第35卷 第8期 焊接学报 Vol. 35 No. 8
2014年8月 TRANSACTIONS OF THE CHINA WELDING INSTITUTION August 2014

激光增强GMAW焊接熔滴过渡控制试验

朱加雷， 焦向东， 乔 溪， 贾存锋*
（北京石油化工学院，机械工程学院，北京 102600）

摘 要：水下环境压力对于焊接熔滴过渡和焊接过程稳定性具有一定的负面阻碍作用，需要提供额外的作用力帮助稳定焊接电弧和改善熔滴过渡状态；为验证激光增强熔滴过渡控制技术的可行性，搭建了空气环境下的相关试验系统，并进行了激光增强前后的熔滴过渡状态对比研究．结果表明，在焊接过程中施加一定功率密度的激光对熔滴过渡行为具有明显的改善作用，可以在一定范围内改善熔滴过渡状态，并可以通过激光控制过渡熔滴的大小，提高焊接过程的稳定性．试验结果为进一步开展激光增强高压干法水下焊接试验奠定了基础．

关键词：激光增强；熔滴过渡；高速摄像
中图分类号：TG 456.5；TP 242.3 **文献标识码**：A **文章编号**：0253-360X(2014)08-0021-04

0 序 言

海洋油气资源开发以及核电的发展，将是国内现阶段及未来较长一段时间解决能源问题的主要渠道，发展与之配套的水下结构物应急修复技术是保障安全稳定运行的重要技术之一[1]．熔化极气体保护焊(gas metal arc welding，GMAW)焊接高效、便捷、易于实现远程控制的自动化，对水下焊接修复非常有利．

稳定的熔滴过渡是在可控热量和质量输入的情况下改善焊接质量．尽管国内外研究人员对熔滴过渡控制进行了大量研究，实现一定程度的GMAW焊接熔滴过渡控制，但电流仍然是熔滴过渡的主要影响因素．对于较大水深的水下GMAW焊接而言，由于反向等离子射流的形成和环境压力的影响，熔滴过渡更加困难，稳定性也更差[2,3]．因此为了在一定的水下压力环境下使用GMAW焊接工艺，同时在较为宽泛的条件下获得稳定的焊接熔滴过渡，需要将熔滴过渡和电流之间的依存关系一定程度上剥离．美国肯塔基大学研究人员提出了激光增强熔化极气体保护焊工艺过程，针对0.8 mm直径焊丝，在80～130 A电流范围内，通过激光增强成功实现了恒定电流的喷射过渡[4,5]，而该电流范围在无激光增强时为短路过渡．

收稿日期：2013-12-20
基金项目：国家自然科学基金资助项目(51205026，51175046)；北京市属高校创新团队建设提升计划资助项目(IDHT20130-516)；北京石油化工学院优秀青年教师和管理骨干培育计划资助项目(BIPT-BPOYTMB-2013)

* 参加此项研究工作的还有李卫强，马正住

1 激光增强原理

通常情况下GMAW焊接的熔滴过渡是多个力共同作用于熔滴的结果，如图1所示，包括重力F_g、表面张力F_σ、电磁力F_{em}、等离子流力F_p，在水下压力环境下还受到反向等离子流力F_d的作用，图1中箭头的方向代表力的方向，箭头向下的为分离力，向上的为保持力．液滴的几何形状由这些力通过静力平衡确定，熔滴在分离前，分离力和保持力是平衡的．对于平焊位置而言，重力、电磁力、等离子流力通常有助于熔滴过渡，而表面张力、压力环境下的反向等离子流力则往往阻碍熔滴过渡．

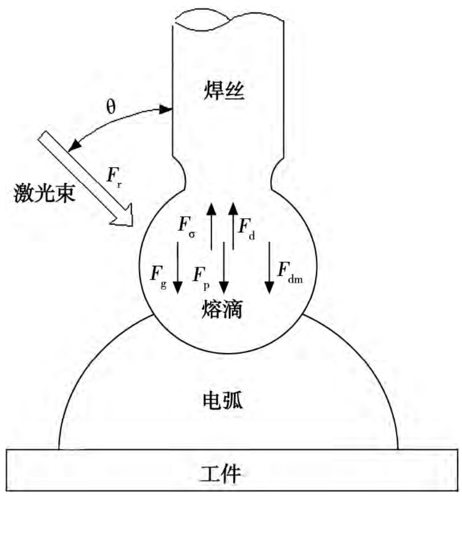

图1 激光增强熔滴过渡原理示意图
Fig. 1 Schematic of laser enhanced droplet transfer

在连续电流无控制的条件下，熔滴过渡模式主

要由电流的大小来确定，增加电流可以增大分离熔滴所需的电磁力，而对于高压干法水下焊接，要求严格控制焊接热输入，因此尽管环境压力不断增加，但焊接电流值必须限定在一定的范围内. 此时必须考虑采用辅助力帮助熔滴分离，以保证焊接质量. 激光的能量密度极大，当用激光照射金属熔滴，会产生一个辐射压力和一个反冲压力 F_r，反冲压力是激光及光致等离子体对熔滴的辐射而使被辐射熔滴表面液态金属产生高速蒸发而产生的反推力，作用于熔滴上的辐射压力相比反冲压力相差几个数量级，可以忽略；而反冲压力可以作为一个辅助分离力，弥补因为相对小电流而缺少的电磁力来使熔滴分离，但与激光复合焊接过程不同，与激光相关的额外热量与焊接所用的电弧热量相比是微不足道的，激光增强熔滴过渡并不会提供明显额外的热量而加速焊丝熔化速度. 激光束产生的反冲压力的大小与激光束功率密度的平方成正比，同时激光束入射方向与焊丝之间的角度 θ 决定着激光反冲压力的方向，从而影响着反冲压力在焊丝轴线方向的有效分离力. 有效分离力的大小又和分离熔滴的尺寸直接相关，由于熔滴横截面上的激光束功率密度与熔滴无关，因此随着熔滴尺寸的增长，激光作用的反冲压力也在增加，最终结果是激光作用在熔滴上的辅助分离力和熔滴自身重力均增加，因此可以通过控制激光束的功率密度等参数来控制熔滴过渡的状态和熔滴的尺寸.

2 试验系统搭建

在常压环境下进行了激光增强熔滴过渡控制验证性试验，根据试验要求搭建了如图 2 所示的焊接试验系统. 为便于高速摄像系统拍摄和激光作用位置固定，焊接过程中焊枪固定，焊接平台带动焊接试板运动. 使用 Olympus 的 i-SPEED 3 高速摄像机进行熔滴过渡的拍摄，此摄像机携带外部可视指示器，最高帧速率为每秒 150 000 帧，可随时确认摄像机录制状态. 背光系统选择美国 Melles Griot 公司生产的 25LHP928—230 型氦氖激光器，光源输出波长为 632.8 nm，额定功率为 35 mW. 高速摄像系统的示意图如图3 所示，高速摄像机采用每秒 4 000 帧的速度进行拍摄. 由 IPG YLR-4000 型连续光纤激光器提供激光光源，激光波长为 1 070 nm. 激光焊接头型号为 YW52，为便于操作调整，将激光焊接头的聚焦镜头更换为 680 mm 的长聚焦镜头. 焊接电源为松下全数字控制脉冲 MIG/MAG 焊机 YD-400GE. 焊接试板材质为 16Mn，焊丝直径为 1.2 mm 的 JM-56，焊接过程中焊丝伸出长度为 15 mm，激光引导光斑作用在焊丝的位置距离焊接试板上表面约 4 mm. 激光入射角度为 45°，激光焊接头聚焦透镜距离焊丝的距离为 635 mm，通过计算得激光作用于焊丝上的光斑直径为 5.12 mm，可以通过此尺寸获得激光的功率密度值.

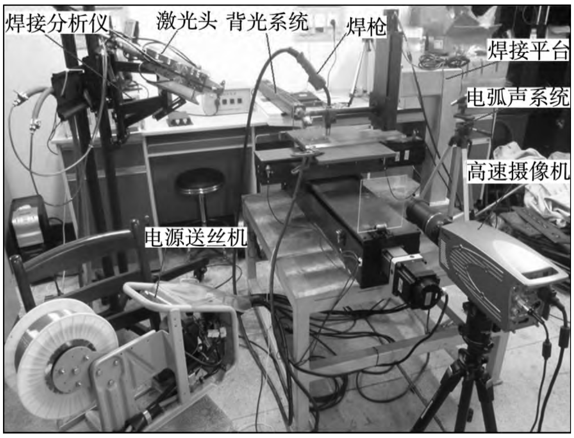

图2 激光增强熔滴过渡试验系统

Fig. 2 Test system of laser enhanced droplet transfer

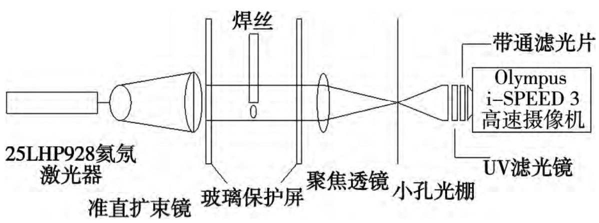

图3 高速摄像系统示意图

Fig. 3 Schematic of high speed camera system

3 激光增强熔滴过渡试验

在通常的 GMAW 焊接中，影响熔滴过渡形式的主要因素包括电流、电弧长度、极性、保护气体、焊丝材质、直径和焊丝伸出长度等参数，电弧长度可以通过电压设定值的改变而改变[6]. 文中采用直流反接，焊接保护气体为 80% Ar + 20% CO_2，总气体流量 20 L/min，对于直径 1.2 mm 焊丝而言，其喷射过渡的临界电流约为 280 ~ 320 A[7]. 为验证激光对熔滴过渡状态的影响，采用表 1 中的工艺参数进行焊接试验.

激光功率密度指的是发射激光照射到熔滴表面上时的激光功率密度. 图 4 ~ 图 7 分别为高速摄像机拍摄的从试验条件 1 至试验条件 4 对应的一个熔滴过渡过程. 从各组对应的高电压、小电流焊接工艺参数以及视频截图可以明显看出，各焊接过程均

表 1　试验焊接工艺参数

Table 1　Test parameters

试验条件	激光功率 P/W	激光功率密度 w/(W·mm^{-2})	入射角 θ/(°)	焊接速度 v/(cm·min^{-1})	设定电流 I/A	设定电压 U/V
1	0	0	45	60	180	34
2	1 524	74.0	45	60	180	34
3	0	0	45	60	150	32
4	1 124	54.6	45	60	150	32

对应明显的大滴滴状过渡. 通过对比可知，图 5 和图 7 中熔滴脱离焊丝时的熔滴尺寸明显小于不使用激光时相同参数下图 4 和图 6 中的熔滴尺寸，因此可以通过在熔滴上施加一定功率密度的激光来控制过渡熔滴的大小. 图 8 为表 1 中 4 组试验数据对应的焊接过程焊接电流和电弧电压波形，从图8 中可

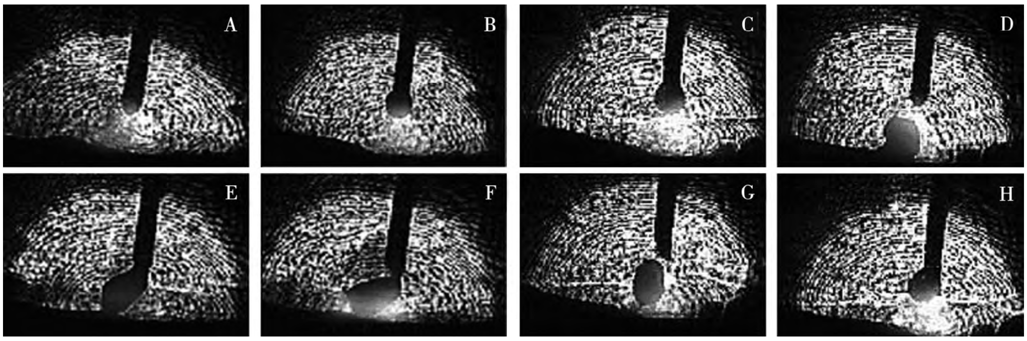

图 4　试验条件 1

Fig. 4　Test parameter 1

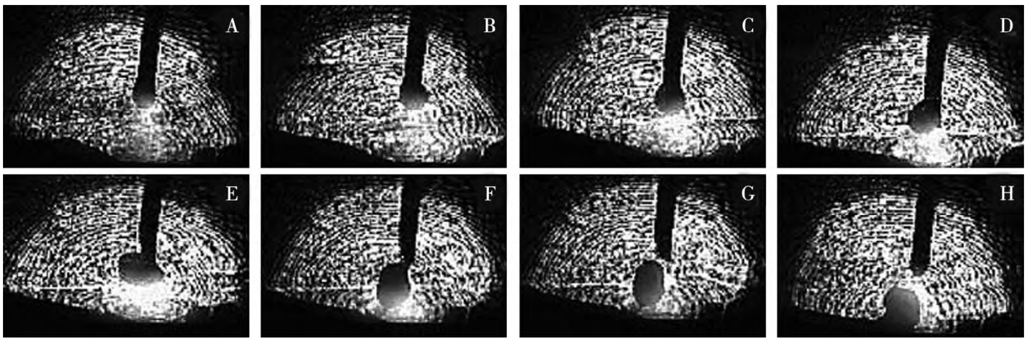

图 5　试验条件 2

Fig. 5　Test parameter 2

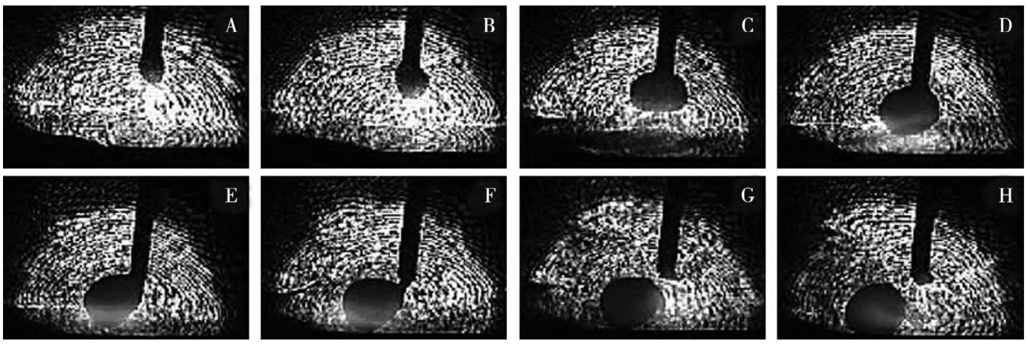

图 6　试验条件 3

Fig. 6　Test parameter 3

以看出,使用激光增强后,焊接电流和电压的波动幅度有所减小,这是因为金属过渡时熔滴被分离成更小直径,弧长和焊丝伸出长度受到的扰动较小,因此电流和电压的波形波动变小,所以在控制熔滴过渡期间,可以根据需要通过辅助激光改变过渡熔滴的直径和电流、电压波形.

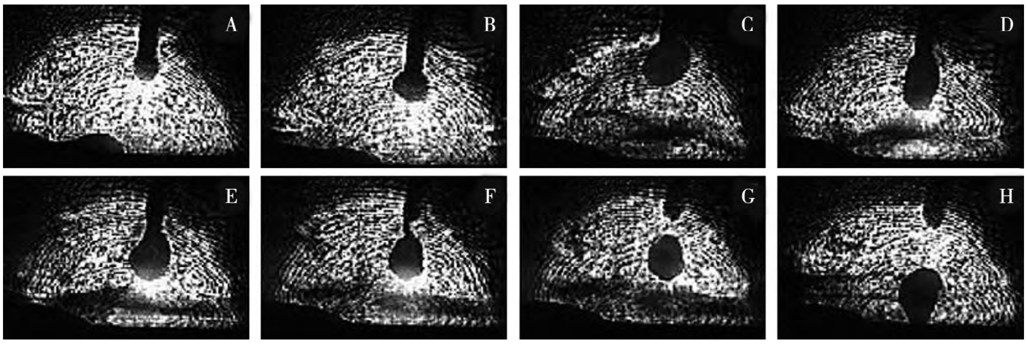

图7 试验条件4

Fig. 7 Test parameter 4

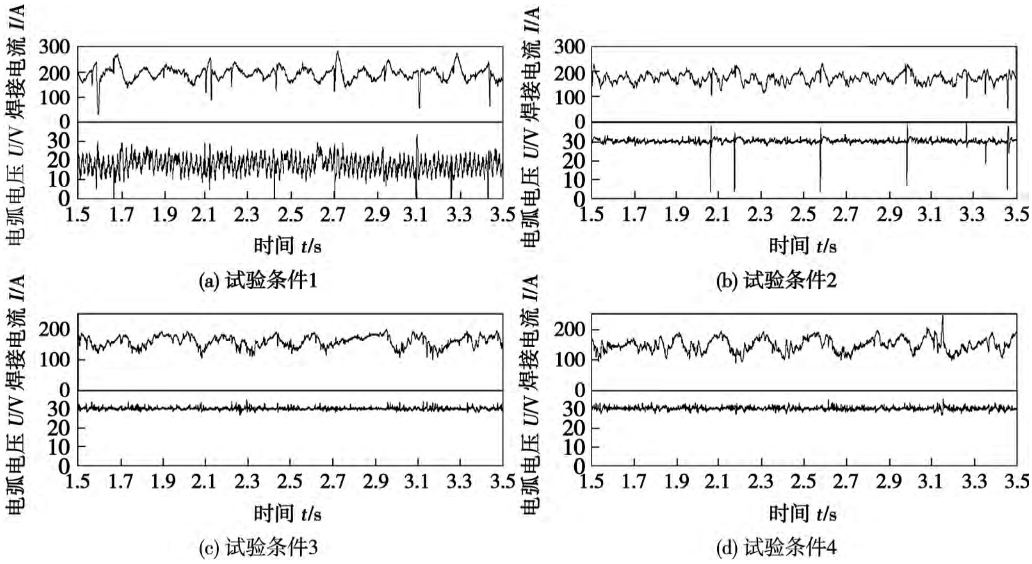

图8 电流电压波形

Fig. 8 Current and voltage waveforms

4 结 论

(1) 建立了一套常压环境下激光增强熔滴过渡控制试验系统,该试验控制系统能够方便的调整激光和焊枪之间相对位置以及激光功率,满足试验研究需要.

(2) 拍摄了清晰的熔滴过渡高速图像,通过对比发现在熔滴上施加一定功率密度的激光能够控制过渡熔滴的大小.

(3) 使用激光增强后,焊接过程的焊接电流、电弧电压波形在一定程度上趋于稳定,印证了激光对熔滴过渡过程和熔滴大小的改善作用.

参考文献:

[1] 黄继强,薛 龙,吕 涛,等. 水下高压空气环境下GMAW电弧特性试验[J]. 焊接学报,2010,31(12):17-19.
Huang Jiqiang, Xue Long, Lü Tao, *et al*. Experiment on characteristics of GMAW arc in underwater hyperbaric air condition[J]. Transactions of the China Welding Institution, 2010, 31(12):17-19.

[2] Mazzaferro J A E, Machado I G. Study of arc stability in underwater shielded metal arc welding at shallow depths[J]. Journal of Mechanical Engineering Science, 2009, 223(3):699-709.

[3] 韦辉亮,李 桓,王旭友,等. 激光-MIG电弧的复合作用及对熔滴过渡的影响[J]. 焊接学报,2011,32(11):41-44.

[下转第29页]

铝合金而言，在焊接接头软化最为严重的区域，母材晶内的非稳态强化相 β'' 相及 β' 相向平衡相 β(Mg_2Si 相) 转变，并聚集形成了粗大的 β 析出相，这是造成软化的根本原因. 焊接接头受热温度在 260 ~ 500 ℃范围内的区域，焊后经简单的时效处理，其硬度无法恢复至原始状态.

参考文献:

[1] 朱　浩，陈　强，陈剑虹. 热影响区几何尺寸对铝合金焊接接头变形及强度影响规律 [J]. 焊接学报，2012，33(5)：77－81.
Zhu Hao，Chen Qiang，Chen Jianhong. Influence rule of HAZ geometrical dimension to aluminum alloy joint' deformation and strength [J]. Transactions of the China Welding Institution，2012，33(5)：77－81.

[2] 朱　亮，陈剑虹. 热影响区软化焊接接头应力分布特征及强度预测 [J]. 焊接学报，2004，25(3)：48－51.
Zhu Liang，Chen Jianhong. Characteristics of stress distribution and prediction of strength in softened zoneaffected with heat of welded joints [J]. Transactions of the China Welding Institution，2004，25(3)：48－51.

[3] 刘静安，谢水生. 铝合金材料的应用与技术开发 [M]. 北京：冶金工业出版社，2004.

[4] 王炎金. 铝合金车体焊接工艺 [M]. 北京：机械工业出版社，2009.

[5] 王元良，骆德阳，王一戎. 我国高速列车焊接技术及其新发展 [J]. 电焊机，2008，38(8)：8－12.
Wang Yuanliang，Luo Deyang，Wang Yirong. Welding and its development of bullet train [J]. Electric Welding Machine，2008，38(8)：8－12.

[6] 王旭友，雷　振，张　健，等. 高速列车 6005A-T6 铝合金型材激光－双丝 MIG 复合焊 [J]. 焊接学报，2012，33(7)：9－12.
Wang Xuyou，Lei Zhen，Zhang Jian，*et al*. Laser-tandem MIG hybrid welding for 6005A-T6 aluminum alloy profile of high-speed train [J]. Transactions of the China Welding Institution，2012，33(7)：9－12.

[7] 朱　亮，龙　林，乔及森. 时效对 6063 铝合金焊接接头性能的影响 [J]. 焊接，2006(5)：26－33.
Zhu Liang，Long Lin，Qiao Jisen. Effects of ageing on the properties of 6063 Al alloy welded joints [J]. Welding & Joining，2006(5)：26－33.

[8] Roven H J，Liu M P，Werenskiold J C. Dynamic precipitation during severe plastic deformation of an Al-Mg-Si aluminum alloy [J]. Materials Science and Engineering，2008(A483－A484)：54－58.

[9] Gu Tierrez-urru Tiai，Munoz-morris M A，Morris D. The effect of coarse second-phase particles and fine precipitates on microstructure refinement and mechanical properties of severe deformed Al alloy [J]. Materials Science and Engineering，2005(A394)：399－410.

[10] Tsaocs，Jengus，Chency，*et al*. Small-angle X-ray scattering study of nanostructure evolution of β'' precipitates in Al-Mg-Si alloy [J]. Scripta Materialia，2005，53(1)：241－245.

[11] Tsaocs，Jengus，Chency，*et al*. Precipitation kinetics and transformation of metastable phases in Al-Mg-Si alloys [J]. Acta Materialia，2006，54(4)：621－631.

作者简介： 吕晓春，男，1978 年出生，硕士，高级工程师. 主要从事钎焊、电弧焊特性等方面的研究工作. 发表论文 20 余篇. Email：lvxiaochun@ 163. com

---

[上接第 24 页]

Wei Huiliang，Li Huan，Wang Xuyou，*et al*. Hybrid interaction of laser and pulsed MIG arc and its influence on metal transfer [J]. Transactions of the China Welding Institution，2011，32(11)：41－44.

[4] Huang Yi，Zhang Yuming. Laser enhanced metal transfer-part 1: system and observations [J]. Welding Journal，2011，90(10)：183s－190s.

[5] Huang Yi，Zhang Yuming. Laser-enhanced GMAW [J]. Welding Journal，2010，89(9)：181s－188s.

[6] 李明利，杨战胜，李　桓，等. 980 MPa 级钢配套焊丝电弧形态和熔滴过渡试验分析 [J]. 焊接学报，2009，30(6)：25－29.
Li Mingli，Yang Zhansheng，Li Huan，*et al*. Testing and analysis of arc shape and globule transfer of welding wire attached to 980 MPa-class steel [J]. Transactions of the China Welding Institution，2009，30(6)：25－29.

[7] 杨月玲. TIG/MAG 组合焊接技术在锅炉压力容器及管道上应用的工艺特点 [J]. 焊接，2006(3)：42－43.
Yang Yueling. Technological characteristic of TIG/MAG compound welding technique being applied to boiler pressure pipeline [J]. Welding & Joining，2006(3)：42－43.

作者简介： 朱加雷，男，1981 年出生，博士，副教授. 主要从事水下焊接与切割技术、机器人自动化及高能束焊接技术等领域的科研和教学工作. 发表论文 20 余篇. Email：zhujialei2002@163.com

Hot corrosion resistance of plasma-sprayed MCrAlY coatings by laser remelting on TiAl alloy surface

WANG Dongsheng[1,2], TIAN Zongjun[1], SHEN Lida[1], HUANG Yinhui[1] (1. College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; 2. College of Mechanical Engineering, Tongling University, Tongling 244000, China). pp 17 – 20

Abstract: The MCrAlY coatings were prepared by plasma spraying on TiAl alloy surface, laser remelting experiment had been carried out and the hot corrosion resistance of TiAl alloy, plasma-sprayed and laser-remelted MCrAlY coatings in 5% Na_2SO_4 + 25% NaCl (mass fraction) molten salt at 850 ℃ were researched. The hot corrosion failure mechanisms of three kinds of materials were analyzed and the influence of laser remelting on hot corrosion behavior of plasma-sprayed MCrAlY coating were discussed. The results show that the plasma-spayed MCrAlY coating has better oxidation resistance than the original TiAl alloy, and the laser-remelted coating has the best oxidation resistance. The hot corrosion of MCrAlY coating included surface oxidation and internal sulfide, and produced Al_2O_3, Cr_2O_3, NiO, $NiCr_2O_4$, Ni_3S_2 and CrS et al.

Key words: laser remelting; plasma spraying; MCrAlY coating; TiAl alloy; hot corrosion resistance

Experiment on metal transfer control of laser enhanced GMAW welding

ZHU Jialei, JIAO Xiangdong, QIAO Xi, JIA Cunfeng (Mechanical Engineering College, Beijing Institute of Petrochemical Technology, Beijing 102600, China). pp 21 – 24, 29

Abstract: Underwater ambient pressure has negative effect on metal transfer and welding processing stability, so extra force is needed to help to stabilize welding arc and improve metal transfer state during underwater welding. To verify the feasibility of laser which enhanced metal transfer control, the related experiment system was built at atmospheric pressure, and contrastive study on metal transfer state with and without laser enhanced was conducted. Results showed that the application of a certain power density of laser could improve metal transfer behavior obviously and the size of droplet could be controlled by laser, the welding stability also could be improved. The result laid a foundation for the further laser enhanced hyperbaric underwater welding experiment.

Key words: laser enhanced; metal transfer; high-speed photograph; experiment

Study on the softening of 6005A-T6 aluminum alloy welding joints for high-speed train

LÜ Xiaochun[1], LEI Zhen[1], ZHANG Jian[1], ZHANG Lihua[2] (1. Harbin Welding Institute, China Academy of Machinery Science & Technology, Harbin 150028, China; 2. XCMG Construction Machinery Co., Ltd. Building Machinery Co., Xuzhou 221004, China). pp 25 – 29

Abstract: Welding thermal cycle curves of 6005A-T6 aluminum alloy by using tandem MIG welding and laser-tandem MIG hybrid welding was tested individually. The softening of the welding joints was studied through welding thermal simulation with heat treatment method. The test results demonstrated that the notable softening in HAZ began as long as the peak temperature of welding thermal cycle curve exceeded 260 ℃, and the most serious softening in HAZ occurred while the peak temperature of welding thermal cycle curve was up to 350 ℃. The unstable phase of β'' and β', the main strengthening phase of 6005A-T6 aluminum alloy, transformed to β (Mg_2Si) which aggregated and grew to block was the main reason why the softening happened. The hardness of the joints in HAZ, where the peak temperature of welding thermal cycle curve was between 260 – 500 ℃, could not recover totally through ageing treatment. The detention time beyond 260 ℃ on the thermal cycle curve of laser-tandem MIG hybrid welding joints was much shorter than that of tandem MIG welding joints, so that the softening of laser-tandem MIG hybrid welding joints was little slighter than that of tandem MIG welding joints.

Key words: high-speed train; 6005A aluminum alloy; laser hybrid welding; softening of welding joints

An improved three-dimensional reconstruction algorithm for microelectronics assembly solder joint

ZHAO Huihuang[1,2], WANG Yaonan[1]. SUN Yaqi[2], WEI Shudi[2] (1. College of Electrical and Information Engineering, Hunan University, Hunan 410082, China; 2. Department of Computer Science, Hengyang Normal University, Hengyang 421008, China). pp 30 – 34, 42

Abstract: Solder joint three-dimensional (3D) reconstruction is one of the key research of microelectronic assembly quality 3D detection and control technology development. During the solder joint 3D reconstruction based on SFS theory, its 3D reconstruction becomes one of the key problems because of existing "high light area" on solder joint surface. In order to resolve the problem, at first, by analyzing the reflection items on solder joint surface, a reflection model is got for microelectronics solder joint according to the characteristics of joint surface and solder joint image. Then, by analyzing the formation principle of "high light area" and modifying the reconstruction result, an improved 3D reconstruction algorithm is proposed for microelectronics assembly solder joint. At last, the experimental results have shown that the "distortion" can be solved and the 3D shape based on the improved illumination model is more satisfactory in decreasing specular reflection influence than that of the traditional methods.

Key words: solder joint; microelectronics assembly; three-dimensional reconstruction; shape from shading

Optimization of transition in stainless steel welding joints S-N curve breaking point

ZHU Guoren[1], CHEN Song[2], WANG Zhenbao[2] (1. Chain Transmission Institute , Jilin University, Changchun 130025, China; 2. Institute of Mechanical Science and Engineering, Jilin University, Changchun 130025, China). pp 35 – 38

Abstract: Based on the ladder method and the group method, the S – N curve of stainless steel welding fittings was drawn. According to comparing drawn S – N curve with the ladder