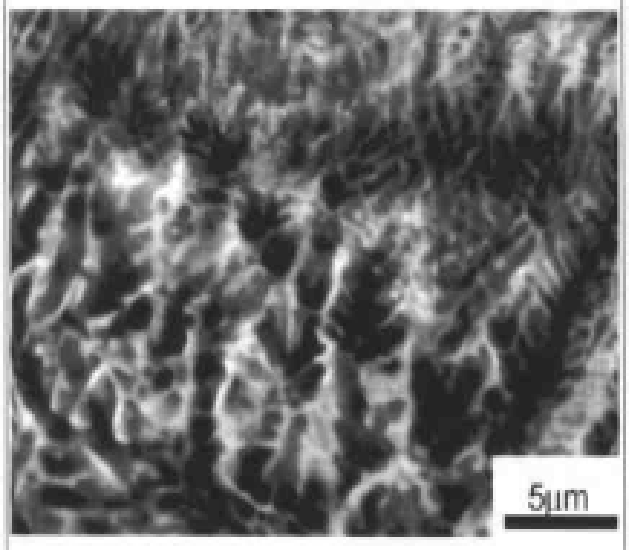

图 4－41 激光熔覆，YAG 激光，基体 Mg 合金，熔覆材料 Al－12.5 Si，SEM 显微组织，扫描速度 2.5mm/s，脉宽 3ms，频率 10Hz，能量 1.19J

Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，scanning speed 2.5mm/s，pulse width 3ms，10Hz，power 1.19J.

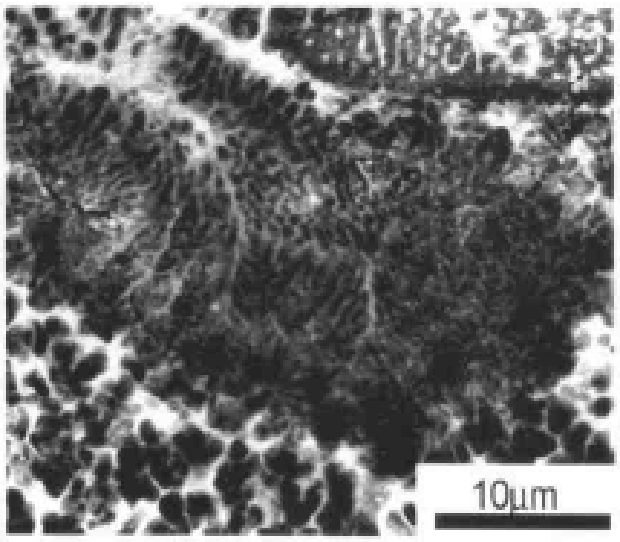

图 4－42 激光熔覆，YAG 激光，基体 Mg 合金，熔覆材料 Al－12.5 Si，SEM 显微组织，扫描速度 0.75mm/s，脉宽 3ms，频率 10Hz，能量 1.0265J

Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，scanning speed 0.75mm/s，pulse width 3ms，10Hz，power 1.0265J.

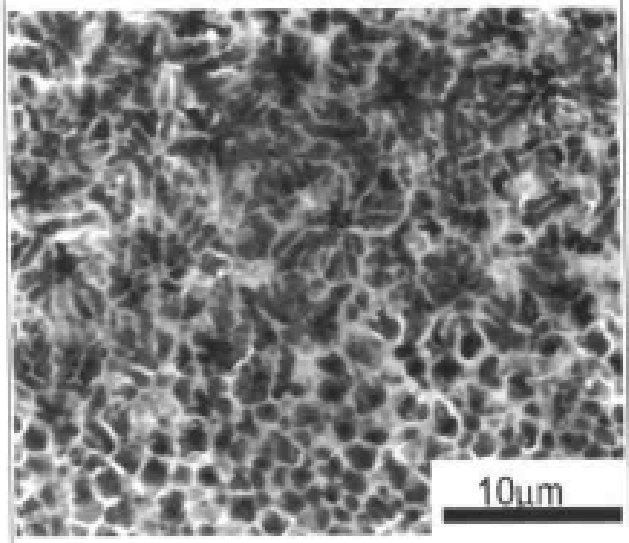

图4－43 激光熔覆，YAG激光，基体Mg合金，熔覆材料Al－12.5 Si，SEM显微组织，扫描速度0.75mm/s，脉宽3ms，频率10Hz，能量1.0265J
Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，scanning speed 0.75mm/s，pulse width 3ms，10Hz，power 1.0265J.

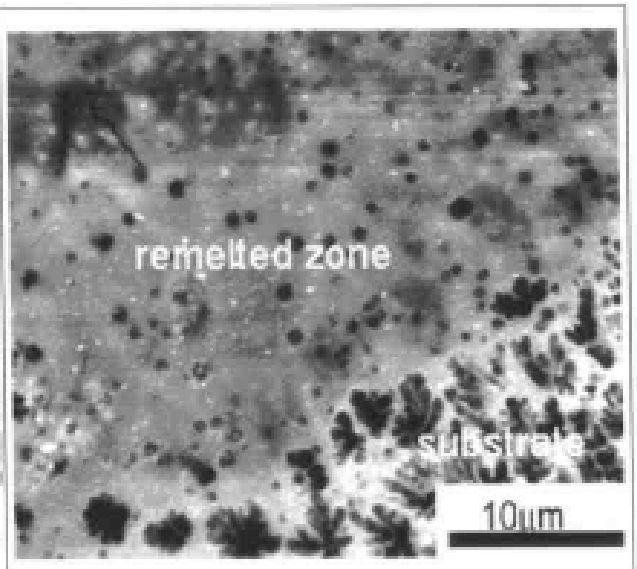

图4－44 激光熔覆，YAG激光，基体Mg合金，熔覆材料Al－12.5 Si，SEM显微组织，显示熔覆区(上部)和基体(下部)，扫描速度0.75mm/s，脉宽3ms，频率15Hz，能量1.0265J
Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph showing laser melted zone(up part) and substrate (low part)，scanning speed 0.75mm/s，pulse width 3ms，15Hz，power 1.0265J.

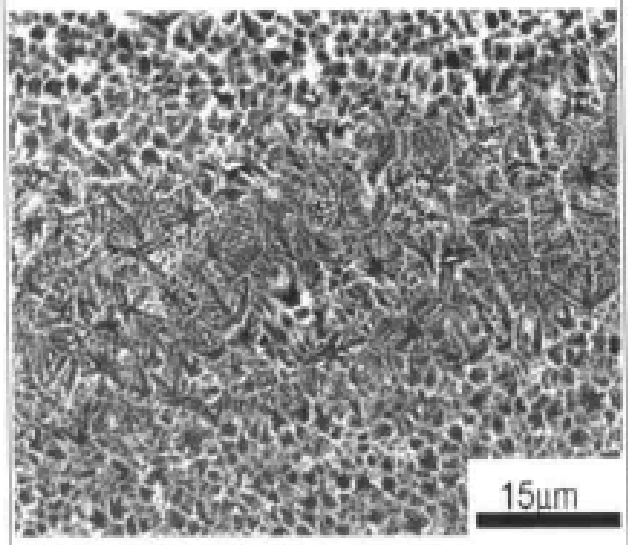

图4－45 激光熔覆，YAG激光，基体Mg合金，熔覆材料Al－12.5 Si，SEM显微组织，扫描速度0.75mm/s，脉宽3ms，频率15Hz，能量1.0265J
Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，scanning speed 0.75mm/s，pulse width 3ms，15Hz，power 1.0265J.

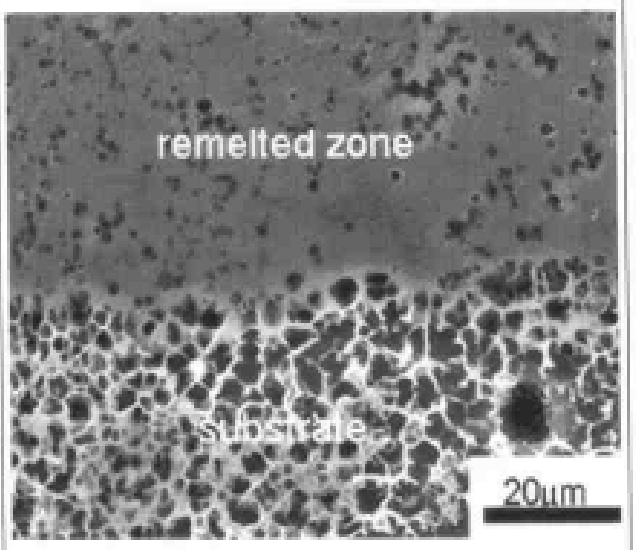

图4－46 激光熔覆，YAG激光，基体Mg合金，熔覆材料Al－12.5 Si，SEM显微组织，显示熔覆区(上部)和基体(下部)，扫描速度0.75mm/s，脉宽3ms，频率17Hz，能量1.0265J
Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，showing laser melted zone(up part) and substrate (low part)，scanning speed 0.75mm/s，pulse width 3ms，17Hz，power 1.0265J.

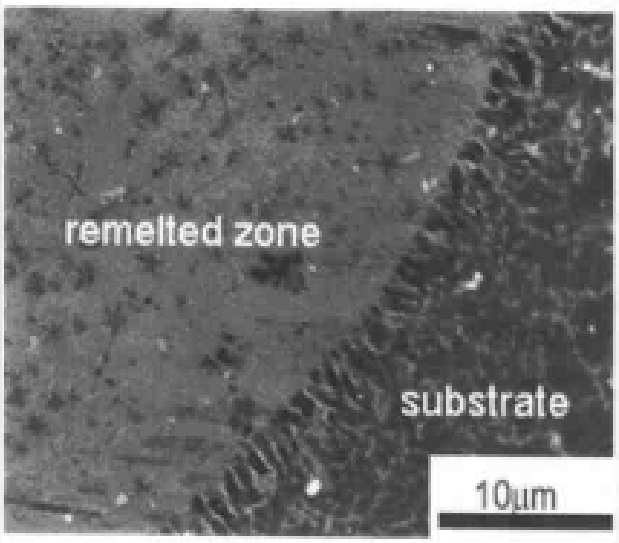

图 4－47 激光熔覆，YAG 激光，基体 Mg 合金，熔覆材料 Al－12.5 Si，SEM 显微组织，显示熔覆区(上部)和基体(下部)，扫描速度 3mm/s，脉宽 3ms，频率 10Hz，能量 0.525J

Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，showing laser melted zone (up part) and substrate (low part)，scanning speed 3mm/s，pulse width 3ms，10Hz，power 0.525J.

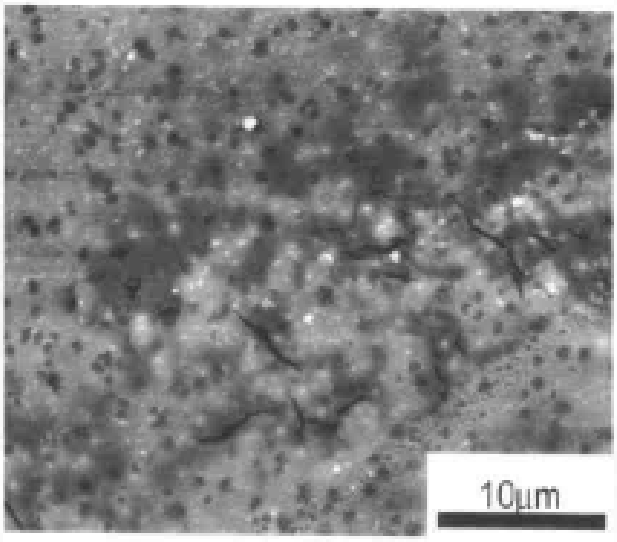

图 4－48 激光熔覆，YAG 激光，基体 Mg 合金，熔覆材料 Al－12.5 Si，SEM 显微组织，显示熔覆区，有裂纹，扫描速度 0.75mm/s，脉宽 3ms，频率 15Hz，能量 1.0265J

Laser cladding of Al－12.5 Si powder on Mg，SEM micrograph，showing cracks，scanning speed 0.75mm/s，pulse width 3ms，15Hz，power 1.0265J.

4.2.4 镁合金/钛－碳－铝激光熔覆

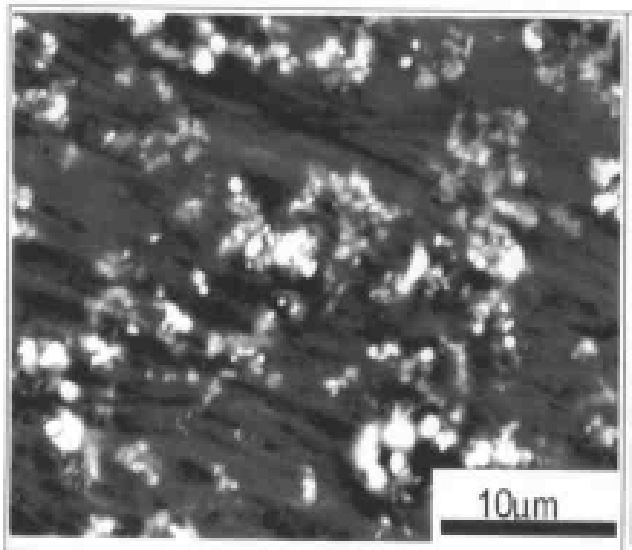

图 4－49 激光熔覆，镁合金基体，C－Ti－Al 熔覆材料，YAG 激光，扫描速度 0.5mm/s，脉宽 5ms，频率 17Hz，能量 0.64J

Laser cladding of C－Ti－Al powder on Mg，YAG laser，scanning speed 0.5mm/s，pulse width 5ms，frequency 17Hz，power 0.64J.

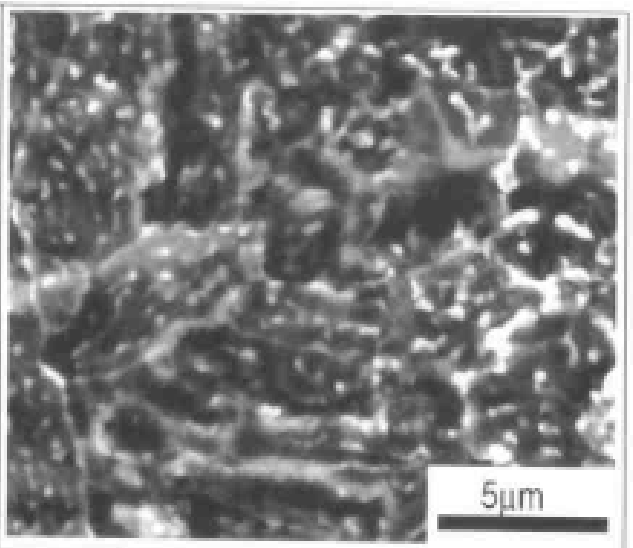

图 4－50 激光熔覆，镁合金基体，C－Ti－Al 熔覆材料，YAG 激光，扫描速度 2mm/s，脉宽 5ms，频率 17Hz，能量 0.562J

Laser cladding of C－Ti－Al powder on Mg，YAG laser，scanning speed 2mm/s，pulse width 5ms，frequency 17Hz，power 0.562J.

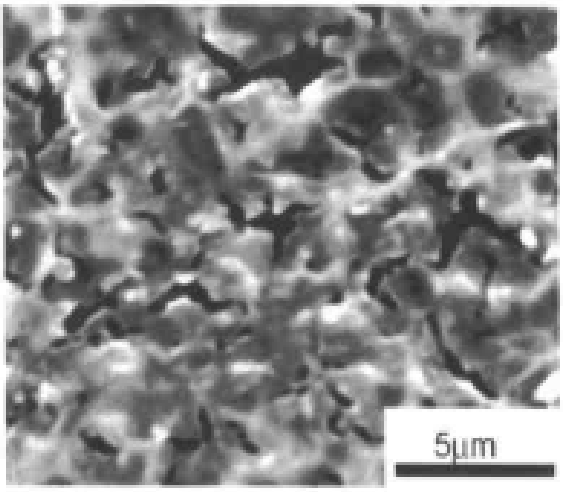

图 4－51　激光熔覆，镁合金基体，C－Ti－Al 熔覆材料，YAG 激光，扫描速度 2.5mm/s，脉宽 3ms，频率 10Hz，能量 0.783J

Laser cladding of C－Ti－Al powder on Mg，YAG laser，scanning speed 2.5mm/s，pulse width 3ms，frequency 10Hz，power 0.783J.

4.3　铸铁合金激光熔覆

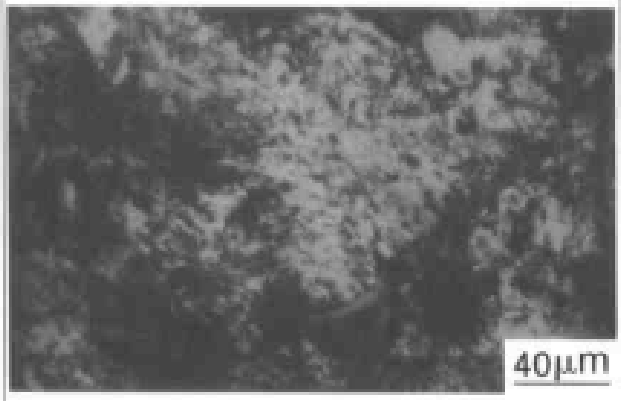

图 4－52　激光熔覆，灰铸铁基体显微组织 化学成分：3.0C－1.52Si－1.01Mn－0.06S－0.08P

Laser cladding，substrate microstructure of gray cast iron，chemical composition：3.0C－1.52Si－1.01Mn－0.06S－0.08P.

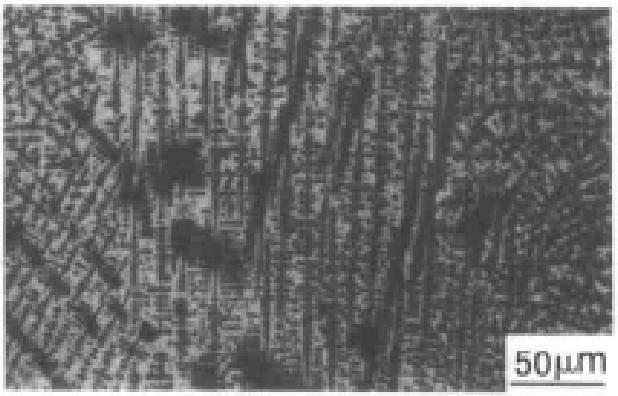

图 4－53　激光熔覆，灰铸铁，CO_2 激光，激光功率 800W，扫描速度 400mm/min，熔覆层组织形貌

Laser cladding，grey cast iron，CO_2 laser，laser power 800W，scanning speed 400mm/min，morphology of cladded layer.

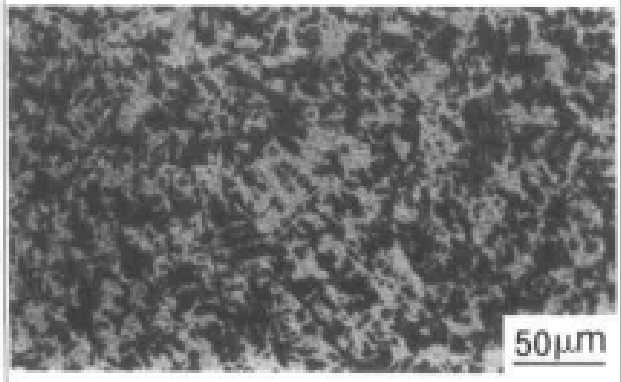

图 4－54　激光熔覆，灰铸铁，激光功率 1200W，扫描速度 400mm/min，熔覆层组织形貌

Laser cladding，grey cast iron，laser power 1200W，scanning speed 400mm/min，morphology of cladded layer.

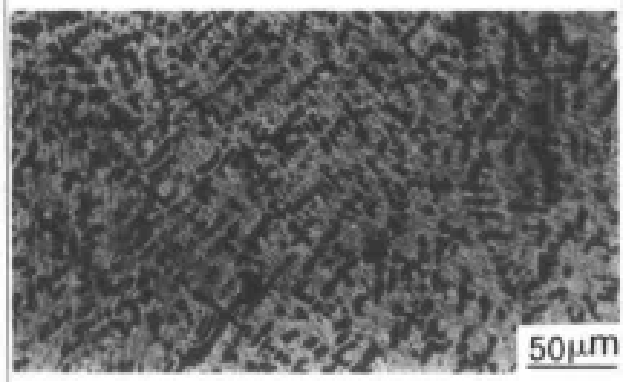

图 4－55 激光熔覆，灰铸铁激光功率 1500W，扫描速度 400mm/min，熔覆层组织形貌

Laser cladding, grey cast iron, laser power 1500W, scanning speed 400mm/min, morphology of cladded layer.

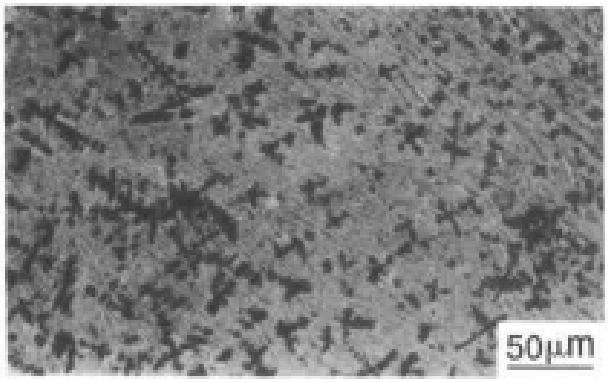

图 4－56 激光熔覆，灰铸铁，激光功率 2000W，扫描速度 400mm/min，熔覆层组织形貌

Laser cladding, grey cast iron, laser power 2000W, scanning speed 400mm/min, morphology of cladded layer.

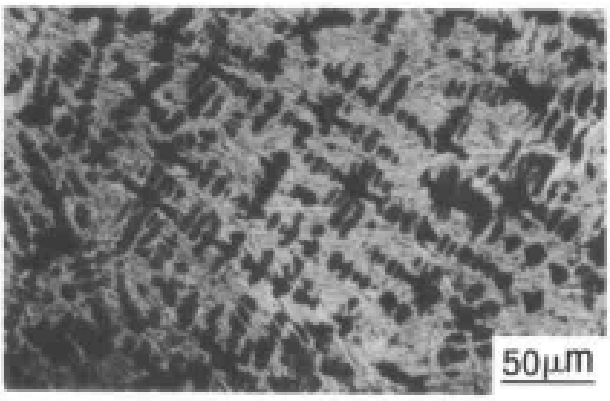

图 4－57 激光熔覆，灰铸铁，激光功率 2500W，扫描速度 400mm/min，熔覆层组织形貌

Laser cladding, grey cast iron, laser power 2500W, scanning speed 400mm/min, morphology of cladded layer.

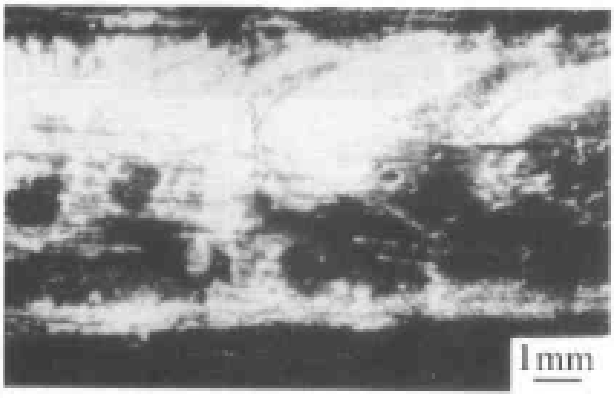

图 4－58 激光熔覆，灰铸铁，激光功率 800W，扫描速度 400mm/min，熔覆层宏观形貌

Laser cladding, grey cast iron, laser power 800W, scanning speed 400mm/min, macro－morphology of cladded layer.

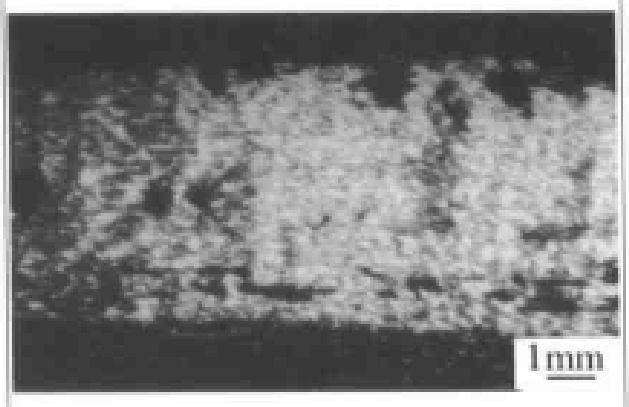

图4－59 激光熔覆，灰铸铁，激光功率1500W，扫描速度400mm/min，熔覆层宏观形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 400mm/min，macro－morphology of cladded layer.

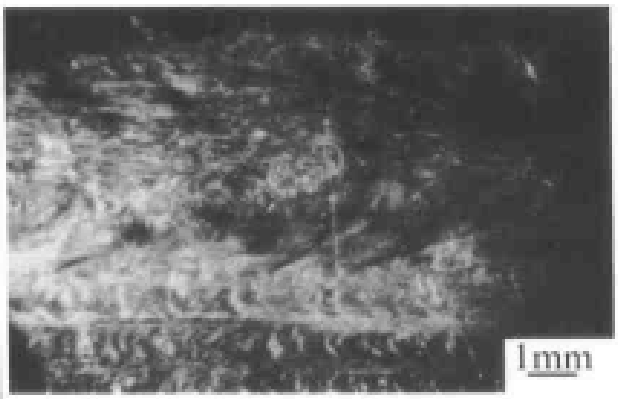

图4－60 激光熔覆，灰铸铁，激光功率2500W，扫描速度400mm/min，熔覆层宏观形貌

Laser cladding，grey cast iron，laser power 2500W，scanning speed 400mm/min，macro－morphology of cladded layer.

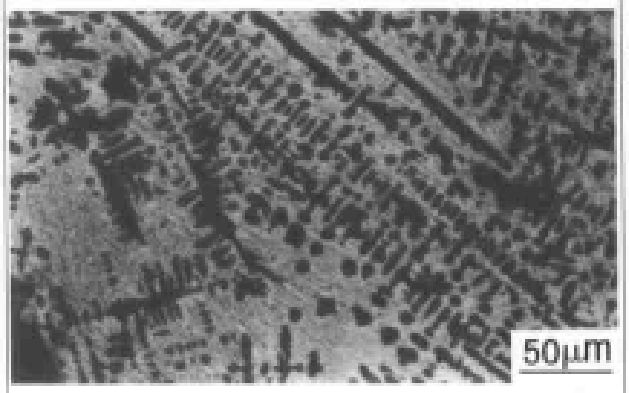

图4－61 激光熔覆，灰铸铁，激光功率1500W，扫描速度150mm/min，熔覆层组织形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 150mm/min，microstructure of cladded layer.

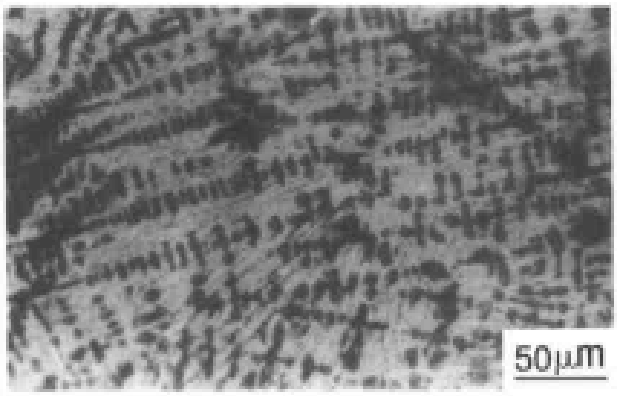

图4－62 激光熔覆，灰铸铁，激光功率1500W，扫描速度300mm/min，熔覆层组织形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 300mm/min，microstructure of cladded layer.

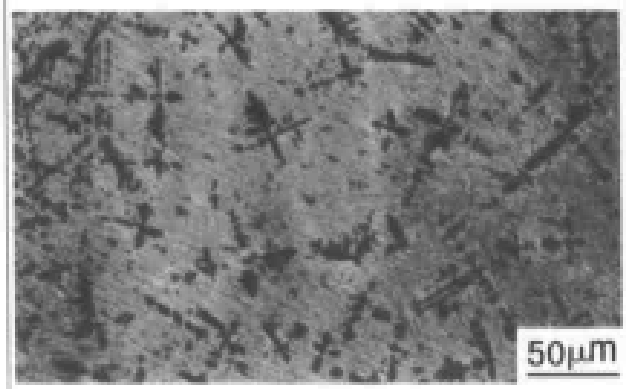

图 4－63 激光熔覆，灰铸铁，激光功率 1500W，扫描速度 700mm/min，熔覆层组织形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 700mm/min，microstructure of cladded layer.

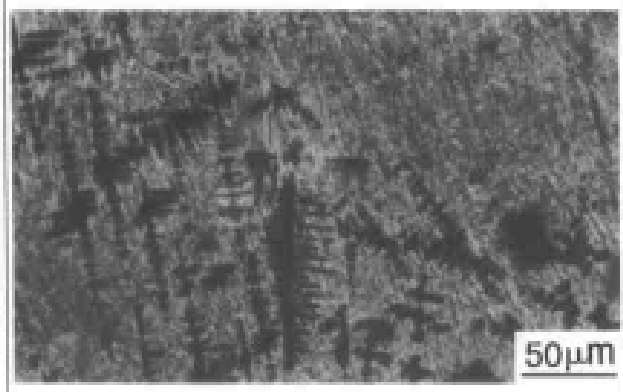

图 4－64 激光熔覆，灰铸铁，激光功率 1500W，扫描速度 1000mm/min，熔覆层组织形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 1000mm/min，microstructure of cladded layer.

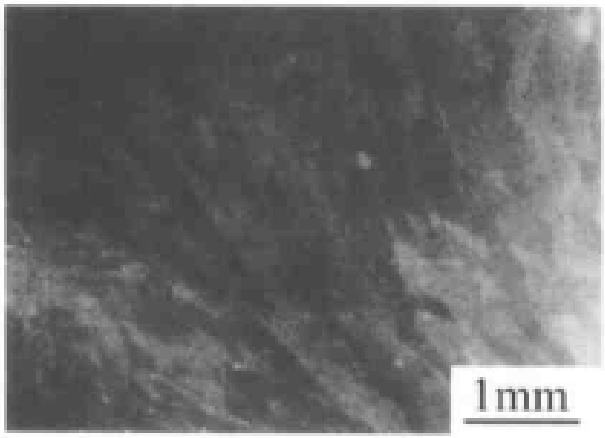

图 4－65 激光熔覆，灰铸铁，激光功率 1500W，扫描速度 150mm/min，熔覆层一次枝晶形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 150mm/min，dendritic morphology of cladded layer.

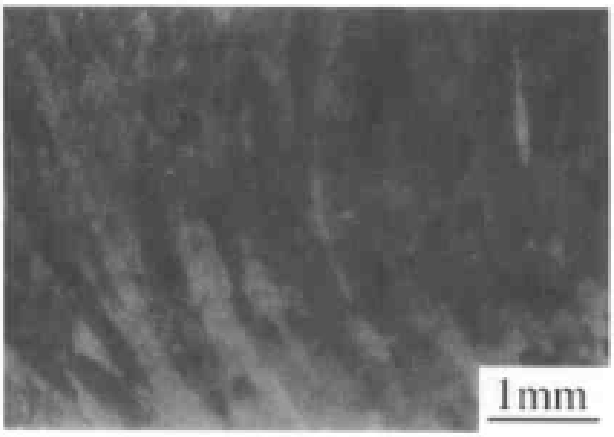

图 4－66 激光熔覆，灰铸铁，激光功率 1500W，扫描速度 400mm/min，熔覆层一次枝晶形貌

Laser cladding，grey cast iron，laser power 1500W，scanning speed 400mm/min，dendritic morphology of cladded layer.

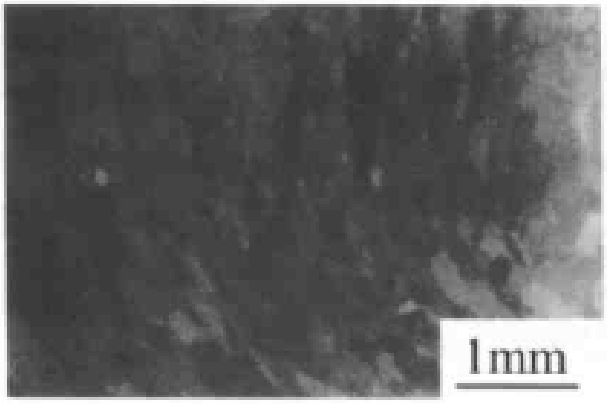

图4－67 激光熔覆，灰铸铁，激光功率1500W，扫描速度1000mm/min，熔覆层一次枝晶形貌
Laser cladding，grey cast iron，laser power 1500W，scanning speed 1000mm/min，dendritic morphology of cladded layer.

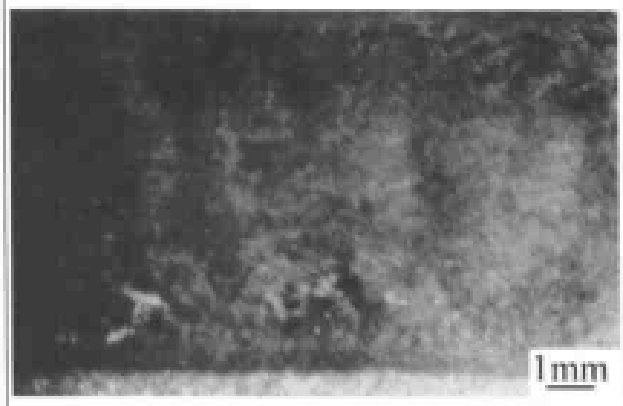

图4－68 激光熔覆，灰铸铁，激光功率1500W，扫描速度150mm/min，熔覆层宏观形貌
Laser cladding，grey cast iron，laser power 1500W，scanning speed 150mm/min，macro－morphology of cladded layer.

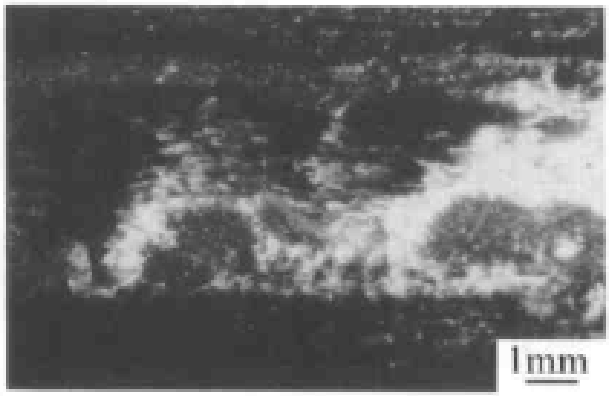

图4－69 激光熔覆，灰铸铁，激光功率1500W，扫描速度700mm/min，熔覆层宏观形貌
Laser cladding，grey cast iron，laser power 1500W，scanning speed 700mm/min，macro－morphology of cladded layer.

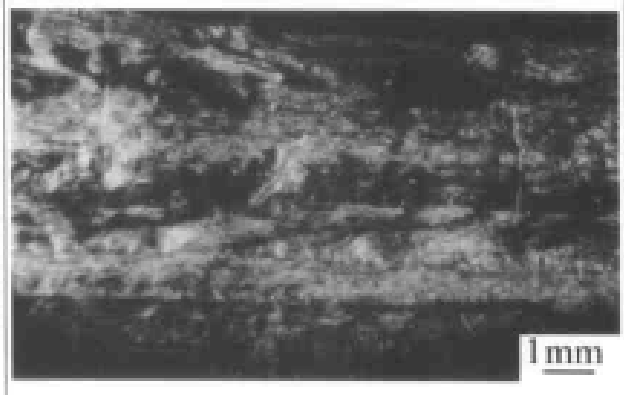

图4－70 激光熔覆，灰铸铁，激光功率1500W，扫描速度1000mm/min，熔覆层宏观形貌
Laser cladding，grey cast iron，laser power 1500W，scanning speed 1000mm/min，macro－morphology of cladded layer.

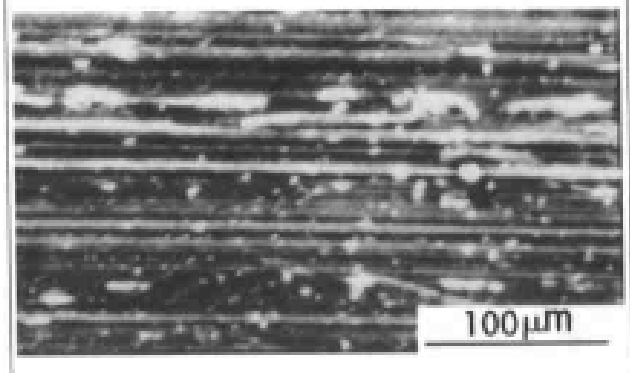

图 4－71　激光熔覆，灰铸铁，激光功率 800W，扫描速度 400mm/min，熔覆层表面磨损形貌

Laser cladding, grey cast iron, laser power 800W, scanning speed 400mm/min, worn morphology of cladded layer.

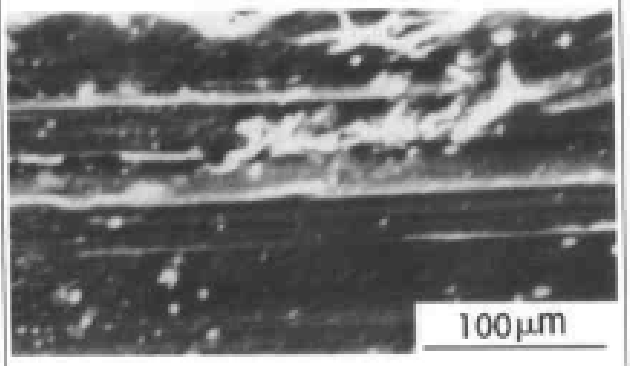

图 4－72　激光熔覆，灰铸铁，激光功率 2500W，扫描速度 400mm/min，熔覆层表面磨损形貌

Laser cladding, grey cast iron, laser power 2500W, scanning speed 400mm/min, worn morphology of cladded layer.

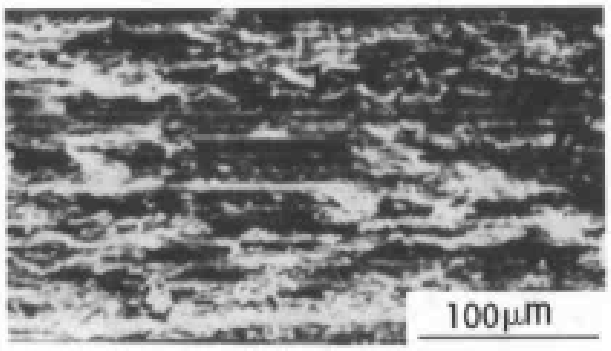

图 4－73　激光熔覆，灰铸铁，激光功率 1500W，扫描速度 150mm/min，熔覆层表面磨损形貌

Laser cladding, grey cast iron, laser power 1500W, scanning speed 150mm/min, worn morphology of cladded layer.

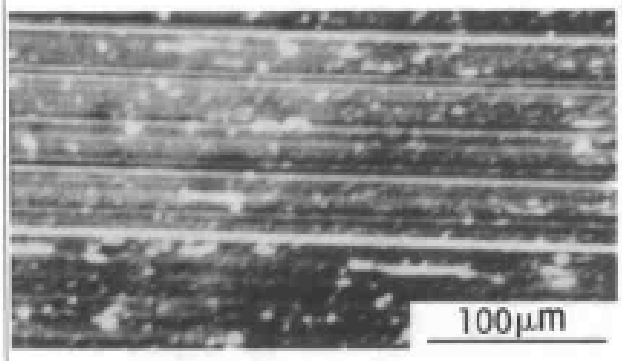

图 4－74　激光熔覆，灰铸铁，激光功率 1500W，扫描速度 1000mm/min，熔覆层表面磨损形貌

Laser cladding, grey cast iron, laser power 1500W, scanning speed 1000mm/min, worn morphology of cladded layer.

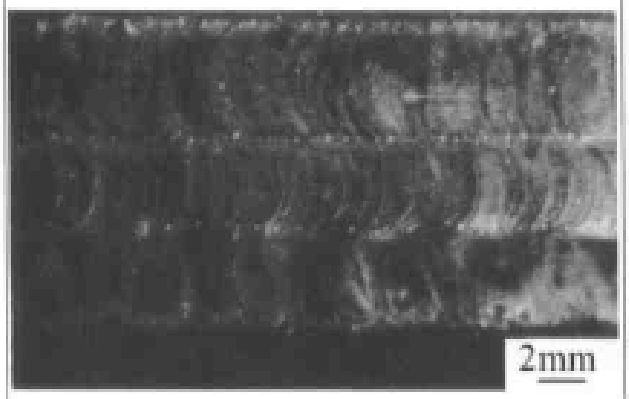

图4－75 激光熔覆，灰铸铁，试板厚度为15mm，搭接，熔覆层宏观形貌

Laser cladding, grey cast iron, thickness of sample plate 15mm, overlapping, macro－morphology of cladded layer.

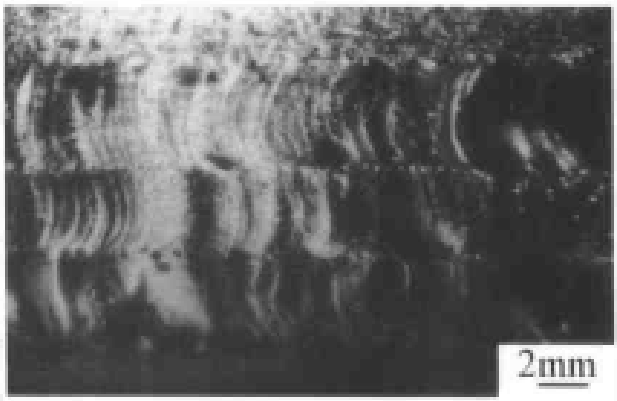

图4－76 激光熔覆，灰铸铁，试板厚度为30mm，搭接，熔覆层宏观形貌

Laser cladding, grey cast iron, thickness of sample plate 30mm, overlapping macro－morphology of cladded layer.

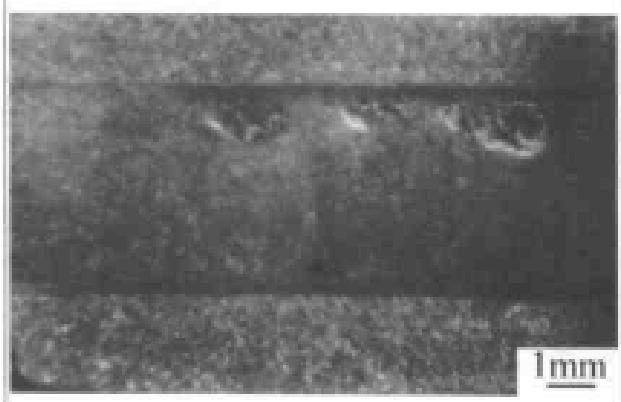

图4－77 激光熔覆，灰铸铁，试板长度为90mm，熔覆层宏观形貌

Laser cladding, grey cast iron, length of sample plate 90mm, macro－ morphology of cladded layer.

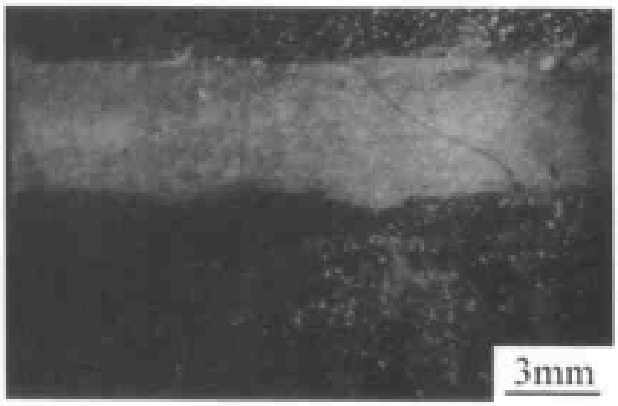

图4－78 激光熔覆，灰铸铁，试板长度为150mm，熔覆层宏观形貌，有裂纹

Laser cladding, grey cast iron, length of sample plate 150mm, macro－ morphology of cladded layer with cracks.

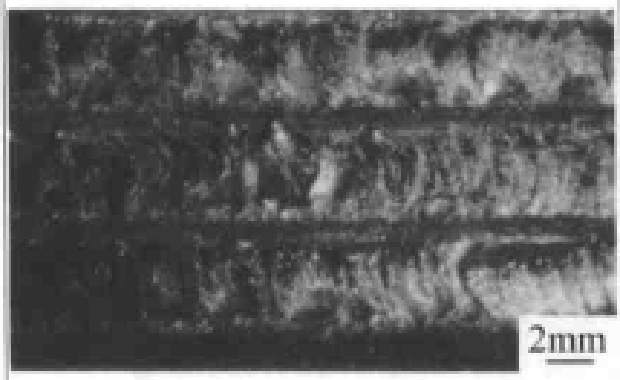

图 4－79　激光熔覆，灰铸铁，无搭接，熔覆层宏观形貌

Laser cladding，grey cast iron，macro－morphology of cladding layer without overlapping.

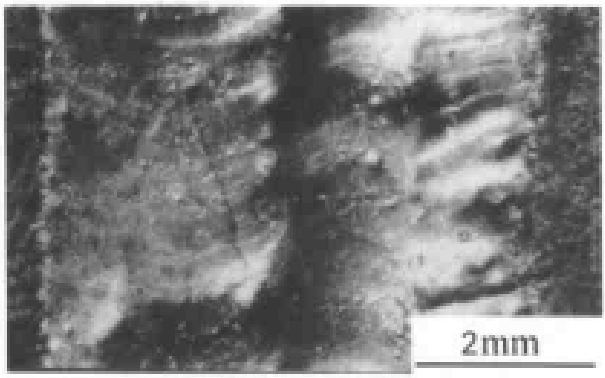

图 4－80　激光熔覆，灰铸铁，搭接量为 30%时熔覆层宏观形貌

Laser cladding，grey cast iron，macro－morphology of cladding layer with 30% overlapping between two traces.

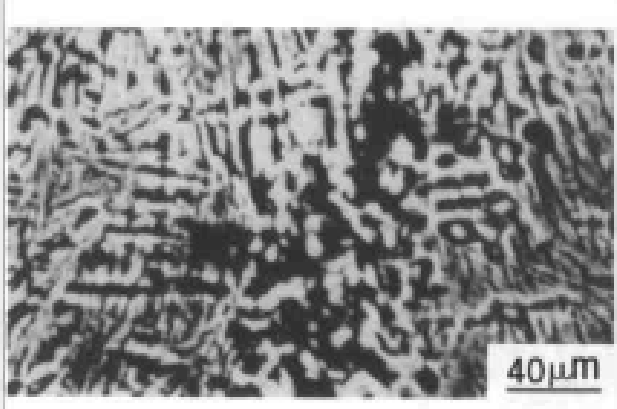

图 4－81　激光熔覆，灰铸铁，搭接区熔覆层显微组织

Laser cladding，grey cast iron，microstructure of overlapping area of cladding layer.

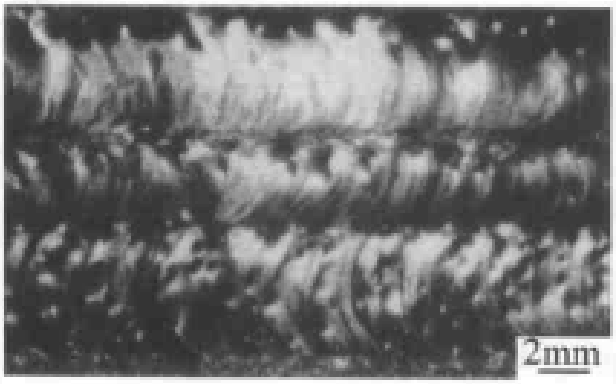

图 4－82　激光熔覆，灰铸铁，3 道搭接时熔覆层宏观形貌

Laser cladding，grey cast iron，macro－morphology of cladding layer with overlapping of 3 traces.

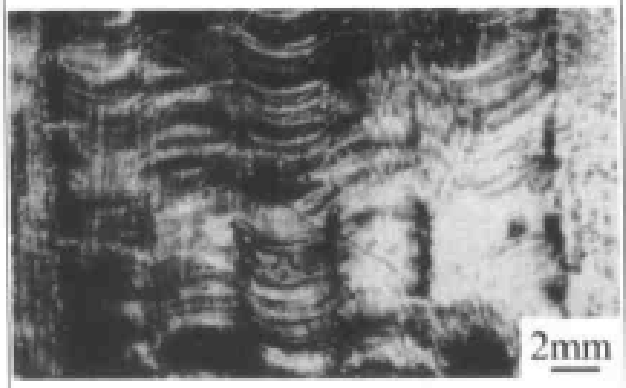

图4－83 激光熔覆，灰铸铁，5道搭接时熔覆层宏观形貌，有裂纹

Laser cladding, grey cast iron, macro－morphology of cladding layer with overlapping of 5 traces, showing cracks.

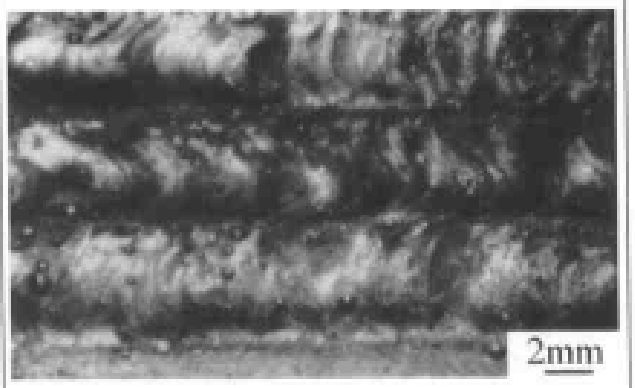

图4－84 激光熔覆，灰铸铁，未加拘束条件下熔覆层宏观形貌

Laser cladding, grey cast iron, macro morphology of cladding layer without limit condition.

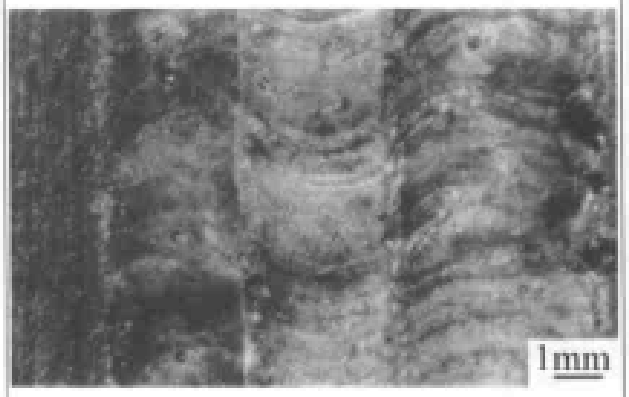

图4－85 激光熔覆，灰铸铁，拘束条件下熔覆层宏观形貌

Laser cladding, grey cast iron, macro morphology of cladding layer with limit condition.

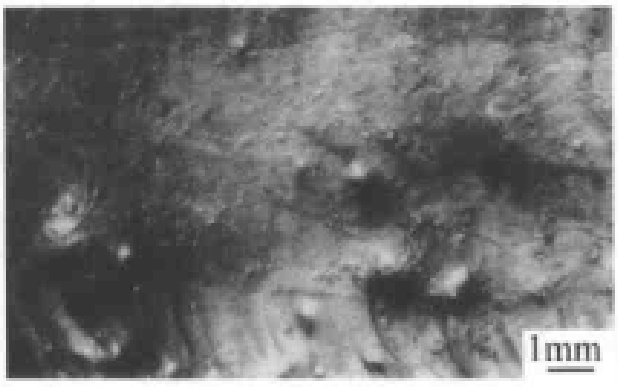

图4－86 激光熔覆，灰铸铁，冷却水拘束条件下熔覆层宏观形貌，有裂纹

Laser cladding, grey cast iron, macro— morphology of cladding layer limited with cooling water, showing cracks.

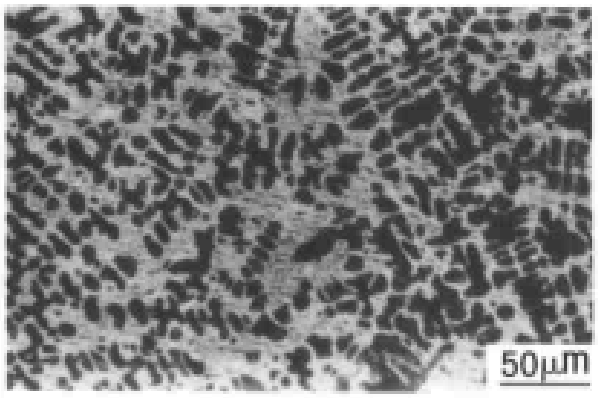

图 4－87 激光熔覆，灰铸铁，熔覆材料 C 质量分数为 2.72%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 2.72%C, morphology of cladding layer.

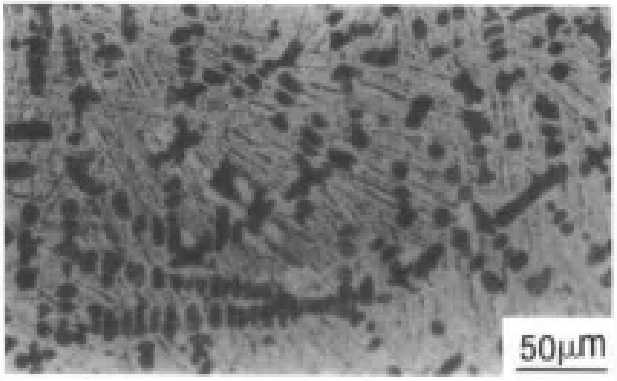

图 4－88 激光熔覆，灰铸铁，熔覆材料 C 质量分数为 3.46%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 3.46%C, morphology of cladding layer.

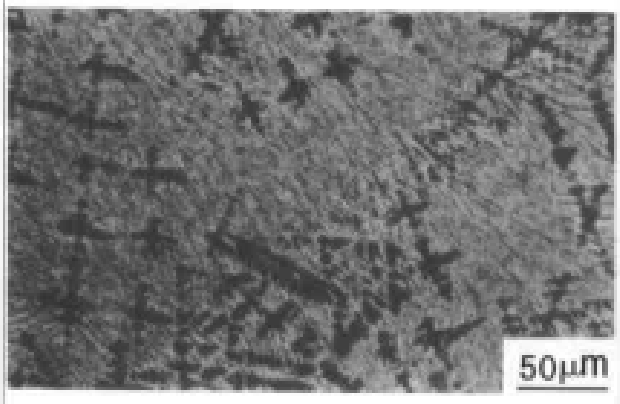

图 4－89 激光熔覆，灰铸铁，熔覆材料 C 质量分数为 4.05%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 4.05%C, morphology of cladding layer.

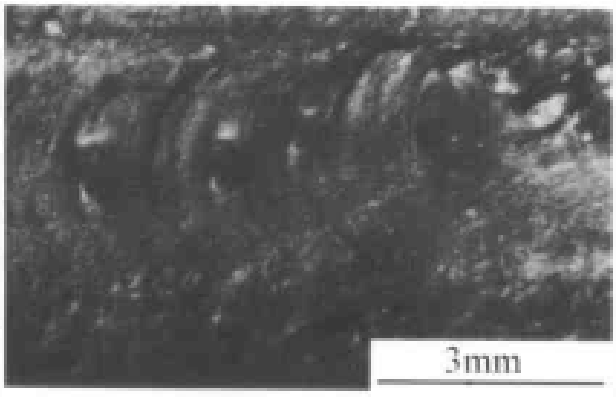

图 4－90 激光熔覆，灰铸铁，熔覆材料 C 质量分数为 2.72%，单道熔覆层宏观形貌

Laser cladding, grey cast iron, cladding material containing 2.72%C, macro－morphology of cladding layer with single trace.

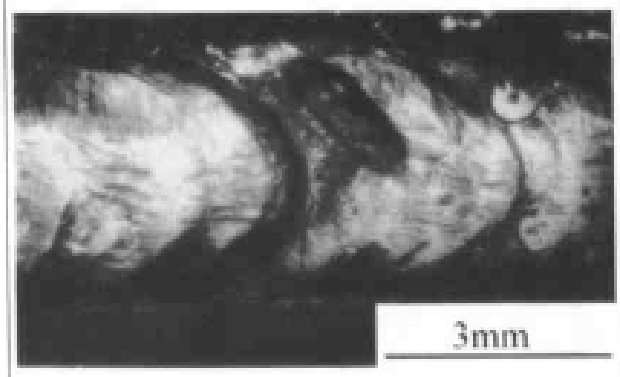

图4－91 激光熔覆，灰铸铁，熔覆材料C质量分数为4.05%，单道熔覆层宏观形貌

Laser cladding, grey cast iron, cladding material containing 4.05%C, macro-morphology of cladding layer with single trace.

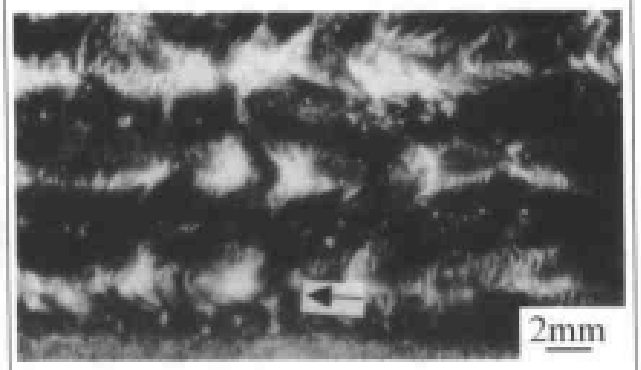

图4－92 激光熔覆，灰铸铁，熔覆材料C质量分数为2.72%，3道熔覆层宏观形貌

Laser cladding, grey cast iron, cladding material containing 2.72%C, macro-morphology of cladding layer with overlapping of 3 traces.

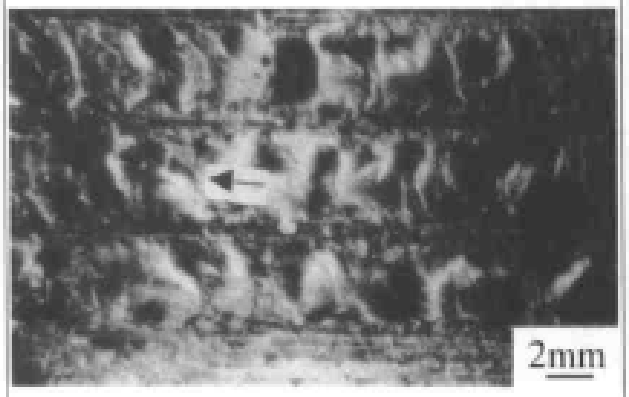

图4－93 激光熔覆，灰铸铁，熔覆材料C质量分数为4.05%，3道熔覆层宏观形貌

Laser cladding, grey cast iron, cladding material containing 4.05%C, macro-morphology of cladding layer with overlapping of 3 traces.

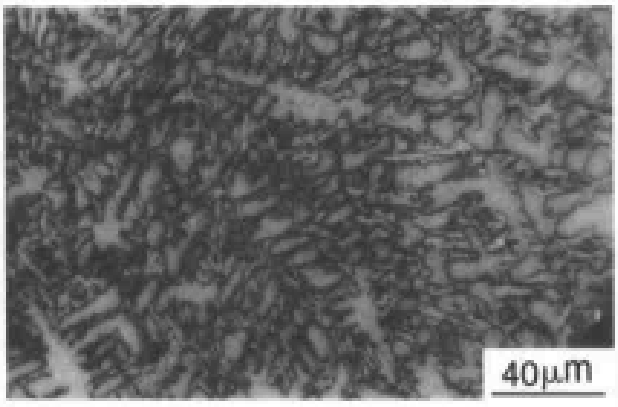

图4－94 激光熔覆，灰铸铁，熔覆材料Si质量分数为0.16%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 0.16%Si, morphology of cladding layer.

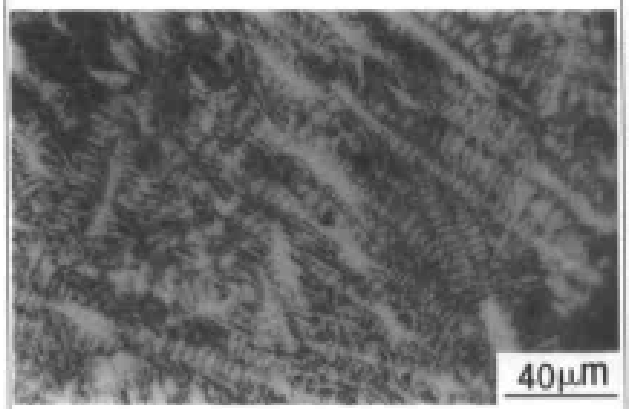

图 4－95 激光熔覆，灰铸铁，熔覆材料 Si 质量分数为 0.57%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 0.57%Si, morphology of cladding layer.

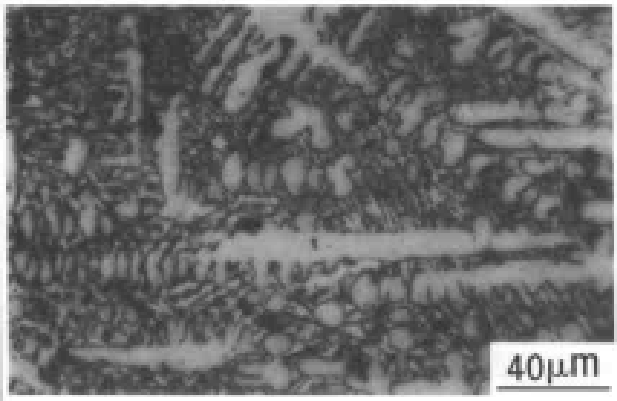

图 4－96 激光熔覆，灰铸铁，熔覆材料 Si 质量分数为 0.82%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 0.82%Si, morphology of cladding layer.

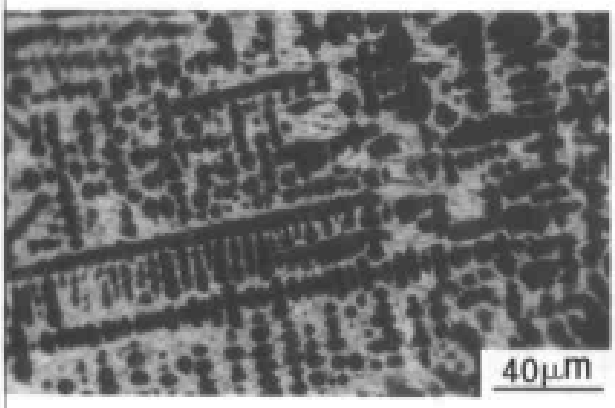

图 4－97 激光熔覆，灰铸铁，熔覆材料 Si 质量分数为 1.24%时熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 1.24%Si, morphology of cladding layer.

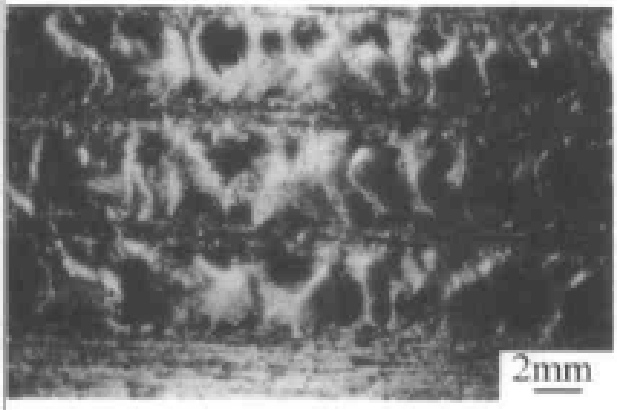

图 4－98 激光熔覆，灰铸铁，熔覆材料 Si 质量分数为 0.57%时 3 道熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 0.57%Si, macro-morphology of cladding layer with overlapping of 3 traces.

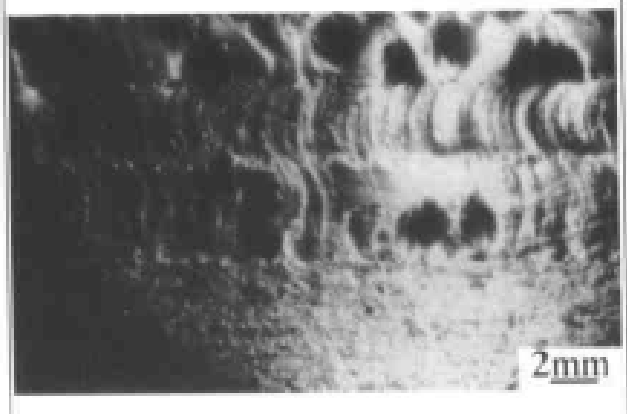

图4－99 激光熔覆，灰铸铁，熔覆材料Si质量分数为1.24%时3道熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 1.24%Si, macro-morphology of cladding layer with overlapping of 3 traces.

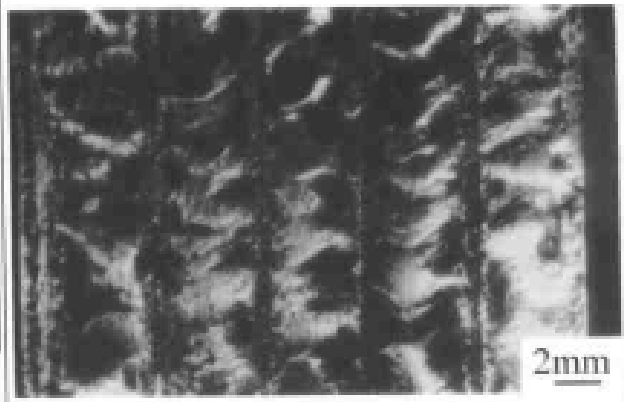

图4－100 激光熔覆，灰铸铁，熔覆材料Si质量分数为0.57%时5道熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 0.57%Si, macro-morphology of cladding layer with overlapping of 5 traces.

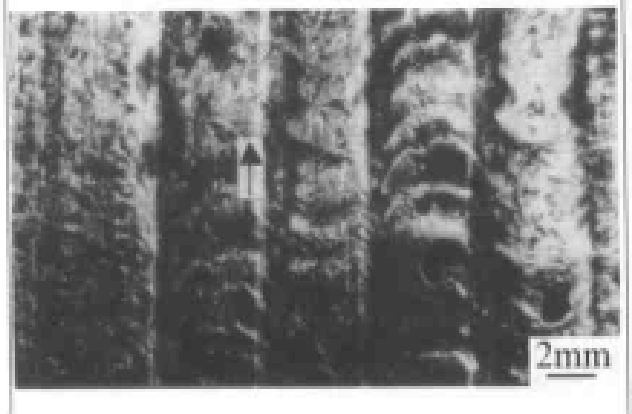

图4－101 激光熔覆，灰铸铁，熔覆材料Si质量分数为1.03%时5道熔覆层组织形貌

Laser cladding, grey cast iron, cladding material containing 1.03%Si, macro-morphology of cladding layer with overlapping of 5 traces.

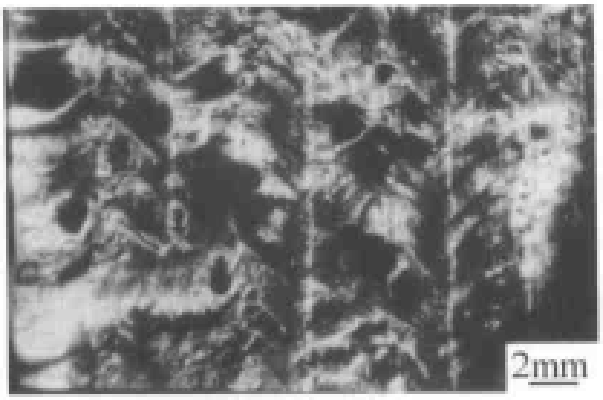

图4－102 激光熔覆，灰铸铁，熔覆材料Si质量分数为0.82%时8道熔覆层宏观形貌

Laser cladding, grey cast iron, cladding material containing 0.82%Si, macro-morphology of cladding layer with overlapping of 8 traces.

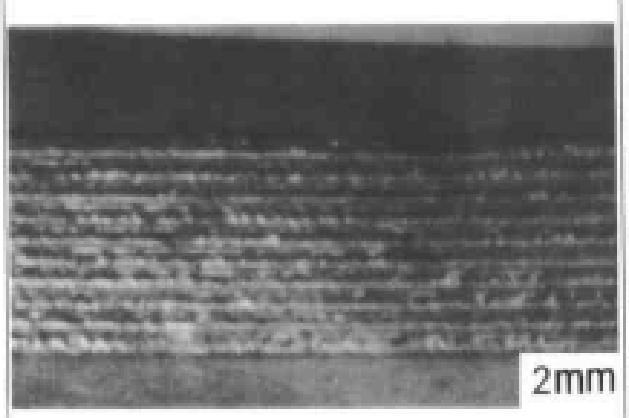

图 4－103 激光熔覆，灰铸铁，熔覆材料 Si 质量分数为 0.16%时 10 道熔覆层宏观形貌

Laser cladding, grey cast iron, cladding material containing 0.16%Si, macro-morphology of cladding layer with overlapping of 10 traces.

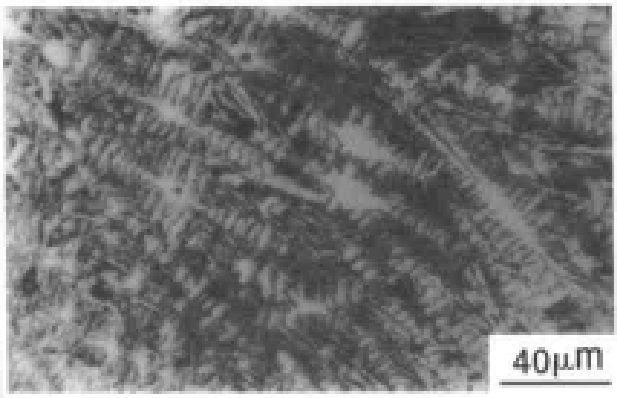

图 4－104 激光熔覆，熔覆材料化学成分为 Fe－3.23C－0.57Si－0.56Cu，熔覆层组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－0.56Cu, morphology of cladding layer.

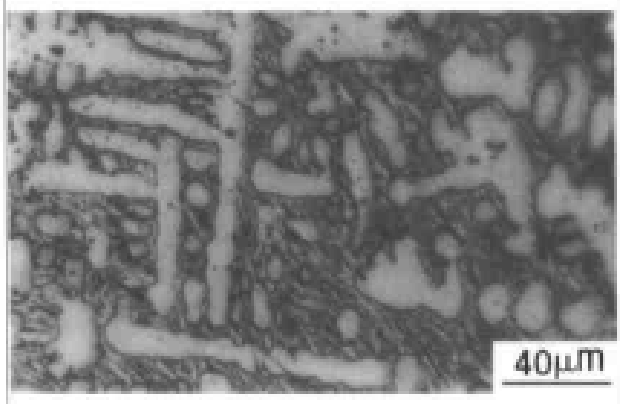

图 4－105 激光熔覆，熔覆材料化学成分为 Fe－3.23C－0.57Si－1.13Cu，熔覆层组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－1.13Cu, morphology of cladding layer.

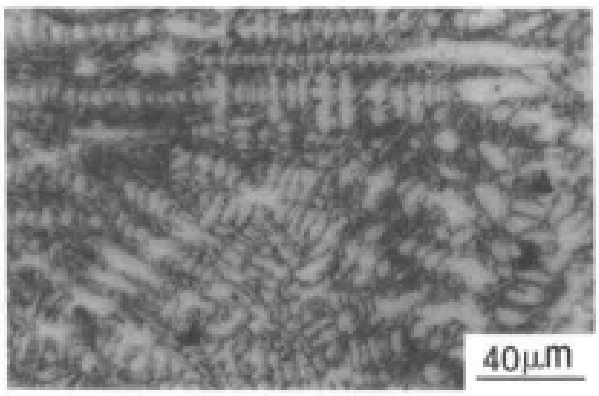

图 4－106 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－1.58Cu，熔覆层组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－1.58Cu, morphology of cladding layer.

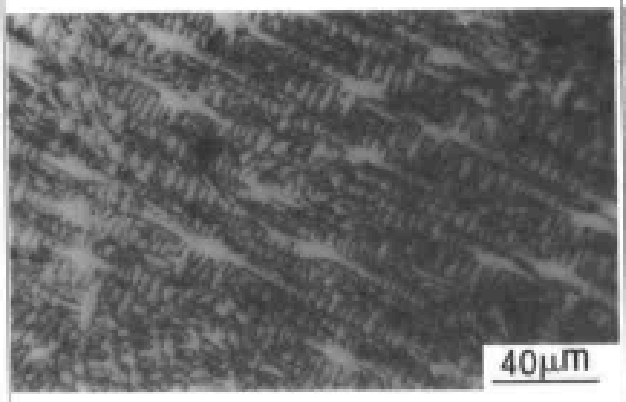

图 4－107　激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－2.36Cu，熔覆层组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－2.36Cu, morphology of cladding layer.

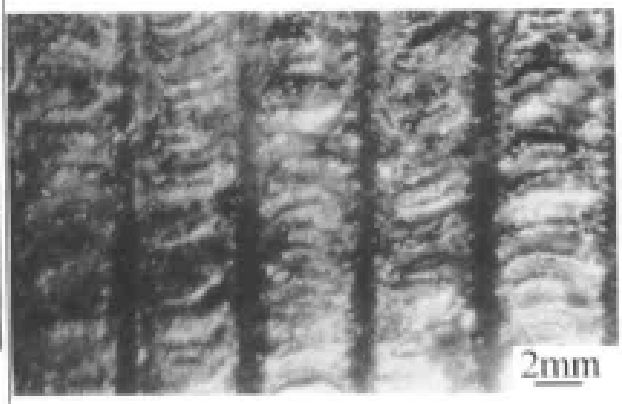

图 4－108　激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－0.56Cu，5 道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－1.58Cu, macro-morphology of cladding layer with overlapping of 5 traces.

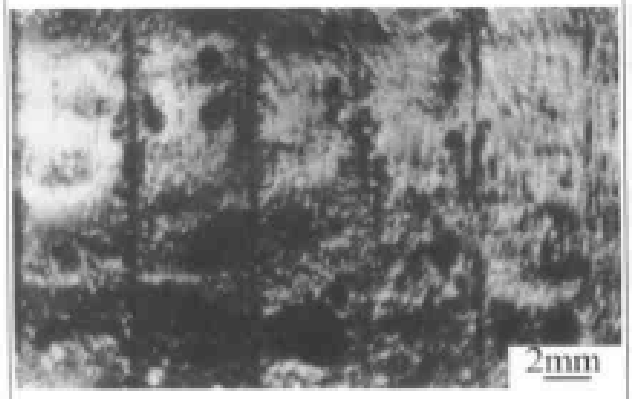

图 4－109　激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－2.36Cu，5 道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－2.36Cu, macro-morphology of cladding layer with overlapping of 5 traces.

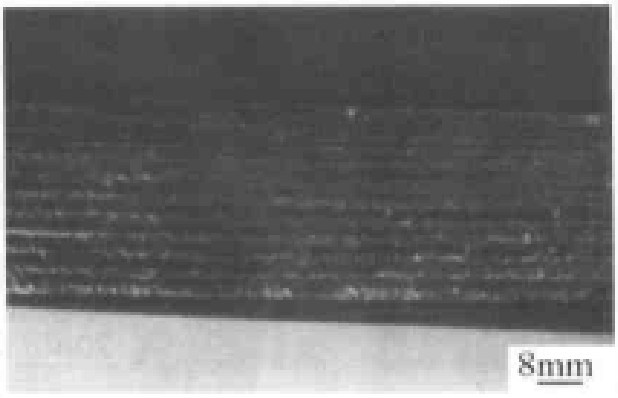

图 4－110　激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－1.13Cu，10 道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－1.13Cu, macro-morphology of cladding layer with overlapping of 10 traces.

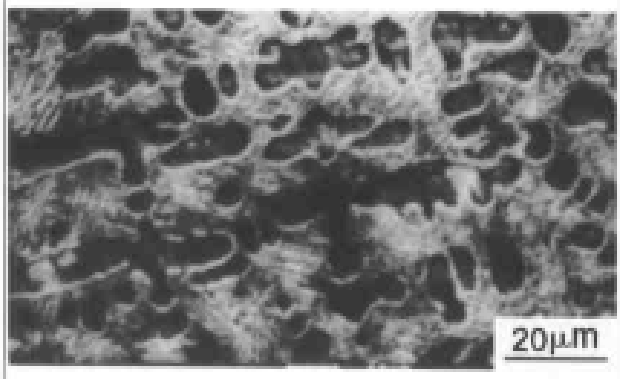

图 4－111 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－1.24Ni，熔覆层组织形貌
Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－1.24Ni, morphology of cladding layer.

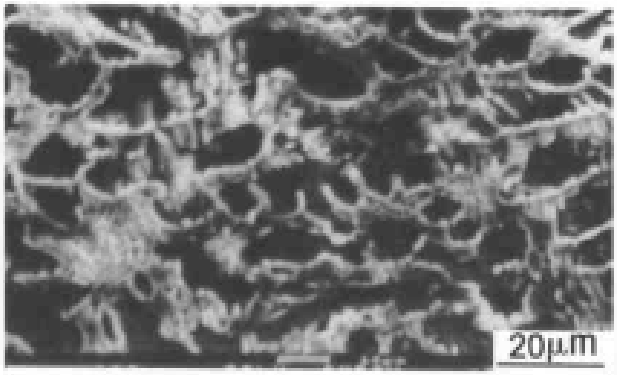

图 4－112 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－2.76Ni，熔覆层组织形貌
Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－2.76Ni, morphology of cladding layer.

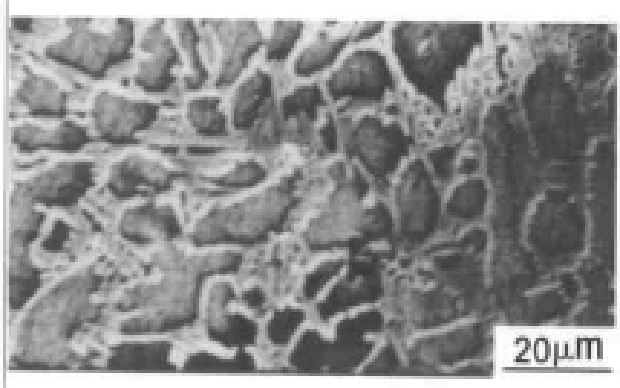

图 4－113 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－4.77Ni，熔覆层组织形貌
Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－4.77Ni, morphology of cladding layer.

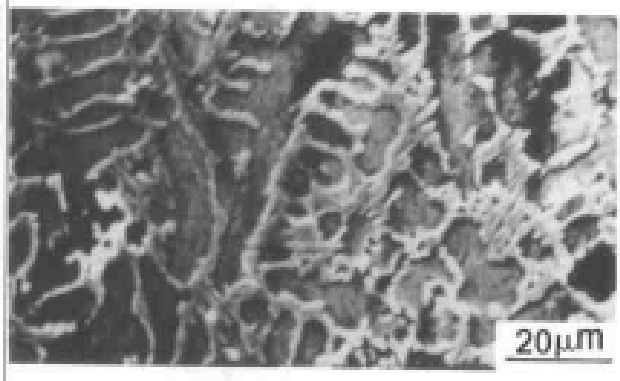

图 4－114 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－7.04Ni，熔覆层组织形貌
Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－7.04Ni, morphology of cladding layer.

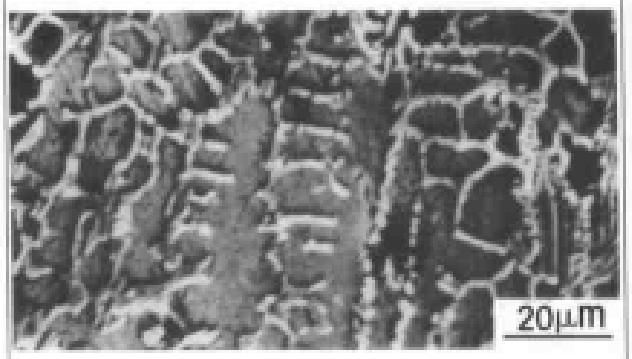

图4－115 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－8.51Ni，熔覆层组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－8.51Ni, morphology of cladding layer.

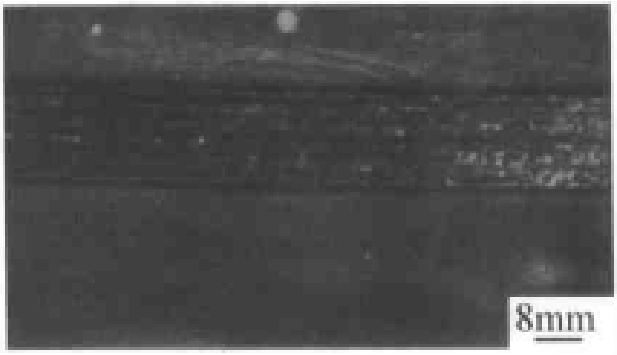

图4－116 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－2.76Ni，5道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－2.76Ni, macro－morphology of cladding layer with overlapping of 5 traces.

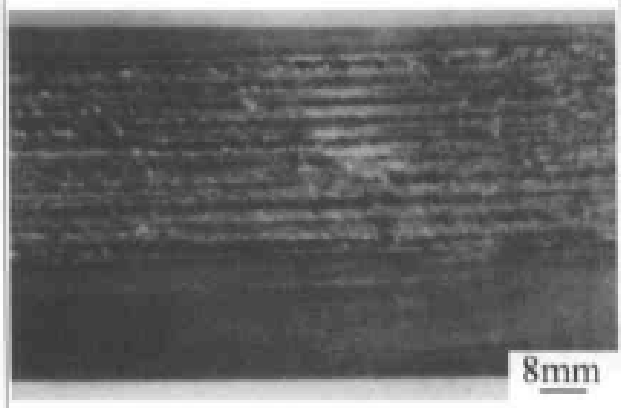

图4－117 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－2.76Ni，10道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－2.76Ni, macro－morphology of cladding layer with overlapping of 10 traces.

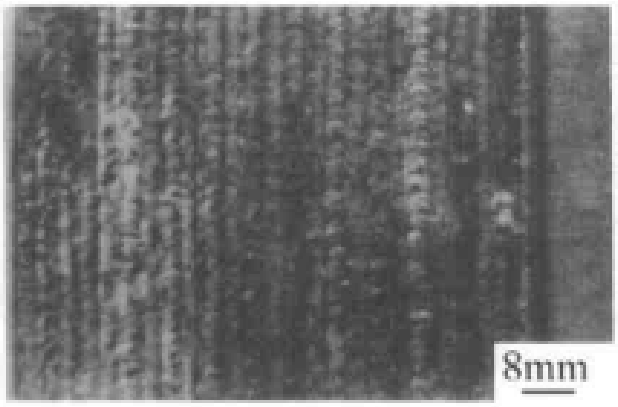

图4－118 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－4.77Ni，25道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－4.77Ni, macro－morphology of cladding layer with overlapping of 25 traces.

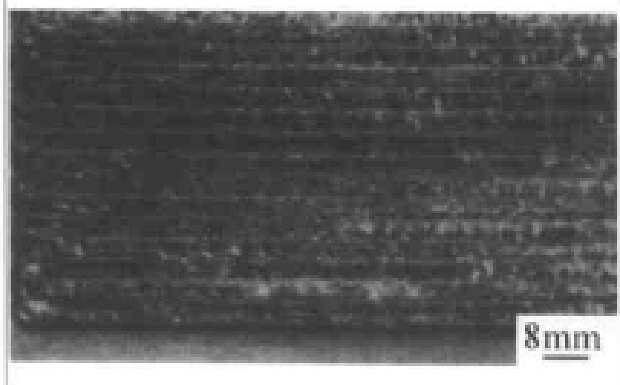

图 4－119 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.22C－0.57Si－0.32K，15 道熔覆层宏观形貌

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－0.32K, macro－morphology of cladding layer with overlapping of 15 traces.

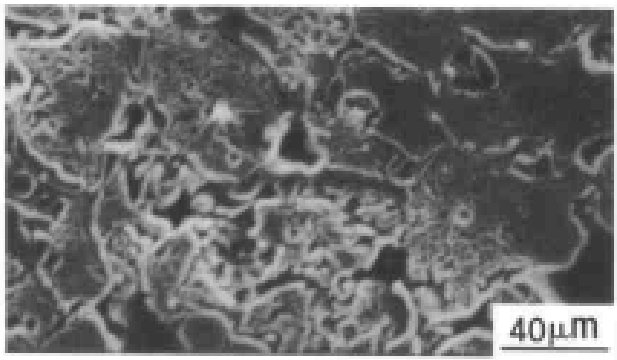

图 4－120 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－4.77Ni－0.17K，熔覆层显微组织

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－4.77Ni－0.17K, morphology of cladding layer.

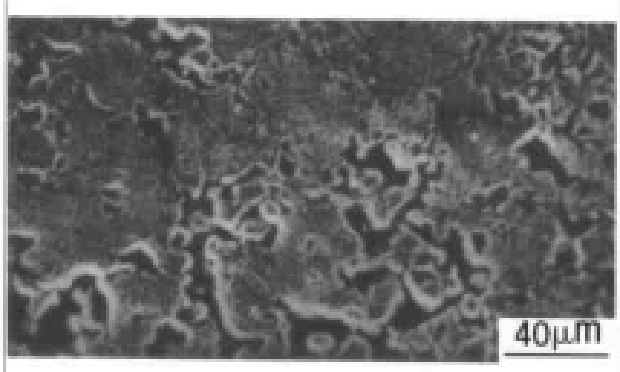

图 4－121 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－3.23C－0.57Si－4.77Ni－0.28K，熔覆层显微组织

Laser cladding, grey cast iron, chemical composition: Fe－3.23C－0.57Si－4.77Ni－0.28K, morphology of cladding layer.

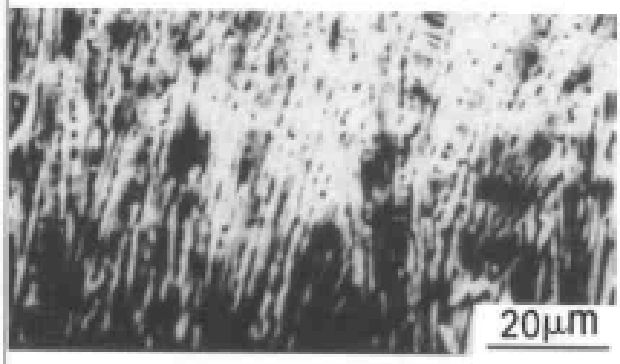

图 4－122 激光熔覆，灰铸铁，熔覆材料化学成分为：Fe－4.12C－0.60Si，共晶莱氏体组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si, morphology of eutectic ledeburite.

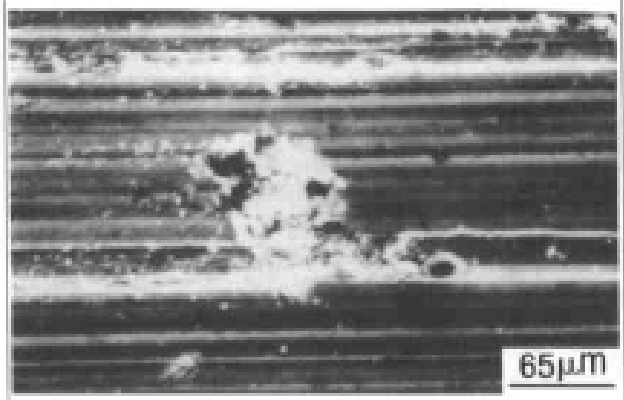

图4－123 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si，纯莱氏体熔覆层磨损形貌

Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si, morphology of pure ledeburite.

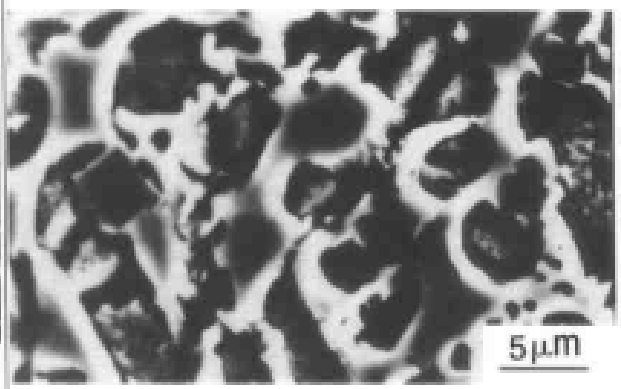

图4－124 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－3.42Ti，组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－3.42Ti, morphology of cladding layer.

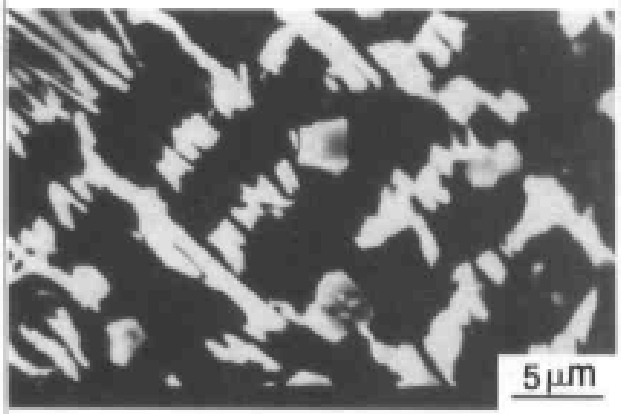

图4－125 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－6.94Ti，组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－6.94Ti, morphology of cladding layer.

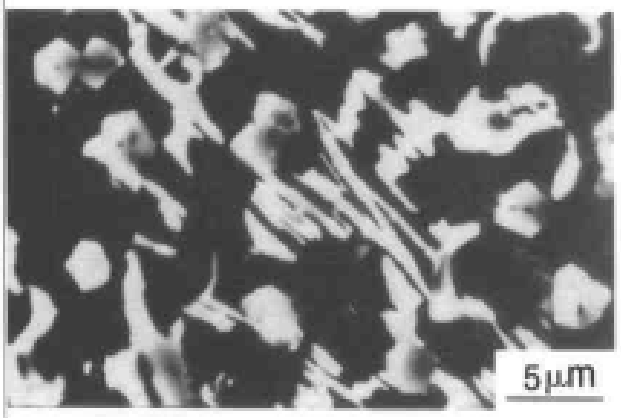

图4－126 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－10.18Ti，组织形貌

Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－10.18Ti, morphology of cladding layer.

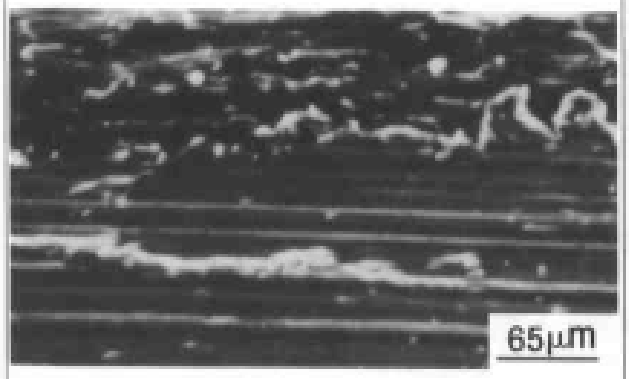

图 4－127 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－3.42Ti，熔覆层磨痕形貌
Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－3.42Ti, worn morphology of cladding layer.

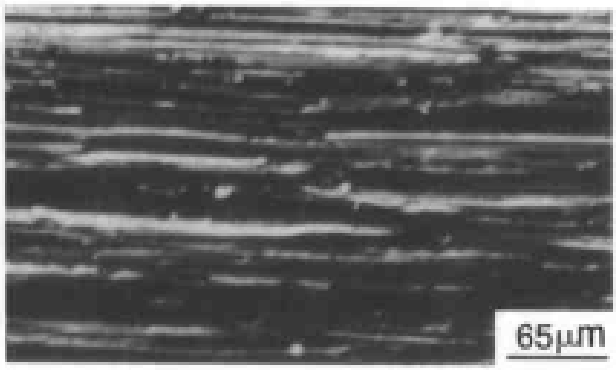

图 4－128 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－6.94Ti，熔覆层磨痕形貌
Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－6.94Ti, worn morphology of cladding layer.

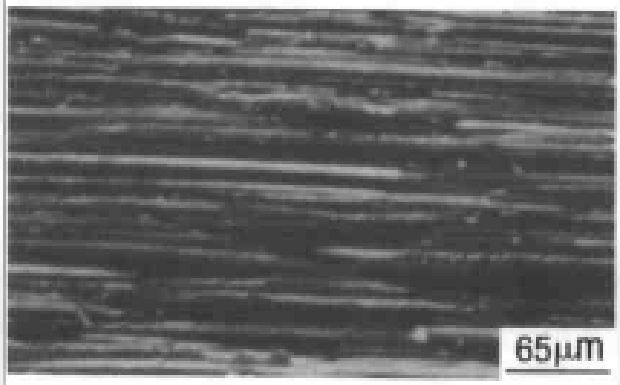

图 4－129 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－10.18Ti，熔覆层磨痕形貌
Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－10.18Ti, worn morphology of cladding layer.

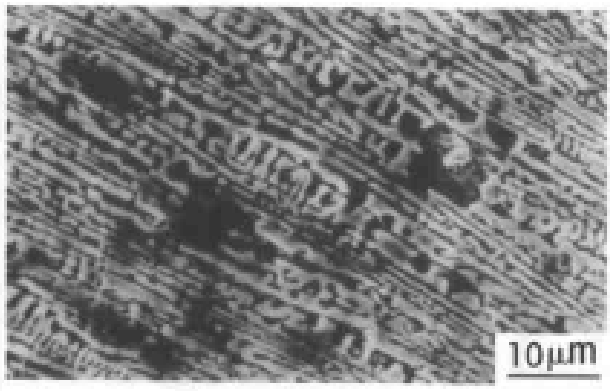

图 4－130 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－3.57V，熔覆层显微组织
Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－3.57V, microstructure of cladding layer.

图 4－131 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－9.84V，熔覆层显微组织
Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－9.84V, microstructure of cladding layer.

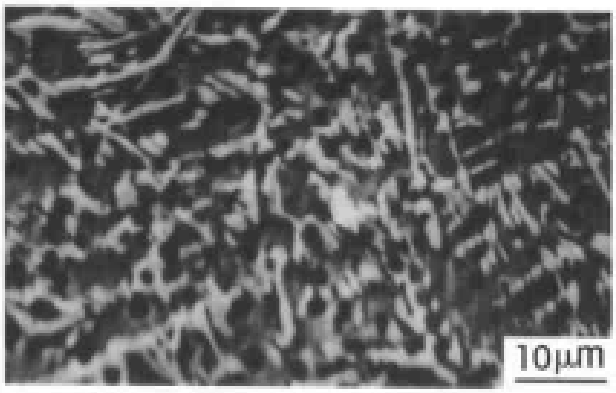

图 4－132 激光熔覆，灰铸铁，熔覆材料化学成分为 Fe－4.12C－0.60Si－12.82V，熔覆层显微组织
Laser cladding, grey cast iron, chemical composition: Fe－4.12C－0.60Si－12.82V, microstructure of cladding layer.

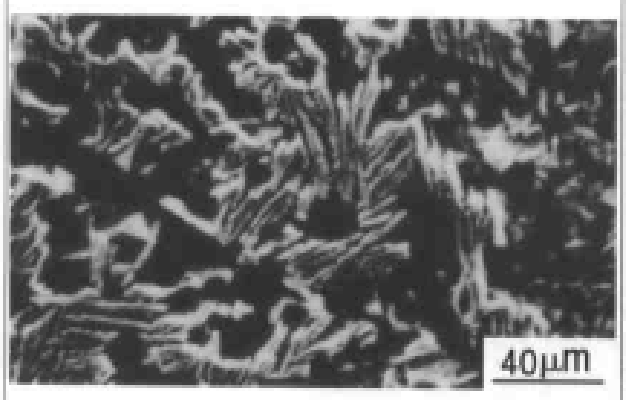

图 4－133 激光熔覆，灰铸铁，熔覆层显微组织
Laser cladding, grey cast iron, microstructure of cladding layer.

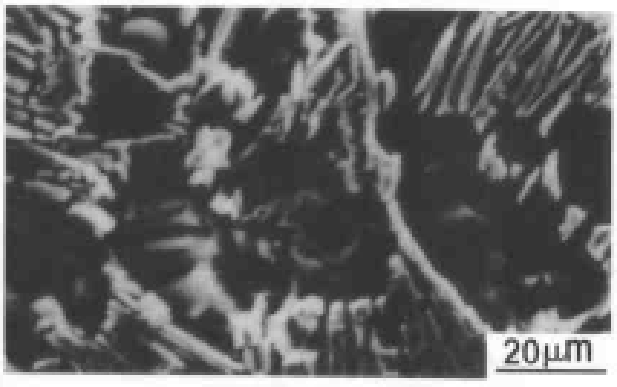

图 4－134 激光熔覆，灰铸铁，冷处理熔覆层显微组织
Laser cladding, grey cast iron, microstructure of cladding layer with liquid nitrogen treatment.

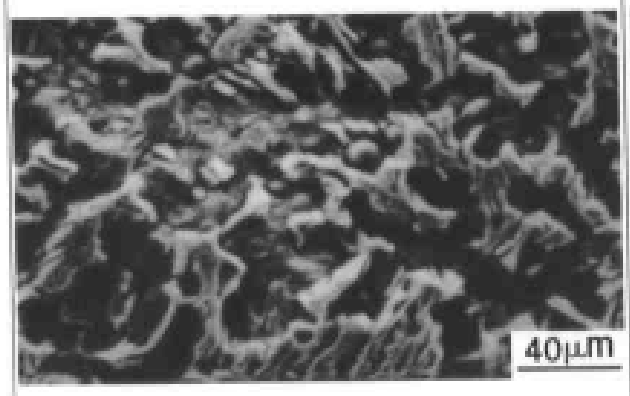

图 4－135 激光熔覆，灰铸铁，熔覆层显微组织
Laser cladding, grey cast iron, microstructure of cladding layer.

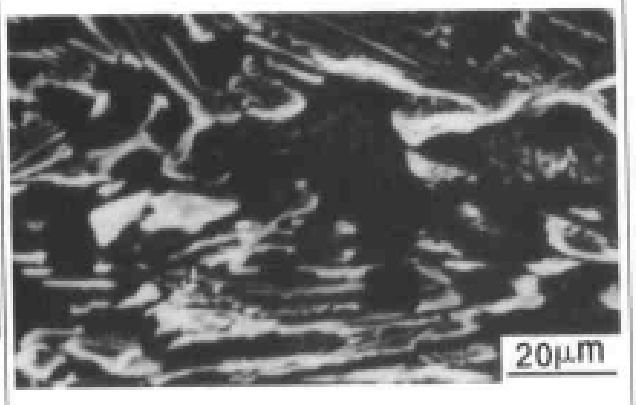

图 4－136 激光熔覆，灰铸铁，冷处理熔覆层显微组织
Laser cladding, grey cast iron, microstructure of cladding layer with liquid nitrogen treatment.

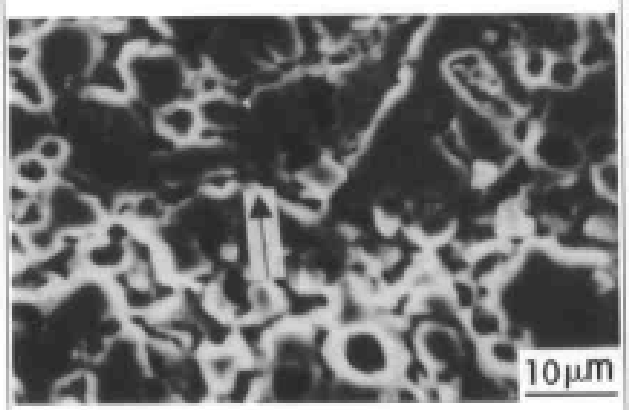

图 4－137 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力 662MPa
Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress of 662MPa.

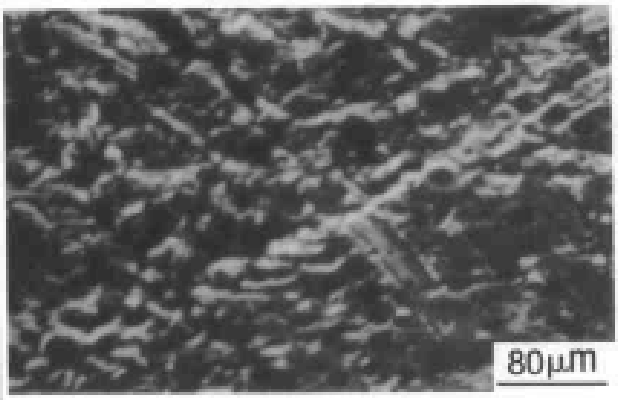

图 4－138 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下
Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

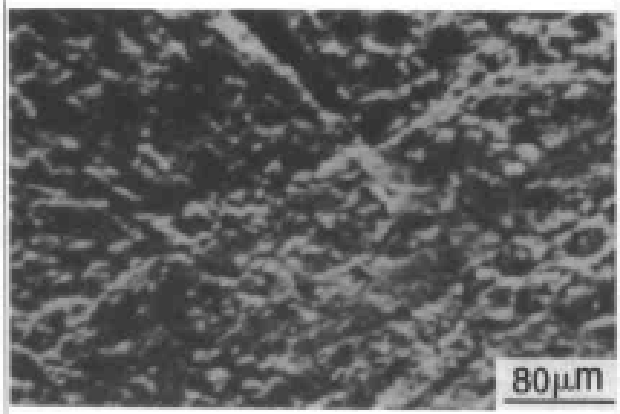

图4-139 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

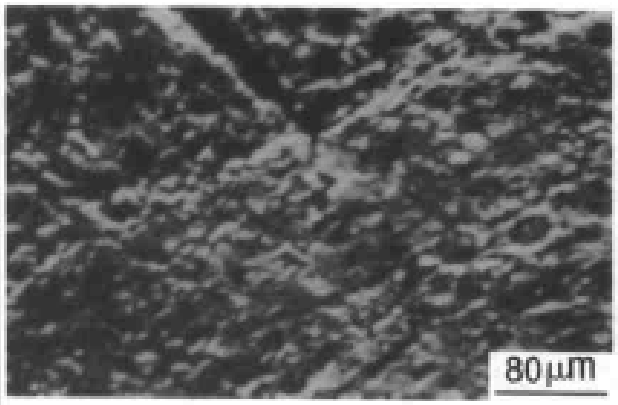

图4-140 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

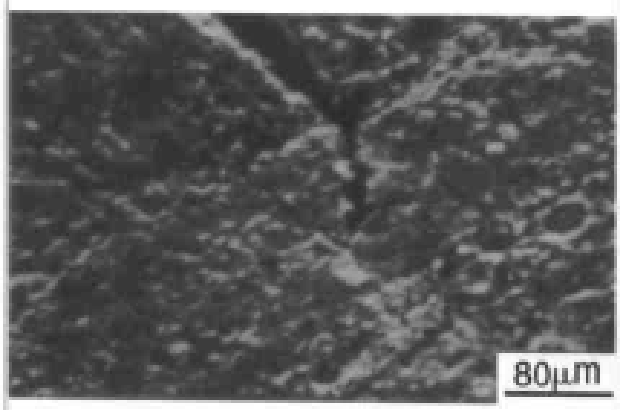

图4-141 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

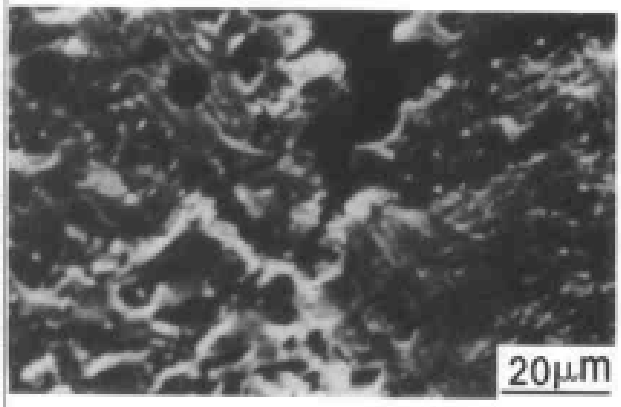

图4-142 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

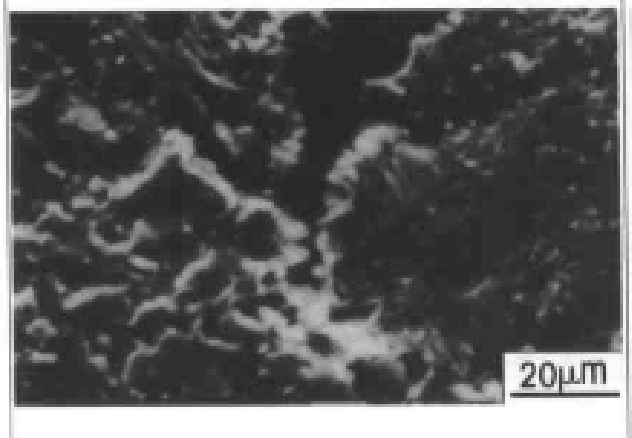

图 4－143 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

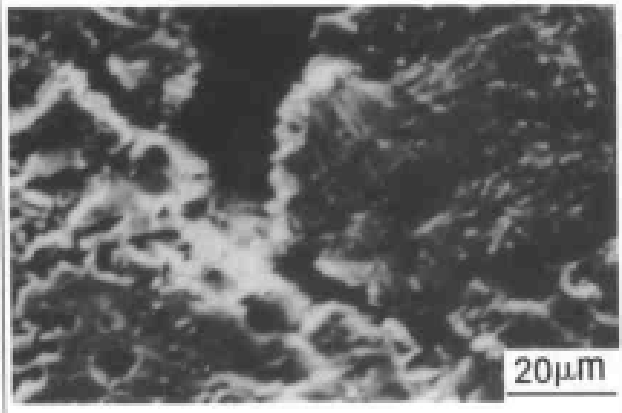

图 4－144 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initiation and propagation of cracks in cladding layer with additional stress.

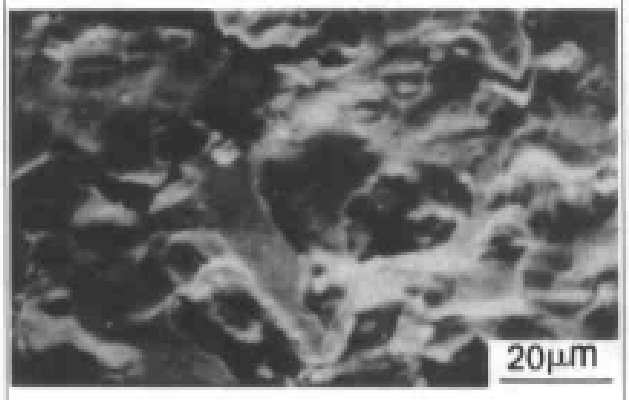

图 4－145 激光熔覆，灰铸铁，熔覆层裂纹萌生及扩展，外加应力下

Laser cladding, grey cast iron, initia tion and propagation of cracks in cladding layer with additional stress.

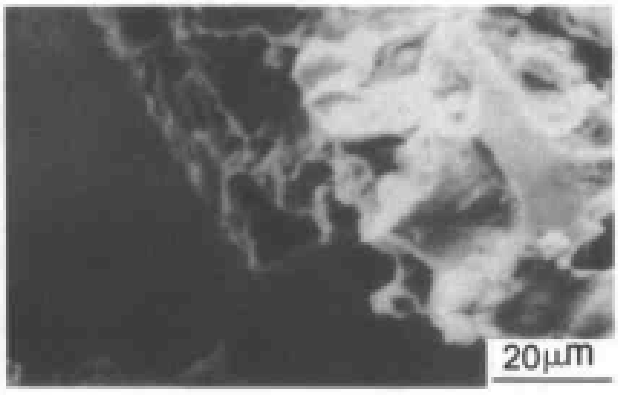

图 4－146 激光熔覆，灰铸铁，熔覆层动态拉伸断口形貌（断裂区）

Laser cladding, grey cast iron, dynamic tensile fracture morphology in the fractural area.

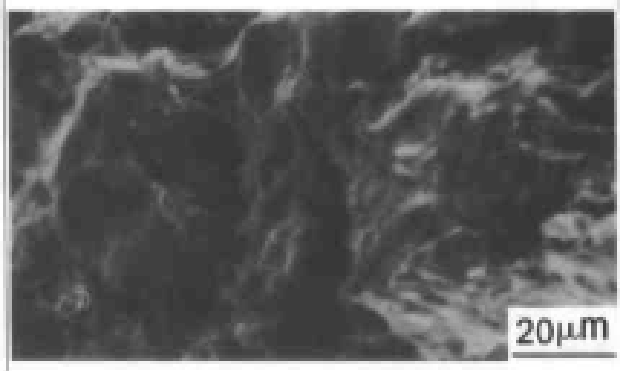

图4－147 激光熔覆，灰铸铁，熔覆层动态拉伸断口形貌（裂纹萌生区）
Laser cladding, grey cast iron, dynamic tensile fracture morphology in the crack starting area.

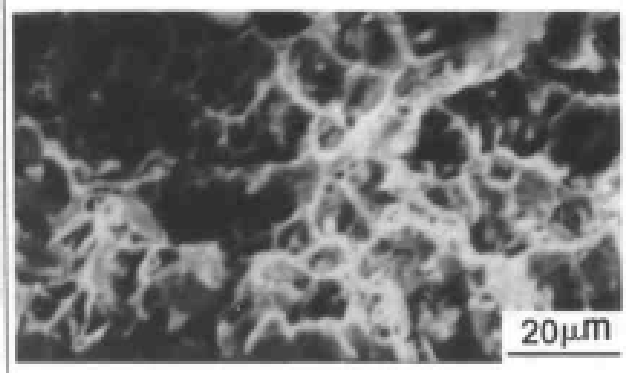

图4－148 激光熔覆，灰铸铁，熔覆层动态拉伸断口形貌(裂纹扩展区)
Laser cladding, grey cast iron, dynamic tensile fracture morphology in the crack propagation area.

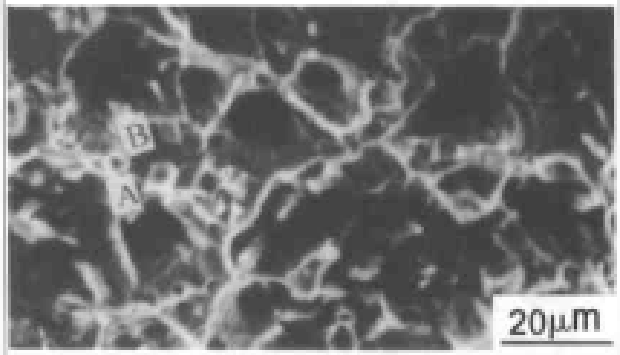

图4－149 激光熔覆，灰铸铁，熔覆层动态拉伸断口形貌(裂纹扩展区)
Laser cladding, grey cast iron, dynamic tensile fracture morphology in the crack propagation area.

4.4 粉末冶金材料激光熔覆

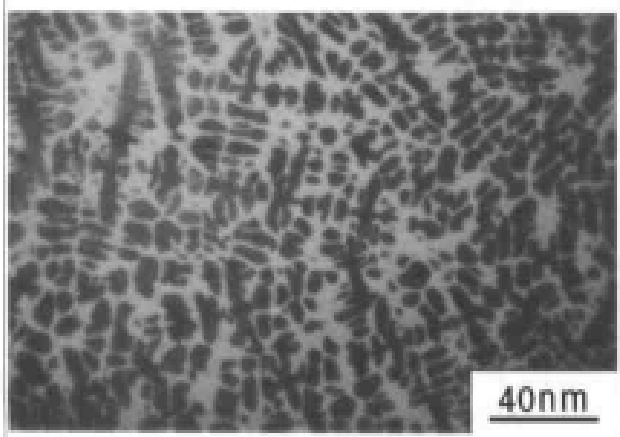

图4－150 粉末冶金材料激光熔覆，基体成分98Fe＋2C，熔覆材料0.3Cr－0.9Ni－0.5Co－0.5Mn－0.6Mo－0.5Cu－0.2C－93.5Fe，CO_2 激光，SEM照片，显示熔覆区
Laser coating of powder metallurgy materials, composition of substrate98% Fe＋2C, coating materials 0.3Cr－0.9Ni－0.5Co－0.5Mn－0.6Mo－0.5Cu－0.2C－93.5Fe, CO_2 laser SEM micrograph, showing coated microstructure in coated layer zone.

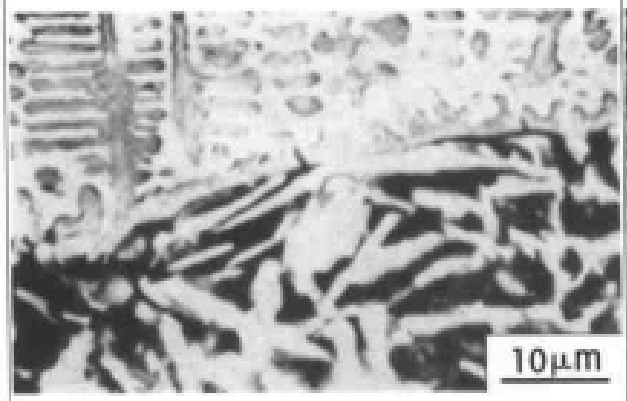

图 4－151　粉末冶金材料激光熔覆，基体成分 98Fe＋2C，熔覆材料 0.3Cr－0.9Ni－0.5Co－0.5Mn－0.6Mo－0.5Cu－0.2C－93.5Fe，CO_2 激光，SEM 照片，显示熔覆区（上部）和热影响区组织（下部）

Laser coating of powder metallurgy materials, composition of substrate98Fe＋2C, coating materials 0.3Cr－0.9Ni－0.5Co－0.5Mn－0.6Mo－0.5Cu－0.2C－93.5Fe, CO_2 laser, SEM micrograph, showing coating layer (up part) and heat affected zone (low part).

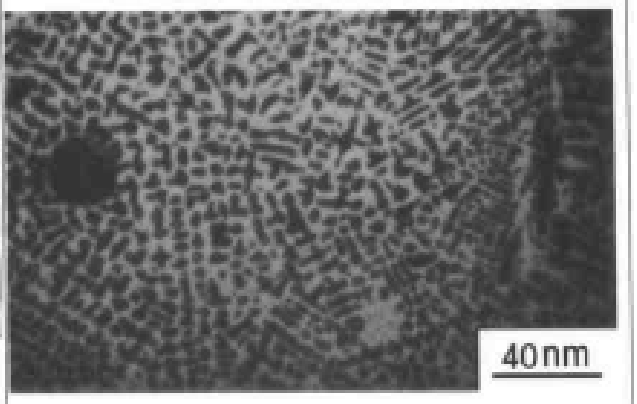

图 4－152　粉末冶金材料激光熔覆，基体成分 98Fe＋2C，熔覆材料 0.3Cr－0.9Ni－0.5Co－0.5Mn－0.6Mo－0.5Cu－0.2C－93.5Fe，CO_2 激光，SEM 照片，显示熔覆区中的孔洞

Laser coating of powder metallurgy materials, composition of substrate98Fe＋2C, coating materials 0.3Cr－0.9Ni－0.5Co－0.5Mn－0.6Mo－0.5Cu－0.2C－93.5Fe, CO_2 laser, SEM micrograph, showing pore in coating layer.

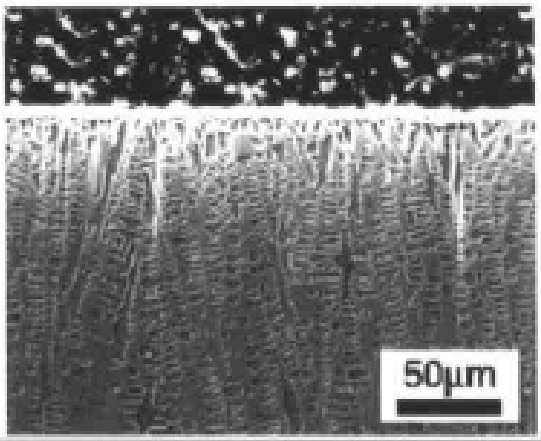

图 4－153　激光熔覆，熔覆材料为 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co 余量，T10 钢基体，CO_2 激光，功率 1500～1700W，扫描速度 5mm/s，透镜焦距为 300mm，保护气为 N，送粉速率为 10g/min。SEM 照片，显示基体（上部）和 熔覆区（下部）

Laser cladding of 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co balance on T10 steel, CO_2 laser, power 1500～1700W, scanning rate 5mm/s, foucs distance 300mm, cladding with N, SEM photograph showing both substrate (up part) and cladding region (low part).

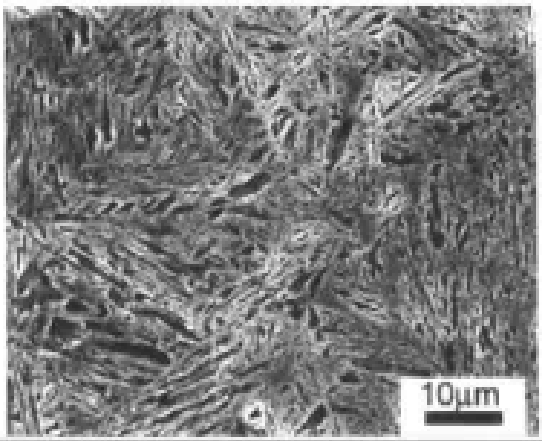

图 4－154　激光熔覆，熔覆材料为 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co 余量，T10 钢基体，CO_2 激光，功率 1500～1700W，扫描速度 5mm/s，透镜焦距为 300mm，保护气为 N，送粉速率为 10g/min ，SEM 照片，显示热影响区组织

Laser cladding of 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co balance on T10 steel, CO_2 laser, power 1500～1700W, scanning rate 5mm/s, foucs distance 300mm, cladding with N, SEM photograph heat affected zone.

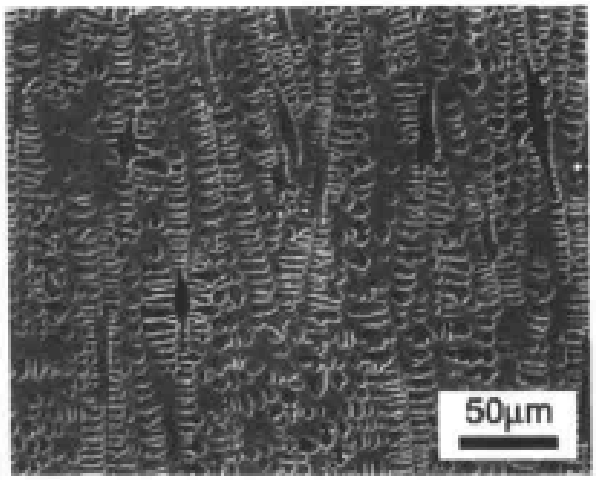

图4－155 激光熔覆，熔覆材料为5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co余量，T10钢基体，CO_2激光，功率1500～1700W，扫描速度5mm/s，透镜焦距为300mm，保护气为N，送粉速率为10g/min，SEM照片，显示熔覆区底部组织

Laser cladding of 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co balance on T10 steel, CO_2 laser, power 1500～1700W, scanning rate 5mm/s, fouces distance 300mm, cladding with N, SEM photograph showing cladding region(low part).

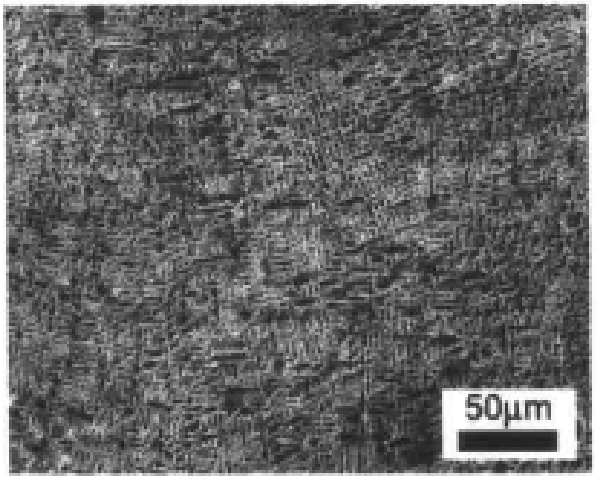

图4－156 激光熔覆，熔覆材料为5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co余量，T10钢基体，CO_2激光，功率1500～1700W，扫描速度5mm/s，透镜焦距为300mm，保护气为N，送粉速率为10g/min，SEM照片，显示熔覆区顶部(表层)组织

Laser cladding of 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co balance on T10 steel, CO_2 laser, power 1500～1700W, scanning rate 5mm/s, fouces distance 300mm, cladding with N, SEM photograph showing cladding region(top part, surface).

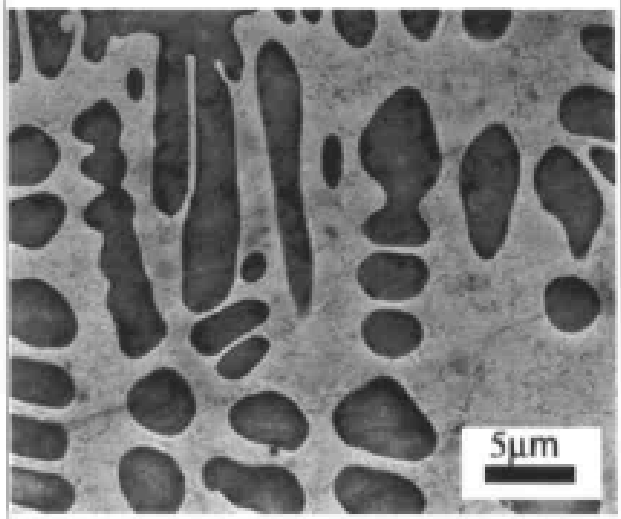

图4－157 激光熔覆，熔覆材料为5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co余量，T10钢基体，CO_2激光，功率1500～1700W，扫描速度5mm/s，透镜焦距为300mm，保护气为N，送粉速率为10g/min，SEM照片，显示熔覆区组织(高倍)

Laser cladding of 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co balance on T10 steel, CO_2 laser, power 1500～1700W, scanning rate 5mm/s, fouces distance 300mm, coated in N, SEM photograph showing cladding region (high magnification).

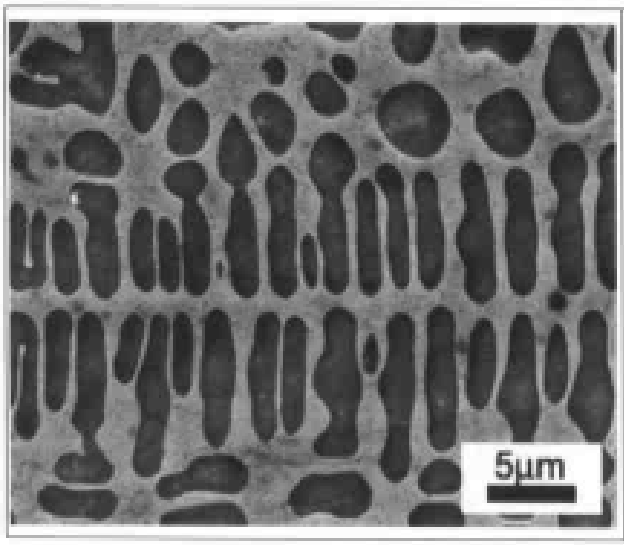

图 4－158 激光熔覆，熔覆材料为 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co 余量，T10 钢基体，CO_2 激光，功率 1500～1700W，扫描速度 5mm/s，透镜焦距为 300mm，保护气为 N，送粉速率为 10g/min，SEM 照片，显示熔覆区组织(高倍)

Laser cladding of 5Fe－0.5－1.0C－19.0－23.0Cr－1.0－3.0Si－1.5－2.0B－7.0－9.0W－Co balance on T10 steel, CO_2 laser, power 1500～1700W, scanning rate 5mm/s, foucs distance 300mm, coated in N, SEM photograph showing coated region (high magnification).

参 考 文 献

[4.1] Hu Jiandong, Luan Jingfei, Zhou Zhenfeng. Wear resistance of austenite－TiC－graphite microstructures prepared by laser coating. Materials Science and Technology, 2001 (17): 588

第5章　激光焊接

激光焊接(laser welding)是以细聚焦的高能激光束辐射焊件进行焊接的方法。它具有输入热量少、焊接速度高、焊缝热变形和热影响区小、深宽比大、组织细、韧性好等优点；焊接时无机械接触，焊件精度高，有利于实现在线质量监控和自动化生产；生产效率高，经济效益显著。在激光加工应用领域激光焊接占的比重较大，大功率激光焊接主要分布在汽车制造业，实施激光焊接的功率密度通常很高，使材料发生熔化，获得焊接。

按激光器的输出方式可以把激光焊划分为脉冲激光焊和连续激光焊（Nd：YAG激光也能进行连续缝焊)；而根据激光焊时焊缝的形成特点又可以把激光焊划分为热传导焊和深熔化焊，前者使用的激光功率密度较低，熔化区形成时间较长，且深度较浅，多用于小型零件的焊接。后者使用的激光功率密度较高，激光辐射区的熔化速度快，在金属熔化的同时伴随着强烈的汽化。激光焊能获得较深的焊缝，焊缝的深宽比很大，可达12:1。

激光焊接时激光是通过很小的直径向材料“注入”热量，材料的升温速度很快，材料能在极短的时间内达到很高的温度。工件的穿透深度可以通过激光功率密度来控制。

激光焊接时材料的熔化在很短的周期内完成，并以很快的速度凝固，导致焊缝组织与常规熔凝组织区别较大。熔化金属首先在固液相界面结晶，然后向熔化区内部迅速长大，在熔区底部和侧面结晶的晶体外延长大，最后在熔区的中心处相遇，结晶金属的形貌受冷却速度等因素影响。

对于钢铁材料，在半熔化区基体一侧，存在区域很窄的固态相变区，该区发生奥氏体相变。由于激光加热周期短的缘故，钢中的渗碳体或铸铁中的石墨很难实现均匀化，导致在原渗碳体或石墨位置生成的奥氏体含碳量高，其他区域奥氏体的含碳量低；高碳奥氏体较难完全转变成马氏体，导致组织中有较多残余奥氏体，残余奥氏体是非平衡组织，能在应力的诱发下转变成马氏体，降低接头韧性。和常规焊缝一样，激光焊缝也有缺陷，常见的缺陷有由金属元素大量蒸发引起的焊缝表面凹陷，组织应力和热应力所引发的裂纹等，还有一些微观缺陷，如气孔、孔隙、微裂纹等缺陷。

激光焊缝的组织形貌与材料本身的性质、激光光斑、功率密度、焊接速度以及保护气体等因素有关。本章给出的金相照片来自薄钢板、铝合金板材以及中碳钢和铸铁材料的焊缝组织。

5.1 薄钢板激光焊接

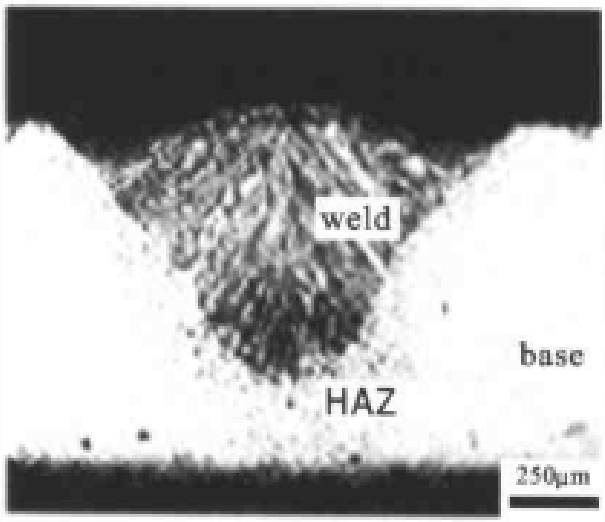

图 5－1 ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 1.3m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 1.3m/min.

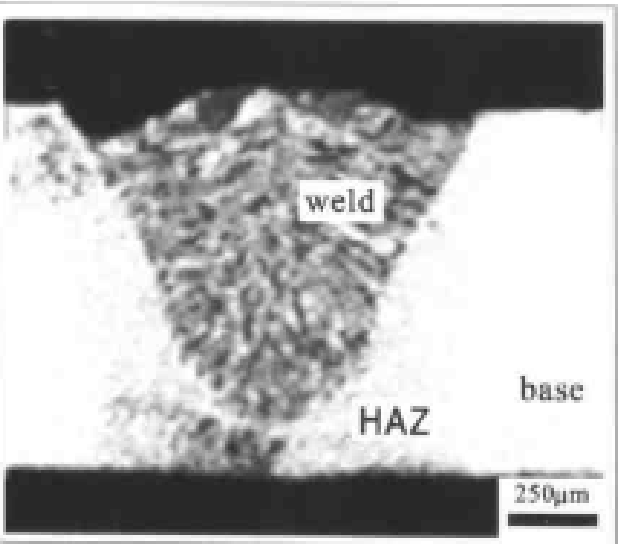

图 5－2 ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 1.6m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 1.6m/min.

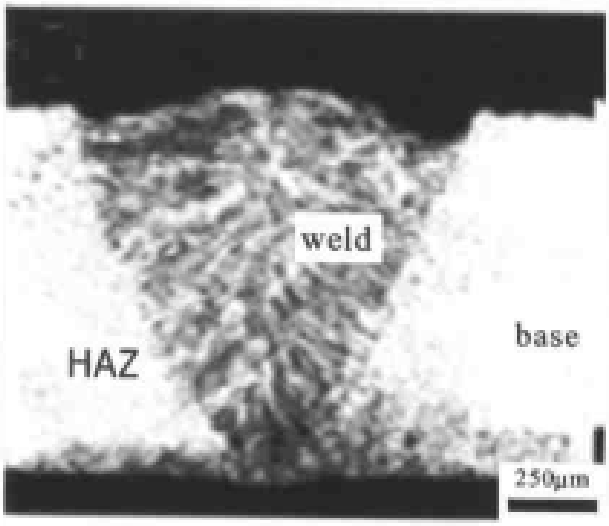

图 5－3 ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 1.9m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 1.9m/min.

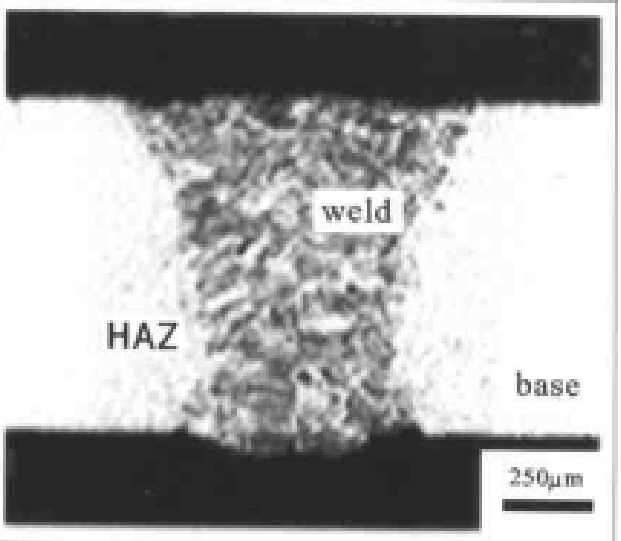

图 5－4 ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 2.2m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 2.2m/min.

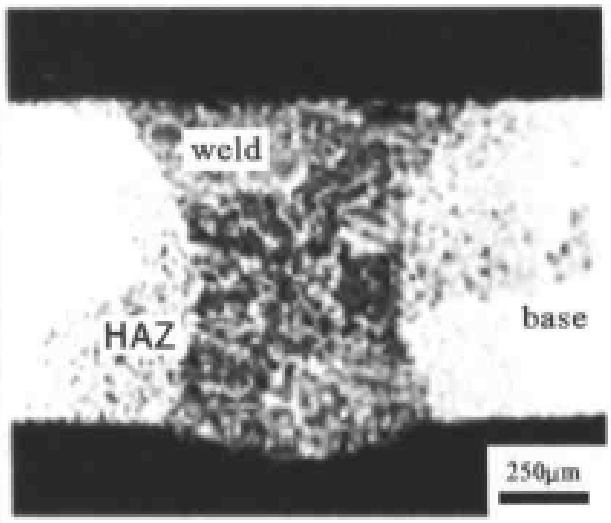

图 5－5　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 2.5m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 2.5m/min.

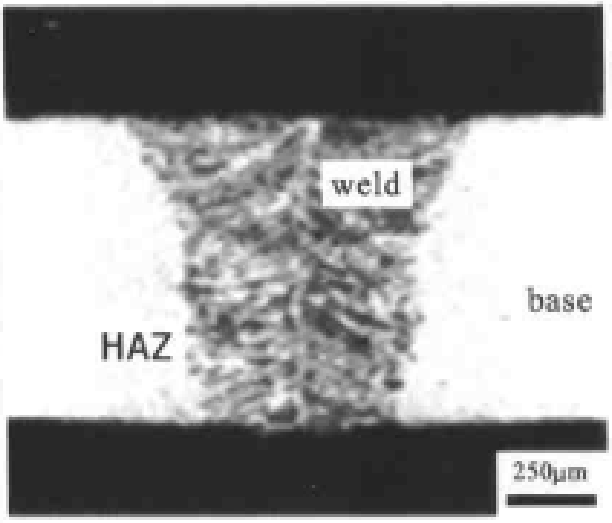

图 5－6　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 2.8m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 2.8m/min.

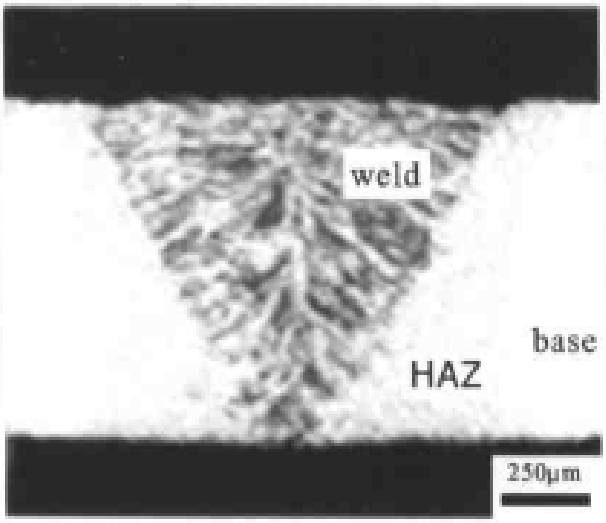

图 5－7　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 3.1m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 3.1m/min.

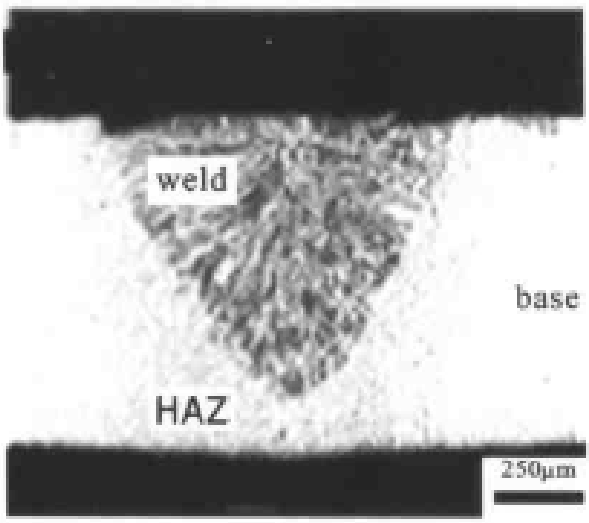

图 5－8　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 3.4m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 3.4m/min.

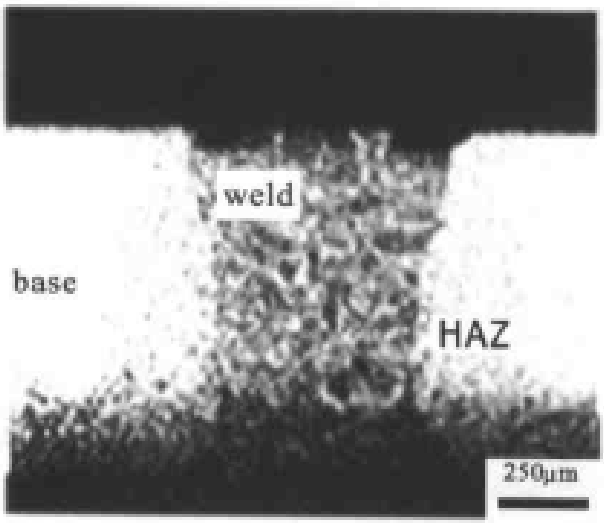

图 5－9　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 3.4m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 3.4m/min.

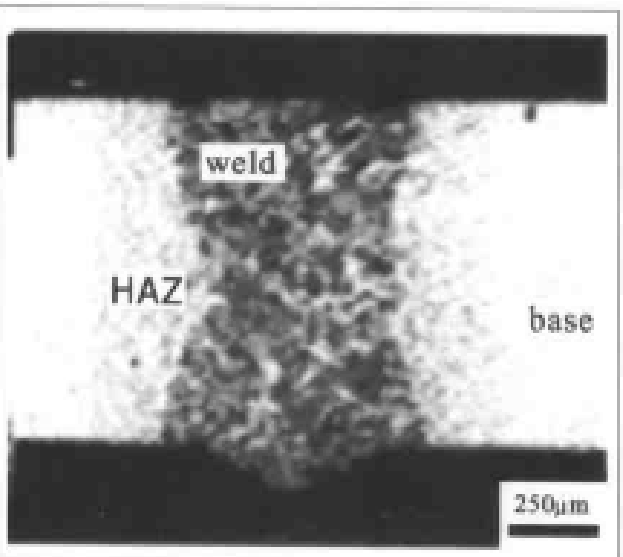

图 5－10　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 3.7m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 3.7m/min.

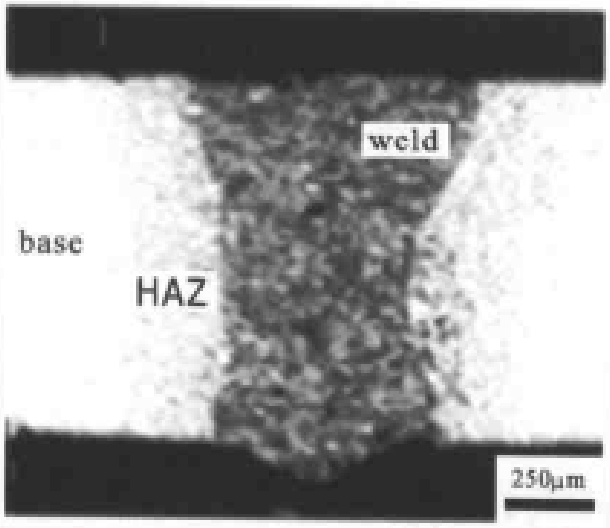

图 5－11　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 4.3m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 4.3m/min.

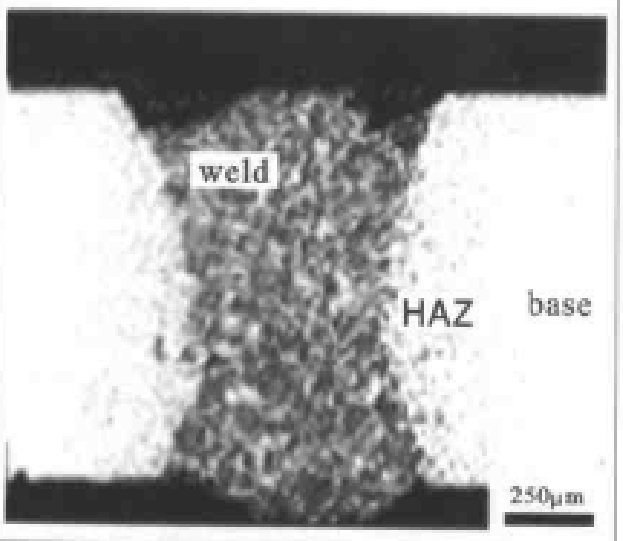

图 5－12　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 4.6m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 4.6m/min.

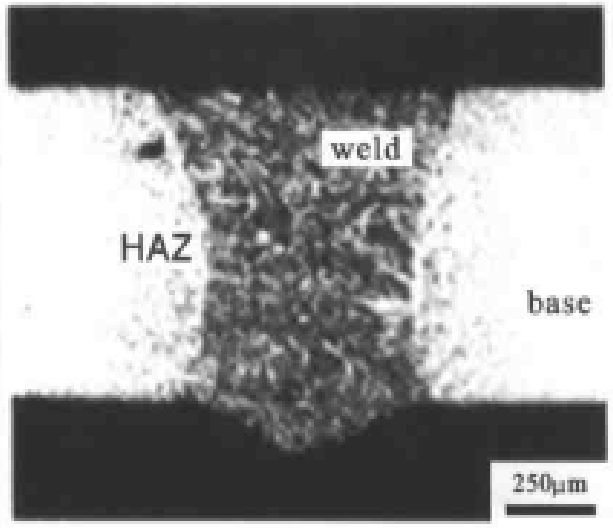

图 5－13　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 4.9m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 4.9m/min.

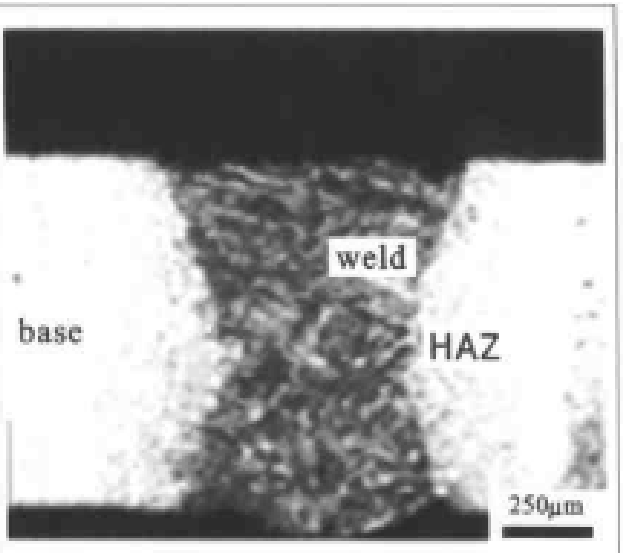

图 5－14　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 5.2m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 5.2m/min.

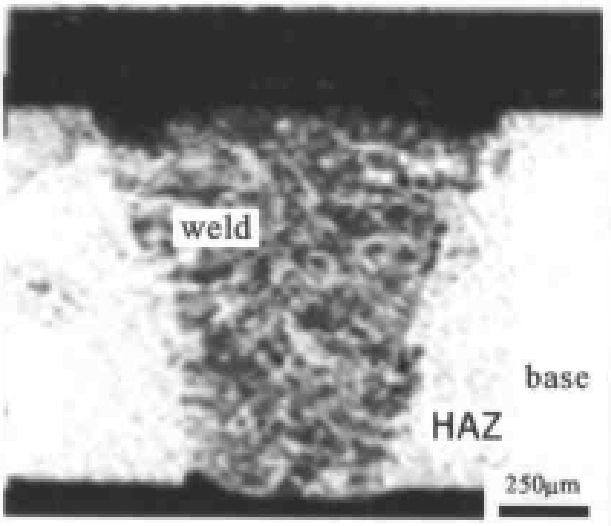

图 5－15　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 5.5m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 5.5m/min.

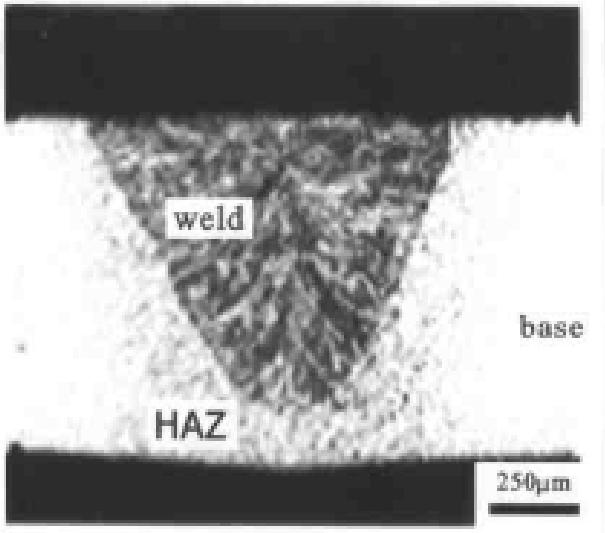

图 5－16　ST14 钢板 CO_2 激光焊对接焊缝正面外观照片，1mm 厚，焊接功率 1000W，焊接速度 5.8m/min

ST14 steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 1mm, welding power 1000W, welding speed 5.8m/min.

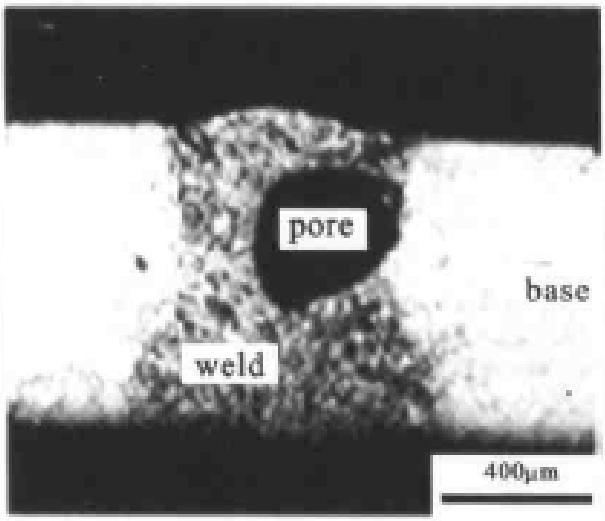

图 5－17 镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 2.2m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 2.2m/min.

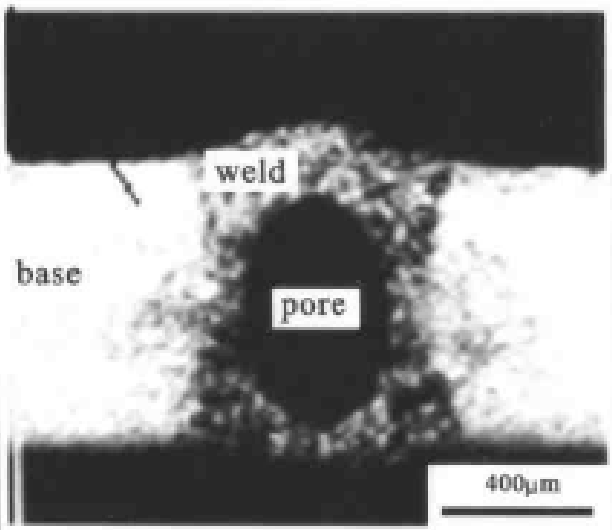

图 5－18 镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 2.5m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 2.5m/min.

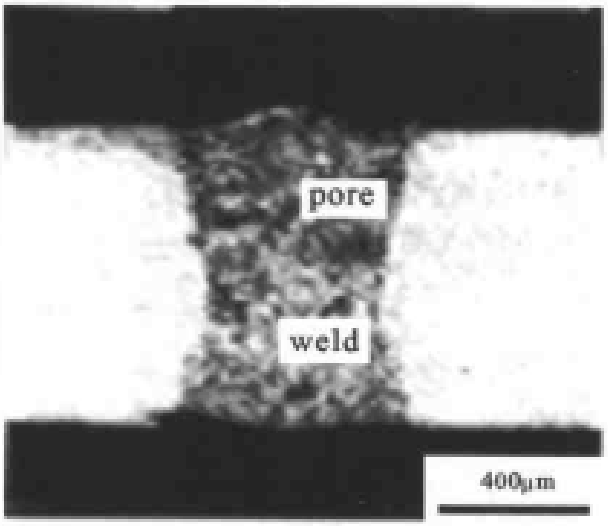

图 5－19 镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 2.8m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 2.8m/min.

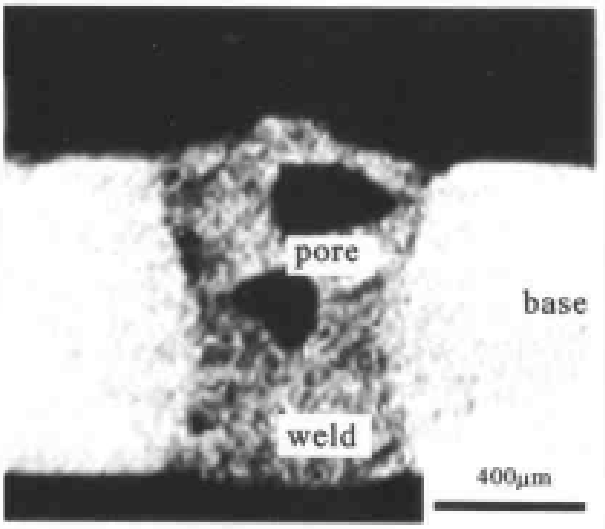

图 5－20 镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 3.1m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 3.1m/min.

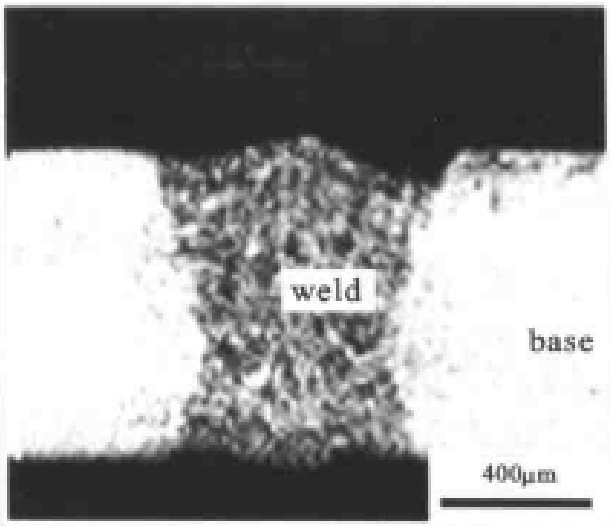

图 5－21　镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 3.4m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 3.4m/min.

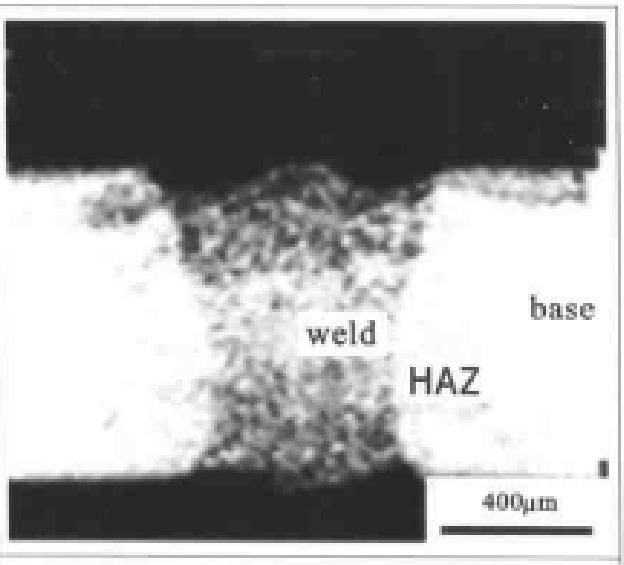

图 5－22　镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 3.7m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 3.7m/min.

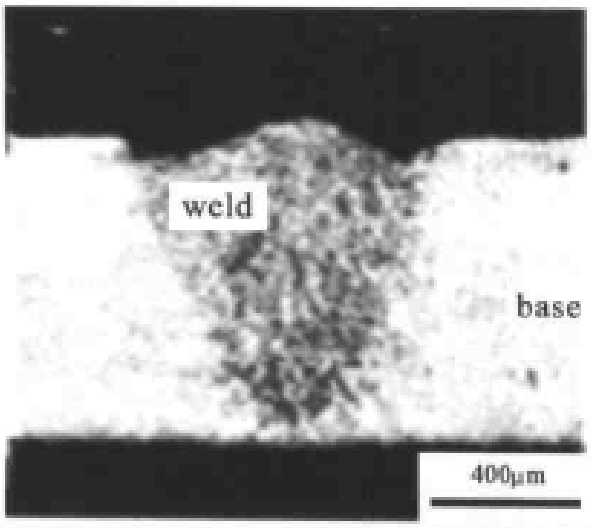

图 5－23　镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 4m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 4m/min.

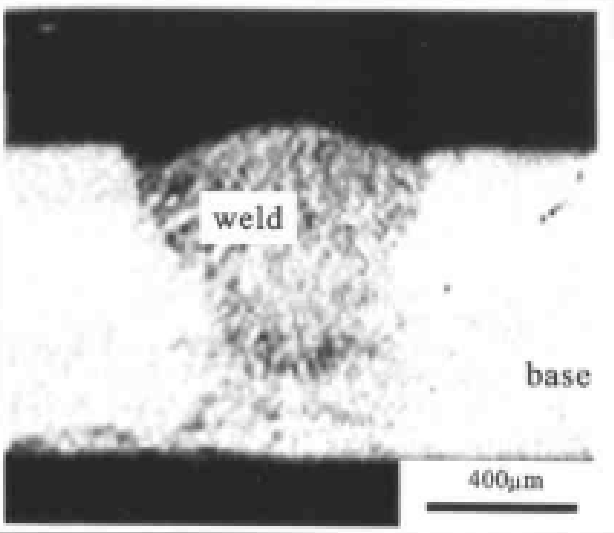

图 5－24　镀锌钢板 CO_2 激光焊对接焊缝正面外观照片，0.8mm 厚，焊接功率 1800W，焊接速度 4.3m/min

Zinc coated steel sheet CO_2 laser welding, SEM metallograph of top bead appearance of butt joint, thickness of plate 0.8mm, welding power 1800W, welding speed 4.3m/min.

5.2 铝合金激光焊接

图 5－25 5754 铝合金，YAG 激光焊对接接头横截面金相照片，板厚 1mm，60×

5754 Al alloy，YAG laser welding，metallograph of a cross butt joint，thickness of plate 1mm，60×.

图 5－26 5754 铝合金 YAG 激光焊对接接头横截面金相照片，板厚 1mm，"1"——基体，"2"——焊缝，500×

5754 Al alloy，YAG laser welding，metallograph of a cross butt joint，thickness of plate 1mm，"1"——base metal，"2"——weld zone，500×.

图 5－27 5754 铝合金 YAG 激光焊对接接头正面金相照片，板厚 1mm，10×

5754 Al alloy，YAG laser welding，metallograph of a top view butt joint，thickness of plate 1mm，10×.

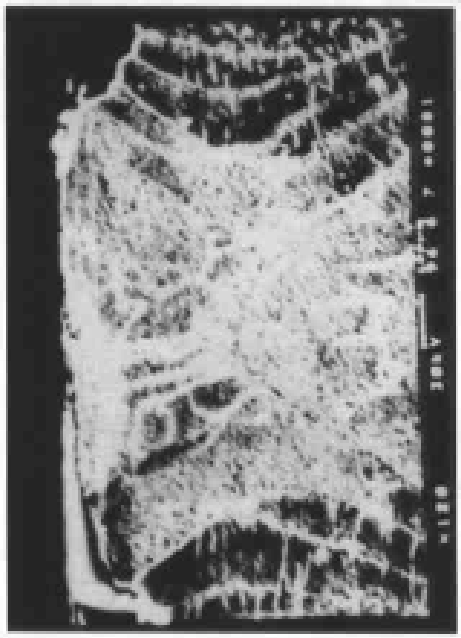

图 5－28 1050 铝合金 YAG 激光焊对接接头扫描电镜照片，1.10mm 厚，100×

1050 Al alloy，YAG laser welding，SEM metallograph of butt joint，thickness of plate 1.10mm，100×.

注：图 5－25 至图 5－30 引自文献[5.1]。

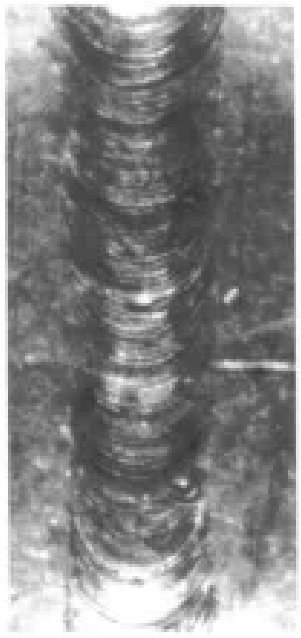

图 5－29　1050 铝合金 YAG 激光焊对接焊缝正面外观照片，1.10mm 厚，16×
1050 Al alloy，YAG laser welding，SEM metallograph of topbead appearance of butt joint，thickness of plate 1.10mm，16×.

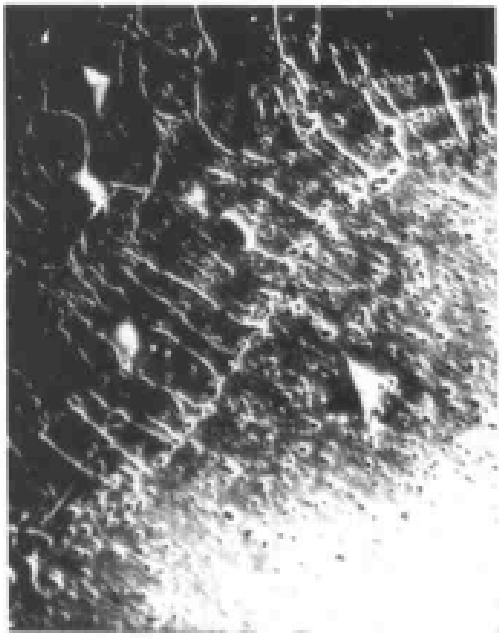

图 5－30　1050 铝合金 YAG 激光焊对接接头横断面金相照片 120×
1050 Al alloy，YAG laser welding，metallograph of cross section butt joint，thickness of plate 1.10mm，120×.

5.3　其他材料的激光焊接

5.3.1　42CrMo/Al/Cu/45# 钢激光焊接

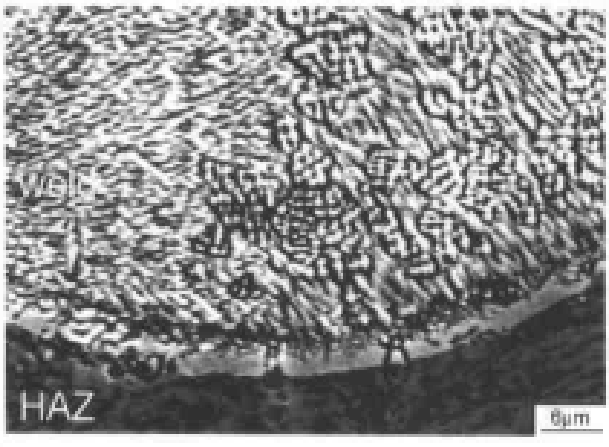

图 5－31　激光焊接，42CrMo（上部材料）/Al/Cu/45#（下部材料），CO_2 激光，焊缝底部，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo(top alloy)/Al/Cu/45# (bottom alloy)，CO_2 laser，bottom of weld，power 3200W，welding speed 2m/min.

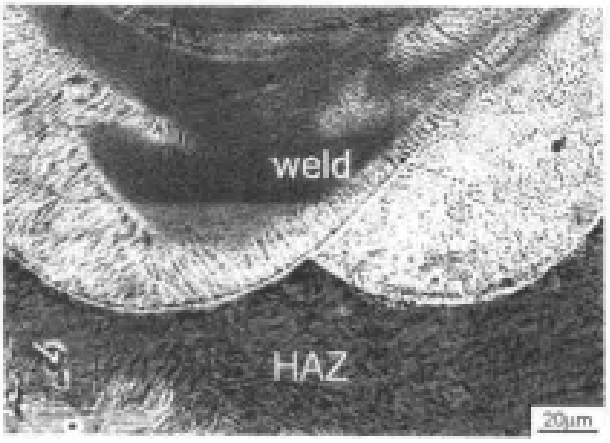

图 5－32　激光焊接，42CrMo（上部材料）/Al/Cu/45#（下部材料），CO_2 激光，焊缝底部，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo(top alloy)/Al/Cu/45# (bottom alloy)，CO_2 laser，bottom of weld，power 3200W，welding speed 2m/min.

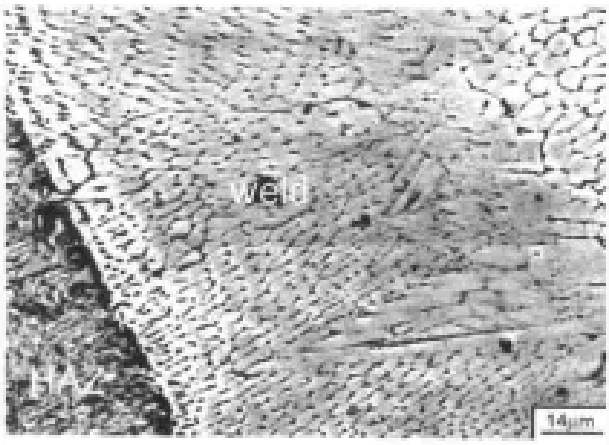

图 5－33 激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，焊缝，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, weld, power 3200W, welding speed 2m/min.

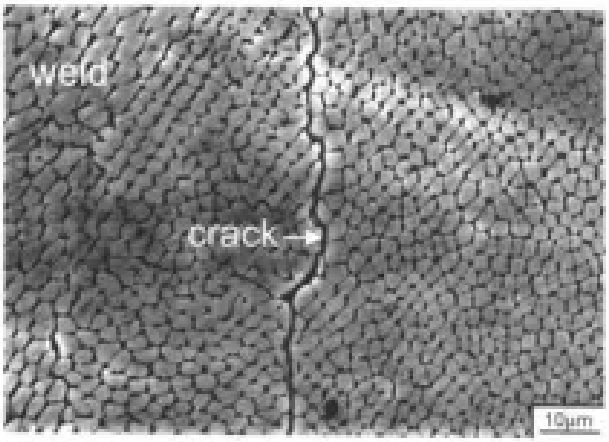

图 5－34 激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，焊缝，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, weld, power 3200W, welding speed 2m/min.

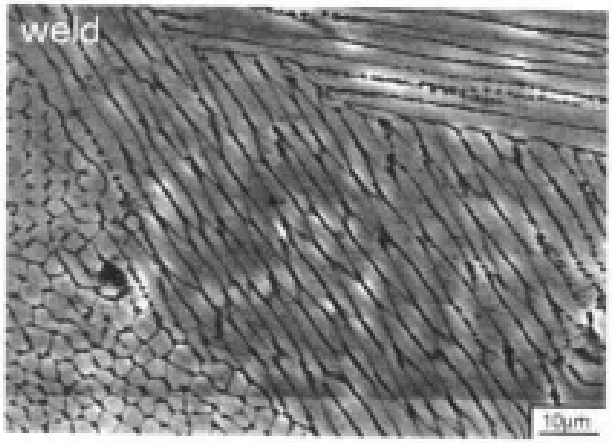

图 5－35 激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，焊缝，功率 3200W，焊接速度2m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, weld, power 3200W, welding speed 2m/min.

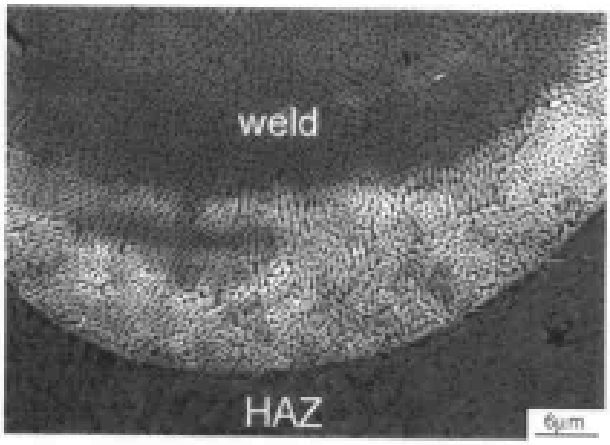

图 5－36 激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，焊缝底部，功率 2800W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, bottom of weld, power 3200W, welding speed 1.75m/min.

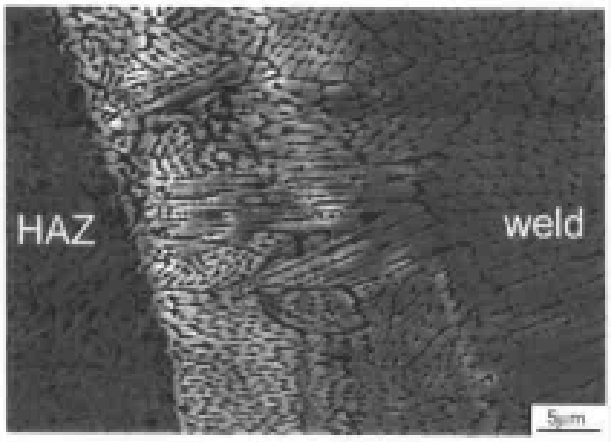

图 5－37　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, power 2800W, welding speed 1.75m/min.

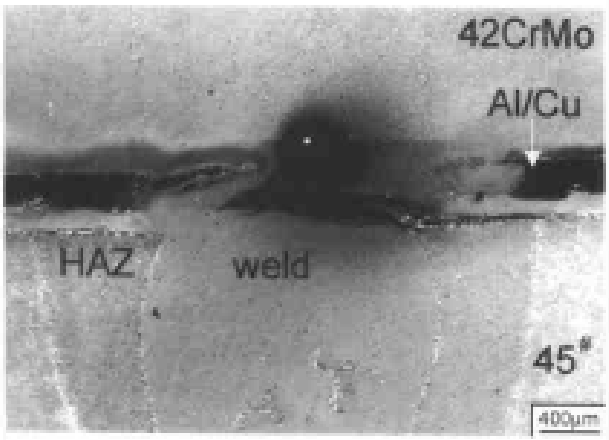

图 5－38　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, power 2800W, welding speed 1.75m/min.

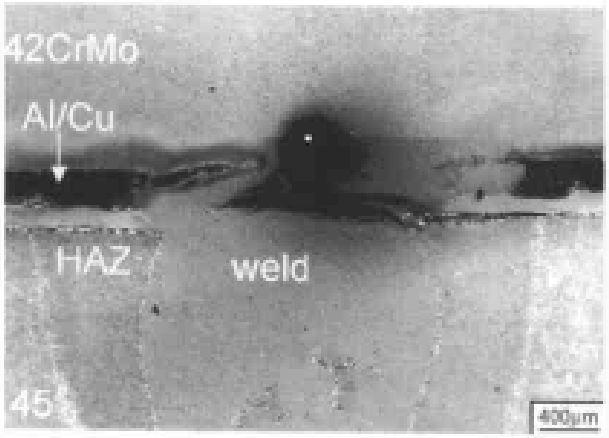

图 5－39　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, power 2800W, welding speed 1.75m/min.

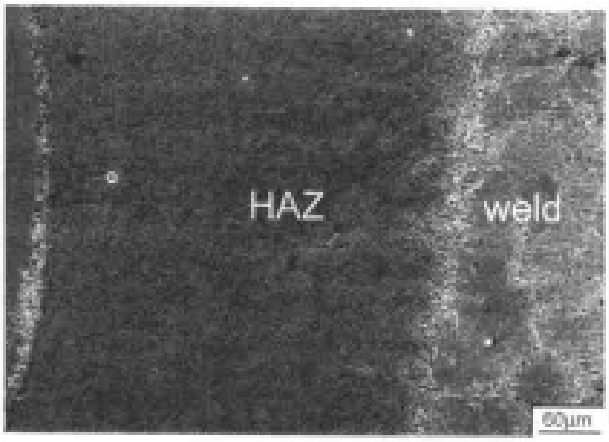

图 5－40　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding, 42CrMo (top alloy)/Al/Cu/45# (bottom alloy), CO_2 laser, power 2800W, welding speed 1.75m/min.

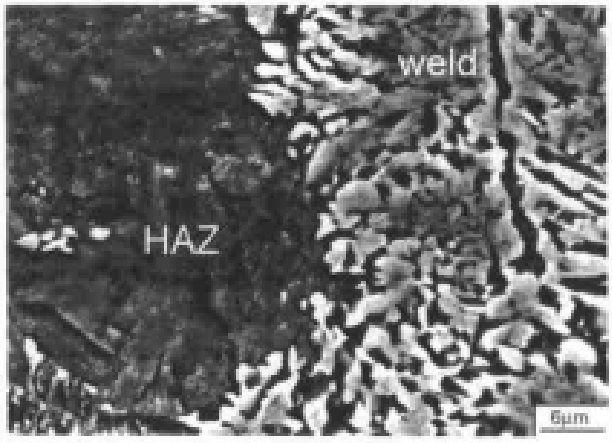

图 5－41　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding，42CrMo (top alloy)/Al/Cu/45# (bottom alloy)，CO_2 laser，power 2800W，welding speed 1.75m/min.

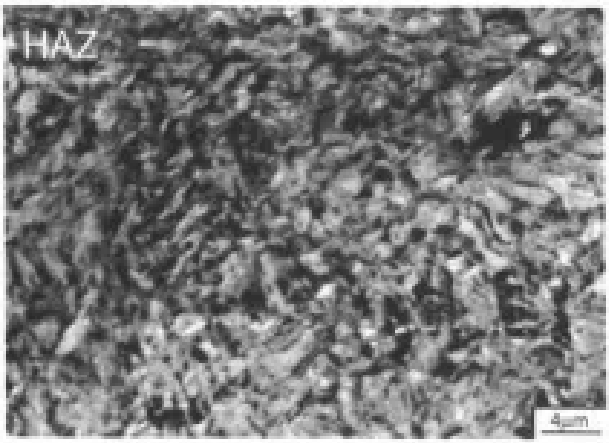

图 5－42　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding，42CrMo (top alloy)/Al/Cu/45# (bottom alloy)，CO_2 laser，power 2800W，welding speed 1.75m/min.

图 5－43　激光焊接，42CrMo(上部材料)/Al/Cu/45#(下部材料)，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding，42CrMo (top alloy)/Al/Cu/45# (bottom alloy)，CO_2 laser，power 2800W，welding speed 1.75m/min.

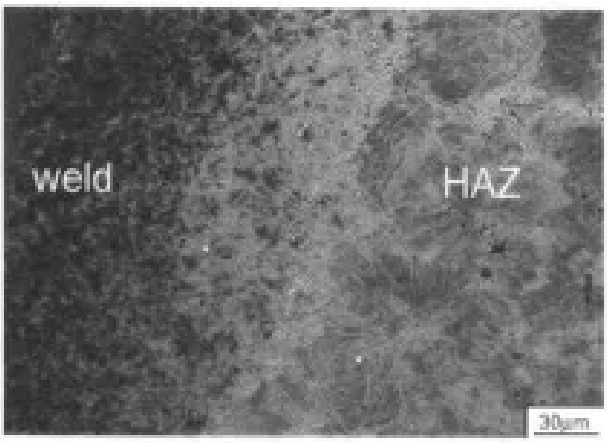

图 5－44　激光焊接 42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45# (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

5.3.2　45#钢激光焊接

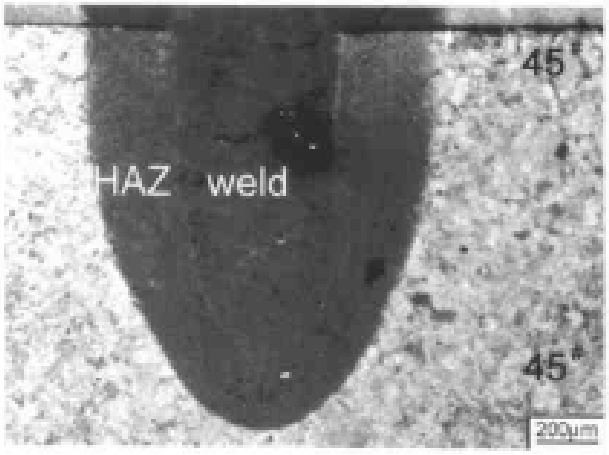

图 5－45　激光焊接，45#钢/45#钢，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45#/45#，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

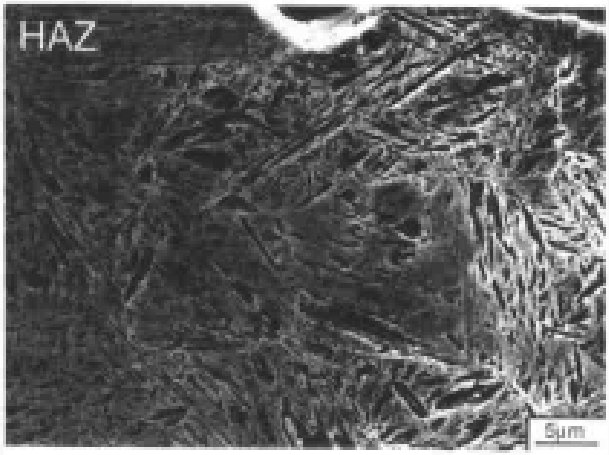

图 5－46　激光焊接，45#，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45#，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

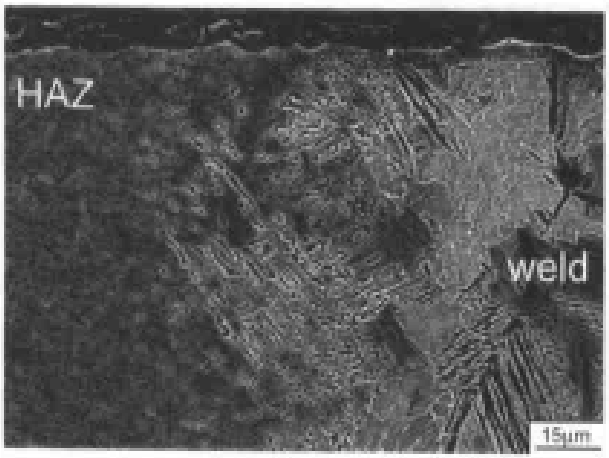

图 5－47　激光焊接，45#，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45#，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

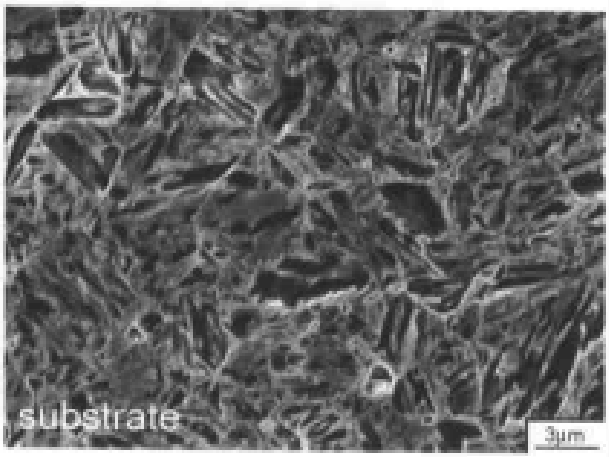

图 5－48　激光焊接，45#，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45#，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

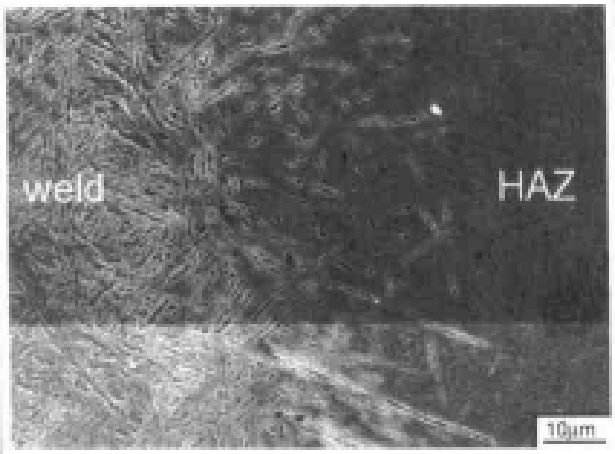

图 5－49　激光焊接，45°，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45°，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

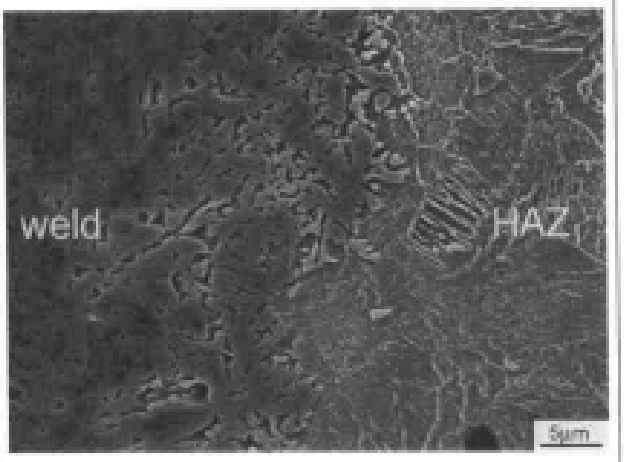

图 5－50　激光焊接，45°，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45°，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

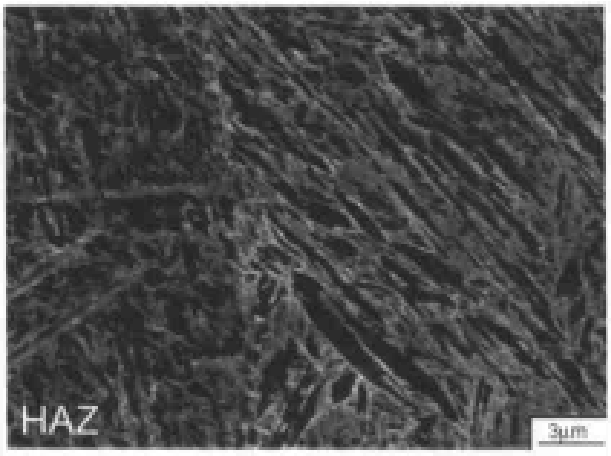

图 5－51　激光焊接，45°，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45°，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

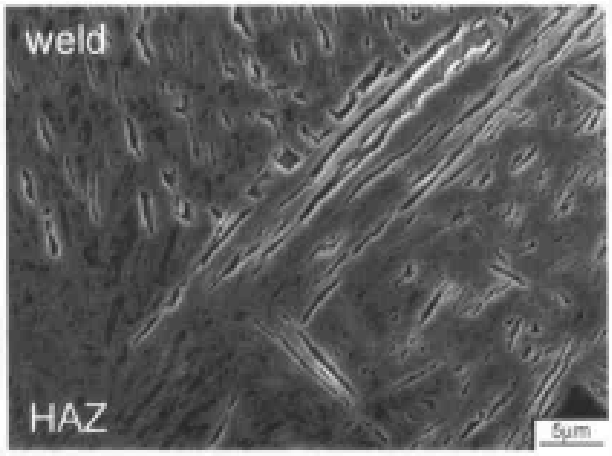

图 5－52　激光焊接，45°，CO_2 激光，功率 3200W，焦距 200mm，焊接速度 2m/min
Laser welding，45°，CO_2 laser，power 3200W，foci 200mm，welding speed 2m/min.

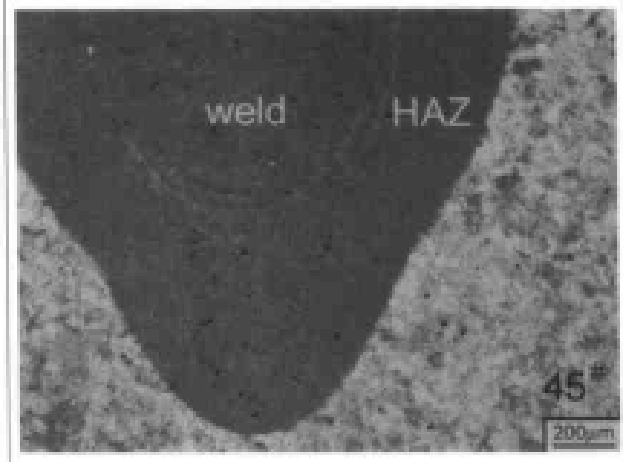

图 5－53　激光焊接，45#，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45#，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

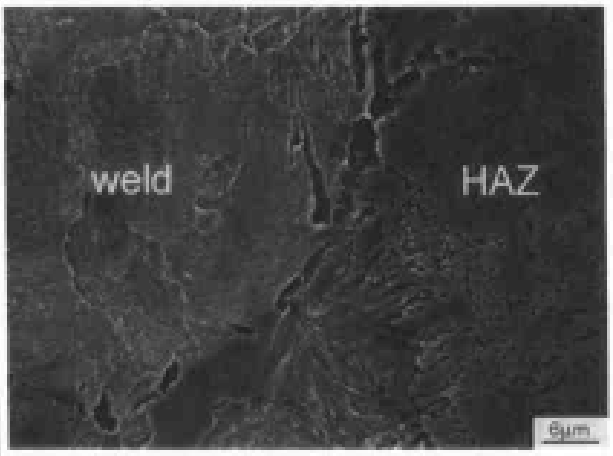

图 5－54　激光焊接，45#，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45#，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

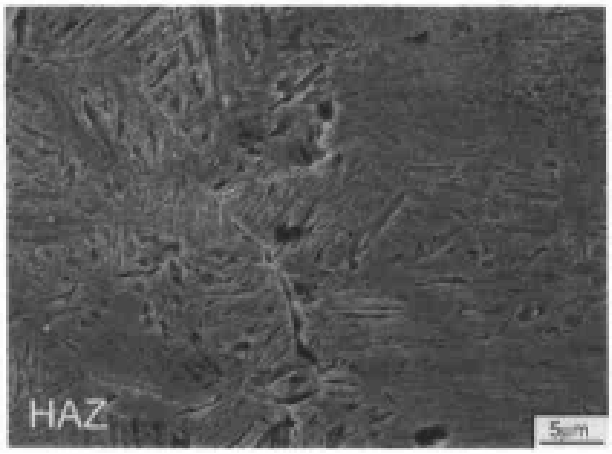

图 5－55　激光焊接，45#，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45#，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

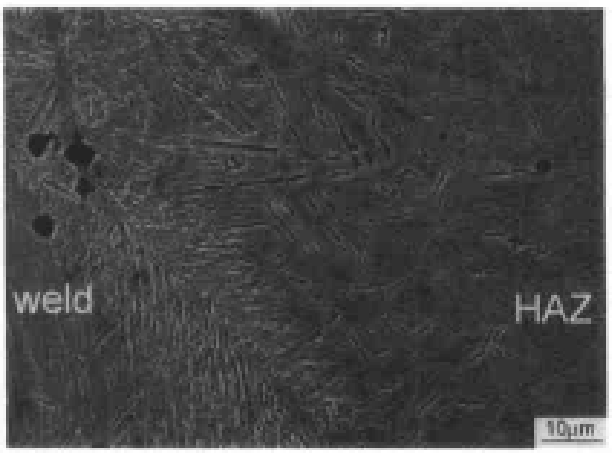

图 5－56　激光焊接，45#，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45#，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

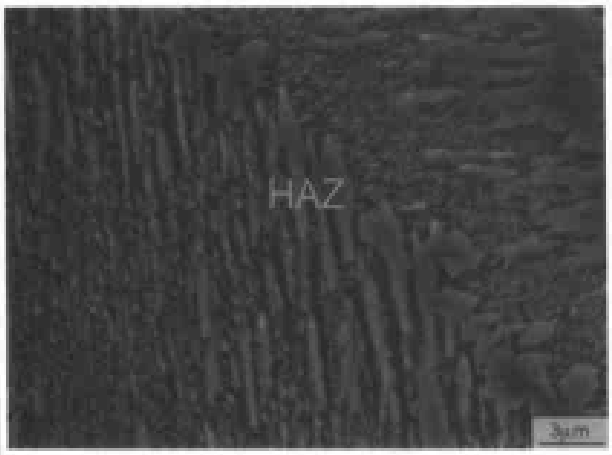

图 5－57　激光焊接，45°，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45°，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

图 5－58　激光焊接，45°，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45°，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

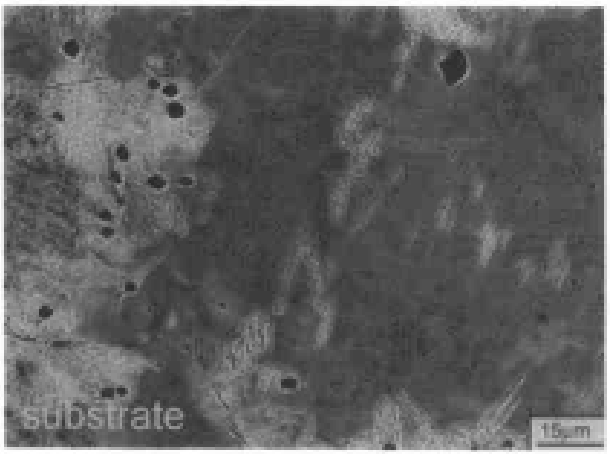

图 5－59　激光焊接，45°，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45°，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

图 5－60　激光焊接，45°，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min
Laser welding，45°，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

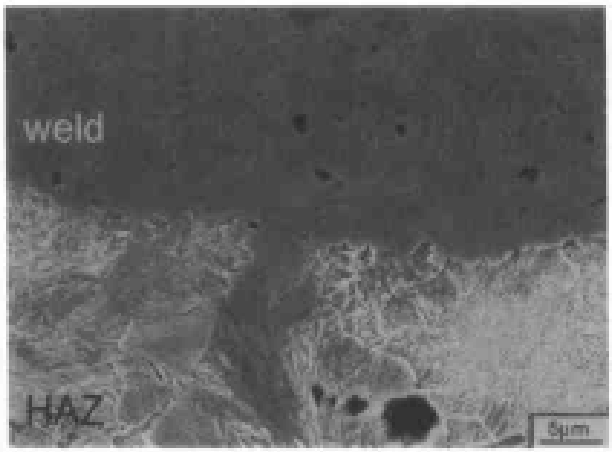

图5－61 激光焊接，45°，CO_2 激光，功率2800W，焦距150mm，焊接速度1.75m/min
Laser welding，45°，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

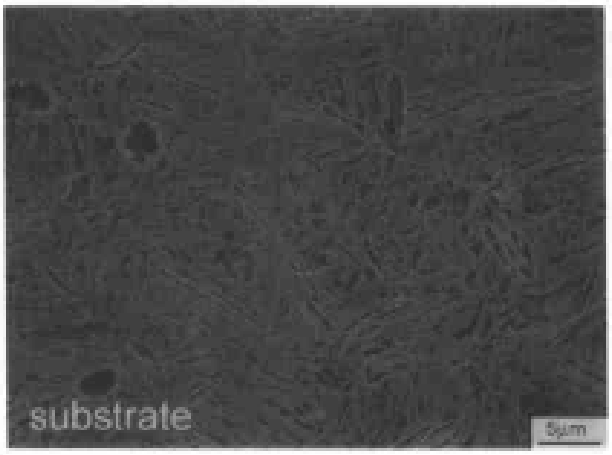

图5－62 激光焊接，45°，CO_2 激光，功率2800W，焦距150mm，焊接速度1.75m/min
Laser welding，45°，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

5.3.3 42CrMo/42CrMo钢激光焊接

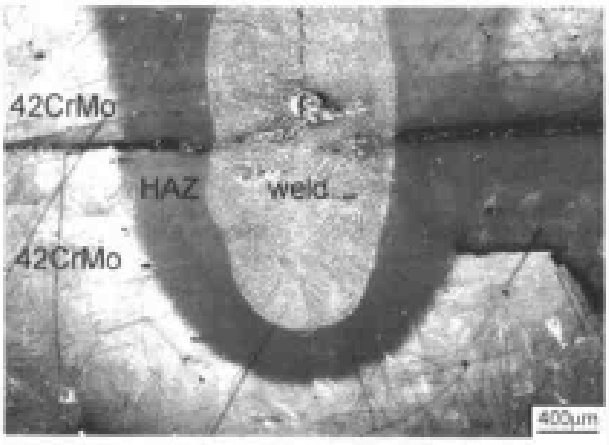

图5－63 激光焊接，42CrMo合金/42CrMo合金，CO_2 激光，功率3200W，焊接速度2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，power 3200W，welding speed 2m/min.

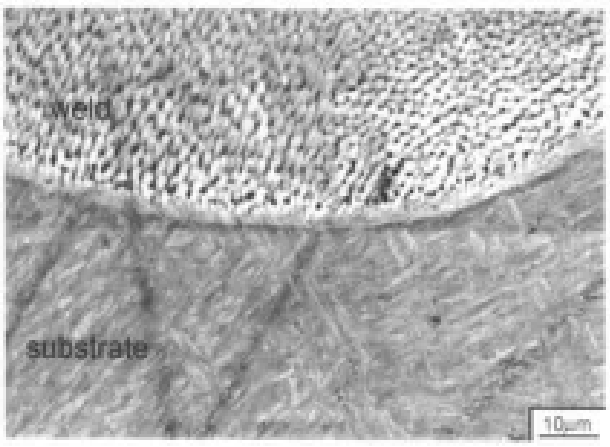

图5－64 激光焊接，42CrMo合金/42CrMo合金，CO_2 激光，焊缝底部，功率3200W，焊接速度2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，bottom of weld，power 3200W，welding speed 2m/min.

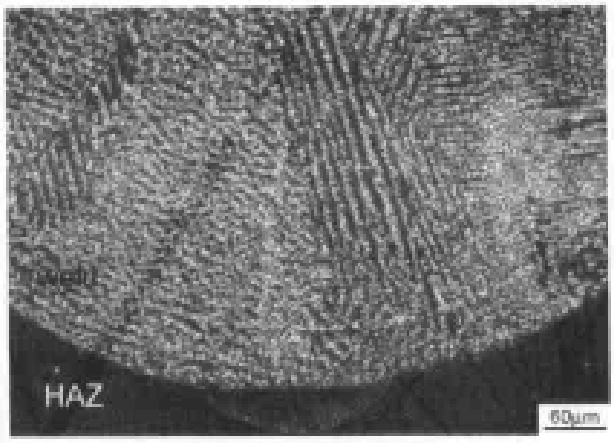

图 5－65 激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，焊缝底部，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，bottom of weld，power 3200W，welding speed 2m/min.

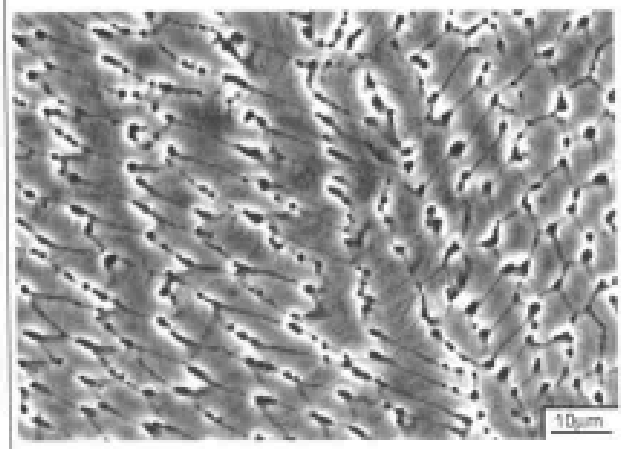

图 5－66 激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，焊缝，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，weld，power 3200W，welding speed 2m/min.

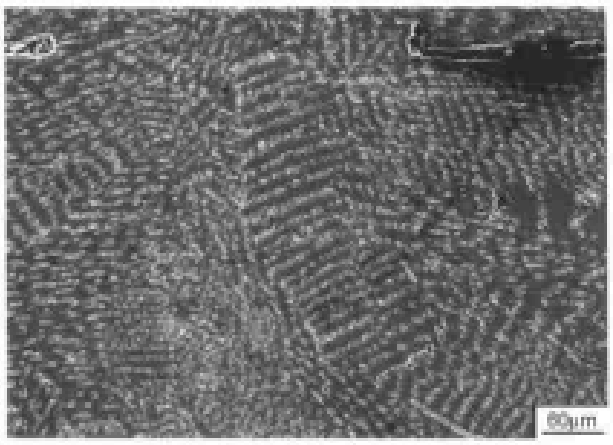

图 5－67 激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，焊缝，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，weld，power 3200W，welding speed 2m/min.

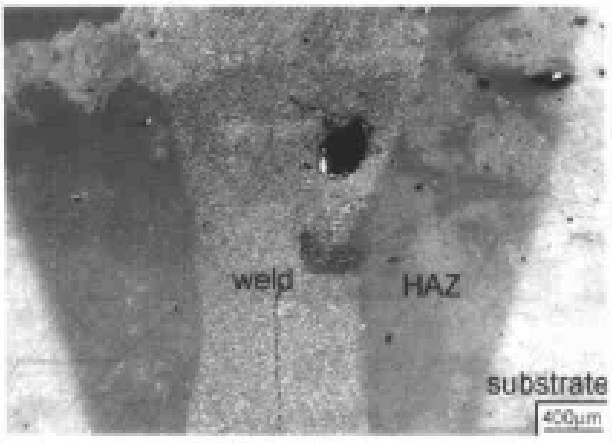

图 5－68 激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，焊缝，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，weld，power 3200W，welding speed 2m/min.

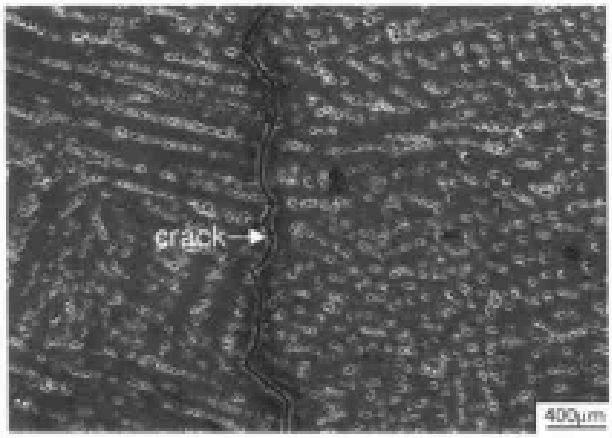

图5—69 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，焊缝，功率3200W，焊接速度2m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，weld，power 3200W，welding speed 2m/min.

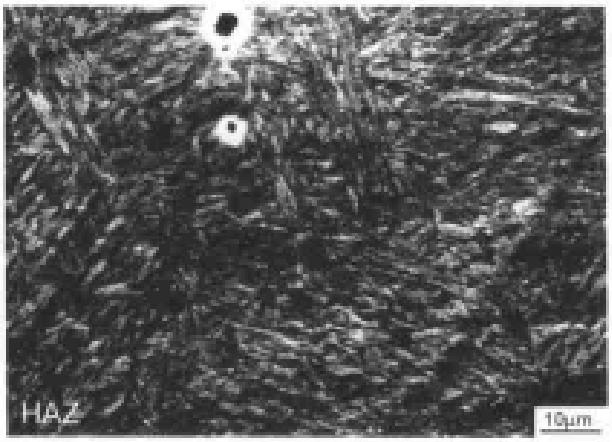

图5—70 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，功率3200W，焊接速度2m/min
Laser welding，42CrMo alloy/42CrMo alloy，CO_2 laser，power 3200W，welding speed 2m/min.

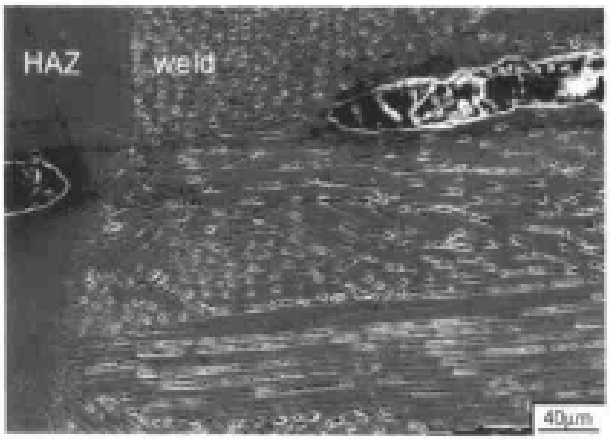

图5—71 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，功率3200W，焊接速度2m/min
Laser welding，42CrMo alloy/42CrMo alloy，CO_2 laser，power 3200W，welding speed 2m/min.

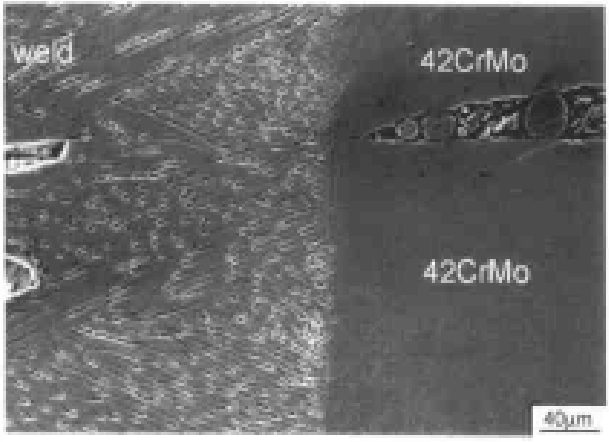

图5—72 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，功率3200W，焊接速度2m/min
Laser welding，42CrMo alloy/42CrMo alloy，CO_2 laser，power 3200W，welding speed 2m/min.

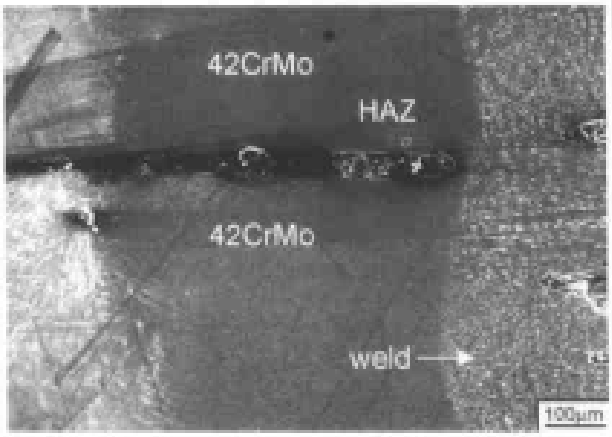

图 5－73　激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，功率 3200W，焊接速度 2m/min
Laser welding，42CrMo alloy/42CrMo alloy，CO_2 laser，power 3200W，welding speed 2m/min.

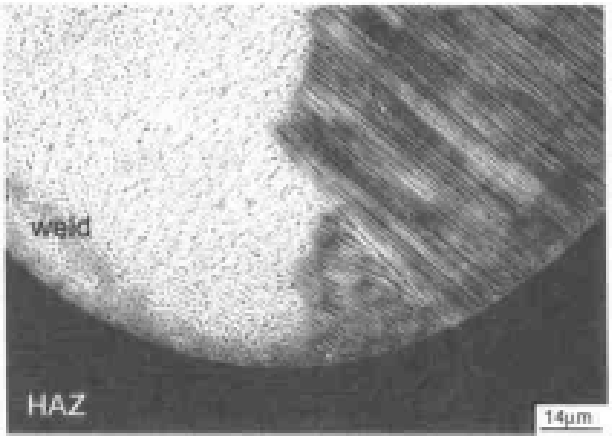

图 5－74　激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，焊缝底部，功率 2800W，焊接速度 1.75m/min
Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，bottom of weld，power 2800W，welding speed 1.75m/min.

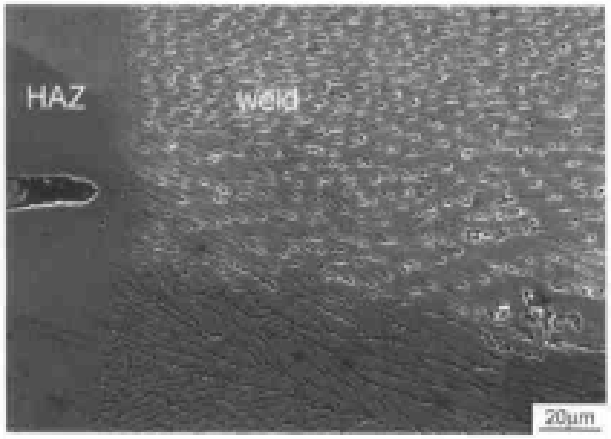

图 5－75　激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，功率 2800W，焊接速度 1.75m/min
Laser welding，42CrMo alloy/42CrMo alloy，CO_2 laser，power 2800W，welding speed 1.75m/min.

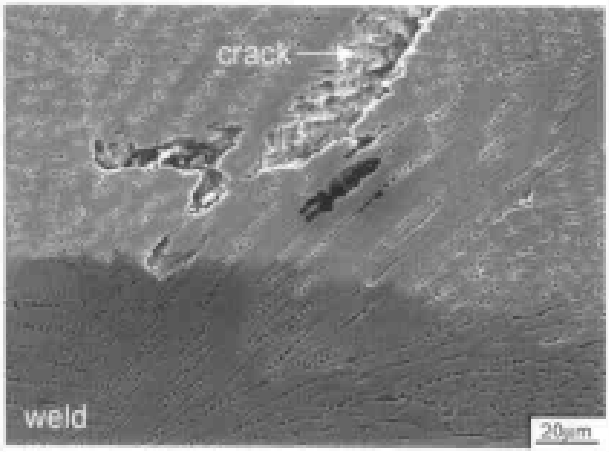

图 5－76　激光焊接，42CrMo 合金，CO_2 激光，功率 2800W，焊接速度 1.75m/min
Laser welding，42CrMo alloy，CO_2 laser，power 2800W，welding speed 1.75m/min.

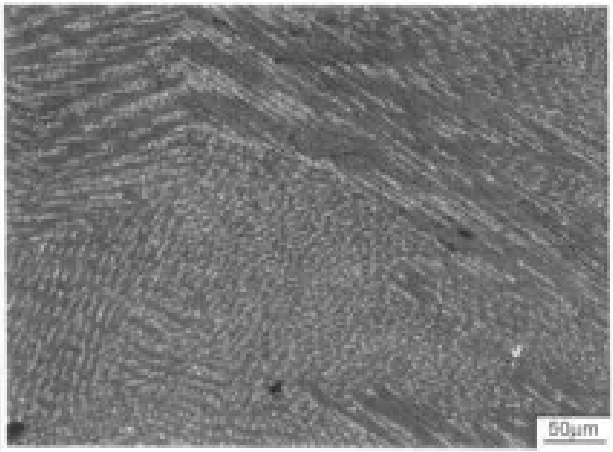

图5—77 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，焊缝，功率2800W，焊接速度1.75m/min

Laser welding, 42CrMo alloy /42CrMo alloy, CO_2 laser, weld, power 2800W, welding speed 1.75m/min.

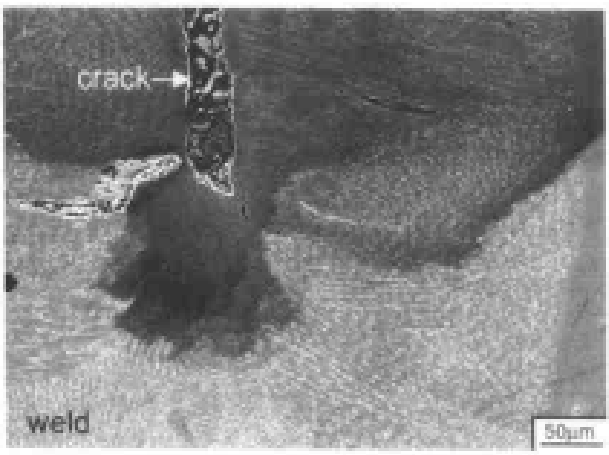

图5—78 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，焊缝底部，功率2800W，焊接速度1.75m/min

Laser welding, 42CrMo alloy /42CrMo alloy, CO_2 laser, bottom of weld, power 2800W, welding speed 1.75m/min.

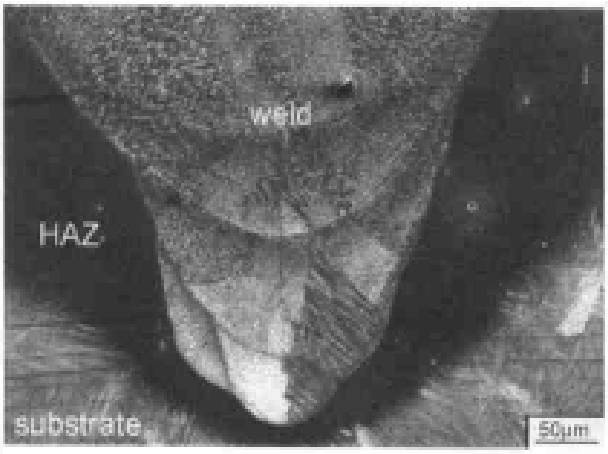

图5—79 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，焊缝底部，功率2800W，焊接速度1.75m/min

Laser welding, 42CrMo alloy /42CrMo alloy, CO_2 laser, bottom of weld, power 2800W, welding speed 1.75m/min.

图5—80 激光焊接，42CrMo合金/42CrMo合金，CO_2激光，功率2800W，焊接速度1.75m/min

Laser welding, 42CrMo alloy /42CrMo alloy, CO_2 laser, power 2800W, welding speed 1.75m/min.

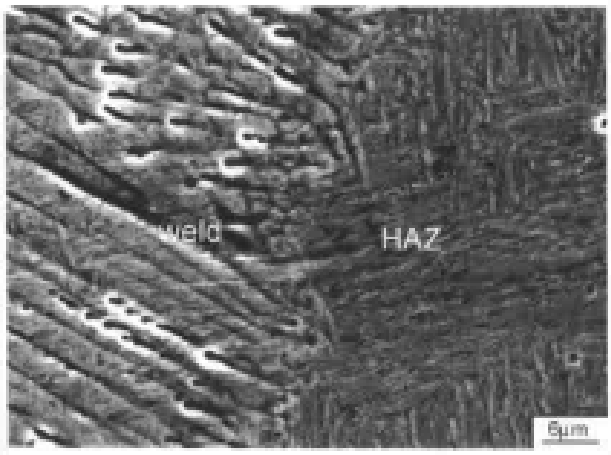

图 5－81 激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，功率 2800W，焊接速度 1.75m/min

Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，power 2800W，welding speed 1.75m/min.

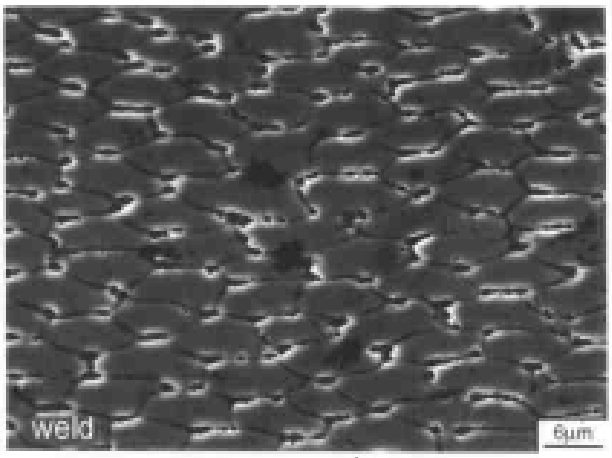

图 5－82 激光焊接，42CrMo 合金/42CrMo 合金，CO_2 激光，焊缝，功率 2800W，焊接速度 1.75m/min

Laser welding，42CrMo alloy /42CrMo alloy，CO_2 laser，weld，power 2800W，welding speed 1.75m/min.

5.3.4 42CrMo/45#钢激光焊接

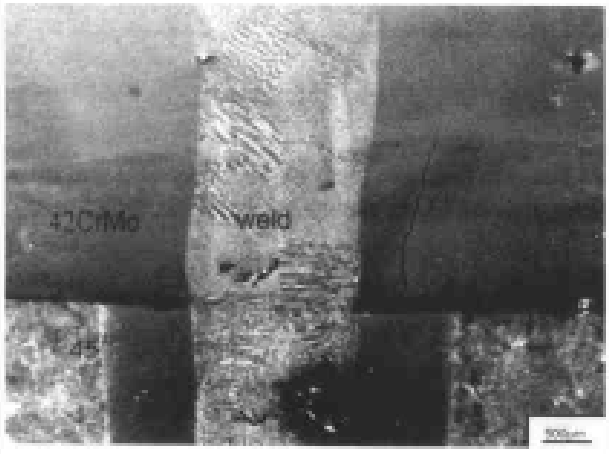

图 5－83 激光焊接，42CrMo(上部材料)/45#(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding，42CrMo (top alloy)/45# (bottom alloy)，CO_2 laser，power 3200W，welding speed 2m/min.

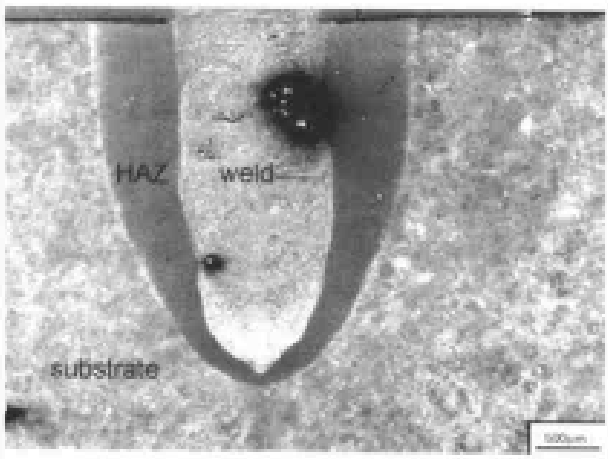

图 5－84 激光焊接，42CrMo(上部材料)/45#(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding，42CrMo (top alloy)/45# (bottom alloy)，CO_2 laser，power 3200W，welding speed 2m/min.

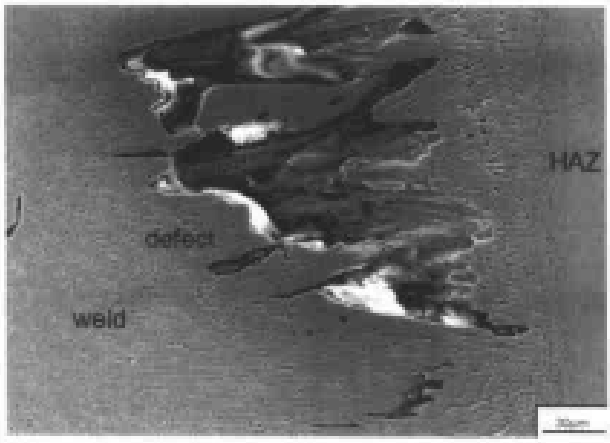

图 5－85　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/45° (bottom alloy), CO_2 laser, power 3200W, welding speed 2m/min.

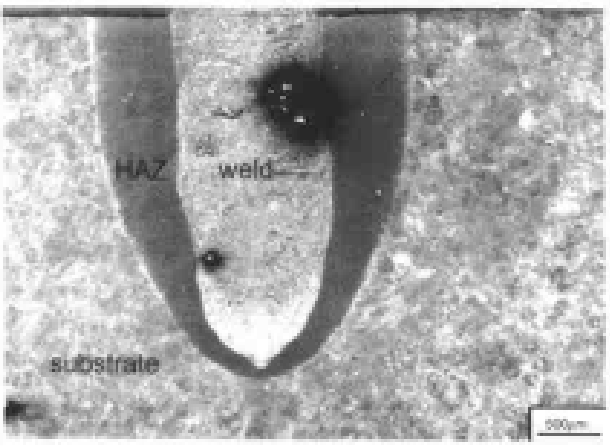

图 5－86　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/45° (bottom alloy), CO_2 laser, power 3200W, welding speed 2m/min.

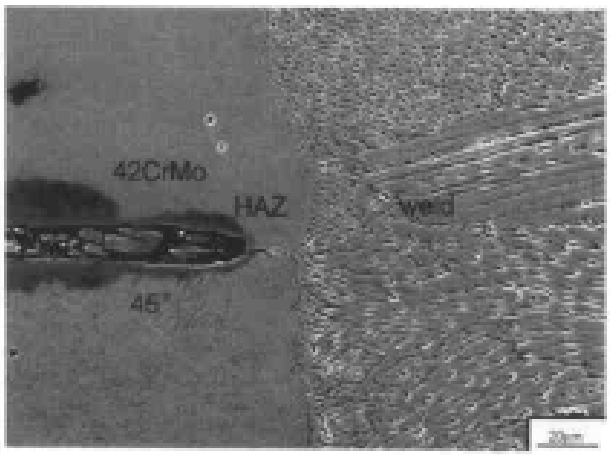

图 5－87　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/45° (bottom alloy), CO_2 laser, power 3200W, welding speed 2m/min.

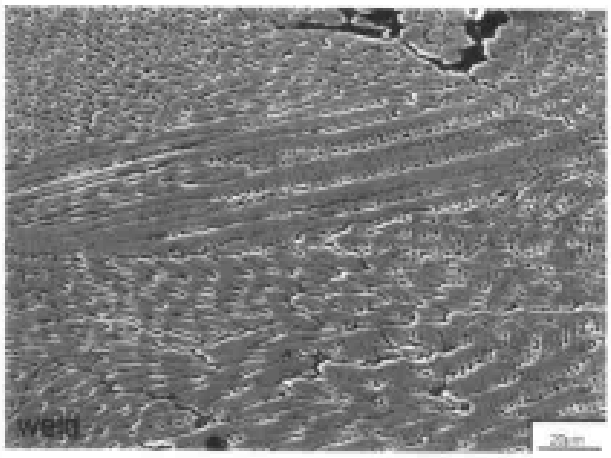

图 5－88　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/45° (bottom alloy), CO_2 laser, power 3200W, welding speed 2m/min.

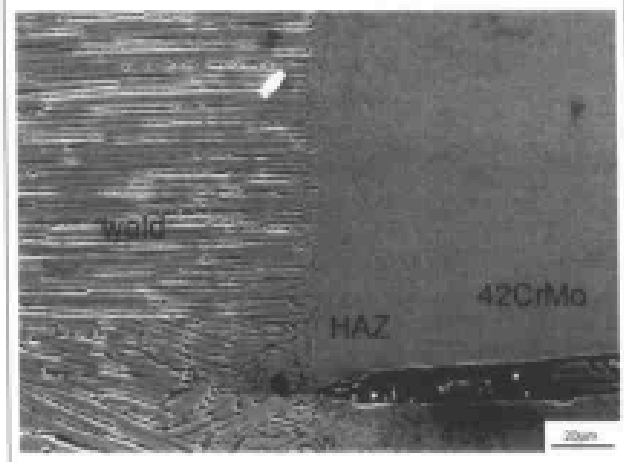

图 5－89　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，power 3200W，welding speed 2m/min.

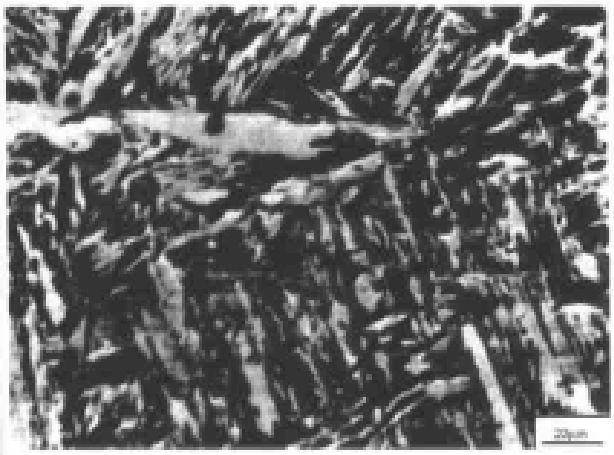

图 5－90　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，热影响区组织，功率 3200W，焊接速度 2 m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，microstructure in heat affected zone，power 3200W，welding speed 2m/min.

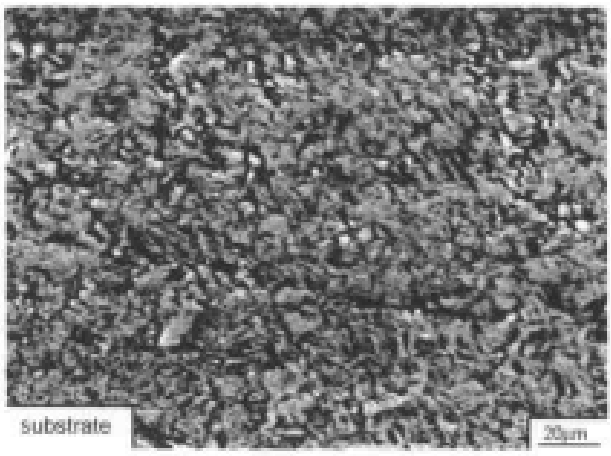

图 5－91　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，热影响区组织，功率 3200W，焊接速度 2m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，microstructure in heat affected zone，power 3200W，welding speed 2m/min.

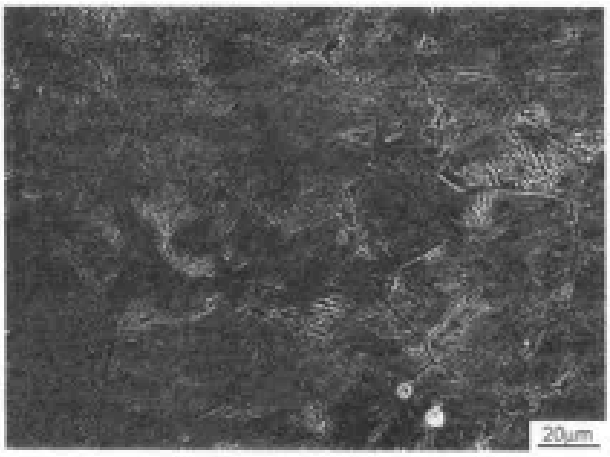

图 5－92　激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，热影响区组织，功率 3200W，焊接速度 2m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，microstructure in heat affected zone，power 3200W，welding speed 2m/min.

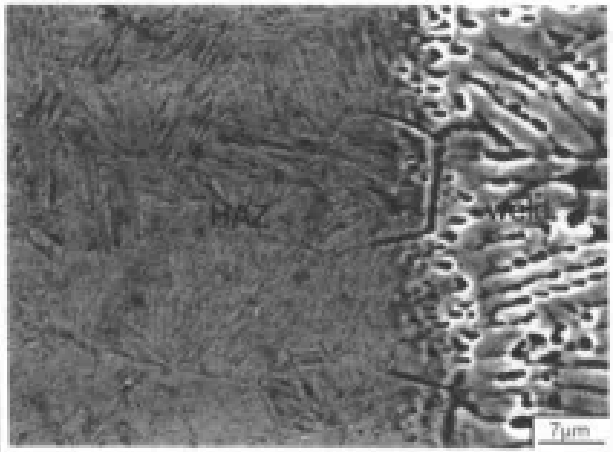

图5－93 激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率3200W，焊接速度2m/min，热影响区

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，power 3200W，welding speed 2m/min，heat affected zone.

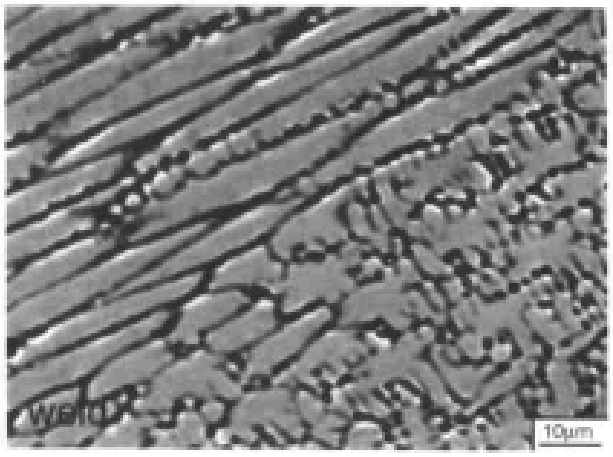

图5－94 激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率3200W，焊接速度2m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，power 3200W，welding speed 2m/min.

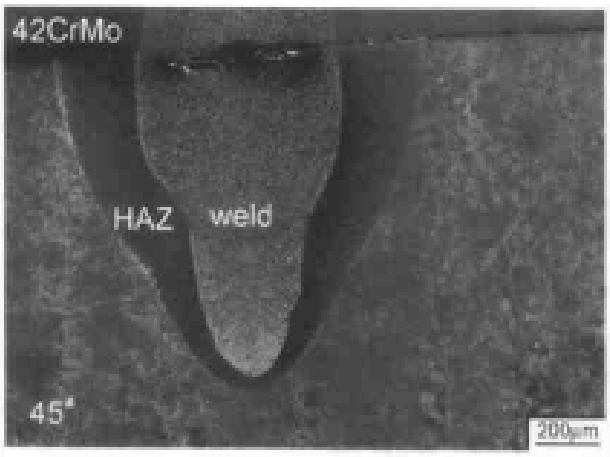

图5－95 激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率3200W，焊接速度2m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，power 3200W，welding speed 1.75m/min.

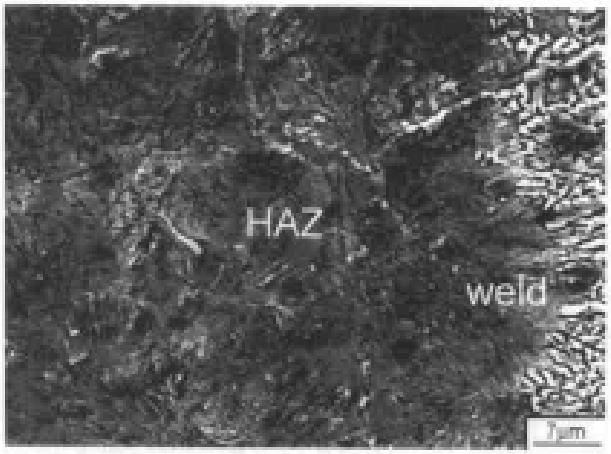

图5－96 激光焊接，42CrMo(上部材料)/45°(下部材料)，CO_2 激光，功率3200W，焊接速度2m/min

Laser welding，42CrMo (top alloy)/45° (bottom alloy)，CO_2 laser，power 3200W，welding speed 1.75m/min.

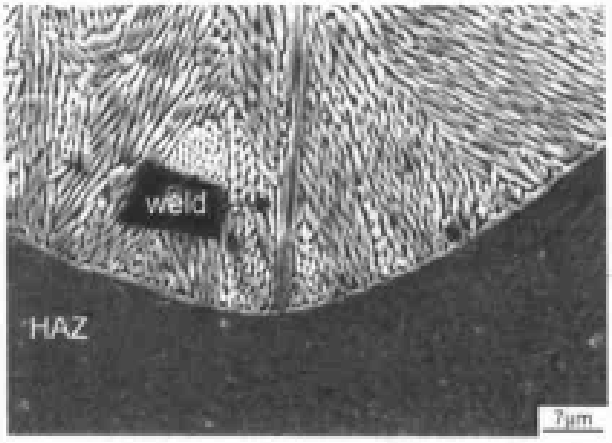

图 5－97 激光焊接，42CrMo(上部材料)/45#(下部材料)，CO_2 激光，焊缝底部，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/45# (bottom alloy), CO_2 laser, bottom of weld, power 3200W, welding speed 1.75m/min.

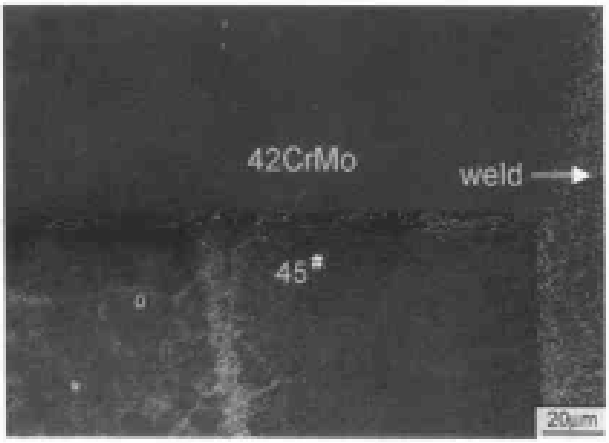

图 5－98 激光焊接，42CrMo(上部材料)/45#(下部材料)，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, 42CrMo (top alloy)/45# (bottom alloy), CO_2 laser, power 3200W, welding speed 1.75m/min.

5.3.5 42CrMo/Al/Cu/45#钢激光焊接

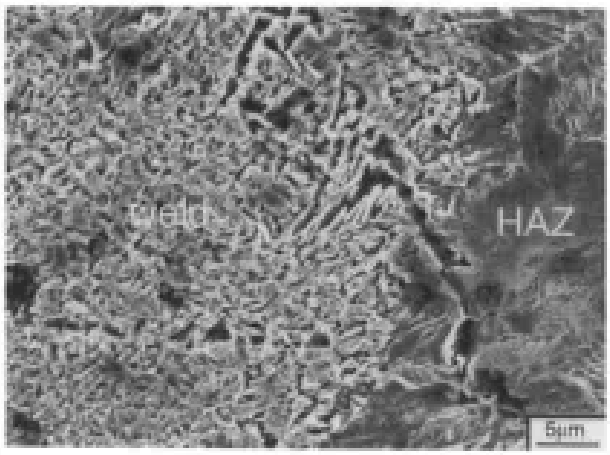

图 5－99 激光焊接，42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding, 42CrMo/Al/Cu (top alloy)/45# (bottom alloy), CO_2 laser, power 2800W, foci 150mm, welding speed 1m/min.

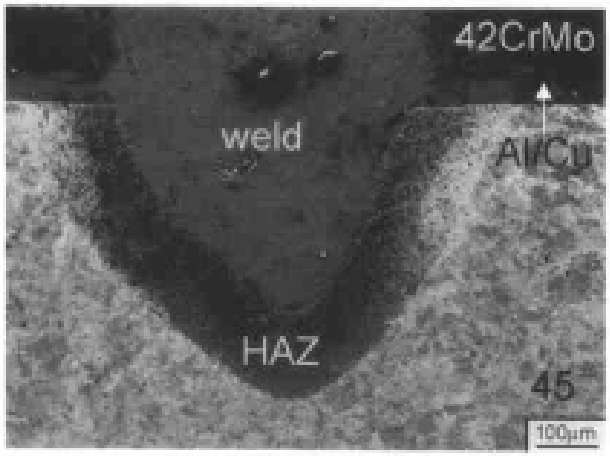

图 5－100 激光焊接，42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding, 42CrMo/Al/Cu (top alloy)/45# (bottom alloy), CO_2 laser, power 2800W, foci 150mm, welding speed 1m/min.

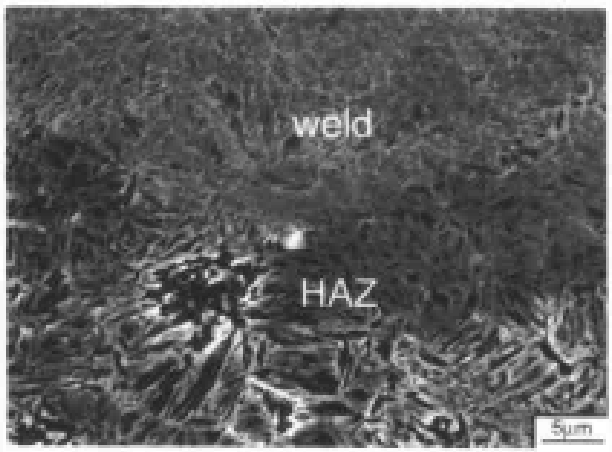

图 5－101　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

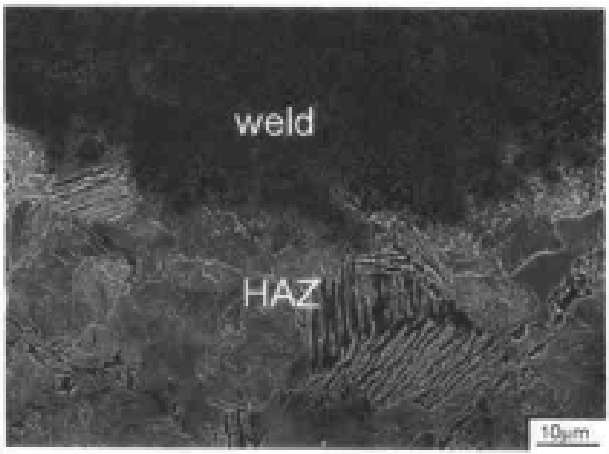

图 5－102　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

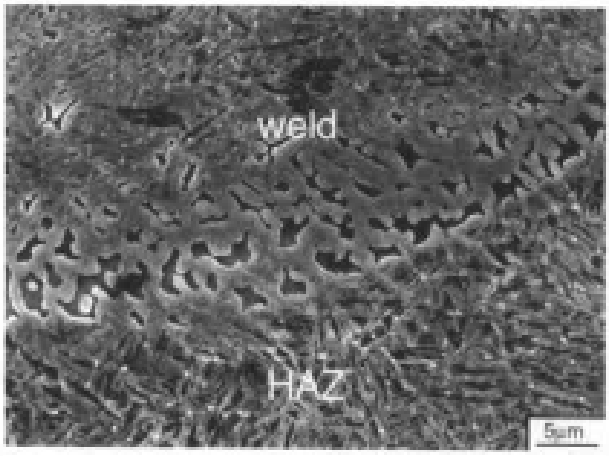

图 5－103　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

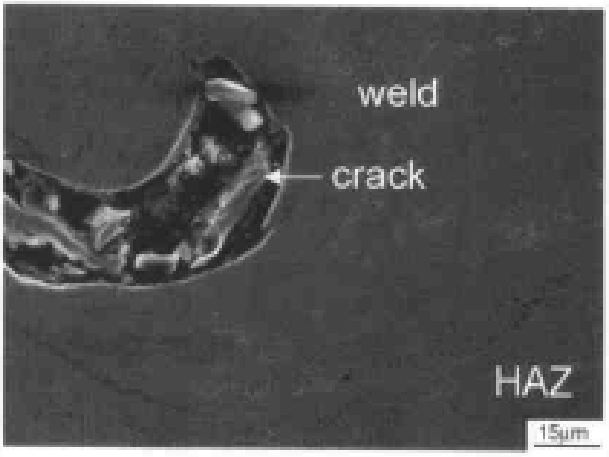

图 5－104　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

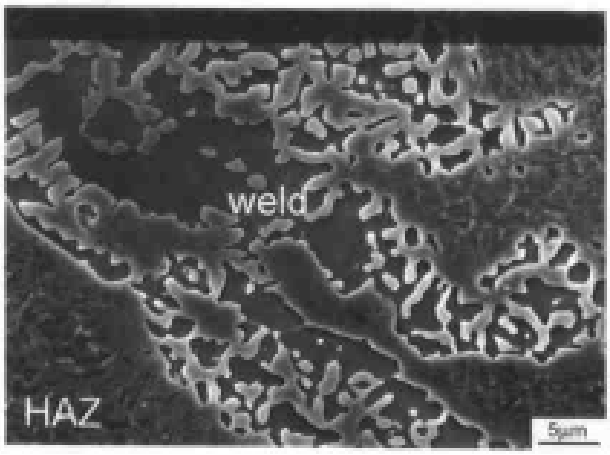

图 5－105 激光焊接，42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding, 42CrMo/Al/Cu (top alloy)/45# (bottom alloy), CO_2 laser, power 2800W, foci 150mm, welding speed 1m/min.

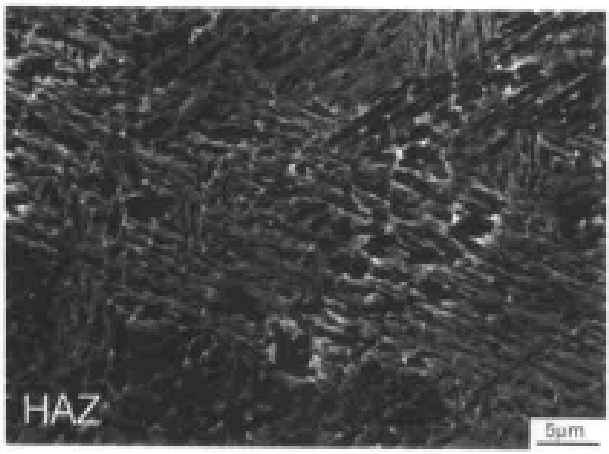

图 5－106 激光焊接，42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding, 42CrMo/Al/Cu (top alloy)/45# (bottom alloy), CO_2 laser, power 2800W, foci 150mm, welding speed 1m/min.

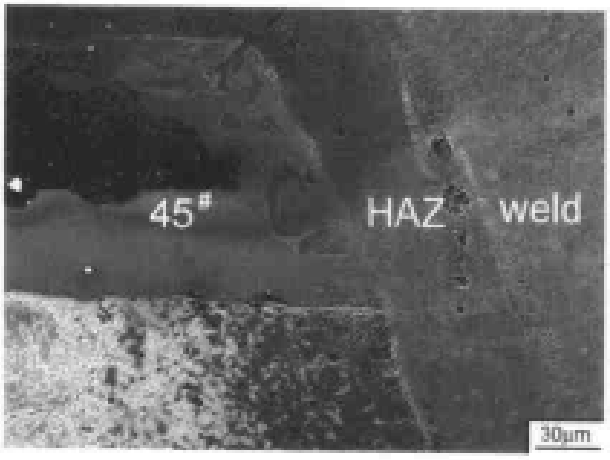

图 5－107 激光焊接，42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding, 42CrMo/Al/Cu (top alloy)/45# (bottom alloy), CO_2 laser, power 2800W, foci 150mm, welding speed 1m/min.

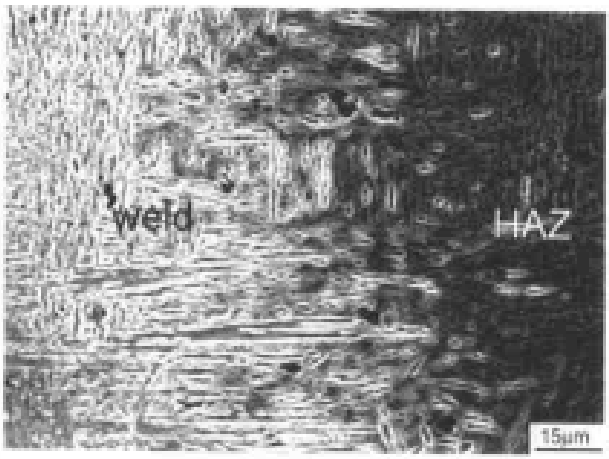

图 5－108 激光焊接，42CrMo/Al/Cu(上部材料)/45#(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding, 42CrMo/Al/Cu (top alloy)/45# (bottom alloy), CO_2 laser, power 2800W, foci 150mm, welding speed 1m/min.

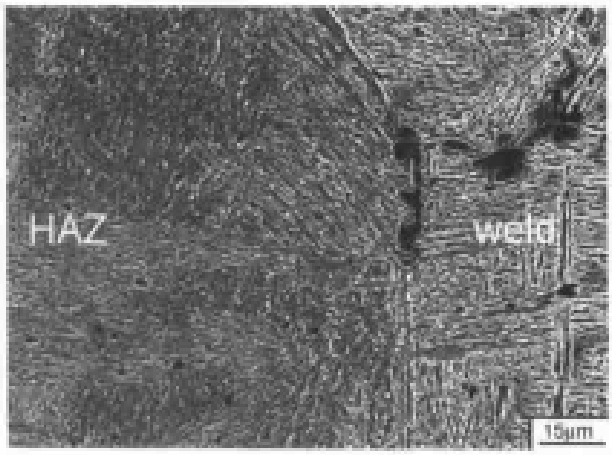

图 5－109　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

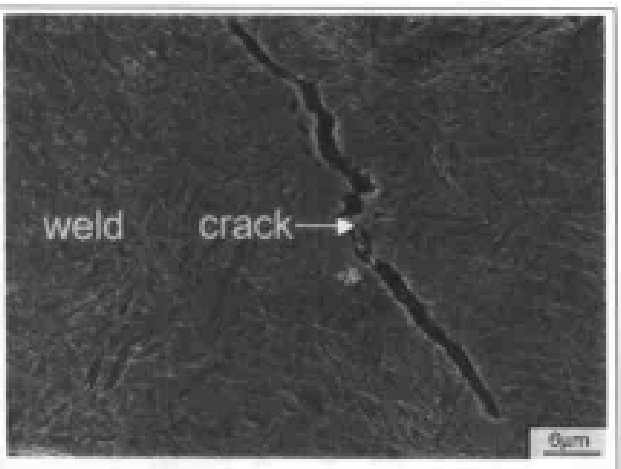

图 5－110　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

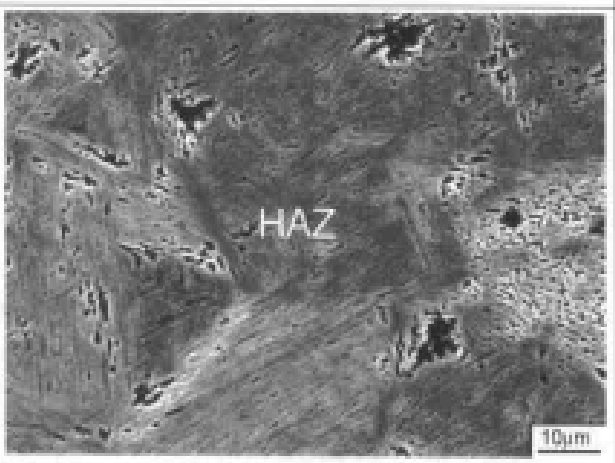

图 5－111　激光焊接，42CrMo/Al/Cu(上部材料)/45°(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1m/min

Laser welding，42CrMo/Al/Cu (top alloy)/45° (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

5.3.6　42CrMo/Al/Cu/42CrMo 激光焊接

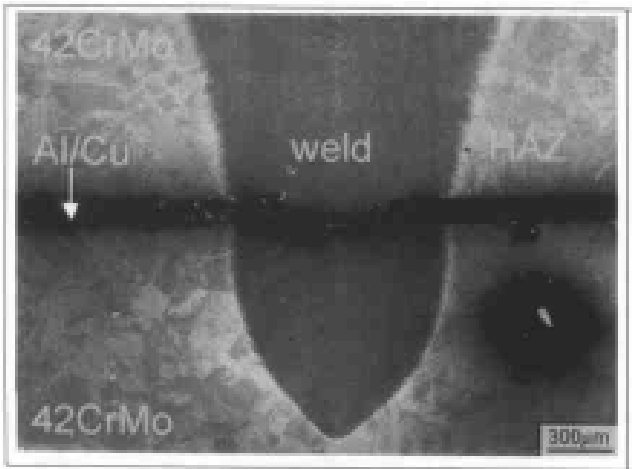

图 5－112　激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

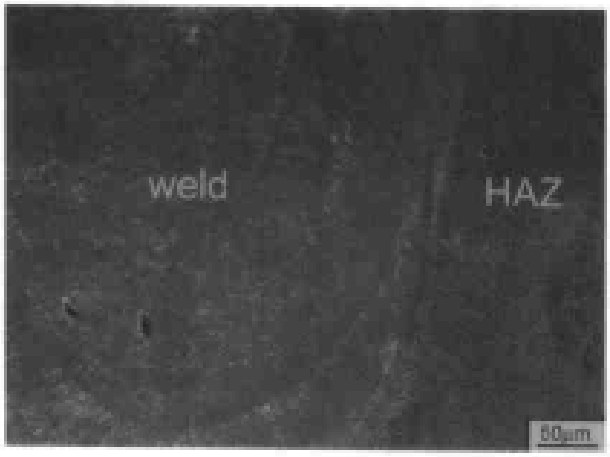

图 5－113 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

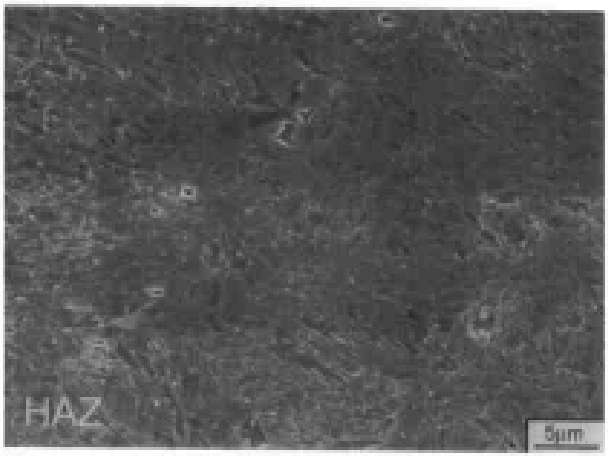

图 5－114 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

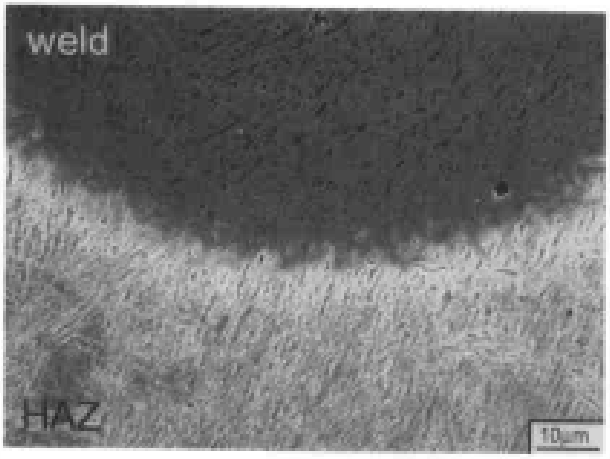

图 5－115 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

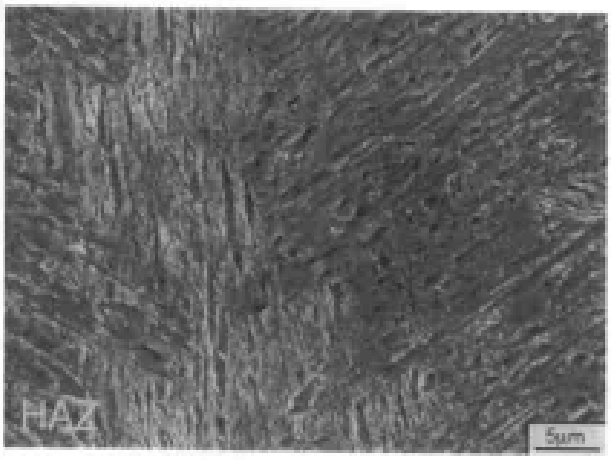

图 5－116 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率 2800W，焦距 150mm，焊接速度 1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

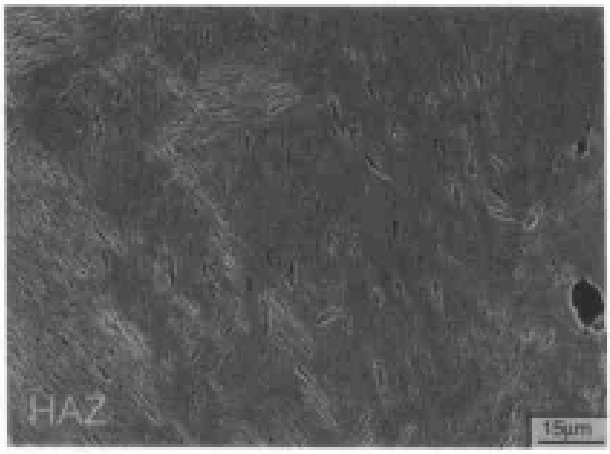

图5－117 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率2800W，焦距150mm，焊接速度1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

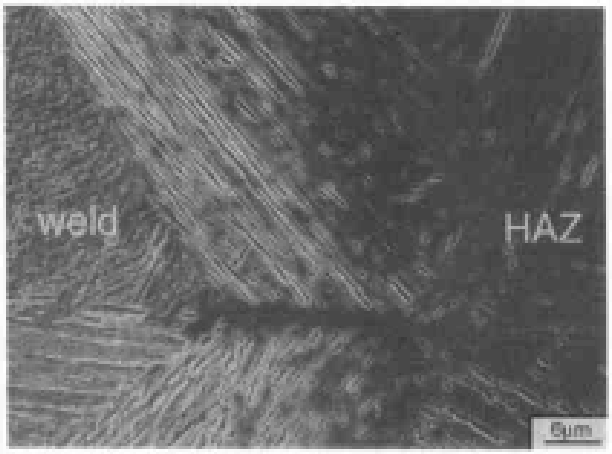

图5－118 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率2800W，焦距150mm，焊接速度1.75m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1.75m/min.

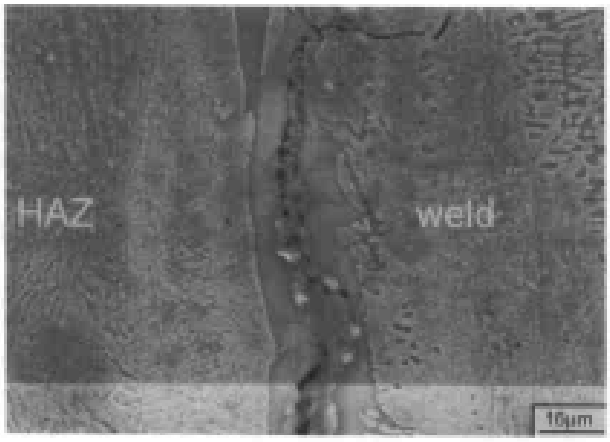

图5－119 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率2800W，焦距150mm，焊接速度1m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

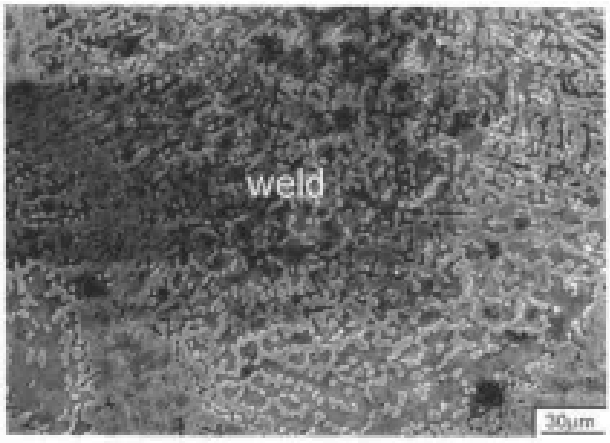

图5－120 激光焊接，42CrMo/Al/Cu(上部材料)/42CrMo(下部材料)，CO_2 激光，功率2800W，焦距150mm，焊接速度1m/min

Laser welding，42CrMo/Al/Cu(top alloy)/42CrMo (bottom alloy)，CO_2 laser，power 2800W，foci 150mm，welding speed 1m/min.

5.3.7 铸铁激光焊接

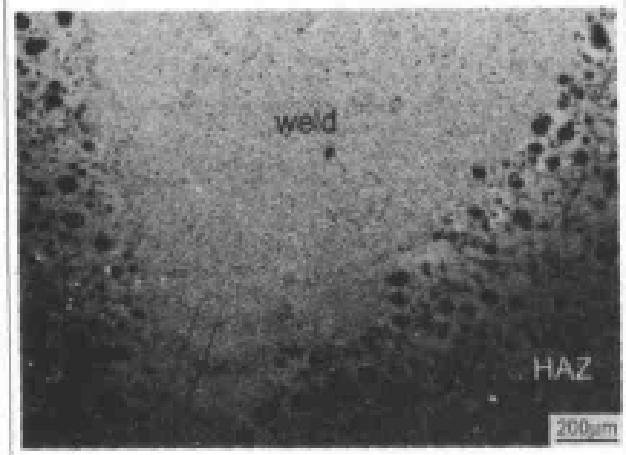

图 5－121 激光焊接，铸铁，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, cast iron, CO_2 laser, power 3200W, welding speed 2m/min.

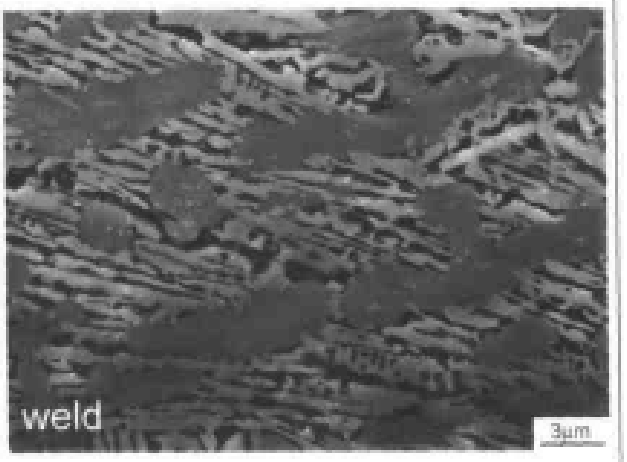

图 5－122 激光焊接，铸铁，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, cast iron, CO_2 laser, power 3200W, welding speed 2m/min.

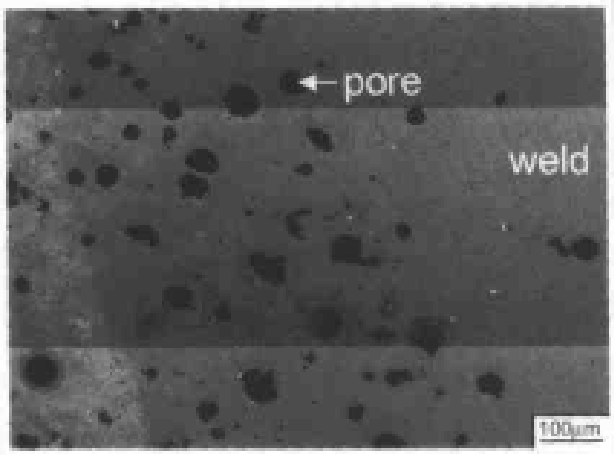

图 5－123 激光焊接，铸铁，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, cast iron, CO_2 laser, power 3200W, welding speed 2m/min.

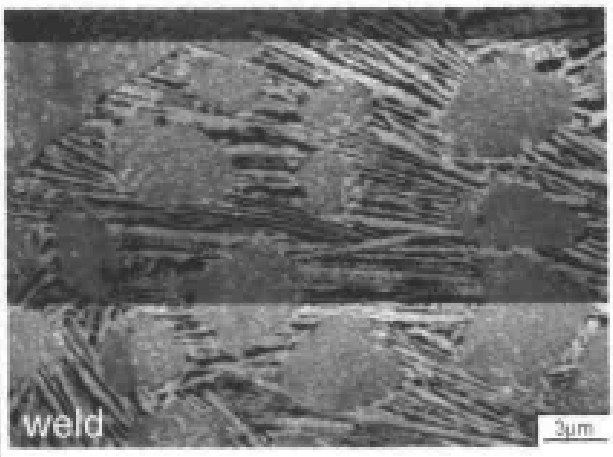

图 5－124 激光焊接，铸铁，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, cast iron, CO_2 laser, power 3200W, welding speed 2m/min.

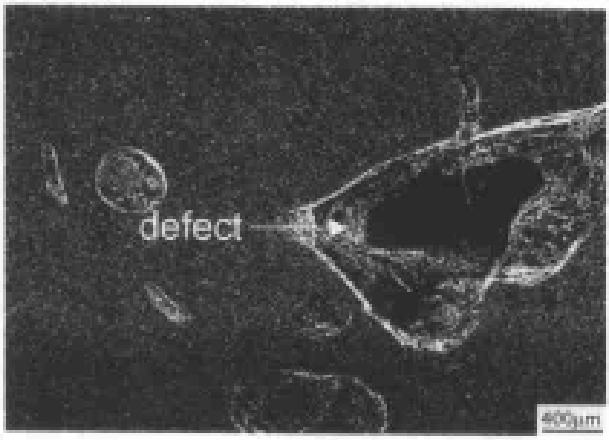

图 5－125　激光焊接，铸铁，CO_2 激光，功率 3200W，焊接速度 2m/min

Laser welding, cast iron, CO_2 laser, power 3200W, welding speed 2m/min.

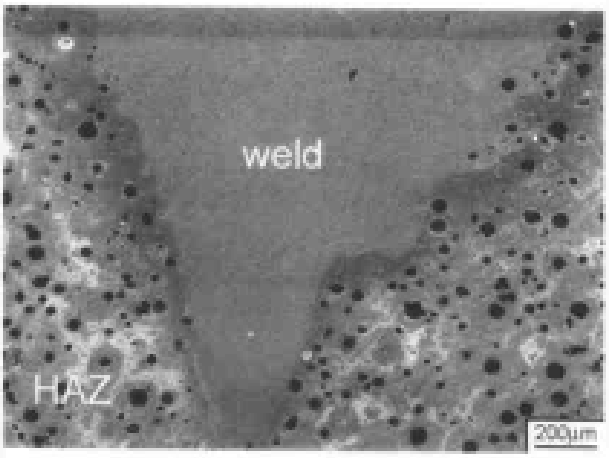

图 5－126　激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焦点间距 0.7mm，焊接速度1m/min

Laser welding, cast iron, CO_2 laser, power 3200W, foci 150mm, distance between focuses 0.7mm, welding speed 1m/min.

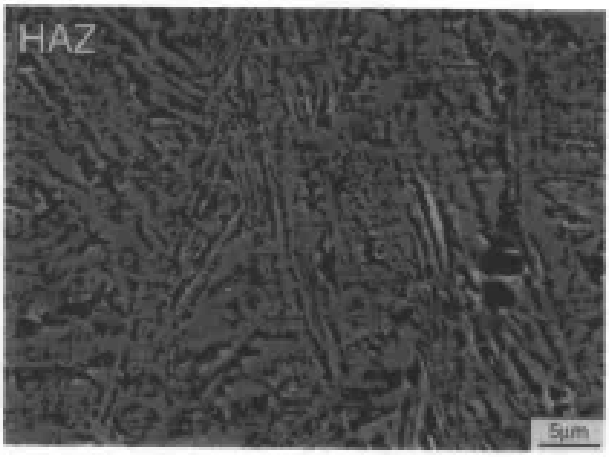

图 5－127　激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焦点间距 0.7mm，焊接速度1m/min

Laser welding, cast iron, CO_2 laser, power 3200W, foci 150mm, distance between focuses 0.7mm, welding speed 1m/min.

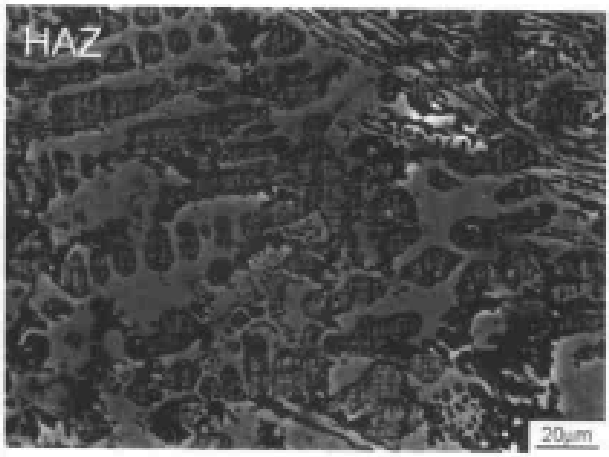

图 5－128　激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焦点间距 0.7mm，焊接速度1m/min

Laser welding, cast iron, CO_2 laser, power 3200W, foci 150mm, distance between focuses 0.7mm, welding speed 1m/min.

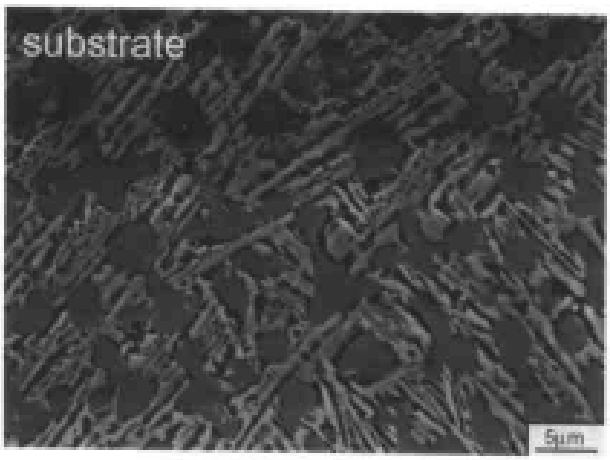

图 5－129 激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焊接速度 1m/min
Laser welding, cast iron, CO_2 laser, power 3200W, focus distance 150mm, welding speed 1m/min.

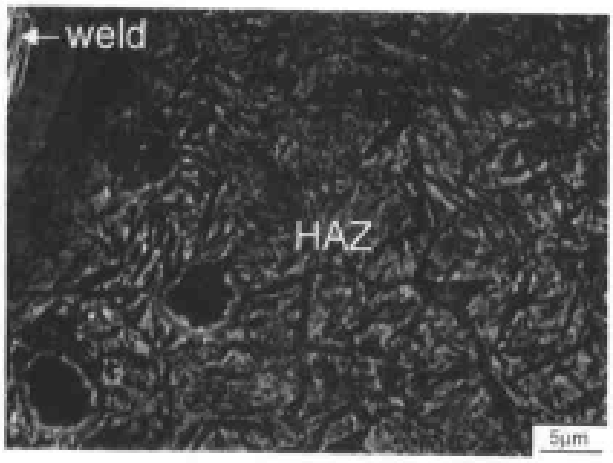

图 5－130 激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焊接速度 1m/min
Laser welding, cast iron, CO_2 laser, power 3200W, focus distance 150mm, welding speed 1m/min.

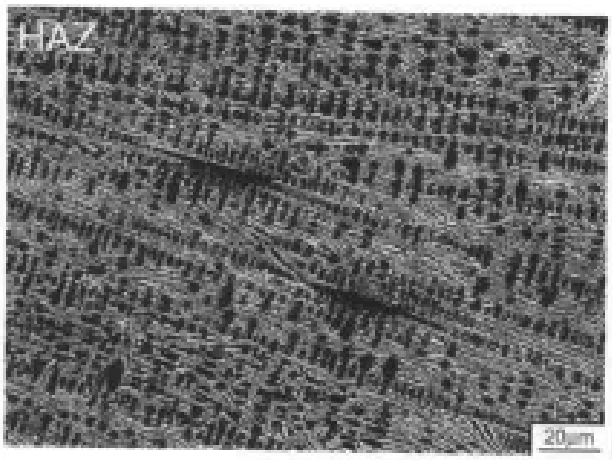

图 5－131 激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焊接速度 1m/min
Laser welding, cast iron, CO_2 laser, power 3200W, focus distance 150mm, welding speed 1m/min.

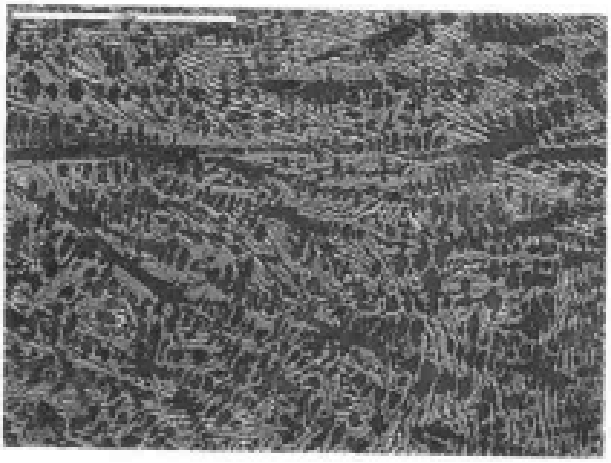

图 5－132 激光焊接，铸铁，CO_2 激光，功率 3200W，焦距 150mm，焊接速度 1m/min
Laser welding, cast iron, CO_2 laser, power 3200W, focus distance 150mm, welding speed 1m/min.

第6章　激光烧结

激光烧结(laser sintering)是以激光为热源，通过辐射加热的方法将粉末或压坯直接烧结成零件。激光烧结分为选择激光烧结、压坯激光烧结和激光点火自蔓延反应烧结。选择激光烧结(SLS)是近几十出现的一种新技术[6.1]，它是在计算机的控制下用激光把粉末材料逐层烧结成模型，属于激光造型技术。

压坯激光烧结是以激光束为热源对PM压坯进行辐射，使烧结体在短时间内获得高热量，烧结体所承受的烧结温度通常超过常规烧结温度，导致压坯以液相烧结方式被烧结成具有良好组织和性能的烧结材料[6.2][6.3][6.4]。压坯激光烧结有以下几个特点：

1. 烧结温度高，烧结周期短，有利于实现液相烧结；
2. 辐射加热，节省加热体；
3. 有利于激光能量的吸收；
4. 有利于和热挤压合金化及淬火等其他工艺组成复合工艺。

用压坯激光烧结技术烧结成了机车制动胀圈(成分为wt%*：1.6C，2.5Cu，2.5MoS_2和93.4Fe)，烧结零件的孔隙度为10%～15%，硬度在HB 130～142之间，组织为细层片状珠光体，少量分布在晶界上的网状渗碳体为$CuMo_2S_{3-x}$[6.5]；铜基电力机车受电弓滑板，烧结件的硬度为HRB 82.5；冲击值6.41 J/cm^2，达到了常规烧结零件的性能指标。另外压坯激光烧结可以制备梯度功能材料[6.6]。

激光点火自蔓延反应烧结时烧结体发生放热反应，使材料通过自蔓延方式完成烧结，激光起点火作用，是近期发展起来的，是激光加工技术和传统粉末冶金技术的结合。激光点火自蔓延反应烧结的特点是点火时间短，烧结速度快，常采用的材料有Ni－Al[6.7][7.8]体系等。

6.1　铁基合金激光烧结

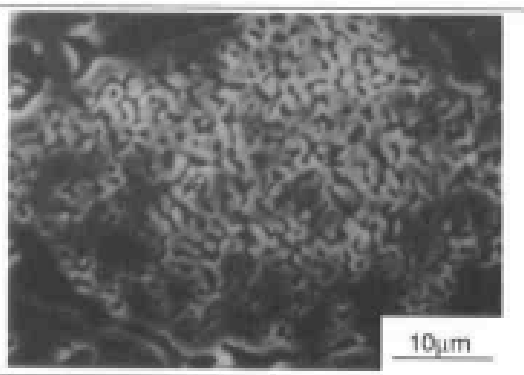

图6－1　激光烧结，Fe－3C粉末合金，CO_2激光，功率密度50W/cm^2，烧结时间5s，共晶组织
Laser sintering，Fe－3C powder alloy，CO_2 laser，power density 50W/cm^2，sintering time 5s，eutectic structure.

*：wt%为质量分数，下同。

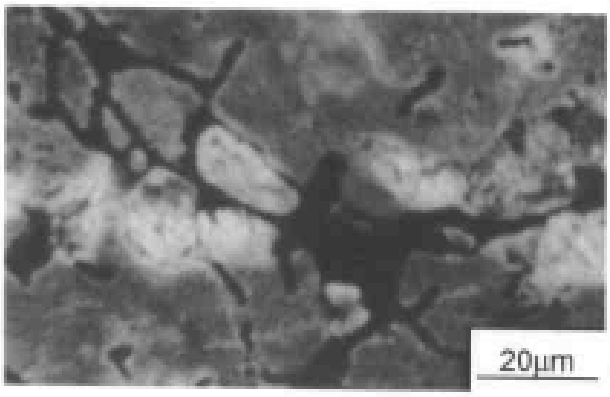

图 6－2 激光烧结，Fe－8C 粉末合金，CO_2 激光，功率密度 50W/cm²，烧结时间 5s，未透烧组织

Laser sintering，Fe－8C powder alloy，CO_2 laser，power density 50W/cm²，sintering time 5s，uncompleted sintered structure.

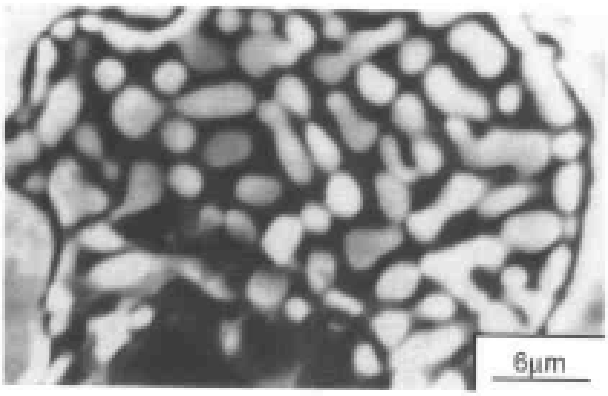

图 6－3 激光二次烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，含共晶产物的烧结组织

Laser sintering for two times，Fe－5Cu－20C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，eutectic product in sintered structure.

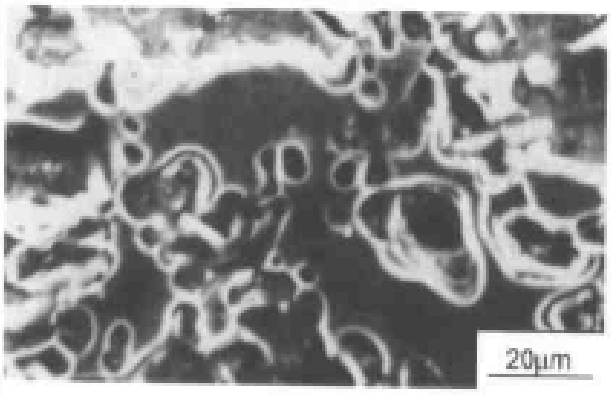

图 6－4 激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 40s，含孔洞的烧结组织

Laser sintering，Fe－5Cu－20C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 40s，pores in sintered structure.

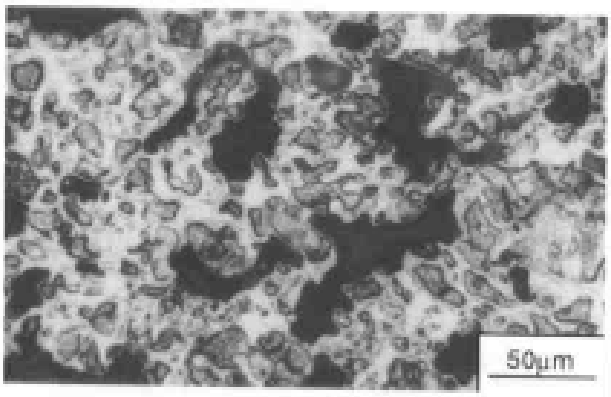

图 6－5 激光烧结，Fe－5Cu 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，烧结组织

Laser sintering，Fe－5Cu powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，sintering structure.

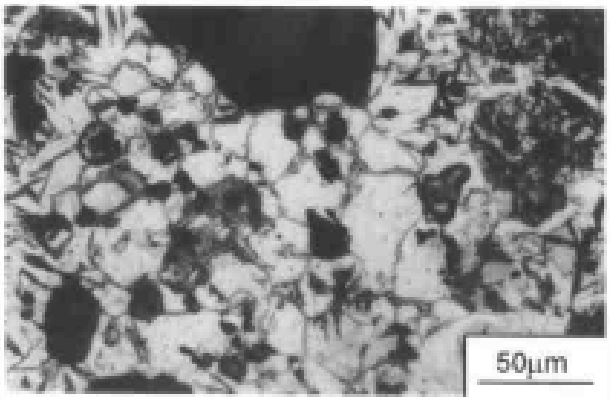

图 6－6　激光烧结，Fe－5Cu－10C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，烧结组织

Laser sintering，Fe－5Cu－10C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，sintering structure.

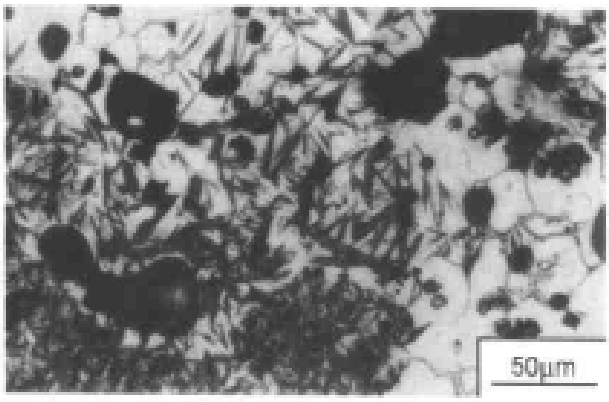

图 6－7　激光烧结＋淬火，Fe－5Cu－2C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，烧结组织

Laser sintering and quenching，Fe－5Cu－2C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，sintered and quenched structure.

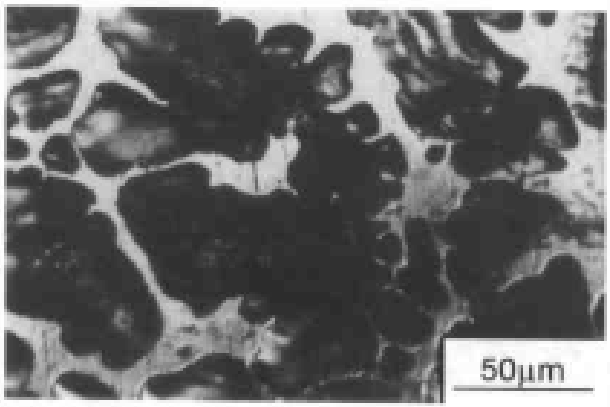

图 6－8　激光二次烧结，Fe－20Cu 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，烧结组织

Laser sintering for two times，Fe－20Cu powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，sintered structure.

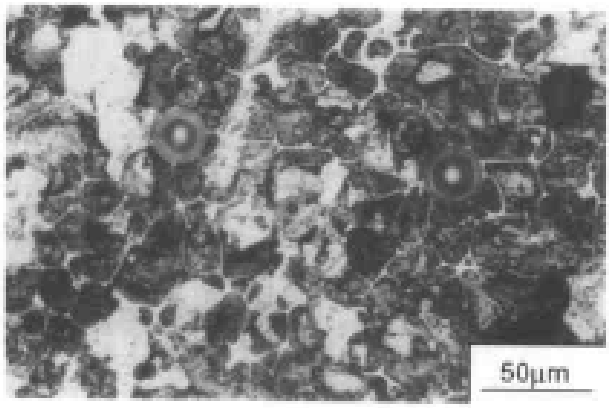

图 6－9　激光烧结，Fe－10Cu 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，烧结组织

Laser sintering，Fe－10Cu powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，sintered structure.

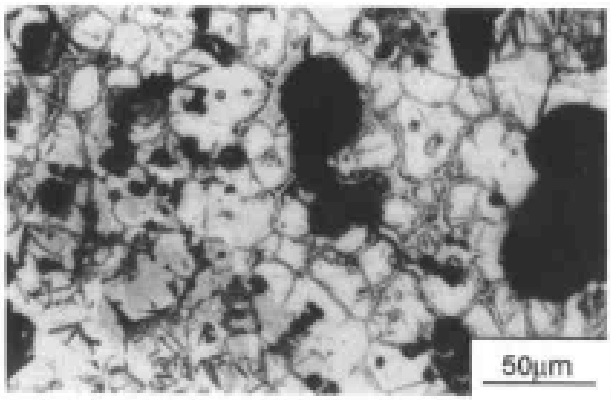

图 6－10　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 40s，含孔洞的烧结组织

Laser sintering，Fe－5Cu－20C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 40s，pores in sintered structure.

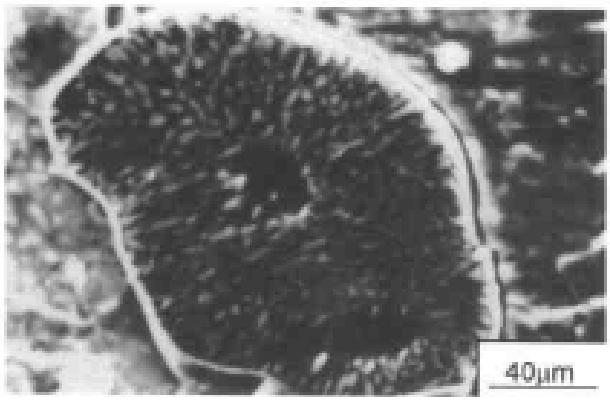

图 6－11　激光烧结，Fe－8C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，烧结组织

Laser sintering，Fe－8C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，sintered structure.

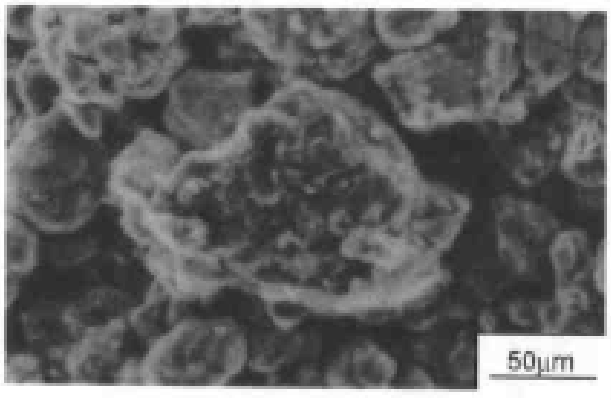

图 6－12　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 5s，未透烧组织

Laser sintering，Fe－5Cu－20C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 5s，uncompleted sintered structure.

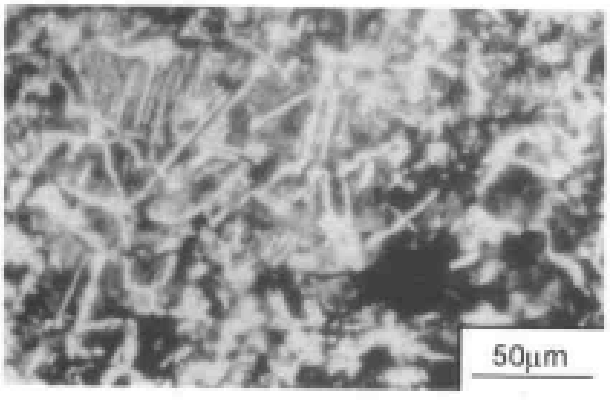

图 6－13　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 100W/cm²，烧结时间 30s，含渗碳体烧结组织

Laser sintering，Fe－5Cu－20C powder alloy，CO_2 laser，power density 100W/cm²，sintering time 30s，cementite in sintered structure.

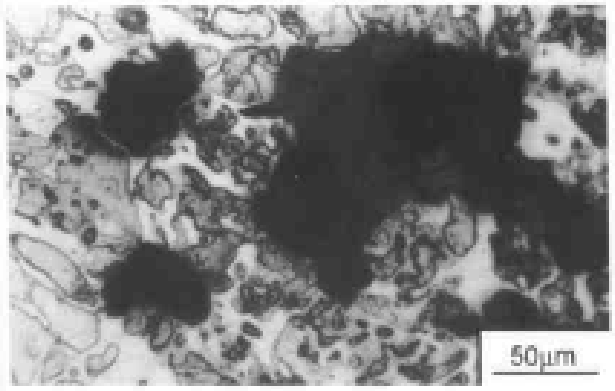

图 6－14　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 30W/cm²，烧结时间 30s，含石墨烧结组织

Laser sintering, Fe－5Cu－20C powder alloy, CO_2 laser, power density 30W/cm², sintering time 30s, graphite in sintered structure.

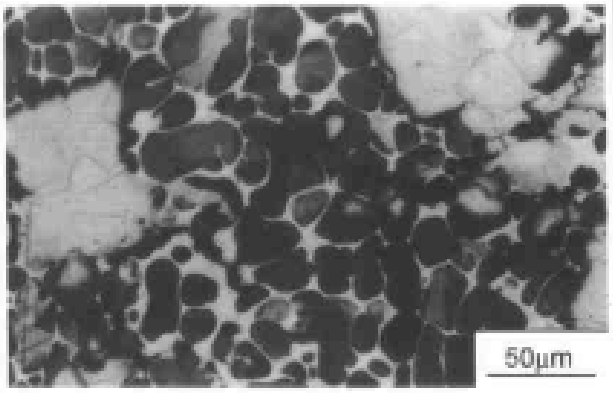

图 6－15　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 80W/cm²，烧结时间 50s，烧结组织

Laser sintering, Fe－5Cu－20C powder alloy, CO_2 laser, power density 80W/cm², sintering time 50s, sintered structure.

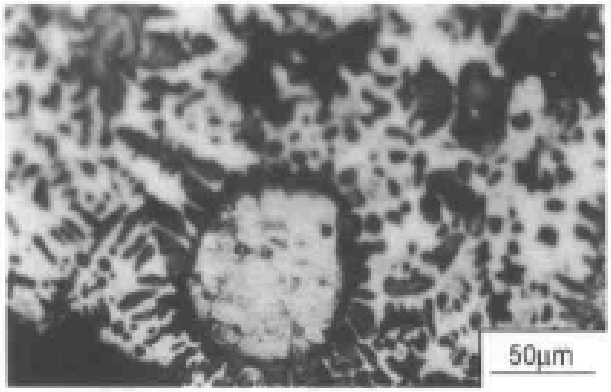

图 6－16　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 80W/cm²，烧结时间 30s，含枝晶的烧结组织

Laser sintering, Fe－5Cu－20C powder alloy, CO_2 laser, power density 80W/cm², sintering time 30s, dendrites in sintered structure.

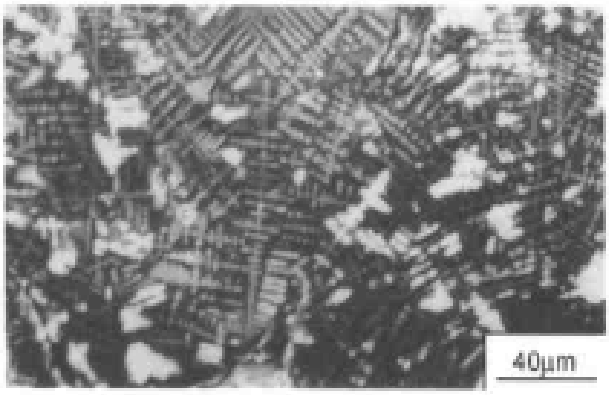

图 6－17　激光烧结，Fe－20C 粉末合金，CO_2 激光，功率密度 80W/cm²，烧结时间 30s，含枝晶的烧结组织

Laser sintering, Fe－20C powder alloy, CO_2 laser, power density 80W/cm², sintering time 30s, dendrites in sintered structure.

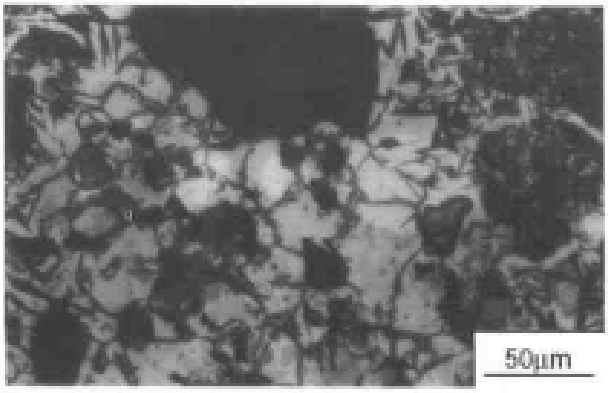

图 6－18　激光烧结，Fe－5Cu－20C 粉末合金，CO_2 激光，功率密度 60W/cm²，烧结时间 30s，含石墨和马氏体烧结组织

Laser sintering, Fe－5Cu－20C powder alloy, CO_2 laser, power density 60W/cm², sintering time 30s, graphite and martensite in sintered structure.

6.2 镍—铝合金激光烧结

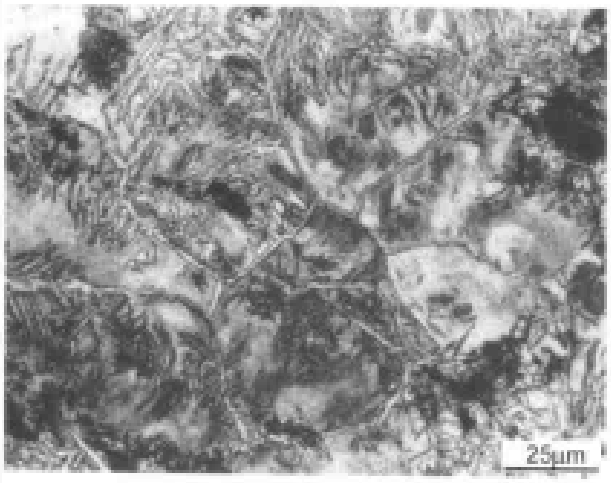

图 6—19 激光烧结，Ni—35at%* Al 合金，CO_2 激光，激光功率 1000W

Microstructure of Ni—35at% Al of laser synthesized sample, CO_2 laser, power 1000W (optical micrograph).

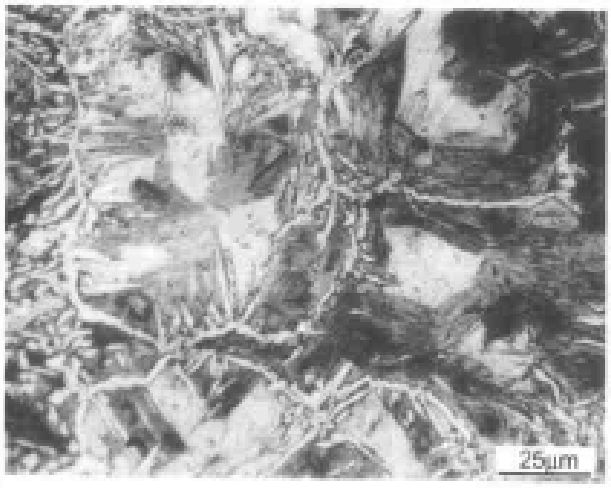

图 6—20 激光烧结，Ni—42at% Al 合金，CO_2 激光，激光功率 1000W

Microstructure of Ni—42at% Al of laser synthesized sample, CO_2 laser, power 1000W (optical micrograph).

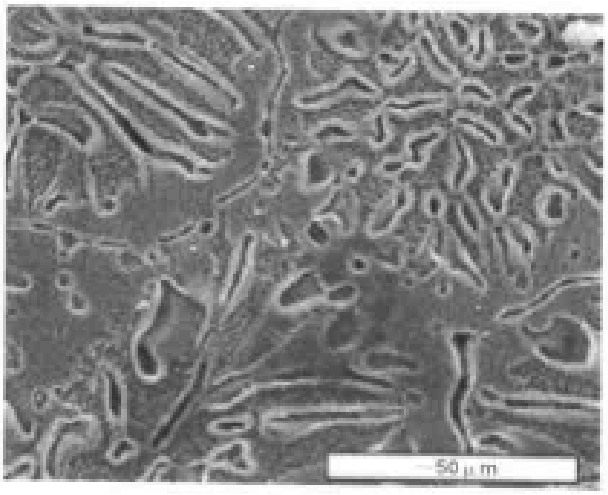

图 6—21 激光烧结，Ni—25at% Al 合金，CO_2 激光，激光功率 1000W

Microstructure of Ni—25at% Al of laser synthesized sample, CO_2 laser, power 1000W (optical micrograph).

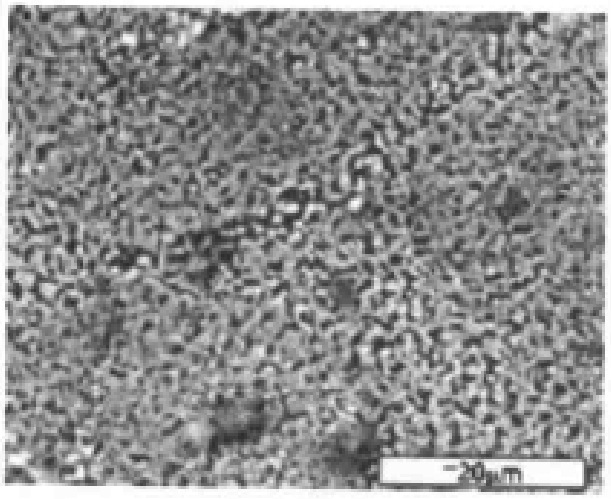

图 6—22 激光烧结，Ni—50at% Al 合金，CO_2 激光，激光功率 1000W

Microstructure of Ni—50at% Al of laser synthesized sample, CO_2 laser, power 1000W (optical micrograph).

*：at%为原子数分数。

6.3　其他合金的激光烧结

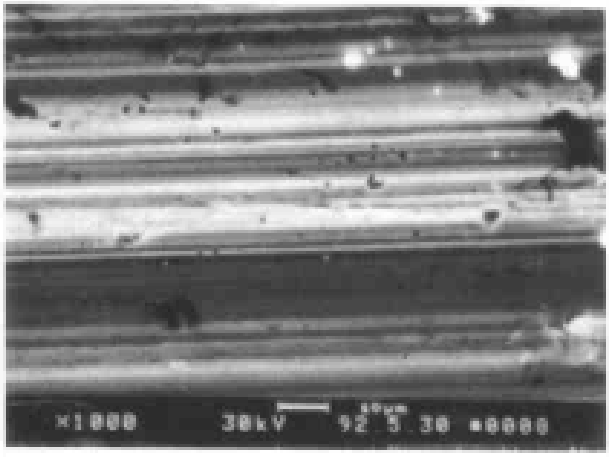

图 6－23　激光烧结，Cu－Sn－C 合金，CO_2 激光，SEM 照片，磨损新貌

Laser sintering，Cu－Sn－C alloy，CO_2 laser，SEM photograph，showing morphology of worn surface for the laser－sintered specimen.

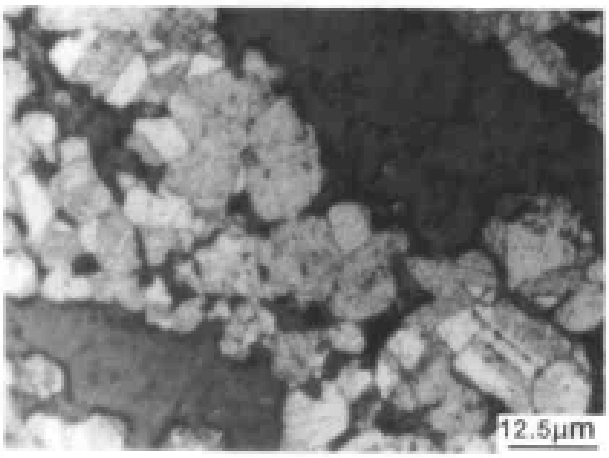

图 6－24　激光烧结，Cu－Sn－C 合金，Cu－Sn 相＋石墨相(黑色)，CO_2 激光，光学照片，显示激光烧结微观组织

Laser sintering，Cu－Sn－C alloy，Cu－Sn and graphite (black) phases，CO_2 laser，optical photograph，showing microstructure for laser－sintered specimens.

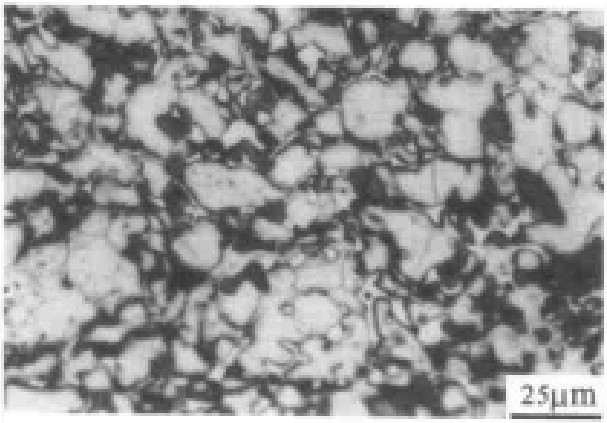

图 6－25　激光烧结，Fe－Cu 合金，CO_2 激光，烧结30s，烧结组织

Laser sintering，Fe－Cu alloy，CO_2 laser，sintering time 30s，showing sintered microstructure.

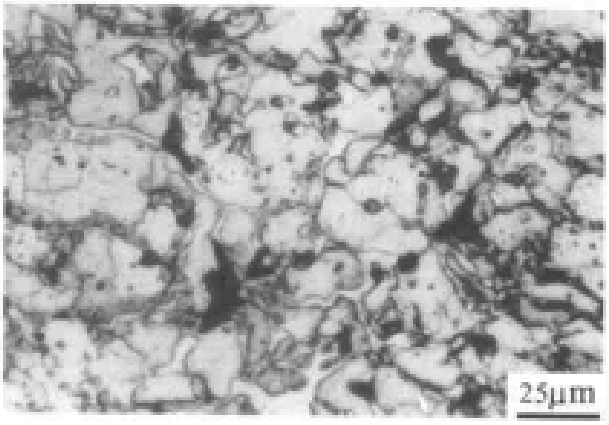

图 6－26　激光烧结，Fe－Cu 合金，CO_2 激光，烧结30s，未透烧组织

Laser sintering，Fe－Cu alloy，CO_2 laser，sintering time 30s，showing uncompleted sintered microstructure.

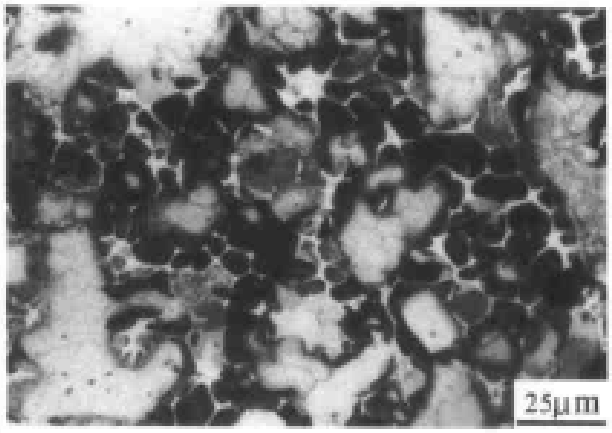

图 6－27　激光烧结，Fe－Cu 合金，CO_2 激光，烧结30s，透烧组织

Laser sintering，Fe－Cu alloy，CO_2 laser，sintering time 30s，showing sintered microstructure.

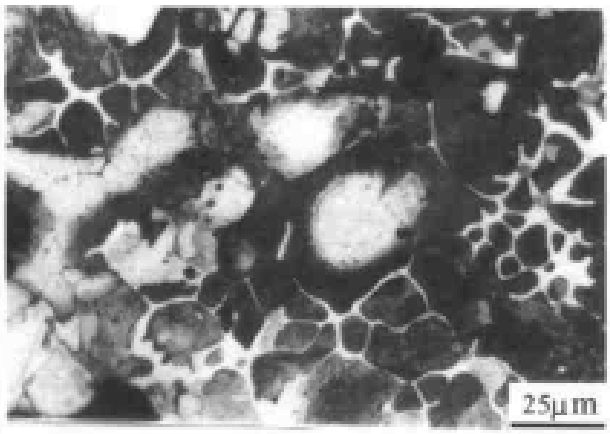

图 6－28　激光烧结，Fe－Cu 合金，CO_2 激光，3 次烧结各 30s，透烧组织

Laser sintering，Fe－Cu alloy，CO_2 laser，sintering three times，every time is 30s，showing sintered microstructure.

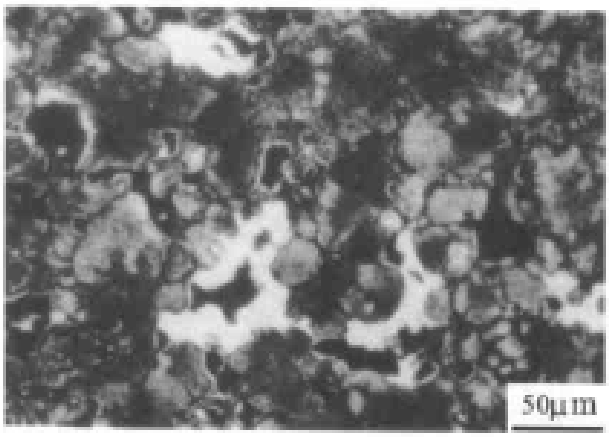

图 6－29　激光烧结，Fe－8Cu 合金，CO_2 激光，烧结 20s，显微组织

Laser sintering，Fe－8Cu alloy，CO_2 laser，showing microstructures of Fe－8Cu samples sintered for 20s.

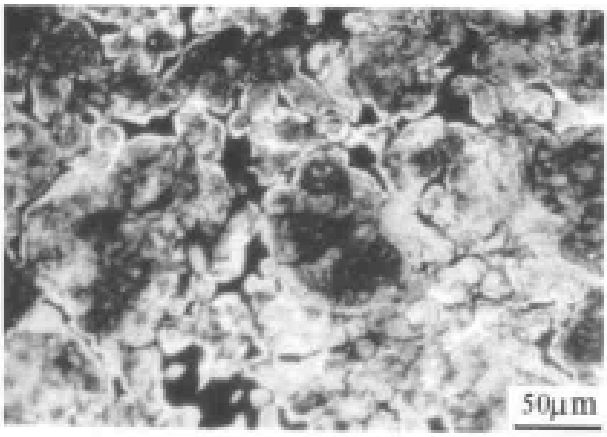

图 6－30　激光烧结，Fe－8Cu 合金，CO_2 激光，烧结 30s，显微组织

Laser sintering，Fe－8Cu alloy，CO_2 laser，sintering time 30s，showing microstructure.

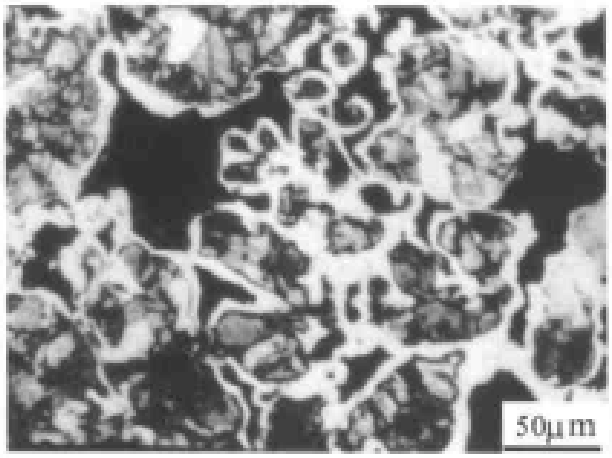

图 6－31　激光烧结，Fe－8Cu 合金，CO_2 激光，烧结 40s，显微组织

Laser sintering，Fe－8Cu alloy，CO_2 laser，sintering time 40s，showing microstructure.

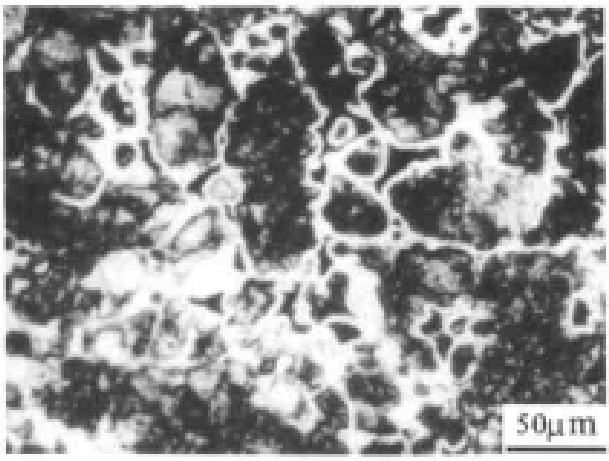

图 6－32　激光烧结，Fe－8Cu 合金，CO_2 激光，烧结 50s，显微组织

Laser sintering，Fe－8Cu alloy，CO_2 laser，sintering time 50s，showing microstructure.

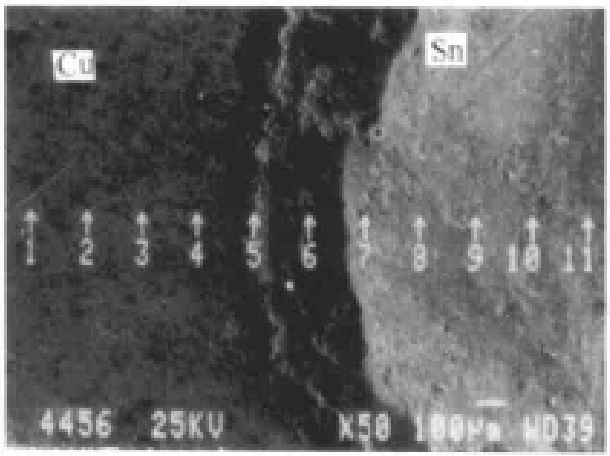

图 6－33　激光烧结，Cu－Sn 合金，CO_2 激光，烧结30s，烧结组织

Laser sintering，Cu－Sn alloy，CO_2 laser，sintering time 30s，showing sintered microstructure.

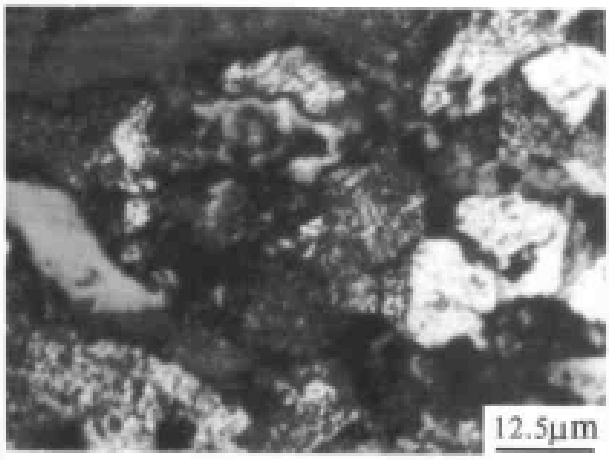

图 6－34　激光烧结，Cu－Sn－C 合金，CO_2 激光，烧结 60s，显微组织

Laser sintering，Cu－Sn－C alloy，CO_2 laser，sintering time 60s，showing microstructure.

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第7章　特种激光加工

这里定义的特种激光加工(special laser processes)是指激光制粉(laser fabricating powder)和激光制膜(pulsed laser deposition，PLD)，前者涉及18幅照片，后者20幅。粉末材料的应用非常广泛，制备粉末材料的方法比较多，常用方法有雾化法和还原法。激光制粉是一种特殊制粉方法，它适合于制备纳米级化合物粉末材料，本节给出了用激光制粉方法制成的TiC粉末的照片。

自70年代以来，制膜技术得到迅猛发展，已成为当代真空技术和材料科学中的活跃研究领域。常规制膜技术有蒸镀、离子镀、溅射镀膜、化学气相沉积、PCVD、MOCVD、分子束外延、液相生长等。脉冲激光蒸镀是近些年发展起来的新技术，其方法是把靶材和衬底材料放置在真空室内，一束聚焦的激光辐射到靶材上，使被辐射区域的物质烧蚀物择优地沿着靶的法线方向传输，沉积到前方的衬底上形成一层薄膜，它的优点是容易制备多层膜和异质膜，工艺简单，灵活性大，可以在光栅的控制下有选择的镀膜。金属膜激光氧化处理获得氧化膜，是一种新的膜氧化技术。金属膜激光氧化处理的氧化基材有Al[7.1]、Ti[7.2]、W[7.3]、低碳钢[7.4]、Si [7.5]和Cr薄膜 [7.6]及[7.7]。

7.1　激光制粉

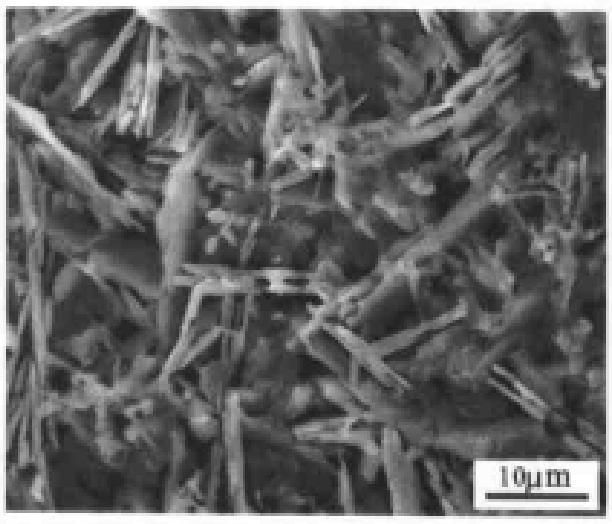

图7－1　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C的原子比为0.5，它与40wt%Al混合
Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C=0.5 in atomic ratio，40wt%Al (LISHS)。

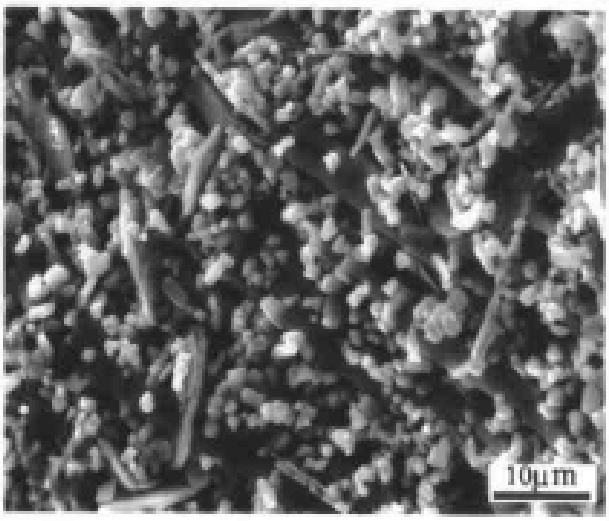

图7－2　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C的原子比为0.6，它与40wt%Al混合
Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C=0.6 in atomic ratio，40wt%Al (LISHS)。

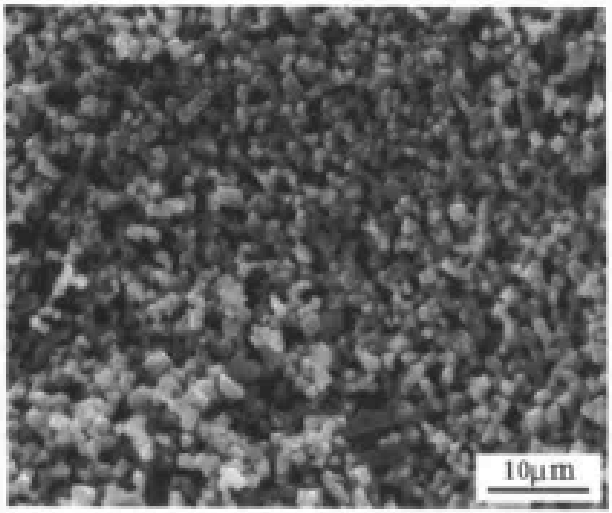

图 7－3　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.7，它与 40wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝0.7 in atomic ratio, 40wt% Al (LISHS).

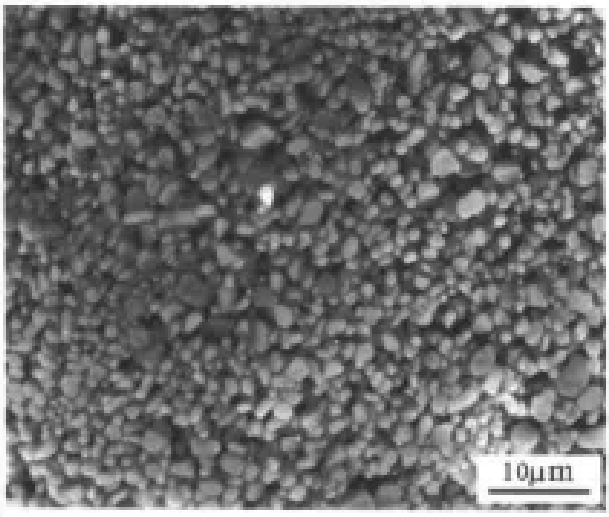

图 7－4　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.8，它与 40wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝0.8 in atomic ratio, 40wt% Al (LISHS).

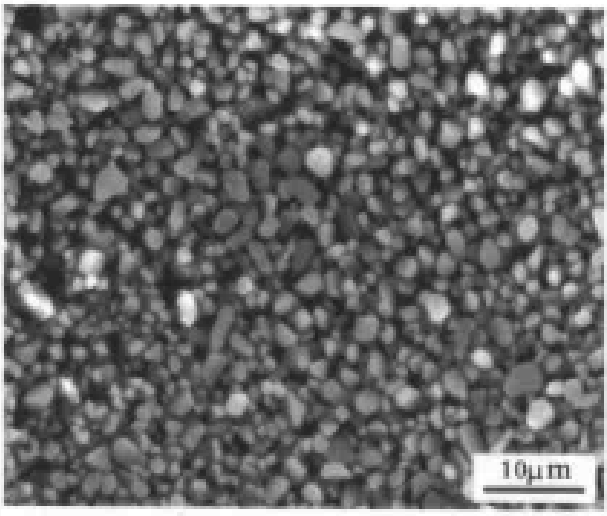

图 7－5　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.9，它与 40wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝0.9 in atomic ratio, 40wt% Al (LISHS).

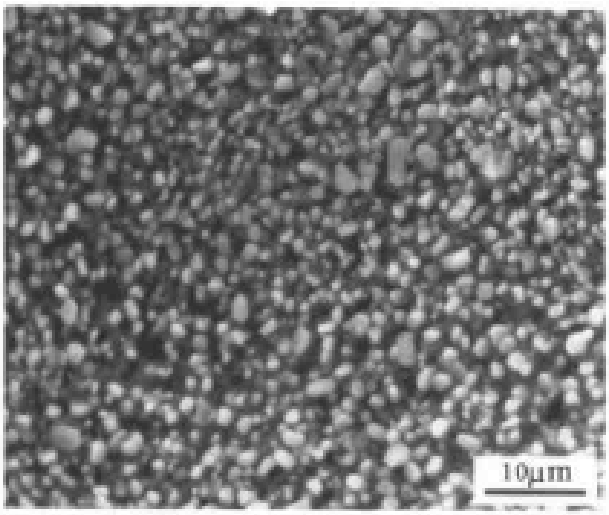

图 7－6　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，40wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝1.0 in atomic ratio, 40wt% Al (LISHS).

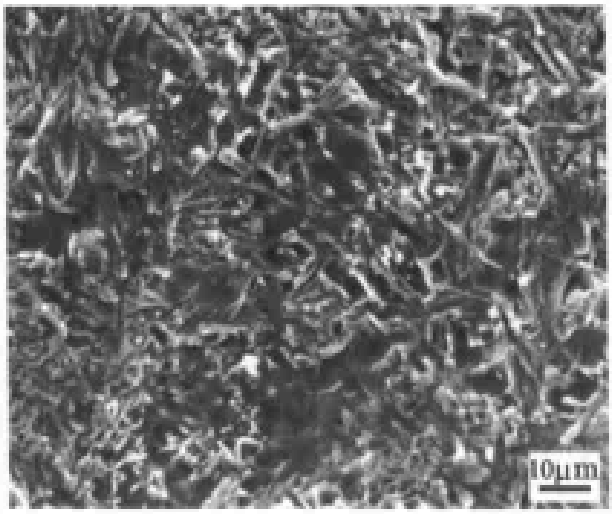

图 7－7　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.5，它与 40wt% Cu 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝0.5 in atomic ratio，40wt% Cu (LISHS).

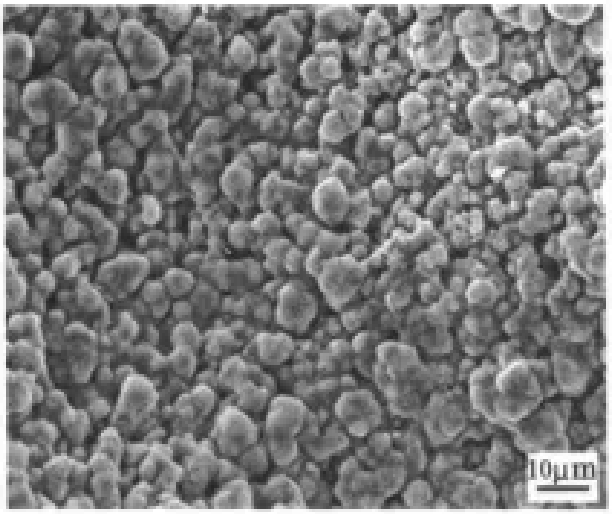

图 7－8　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.6，它与 40wt% Cu 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝0.6 in atomic ratio，40wt% Cu (LISHS).

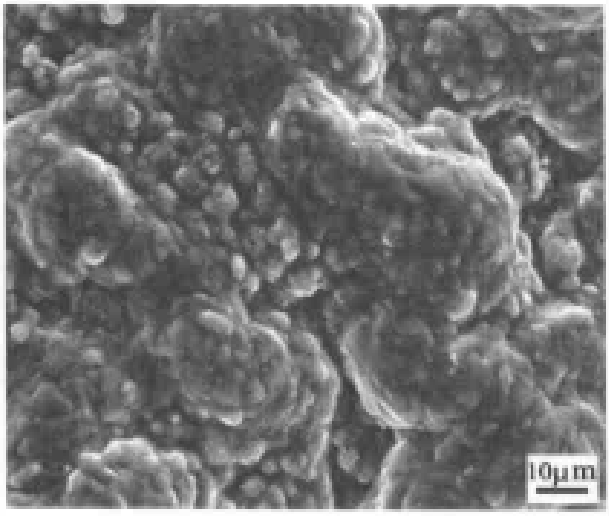

图 7－9　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.7，它与 40wt% Cu 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝0.7 in atomic ratio，40wt% Cu (LISHS).

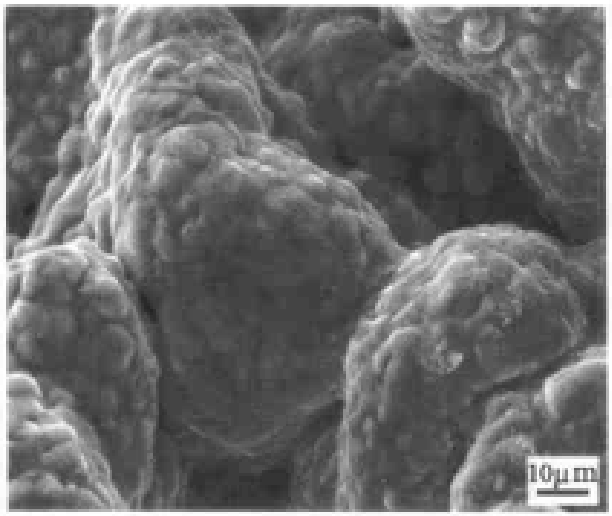

图 7－10　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.8，它与 40wt% Cu 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝0.8 in atomic ratio，40wt% Cu (LISHS).

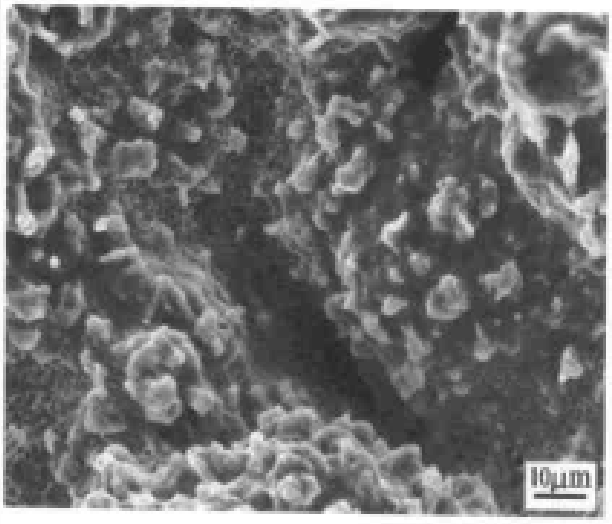

图 7－11 激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 0.9，它与 40wt% Cu 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝0.9 in atomic ratio, 40wt% Cu (LISHS).

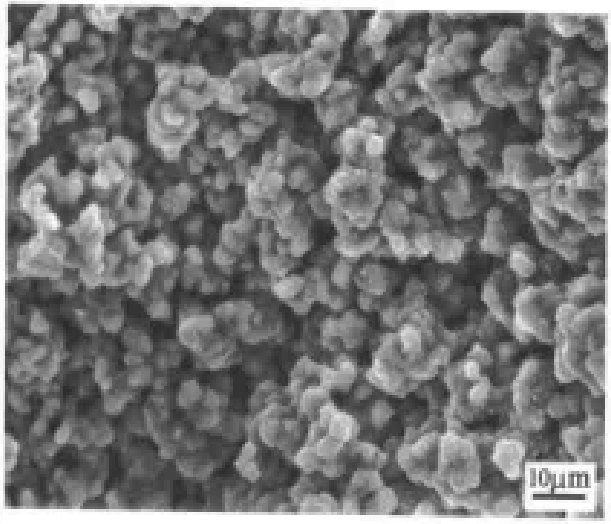

图 7－12 激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 40wt% Cu 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝1.0 in atomic ratio, 40wt% Cu (LISHS).

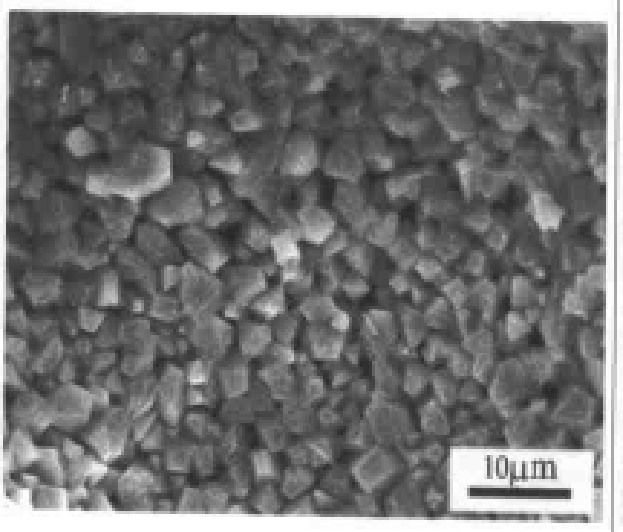

图 7－13 激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 20wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝1.0 in atomic ratio, 20wt% Al (LISHS).

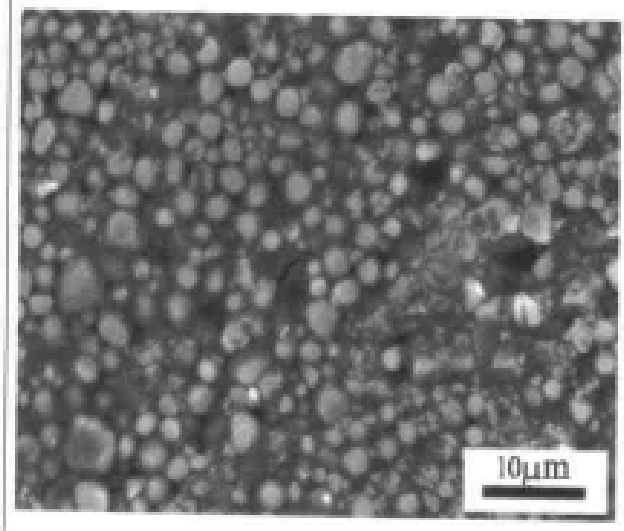

图 7－14 激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 25wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis, CO_2 laser, composition: Ti/C＝1.0 in atomic ratio, 25wt% Al (LISHS).

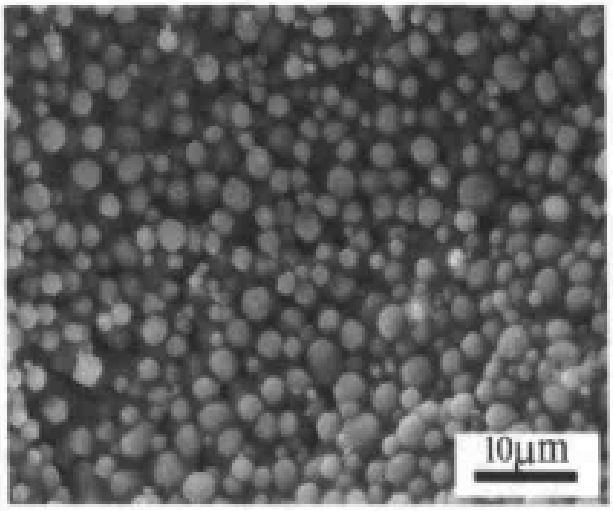

图 7－15　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 30wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝1.0 in atomic ratio，30wt% Al (LISHS).

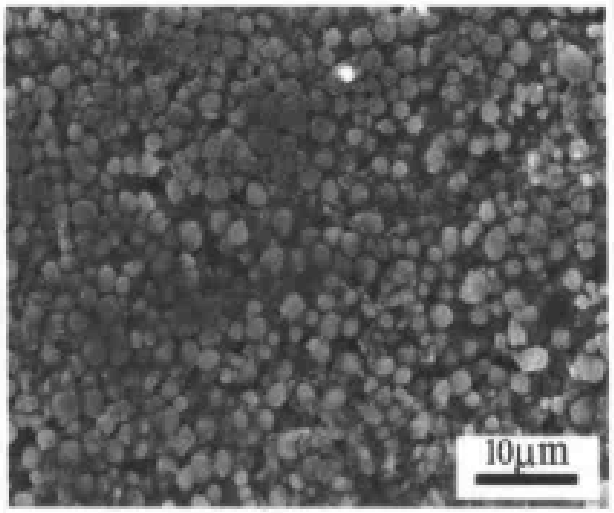

图 7－16　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 40wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝1.0 in atomic ratio，40wt% Al (LISHS).

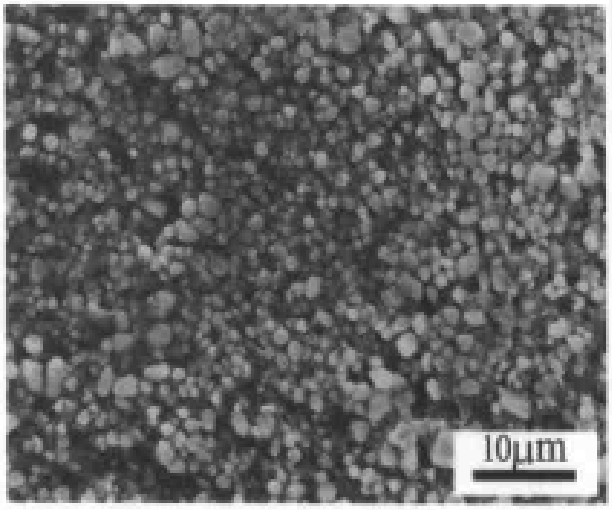

图 7－17　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 45wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝1.0 in atomic ratio，45wt% Al (LISHS).

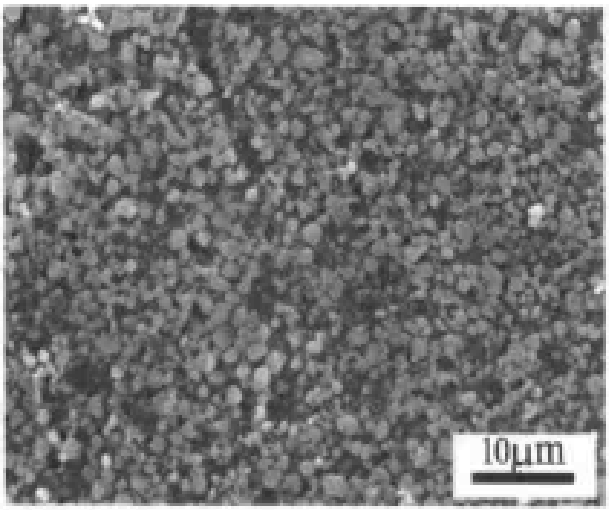

图 7－18　激光自蔓延烧结制备粉末材料，CO_2 激光，材料成分：Ti/C 的原子比为 1.0，它与 50wt% Al 混合

Fabrication powder with laser igniting self－propagating high－temperature synthesis，CO_2 laser，composition：Ti/C＝1.0 in atomic ratio，50wt% Al (LISHS).

7.2 激光制膜

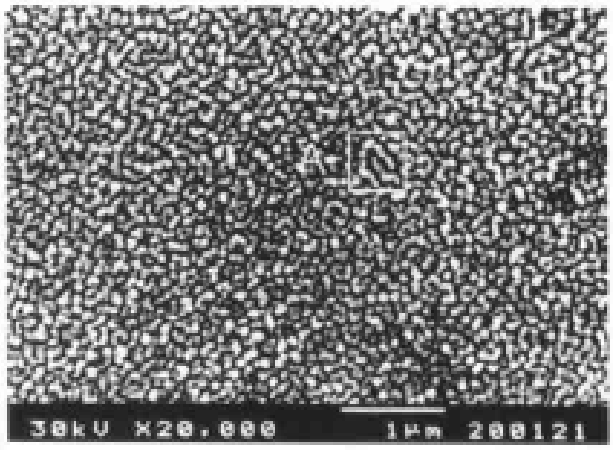

图 7－19 激光制膜，形成的膜材料 Cr_2O_3，YAG 激光，能量密度 30mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 30mJ/cm².

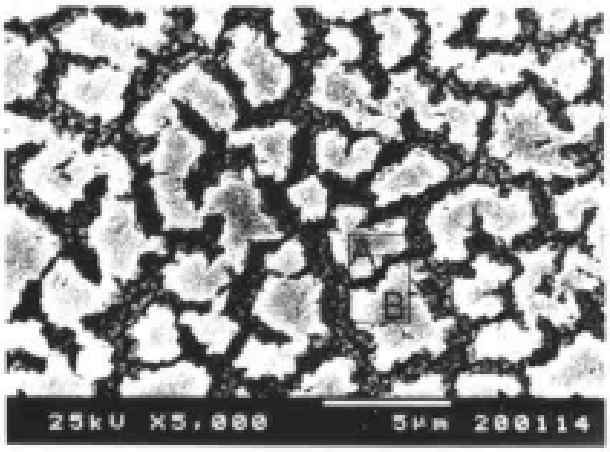

图 7－20 激光制膜，形成的膜材料 Cr_2O_3（含裂纹），YAG 激光，能量密度(35～100)mJ/cm²

Laser deposition, deposited Cr_2O_3 film with cracks, YAG laser, laser density (35～100)mJ/cm².

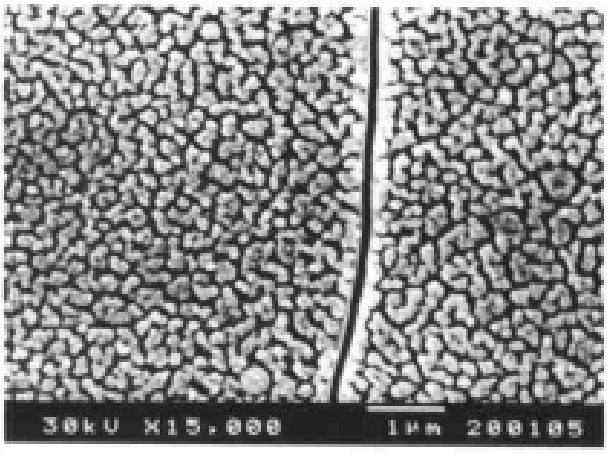

图 7－21 激光制膜，形成的膜材料 Cr_2O_3（含裂纹），YAG 激光，能量密度(10～15)mJ/cm²

Laser deposition, deposited Cr_2O_3 film with cracks, YAG laser, laser density (10～15)mJ/cm².

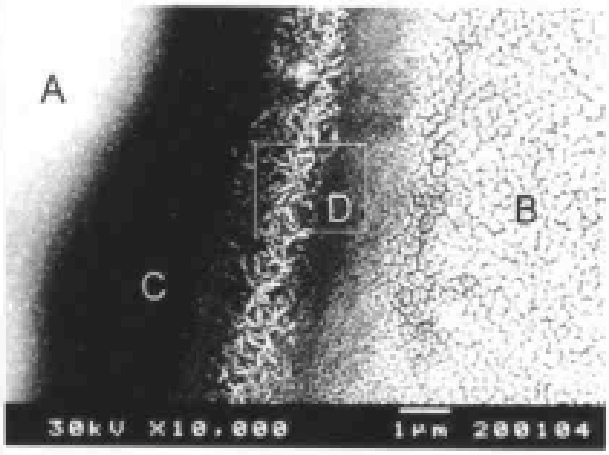

图 7－22 激光制膜，形成的膜材料 Cr_2O_3（未完全氧化），YAG 激光

Laser deposition, deposited Cr_2O_3 film, not well oxidized, YAG laser.

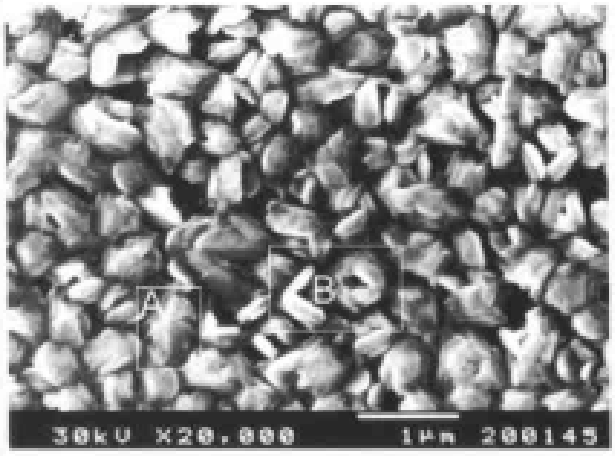

图7－23 激光制膜，经700℃退火的Cr_2O_3膜材料，YAG激光

Laser deposition, deposited Cr_2O_3 film after annealing at 700℃, YAG laser.

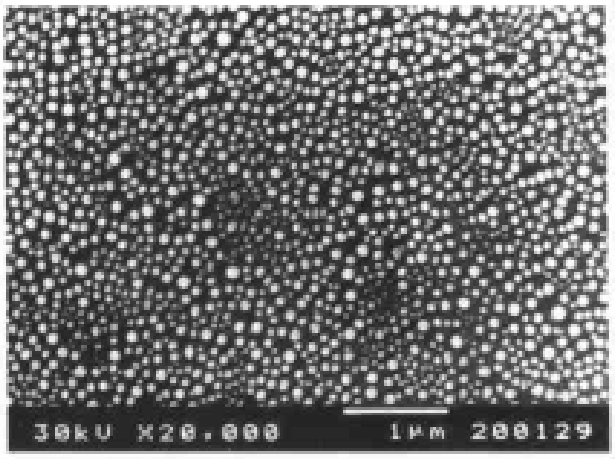

图7－24 激光制膜，形成的膜材料Cr_2O_3，YAG激光，能量密度200mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 200mJ/cm².

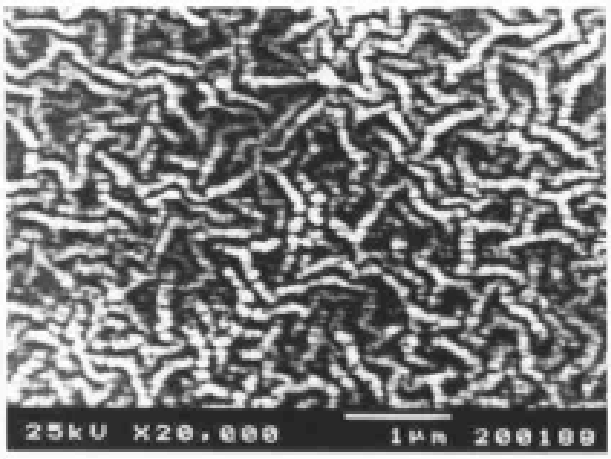

图7－25 激光制膜，形成的膜材料Cr_2O_3，YAG激光，能量密度20mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 20mJ/cm².

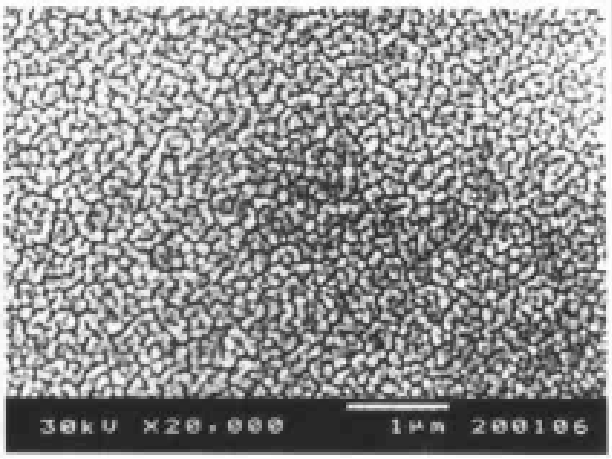

图7－26 激光制膜，形成的膜材料Cr_2O_3，YAG激光，能量密度30mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 30mJ/cm².

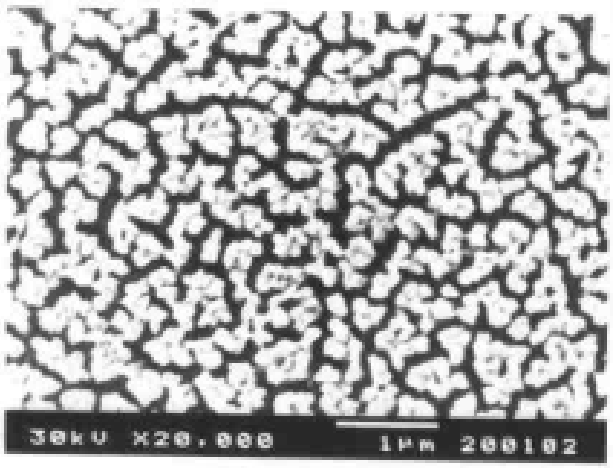

图 7－27 激光制膜，形成的膜材料 Cr_2O_3，YAG 激光，能量密度 50mJ/cm²。
Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 50mJ/cm².

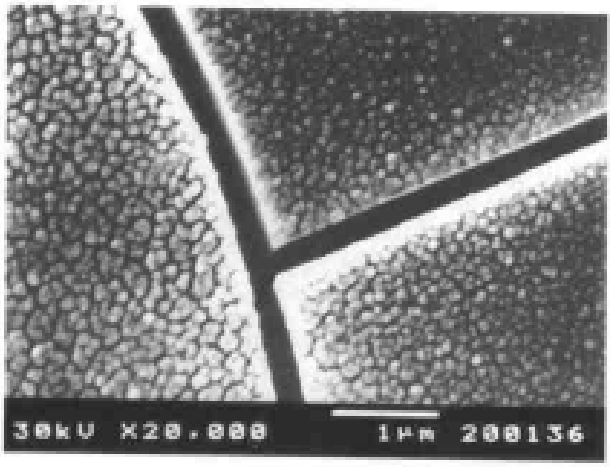

图 7－28 激光制膜，形成的膜材料 Cr_2O_3，YAG 激光，能量密度 100mJ/cm²
Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 100mJ/cm².

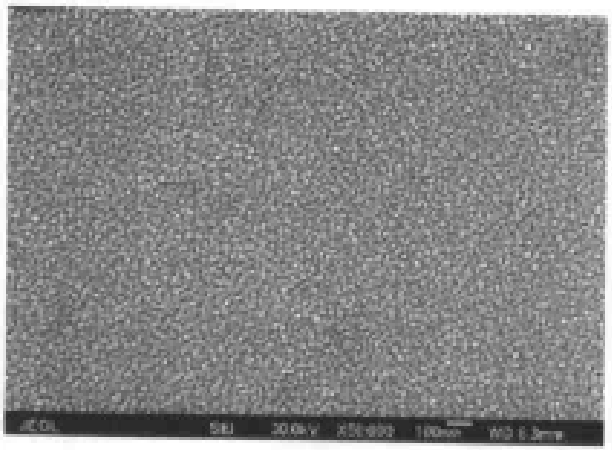

图 7－29 激光制膜，形成的膜材料 Cr_2O_3，YAG 激光，能量密度 15mJ/cm²
Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 15mJ/cm².

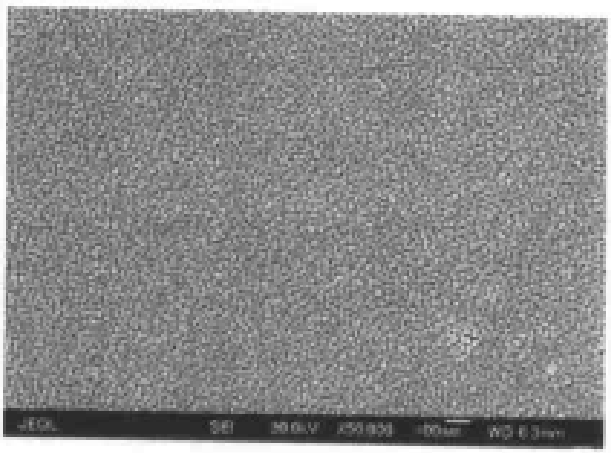

图 7－30 激光制膜，形成的膜材料 Cr_2O_3，YAG 激光，能量密度 30mJ/cm²
Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 30mJ/cm².

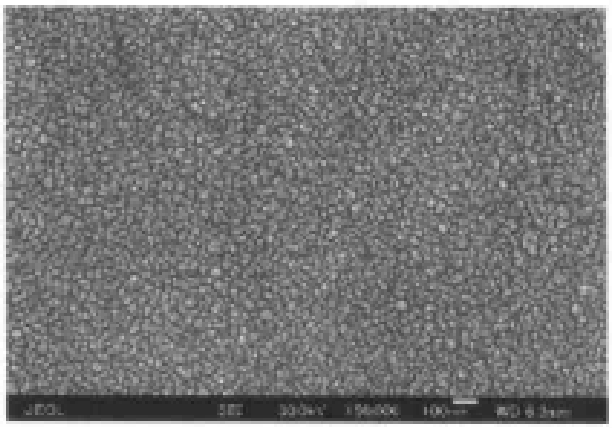

图7－31 激光制膜，形成的膜材料 Cr_2O_3，YAG激光，能量密度 22.5mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 22.5mJ/cm².

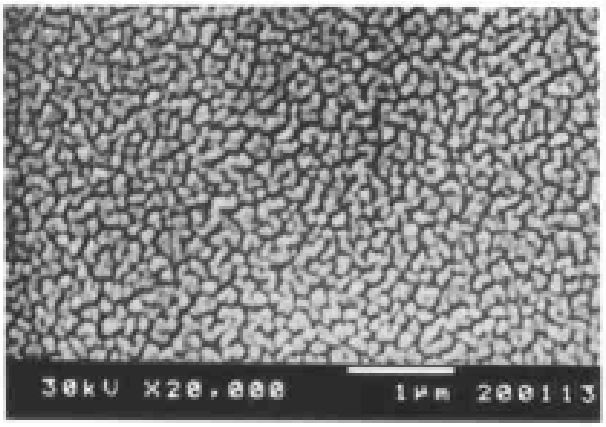

图7－32 激光制膜，形成的膜材料 Cr_2O_3，YAG激光，能量密度 70mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 70mJ/cm².

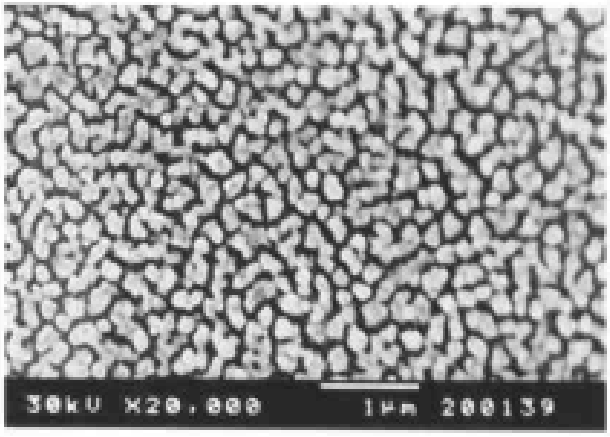

图7－33 激光制膜，形成的膜材料 Cr_2O_3，YAG激光，能量密度 90mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 90mJ/cm².

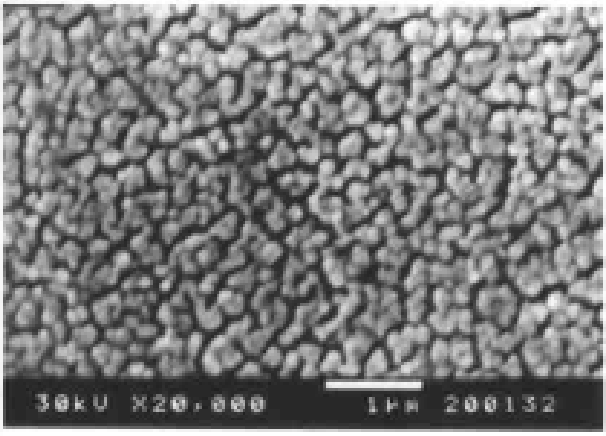

图7－34 激光制膜，形成的膜材料 Cr_2O_3，YAG激光，能量密度 100mJ/cm²

Laser deposition, deposited Cr_2O_3 film, YAG laser, laser density 100mJ/cm².

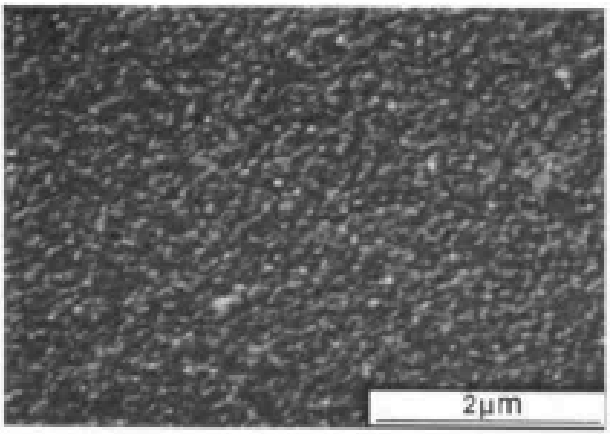

图 7－35 激光制膜，形成的膜材料 Cr_2O_3，600℃退火 15min，YAG 激光

Laser deposition, deposited Cr_2O_3 film, annealed oxidation at 600℃ for 15min in air, YAG laser.

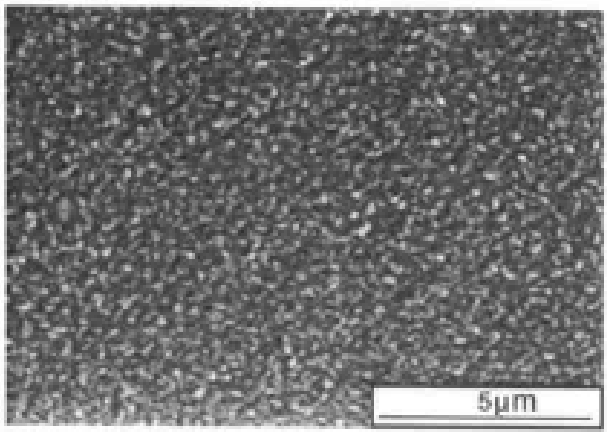

图 7－36 激光制膜，形成的膜材料 Cr_2O_3，700℃退火 15min，YAG 激光

Laser deposition, deposited Cr_2O_3 film, annealed oxidation at 700℃ for 15min in air, YAG laser.

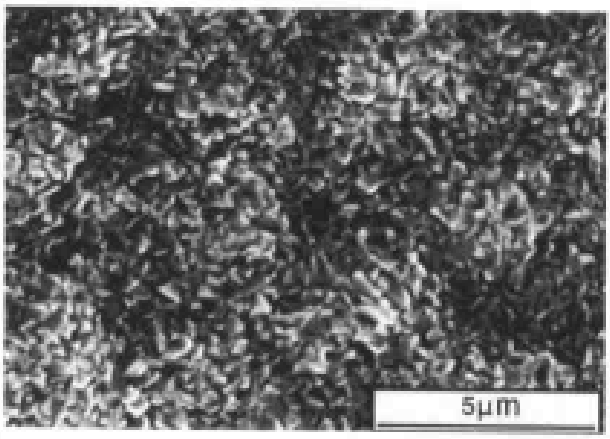

图 7－37 激光制膜，形成的膜材料 Cr_2O_3，800℃退火 15min，YAG 激光

Laser deposition, deposited Cr_2O_3 film, annealed oxidation at 800℃ for 15min in air, YAG laser.

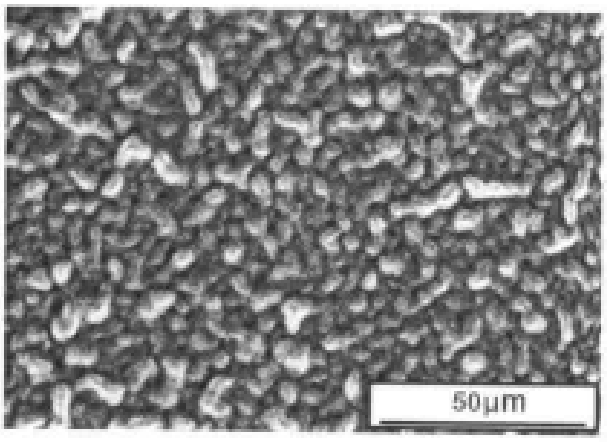

图 7－38 激光制膜，形成的膜材料 Cr_2O_3，800℃退火 15min，YAG 激光

Laser deposition, deposited Cr_2O_3 film, annealed oxidation at 800℃ for 15min in air, YAG laser.

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