

高速 TIG-MIG 复合焊焊缝驼峰及咬边消除机理

娄小飞¹, 陈茂爱¹, 武传松¹, 叶克力²

(1. 山东大学材料连接技术研究所, 济南 250061; 2. 广西机电职业技术学院, 南宁 530007)

摘 要: 搭建了 TIG-MIG 复合焊试验平台及电参数—高速图像同步采集系统, 进行了一系列低碳钢高速 TIG-MIG 复合焊工艺试验, 研究了高速 TIG-MIG 复合焊的电弧形态、熔滴过渡及熔池行为对焊缝成形的影响, 并确定了合适的匹配参数。结果表明, MIG 焊电流在 240 ~ 300 A, 且 TIG 焊电流与 MIG 焊电流相当时, TIG-MIG 复合焊焊接过程稳定, 即使在焊接速度高达 2.5 m/min 时, 焊缝仍无驼峰、咬边等缺陷, 与传统 MIG 焊相比, 熔深增加, 熔宽减小。TIG-MIG 复合焊由于电弧间的相互作用, 两电弧指向发生偏转, 电弧压力减小, 焊接过程不产生弧坑, 且熔宽变窄, 这是避免驼峰和咬边缺陷的主要原因。

关键词: TIG-MIG 复合焊; 高速焊; 驼峰; 咬边

中图分类号: TG 444+.2 **文献标识码:** A **文章编号:** 0253-360X(2014)08-0087-04

0 序 言

随着焊接技术在工业生产中的应用越来越广泛, 焊接速度已成为影响机械制造业生产率的重要指标。普通电弧焊的焊接速度有限, 这是因为在保证焊透的情况下, 只能采用大电流高速焊, 而这会造成咬边、驼峰等焊接缺陷。复合热源焊接和双弧焊成为提高焊接生产率的有效方法, 目前复合热源焊接研究和应用较多的是激光—电弧复合焊, 激光—电弧复合焊尽管具有焊接速度快、焊接变形小、焊接质量好^[1]等优点, 但设备成本高, 灵活性差, 因此双弧焊目前也受到了很大的重视。双弧焊研究和应用较多的是双弧 GMAW、双弧 SAW。双弧 GMAW 焊时需要采用 Ar+CO₂ 或 Ar+O₂ 混合气体保护, 双弧埋弧焊焊剂中本身含有大量的氧化物, 这两种双弧工艺焊接的焊缝氧含量均难以严格控制, 因此尽管在低碳钢及低合金钢的焊接中得到了广泛应用, 但不适合于要求严格控制焊缝氧含量的超高强度钢的焊接^[2]。

TIG 焊具有电弧稳定、焊缝质量好等优点, 但熔深能力小、焊接生产率低; MIG 焊具有熔敷速度和焊接速度大的优点, 但焊接时电弧阴极斑点不断跳跃, 易导致焊道弯曲和咬边缺陷, 而高速焊时则出现驼峰缺陷。将 TIG 焊电弧和 MIG 焊电弧复合起来进行焊接, 克服各种缺点, 发挥各自的优势, 可提高电弧

的稳定性和生产效率, 具有重要的研究意义。Shuhei 等人^[3]将 TIG-MIG 复合焊用于不锈钢的焊接, 发现 TIG-MIG 复合焊比 MIG 焊过程稳定, 且焊接效率和焊接质量均有提高。杨涛等人^[4]基于 PID 闭环控制实现了恒流 TIG 焊和恒压 MIG 焊电弧复合, 并用来焊接低碳钢, 发现 TIG 焊电弧对 MIG 焊电弧具有良好的维弧作用, TIG 焊电弧对熔滴有加热作用, 有效地降低了飞溅, 促进焊缝铺展及成形。以上研究都是在较低的焊接速度下, 文中研究了 TIG-MIG 复合焊用于低碳钢的高速焊接时的电弧形态、熔滴过渡、熔池行为及焊缝成形, 重点研究驼峰及咬边消除机理。

1 试验方法

采用的焊接及检测综合系统如图 1 所示。MIG 焊电源型号为奥太 PULSE MIG500, TIG 焊电源型号为奥太 WSME-500。焊接图像的采集采用 MicroEnable IV 图像采集卡配合 PhotoFocus 公司生产的型号为 MV-D1024E-160 高速 CMOS 摄像机, 利用波长为 800 nm 的光纤激光作为背光光源(GD3-CC311), 采用 808 nm 窄带滤光片进行滤光。TIG-MIG 电流—电压信号的采集利用霍尔电流传感器和电压传感器配合高速 PCI 数据采集卡实现。双焊枪夹持装置为自主设计, 能够实现双焊枪水平、垂直位置及各自倾斜角度的调节。TIG 焊采用直流正接, 焊枪在前, MIG 焊采用直流反接, 焊枪在后。焊接开始时先引燃 TIG 焊电弧, 后引燃 MIG 焊电弧。

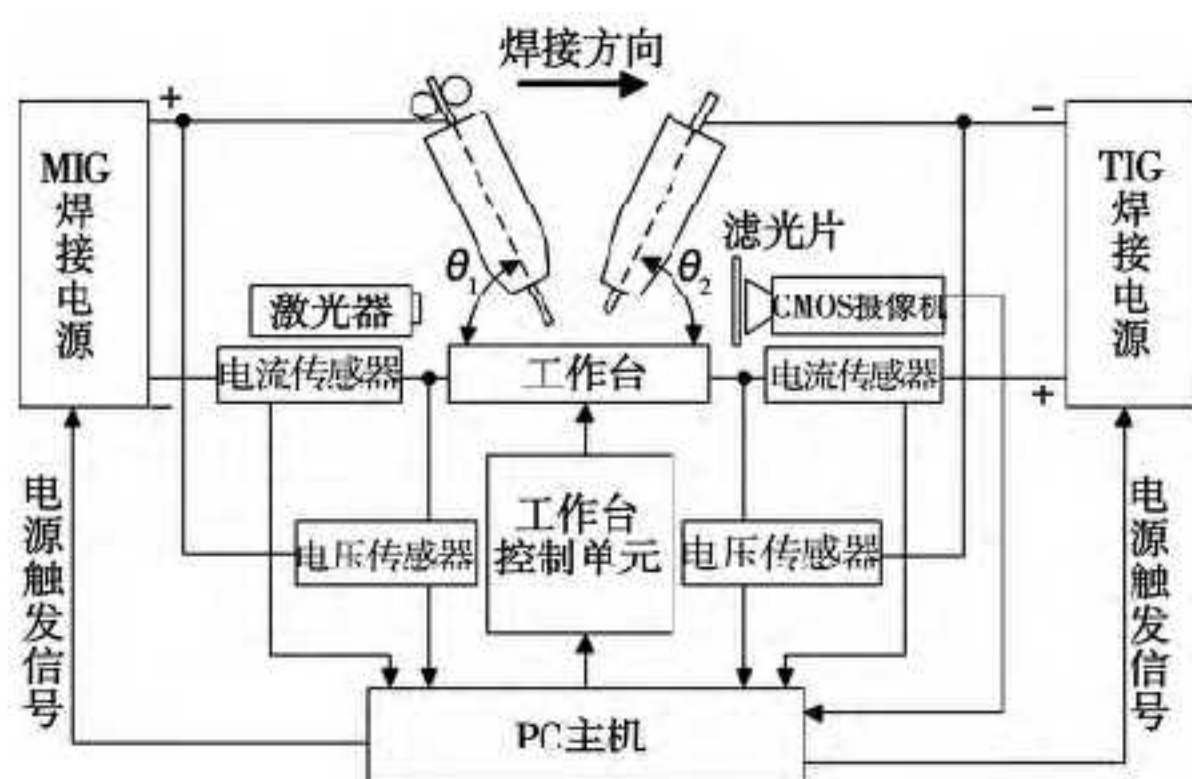


图1 TIG-MIG 复合焊检测系统结构示意图

Fig. 1 Structure diagram of TIG-MIG hybrid welding and testing

表1 TIG-MIG 复合焊工艺参数

Table 1 TIG-MIG hybrid welding parameters

	焊枪倾角 $\theta/(\circ)$	焊接电流 I/A	电弧电压 U/V	焊接速度 $v/(\text{m}\cdot\text{min}^{-1})$	MIG 焊枪喷嘴中心到 工件距离 a/mm	钨极尖端到 工件距离 b/mm	钨极尖端与焊丝的 水平距离 c/mm
MIG 焊	60 ~ 75	240 ~ 300	26 ~ 28	2.0 ~ 2.5	16 ~ 20	3 ~ 4	4 ~ 10
TIG 焊	60 ~ 75	60 ~ 400	—	2.0 ~ 2.5	16 ~ 20	3 ~ 4	4 ~ 10

其中 c 的选取对复合焊效果影响较大,若 c 过小则 MIG 焊熔滴容易污染钨极,且 MIG 焊电弧与 TIG 电弧相互剧烈排斥,焊缝成形严重恶化,若 c 过大则 TIG 焊电弧对 MIG 焊电弧作用不明显, MIG 焊电弧不稳定且在高速焊接时会出现咬边及驼峰缺陷。经过多次试验发现 a, b, c 分别为 16 ~ 18 mm, 3 ~ 4 mm, 4 ~ 6 mm 时电弧最稳定。如无特别说明,试验中 a, b, c 这 3 个参数均控制在上述范围内。

MIG 焊电流在 240 ~ 300 A 范围内,且 TIG 焊电流与 MIG 焊电流相当时焊接过程稳定,能够消除驼峰及咬边缺陷,当 MIG 焊电流小于 240 A 时,熔滴过渡为大滴过渡,电弧不稳定,焊缝成形极差。

2.2 高速 TIG-MIG 复合焊焊缝成形

图 2a 为单 MIG 焊在高速焊接时的焊缝成形,可以明显看到焊趾部位有咬边出现,而且沿焊接方向焊缝金属高低起伏,周期性交替出现“波峰”和“谷底”,即驼峰缺陷。

图 2b 为 TIG-MIG 复合焊在高速焊接时的焊缝成形,可以明显看到焊缝连续、无咬边和驼峰等缺陷,熔宽减小,并且从焊缝截面形貌可以看出熔深较单 MIG 焊有明显的增加。

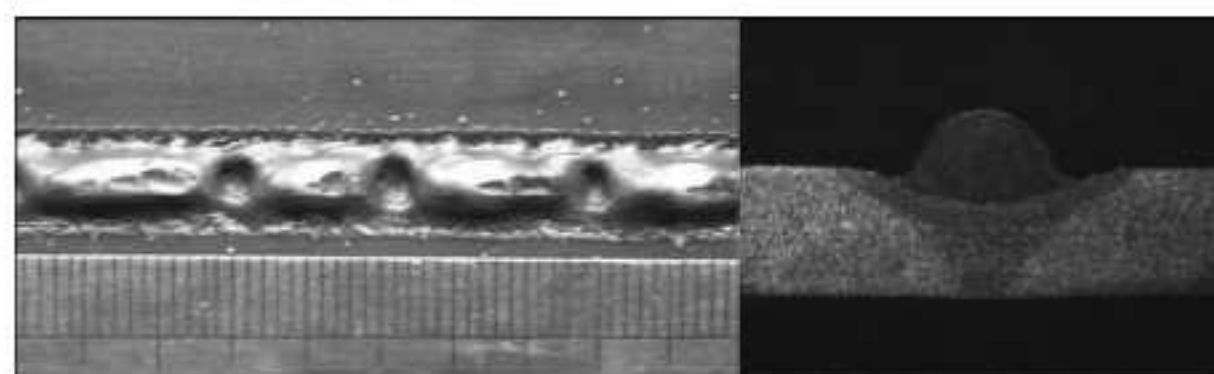
普通电弧焊高速焊时,焊缝两侧发生熔化,熔化金属受表面张力作用容易聚集在焊缝中心部位,由于熔池存在时间短,来不及铺展并润湿焊趾部位,凝固后出现咬边^[5]。冯雷等人^[6]发现在同样的接触角

在 3 mm 厚的 Q235 低碳钢板上进行堆焊试验。MIG 焊采用的焊丝为 H08Mn2SiA,保护气体为流量 16 L/min 的 100% 氩气。TIG 焊采用直径 3 mm 的 2% 铈钨极,保护气体为流量 3 L/min 的 100% 氩气。其它焊接工艺参数如表 1 所示。

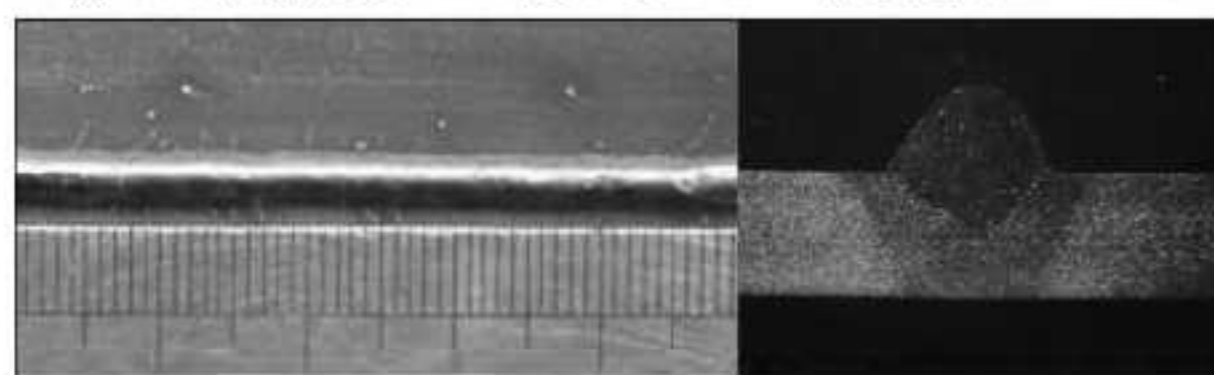
2 试验结果及分析

2.1 焊接工艺参数对复合电弧稳定性的影响

两焊枪相对位置和两电弧电流对复合焊电弧稳定性具有重要的影响。两焊枪相对位置参数主要有 3 个: a 为 MIG 焊枪喷嘴中心到工件距离, b 为钨极尖端到工件距离, c 为钨极尖端与焊丝的水平距离,



(a) MIG焊焊接电流280 A,电弧电压28.1 V,焊接速度2.5 m/min



(b) TIG-MIG复合焊: TIG焊焊接电流280 A, MIG焊焊接电流280 A, 电弧电压28.1 V,焊接速度2.5 m/min

图2 单 MIG 焊与 TIG-MIG 复合焊焊缝形貌对比

Fig. 2 Weld bead and cross section of MIG and TIG-MIG

和熔敷金属量条件下,随熔宽的增大,咬边倾向明显增大,当熔宽小于一定值时,不会发生咬边。

对于驼峰焊道的形成机理, Mendez 等人^[7]利用高速 TIG 焊进行了研究(图 3),认为在通常情况下电弧下方的熔化金属在电弧力的作用下向熔池尾部运动,并在尾部堆积(称为堆积区域),而电弧下方会形成一定深度的弧坑,弧坑下面为一层较薄的液态金属层(称为凹陷区)。然而在大电流高速焊条件下,强大的电弧压力使弧坑下塌严重,凹陷区的金属层变得非常薄,且很大的焊接速度使熔池被拉长变

窄,凹陷区与熔池尾部之间的过渡区因远离电弧,得不到足够的热量而率先凝固,阻止了熔池金属继续向堆积区域的输送,也阻止了尾部金属的回流,则尾部聚集的金属就会形成一个“峰”,而先凝固的过渡区则形成一个“谷”。随着电弧的移动新的驼峰又会形成,而导致一系列连续周期性的驼峰焊道。

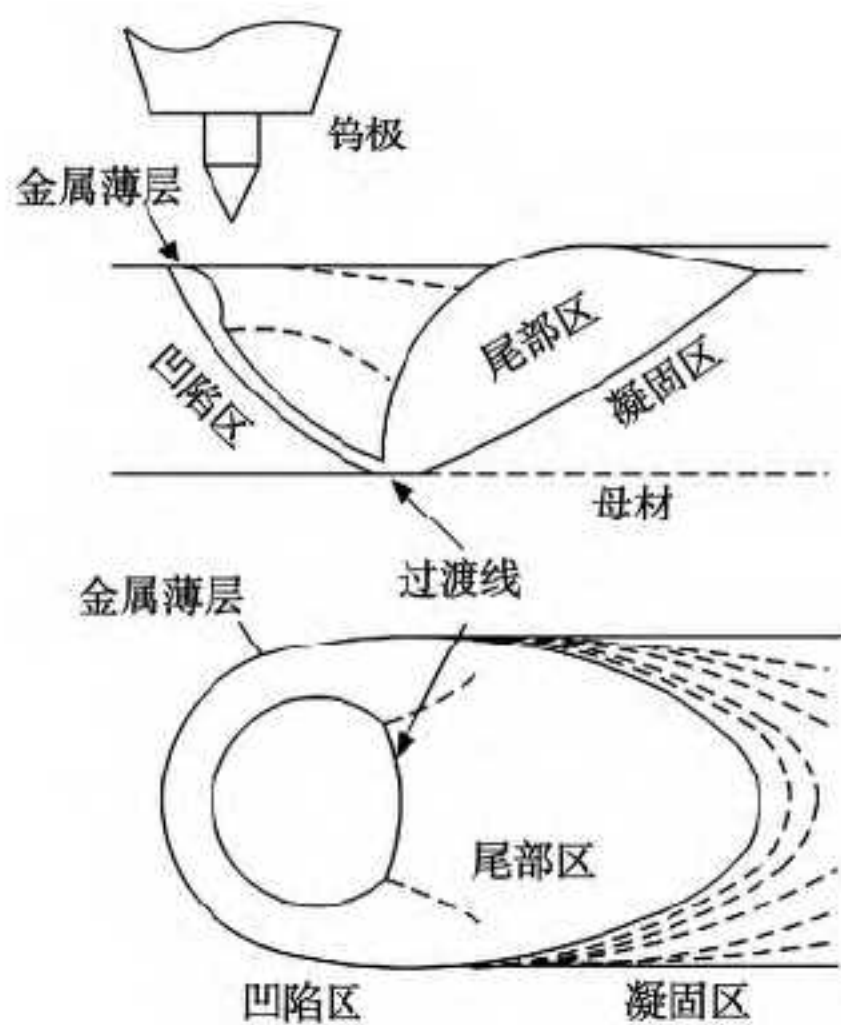


图3 高速 TIG 焊熔池凹坑示意图

Fig. 3 Schematic diagram of high speed TIG gouging region

2.3 高速复合焊驼峰及咬边消除机理探讨

高速 TIG-MIG 复合焊产生的磁场导致两电弧指向发生偏转,电弧压力减弱,不形成弧坑,且焊缝变窄,这些是抑制驼峰及咬边缺陷的主要原因。

图4为单弧焊及 TIG-MIG 复合焊的电弧及熔池的形态。可看出无论是 MIG 焊还是 TIG 焊,由于大电流电弧有一定的挺直性,即使电极倾斜一定角度,依然会在母材上形成弧坑,如图4a和图4b。弧坑对于焊缝成形有重要影响,当熔池中有直径较大的弧坑存在时,焊缝熔宽不可避免地会增大,如前所述,过大的熔宽将增大咬边的倾向,且在高速焊接过程中弧坑与驼峰缺陷有直接关系。

图4c为 TIG-MIG 复合焊过程中电弧的形态,由于 MIG 焊采用直流反接, TIG 焊直流正接,两电弧产生的磁场如图4d所示,两电弧周围磁场分布不均匀,电弧中电荷受到的洛伦兹力也不均匀,表现为电弧从磁力线密集的一侧偏向磁力线稀疏的一侧,即电弧指向发生改变,其作用于母材的压力减小很多,故无论是 TIG 焊电弧还是 MIG 焊电弧的正下面都不易产生弧坑。

图5a为在单 MIG 焊过程中将焊机突然断电得到的熄弧位置焊缝形貌,焊缝尾部有明显的凹坑,使

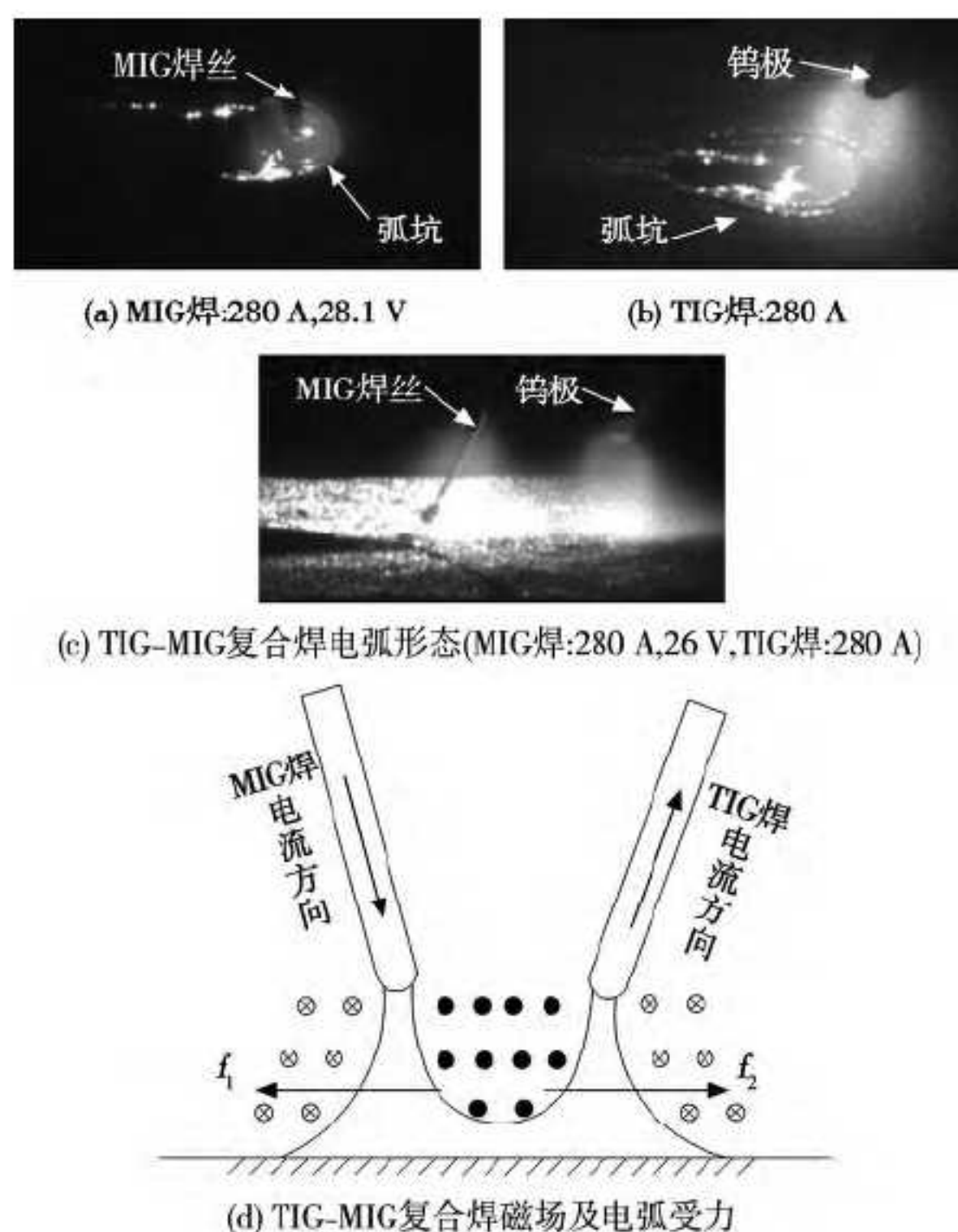


图4 TIG 焊、MIG 焊和 TIG-MIG 复合焊电弧及熔池形态

Fig. 4 Arc and weld pool appearance of TIG, MIG and TIG-MIG

得焊缝变宽。图5b为在 TIG-MIG 复合焊过程中突然断电得到的焊缝尾部形貌,弧坑消失,且复合电弧的有效作用区域变窄,故焊缝也较窄。可见 TIG-MIG 复合焊过程中不形成弧坑,且熔宽变窄是 TIG-MIG 复合焊抑制驼峰及咬边缺陷的主要原因。

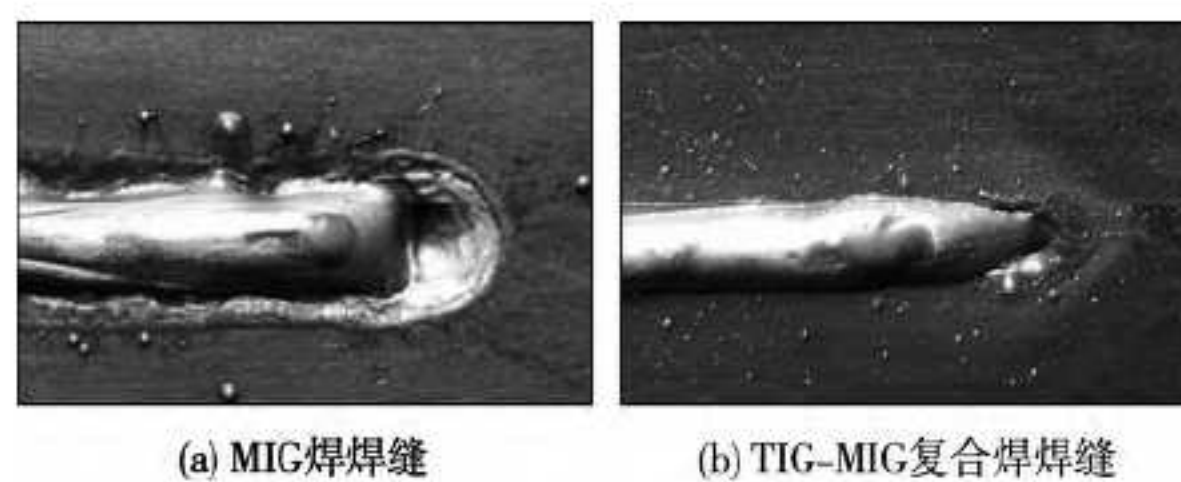


图5 MIG 焊和 TIG-MIG 复合焊焊缝熔池形貌

Fig. 5 Weld pool appearance of MIG and TIG-MIG bead

将 TIG 焊和 MIG 焊复合后熔滴过渡方式也发生很大改变。图6a为单 MIG 焊设定电流 280 A, 电压 28 V 的工艺参数下得到的熔滴过渡图像及电参数波形。可见熔滴直接向弧坑过渡,而且熔滴过渡过程中,经常会出现熔滴尚未脱离焊丝端部便接触熔池的情况,整个焊接过程为射滴过渡夹杂着少量短路过渡,焊接过程稳定性较差,从图6b中的电流及电压的波动也可以看出这种不稳定性。

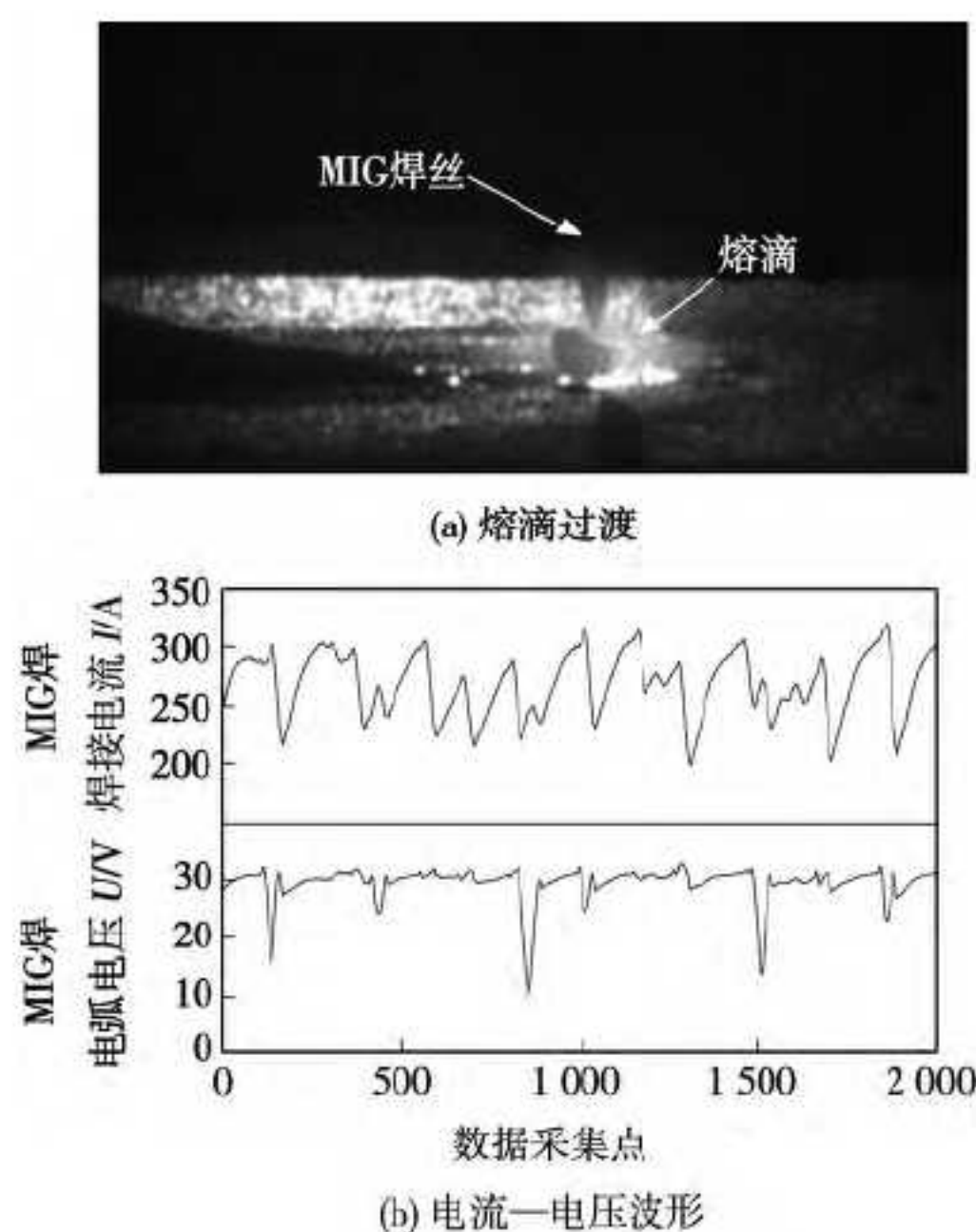


图 6 单 MIG 焊熔滴过渡及电参数波形

Fig. 6 Droplet transfer and current-voltage curve of MIG

图 7 为 TIG-MIG 复合焊设定 TIG 焊电流 280 A, MIG 焊电流 280 A, 电压 26 V 时得到的熔滴过渡图像和电参数波形, 可见无论 TIG 焊电弧还是 MIG 焊电弧都极为稳定, 几乎没有飞溅, 而且由于 TIG 焊电弧磁场的影响, 液态金属流并没有沿焊丝轴向, 而

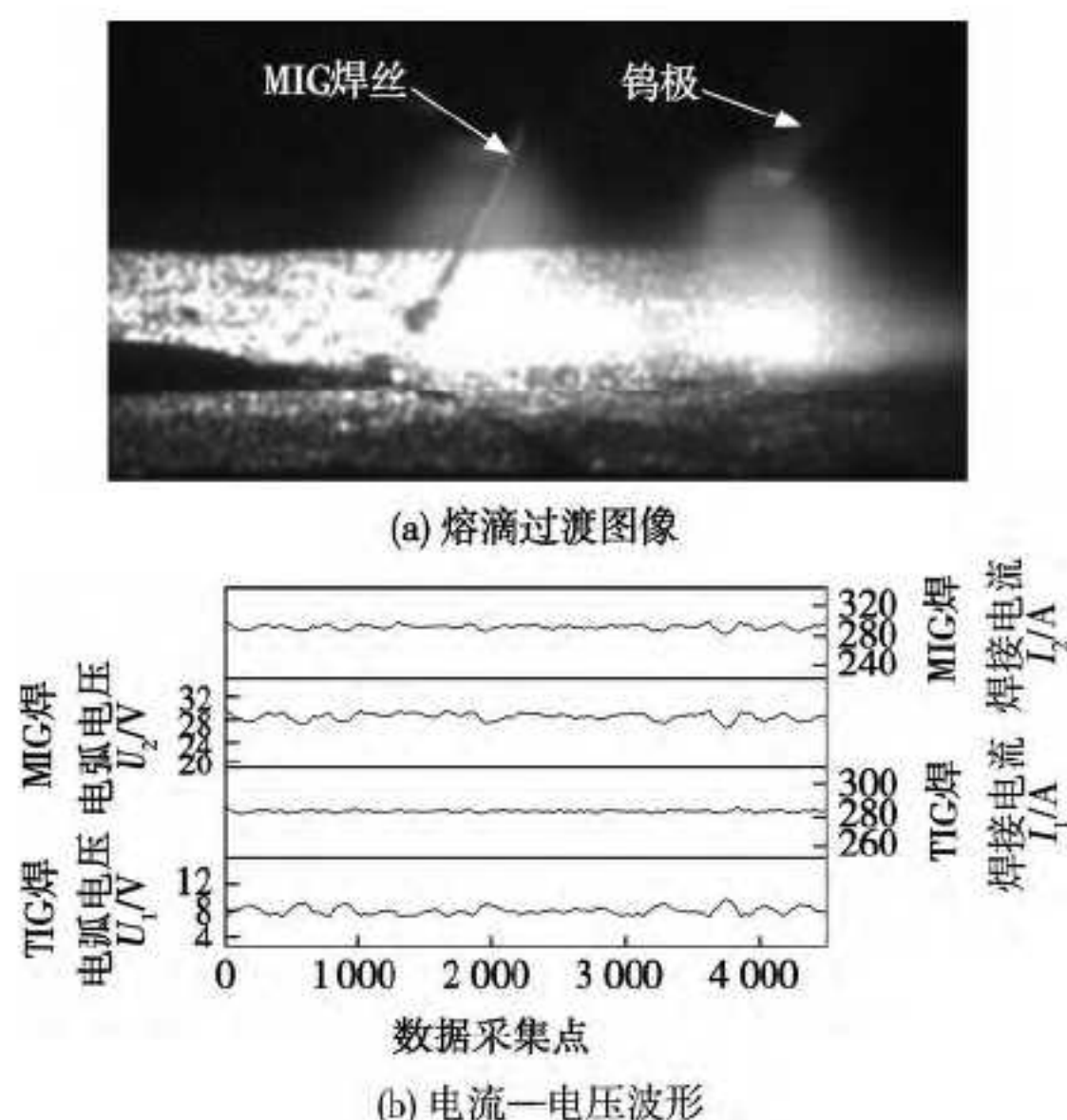


图 7 TIG-MIG 复合焊熔滴过渡及电参数波形

Fig. 7 Droplet transfer and current-voltage curve of TIG-MIG

是与轴向呈一定倾斜角度向母材过渡形成焊缝。

3 结 论

(1) TIG-MIG 复合焊用于低碳钢的高速焊接时, 能显著改善焊缝成形。在焊接速度高达 2.5 m/min 时, 无论 TIG 焊电弧还是 MIG 焊电弧都很稳定, 焊缝无咬边、驼峰等缺陷出现, 且熔深增加。

(2) TIG-MIG 复合焊由于两电弧相互作用, 电弧指向发生偏转, 作用于母材上的电弧压力减弱, 弧坑消失, 熔宽减小, 熔滴过渡方式发生改变, 这些是 TIG-MIG 复合焊用于高速焊接时消除驼峰及咬边缺陷的原因。

参考文献:

- [1] 王 威, 王旭友, 赵子良, 等. 激光-MAG 电弧复合热源焊接过程的影响因素 [J]. 焊接学报, 2006, 27(2): 6-10.
Wang Wei, Wang Xuyou, Zhao Ziliang, et al. Factors of laser-MAG arc hybrid welding process [J]. Transactions of the China Welding Institution, 2006, 27(2): 6-10.
- [2] 王光耀, 杜汉斌, 叶 平, 等. 冶金电化学对埋弧焊接过程中氧迁移的影响 [J]. 机械工程材料, 2006(3): 20-22.
Wang Guangyao, Du Hanbin, Ye Ping, et al. Effect of metallurgical electrochemistry to the oxygen transfer of submerged arc welding process [J]. Mechanical Engineering Materials, 2006(3): 20-22.
- [3] Shuhei, Tomoaki, Toyoyuki, et al. Study for TIG-MIG hybrid welding process [J]. Weld World, 2014(58): 11-18.
- [4] 杨 涛, 张生虎, 高洪明, 等. TIG-MIG 复合焊电弧特性机理分析 [J]. 焊接学报, 2012, 33(7): 25-28.
Yang Tao, Zhang Shenghu, Gao Hongming, et al. Analysis of mechanism for TIG-MIG hybrid arc properties [J]. Transactions of the China Welding Institution, 2012, 33(7): 25-28.
- [5] 杨春利, 林三宝, 张九海, 等. 电弧焊基础 [M]. 哈尔滨: 哈尔滨工业大学出版社, 2003.
- [6] 冯 雷, 陈树君, 殷树言. 高速焊接时焊缝咬边的形成机理 [J]. 焊接学报, 1999, 20(1): 16-21.
Feng Lei, Chen Shujun, Yin Shuyan. Formation mechanism for undercutting during high speed welding [J]. Transactions of the China Welding Institution, 1999, 20(1): 16-21.
- [7] Mendez P F, Eagar T W. Penetration and defect formation in high-current arc welding [J]. Welding Journal, 2003, 82(10): 296-306.

作者简介: 姜小飞, 男, 1988 年出生, 硕士研究生, 主要从事焊接过程检测与控制研究. Email: feixiaolou@126.com

通讯作者: 陈茂爱, 男, 教授. Email: chenmaoai@sdu.edu.cn

are difficult to be conducted. A unified pulsed MIG welding parameters adjusting technology based on least squares method has been proposed in this paper. The optimized fitting curve is achieved and the full advantage of the ideal data that generated in the experiments is utilized by applying a fitting relationship, which obtained through technology experiment, between the large-step welding current and other welding parameters. Besides, easier software program with simple algorithm is realized as well as a wide range of continuous adjustment of the welding parameters. Experiments are conducted after the fitting of single-pulse, double-pulse welding parameters. The experiments results indicate that the welding process is stable to obtain clear fish-scale welding seam with uniformed appearance and fewer spatters. Thus, good stability, reliability and feasibility of the proposed method are well approved.

Key words: least squares method; curve fitting; unified adjustment; digital welder

Crystal orientation in nugget zone of friction stir welded 5083 aluminum alloy plates YUAN Gecheng, LIANG Chunlang, LIU Hong, YUAN Qian (School of Materials and Energy, Guangdong University of Technology, Guangzhou 510006, China). pp 79–82

Abstract: The cold rolled 5083 aluminum alloy plates were welded by friction stir welding (FSW). The characteristics of grains orientation evolution in FSW nugget zone (NZ) was researched by electron backscatter diffraction (EBSD) and orientation imaging microscopy (OIM) with analyzing grain characterization, misorientation distribution, textures distribution and orientation distribution function (ODF). The results show that the dynamic recrystallization occurred in NZ due to the effect of heat and deformation which caused a severe plastic flow. Crystal in nugget zone appears to be equiaxed grain with average size $15.8\ \mu\text{m}$, and fraction of high angle grain boundaries (HAGB) appreciably increased. In the base metal, there were strong Brass texture $\{011\} \langle 211 \rangle$ and S texture $\{123\} \langle 634 \rangle$ that total fractions were above 30.6% and 13.6%, respectively. Conversely, after FSW, B and S textures in the NZ were obviously weakened as total fraction of only 4% and 1.8%, respectively. Furthermore, although the fraction of R texture $\{124\} \langle 211 \rangle$ caused by in-situ recrystallization is up to 7.7%, other common textures in face centered cubic (FCC) metal were weak in the NZ, and every fractions was also below 8%, which means that strong orientation turned into weak orientation in nugget zone.

Key words: 5083 aluminum alloy; friction stir welding; nugget zone; crystal orientation

Test verifies and simulation on welding temperature field of 785 high strength steel for hydraulic support CHI Luxin, SUN Zhaofan, WU Guangfeng (College of Materials Science and Engineering, Chongqing University of Technology, Chongqing, 400050, China). pp 83–86

Abstract: The as-received material was subjected to obtain thermal circling curves of typical position by ANSYS software numerical simulation in the different welding technological parameters on 20 mm thick plate to optimize welding process pa-

rameters and predict microstructures and properties for improving welding quality, compared with the simulation results and the experimental results in the same welding process conditions. It was found that the values of the thermal circling curves were close to the values measured; the simulation width of welding heat affected zone was basically the same as the measured values; the lath bainite was gradually reduced, the granular bainite increased and the grain size also became coarse from base metal to fusion zone.

Key words: 785 steel; numerical simulation; temperature field; microstructure

Humping and undercutting suppression mechanism for high speed TIG-MIG hybrid welding LOU Xiaofei¹, CHEN Maoai¹, WU Chuansong¹, YE Keli² (1. MOE Key Laboratory for Liquid-solid Structure Evolution and Materials processing, Institute for Materials Joining, Shandong University, Jinan 250061, China; 2. Guangxi Technological College of Machinery and Electricity, Nanning 530007, China). pp 87–90

Abstract: A TIG-MIG hybrid welding system was set up. A series of experiments on high speed TIG-MIG hybrid welding of low-carbon steel were launched. The effect of TIG-MIG hybrid arc characteristic, droplet transfer mode and the weld pool behavior on weld bead appearance was researched and the welding parameters were optimized. Excellent arc stability and weld appearance were obtained by setting the same value for MIG and TIG currents in the range of 240–300 A. The penetration increased and weld width decreased compared with the traditional MIG welding. Humping or undercutting were suppressed at a high welding speed up to 2.5 m/min. The suppression of humping and undercutting defects in TIG-MIG hybrid welding may be attributed to the decrease in hybrid arc pressure due to the interaction between TIG and MIG arc, the disappearance of gouging region and decreases in the weld width.

Key words: TIG-MIG hybrid welding; high speed welding; humping; undercutting.

Weldability research on the SA738Gr. B steel DING Lianzheng¹, WANG Kai², MENG Qingsen¹ (1. Material Science and Engineering Institute, Taiyuan University of Technology, Taiyuan 030024, China; 2. Harbin Welding Institute, China Academy of Machinery Science & Technology, Harbin 150028, China). pp 91–94

Abstract: The microstructure transfers were monitored by the expansion tests at the different cooling rates. By using the Gleeble-2000 thermal simulation machine, the impact toughness and the microstructures for the HAZ were also simulated. Furthermore, the weldments were performed to testify the consistency of the simulation specimen and the weldments. The results manifest that with the cooling velocity decreased, the Bainite transfer, the proeutectoid ferrite transfer, and proeutectoid ferrite pearlite transfer take place in sequence. Accordingly the mechanical properties decreased. Under the condition of the multipass welds, the HAZ microstructures of the weldments consist of the mixed microstructure, but the base microstructures are same to that of the thermal simulations at the same cooling rate. The research results have a good direction and references to the welding