第47卷 第4期
2019年4月

华南理工大学学报(自然科学版)
Journal of South China University of Technology
(Natural Science Edition)

Vol. 47 No. 4
April 2019

doi: 10.12141/j.issn.1000-565X.180654

大电流 GMAW 的熔滴过渡行为及控制

肖磊[1,2] 樊丁[1,2†] 郑发磊[3] 黄健康[1,2] 杨文艳[1]

(1. 兰州理工大学 材料科学与工程学院, 甘肃 兰州 730050; 2. 兰州理工大学 省部共建有色金属先进加工与再利用国家重点实验室, 甘肃 兰州 730050; 3. 中联重科股份有限公司 中央研究院, 湖南 长沙 410000)

摘　要: 具有稳定熔滴过渡过程的单丝大电流 GMAW(熔化极气体保护焊)焊接方法拥有其他高效 GMAW 焊接方法不可取代的优势. 通过采集大电流 GMAW 的熔滴过渡高速摄像和焊接电流电压信号,对比分析了大电流 MIG(熔化极惰性气体保护焊)和 MAG(熔化极活性气体保护焊)焊接过程中不同的熔滴过渡行为,分析了焊接电流和保护气体成分对熔滴过渡频率的影响. 结果表明: 大电流 MIG 焊接熔滴过渡形式为单一的旋转射流过渡,且旋转频率随着焊接电流的增大先减小后增大; 大电流 MAG 焊接熔滴过渡形式为摆动和旋转射流混合过渡,且摆动过渡频率会因为液流束与熔池接触短路而增大; 外加磁场能够改变大电流 GMAW 液流束和电弧的旋转方向,减小旋转角度,这一发现为 400 A 以上稳定单丝高效 GMAW 焊接工艺的研发提供了新思路.

关键词: 熔化极气体保护焊; 熔滴过渡; 旋转射流过渡; 摆动过渡; 高速摄像

中图分类号: TG403　　**文章编号:** 1000-565X(2019)04-0127-05

全球钢材产量与日俱增,对应的焊接加工量也相对以前大幅增加,如何大幅提高焊接生产效率成为各国研究人员争相关注的问题. 对于 GMAW 焊接方法,提高焊接生产效率最有效的途径是增大焊接电流,提高焊丝熔化效率,并适当加快焊接速度,使焊接过程达到快速、高熔敷的效果.

国际上影响较大的大电流 GMAW 焊接方法是福尼斯公司推行的 T.I.M.E. 焊接工艺[1],其通过加入特殊的四元保护气体(O_2、CO_2、He、Ar),获得稳定的旋转射流过渡过程,降低焊接飞溅,提高焊缝质量,但是由于四元保护气体配比要求严格,且 He 气对于大多数国家而言属于稀有气体,使得这种方法很难推广. 其他高效焊接方法还有双丝 GMAW 焊接方法[2-4]、三电极高速 MAG 焊(熔化极活性气体保护焊)方法[5-6]、激光-MIG(熔化极惰性气体保护焊)复合焊方法[7]等,也在一定程度上提高了熔敷效率和焊接速度,但由于设备昂贵、装配难度大或工艺参数复杂等缺点限制了其使用范围. 因此,始终有学者致力于单丝高效 GMAW 焊接方法的研究. 殷树言等[8-10]和 Baba 等[11]的研究发现大电流 MAG 焊接过程中,CO_2 的引入会导致液流束尖端附近的电弧过度集中,造成液流束失稳,形成不稳定的摆动过渡,飞溅增大,无法获得成形良好的焊缝; 利用电弧以及液流束的磁场可作用性[12],陈树君等[13-15]通过外加直流磁场来压缩大电流 MAG 焊接电弧,获得了稳定的旋转射流过渡,大大提高了生产效率; Baba 等[11]通过调整焊接电源输出特性,在 570 A 焊接电流下同样获得了成型良好的焊缝. 黄炜等[16-17]根据大电流 GMAW 焊接过程中旋转射流的过渡特点,采

收稿日期: 2019-01-02

基金项目: 国家自然科学基金资助项目(51775256); 甘肃省基础研究创新群体计划项目(17JR5RA107); 甘肃省高校协同创新团队项目(2017C-07)

Foundation item: Supported by the National Natural Science Foundation of China(51775256)

作者简介: 肖磊(1991-),男,博士生,主要从事高效焊接方法及焊接过程数值模拟研究. E-mail: xxxiaolei@aliyun.com

† 通信作者: 樊丁(1961-),男,教授,主要从事焊接物理、焊接智能控制以及激光加工研究. E-mail: fand@lut.cn

用脉冲电流方式加以控制,获得了较为稳定的脉冲旋转喷射过渡过程.

为了更深入地认识400 A以上大电流GMAW焊接过程中的熔滴过渡行为,文中通过高速摄像和电流电压信号采集,对MIG和MAG两种情况下的熔滴过渡行为进行研究,并对比外加纵向磁场前后的MAG焊接熔滴过渡行为和焊缝成形,为后面可控单丝大电流GMAW焊接新工艺的研发做准备.

1 试验方法

对不同焊接电流下MIG/MAG焊接熔滴过渡过程进行高速摄像与电流电压波形采集,并提取旋转射流过渡时的旋转频率和液流束偏角等信息.焊机采用的是送丝机构经过改造后的Pulse MIG-630数字逆变焊接电源,送丝速度最高能达到50 m/min,焊接电压可调至60 V.焊接过程中采用的焊接电压$U=50$ V,喷嘴到工件的距离$L=30$ mm,MIG焊时选用纯Ar保护气,气体流量$Q=20$ L/min,MAG焊时混合CO_2气体流量为2 L/min(CO_2占比约为10%),焊丝直径为1.2 mm,型号为H08Mn2SiA,母材为Q235低碳钢,焊接速度为0.4~0.6 m/min.磁场由自制的磁场发生装置以及安装在焊枪喷嘴上的磁头来产生,磁场频率为60 Hz,磁感应强度为0.002 T.选用奥林巴斯公司推出的型号为i-speed 3的高速摄像机,为了获得清晰的熔滴和液流束形貌,选用波长范围为650±10 nm的窄带滤光片,高速摄像每秒拍摄5000帧,分辨率为804像素×600像素.电流电压波形采集频率为4 kHz,足够对过渡频率在500 Hz以下的熔滴过渡过程进行信息采集、分析.信息采集系统示意图如图1所示.

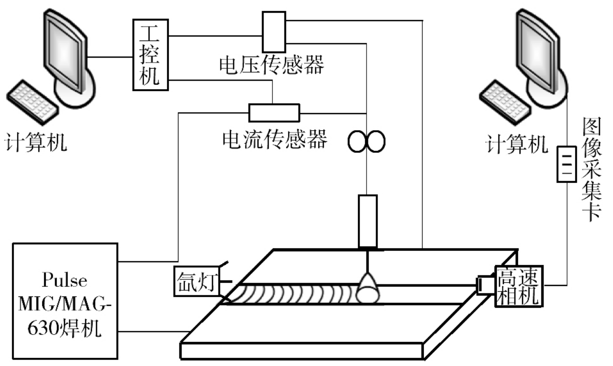


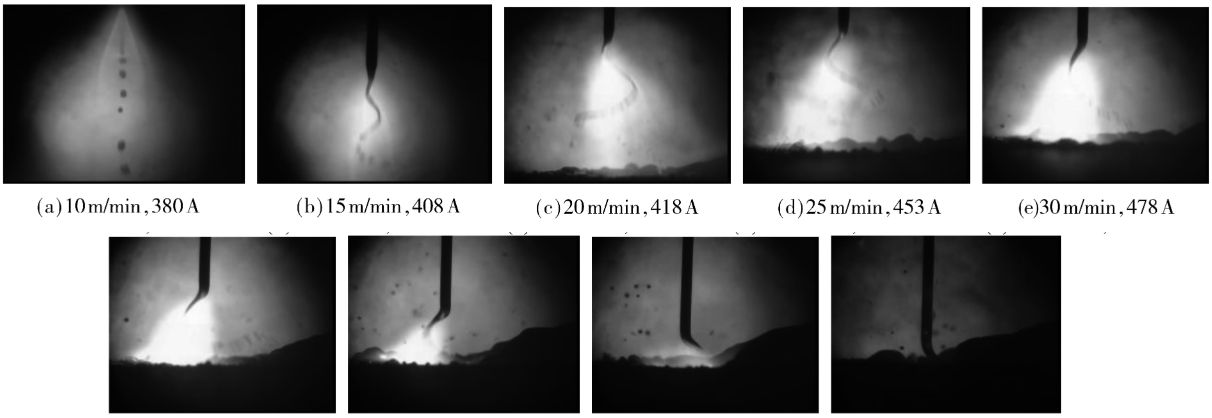
图1 熔滴过渡信息采集系统示意图

Fig.1 Schematic diagram of droplet transfer information collection system

2 试验结果与分析

2.1 大电流GMAW的熔滴过渡过程的高速摄像采集

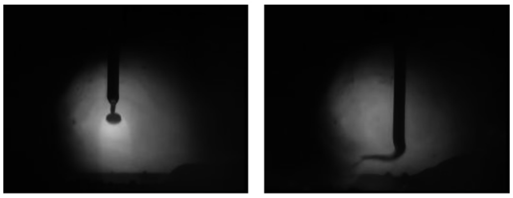
在上述焊接参数下选取不同送丝速度(v_f)进行焊接,拍摄不同焊接电流(I)下MIG/MAG焊接熔滴过渡行为,高速摄像结果如图2、图3所示.随着送丝速度的提高,焊接电流不断增大,MIG焊中电流由10 m/min时的380 A增大到50 m/min时的524 A,如图4所示,MAG焊中电流相对相同送丝速度下的MIG焊接电流要小.已有研究表明,采用直流反接时,保护气体对焊丝的熔化速率的影响很小[10].但是,上述结论是建立在干伸长度不变的条件下,在实际焊接过程中很难保证.本试验对于干伸长度这一参数的选择采用喷嘴到工件的距离来代替.对比图2(c)和图3(a),添加CO_2气体后,能明显观察到电弧收缩,因此电弧的电场强度增大,单位长度电弧电压升高,在相同焊接电压条件下,弧长明显减小,导


(a)10 m/min,380 A (b)15 m/min,408 A (c)20 m/min,418 A (d)25 m/min,453 A (e)30 m/min,478 A

(f)35 m/min,473 A (g)40 m/min,484 A (h)45 m/min,500 A (i)50 m/min,524 A

图2 MIG熔滴过渡行为及电弧形态

Fig.2 Droplet transfer behavior and arc shape of MIG



(a)20 m/min,378 A　(b)30 m/min,424 A

(c) 40 m/min,470 A

图 3　MAG 熔滴过渡行为及电弧形态

Fig. 3　Droplet transfer behavior and arc shape of MAG

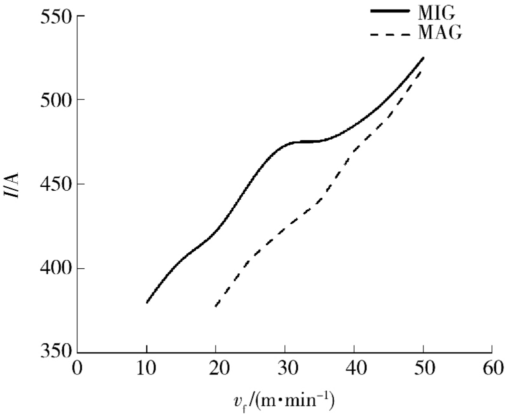


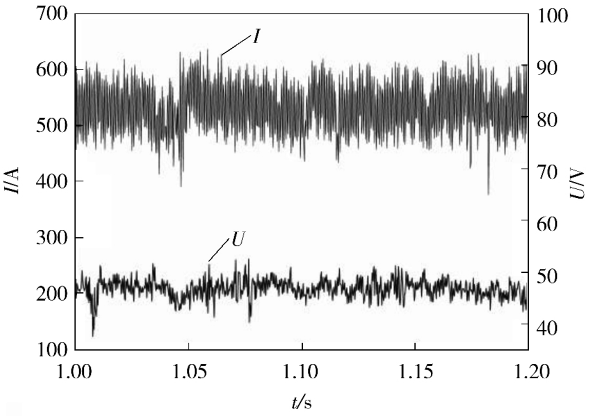
图 4　GMAW 焊接过程中焊接电流与送丝速度的关系

Fig. 4　Relationship between welding current and wire feed rate in GMAW

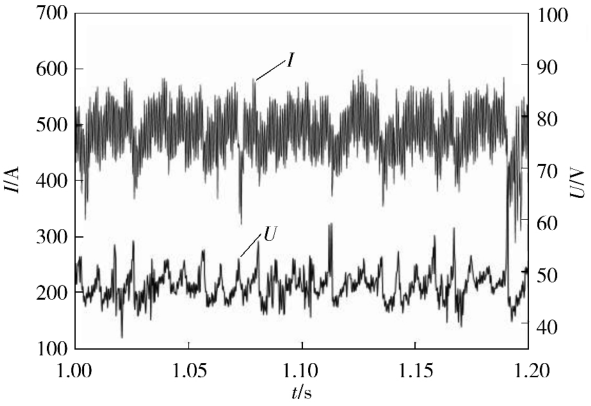
致干伸长度增大,焊丝等熔化曲线向左移动,焊接电流减小. 在 MIG 焊接过程中,熔滴过渡随着焊接电流的增大由射流过渡逐渐转变为旋转射流过渡,弧长逐渐减小; MAG 焊接过程熔滴过渡与其有着明显差异,由于 CO_2 引起的电弧收缩效应,射流过渡区间很窄,液流尖形成后直接进入不稳定的过渡模式,随着焊接电流增大,先是摆动过渡,然后是摆动与旋转混合过渡,这一现象在文献 [11] 中也有提到.

2.2　大电流 GMAW 焊接过程的电信号采集

送丝速度为 40 m/min 时 MIG/MAG 焊接过程中的电流、电压波形如图 5 所示,其中 t 为焊接时间. 由图 5 可知,MIG 焊接过程中的电流、电压波形较 MAG 焊稳定,电流、电压没有较大幅度的波动. 这主要是由二者不同的熔滴过渡形式导致的,MIG 焊接过程中熔滴过渡为稳定的旋转射流过渡,电弧虽然周期性旋转,但整体呈现长度、形态一致,仅仅会在出现外界干扰时产生电弧电压变化,相对应的焊接电流电压波形较为稳定. MAG 焊在该送丝速度下熔滴过渡为混合过渡,液流束时而摆动时而旋转,整个过程中电弧电压频繁发生变化,对应的焊接电流、电压波形不稳定,如图 5(b) 所示.



(a)MIG焊接过程



(b)MAG焊接过程

图 5　GMAW 焊接过程中电信号波形图

Fig. 5　Electrical signal oscillogram of GMAW

2.3　大电流 GMAW 焊接过程液流束的旋转/摆动频率分析

根据高速摄像熔滴过渡过程的视频采集结果,统计 MIG/MAG 焊接过程中的液流束旋转/摆动频率,结果如图 6 所示. MIG 焊液流束旋转频率(f) 在图 2(b) 刚开始旋转时达到最大值 676 Hz,随着送丝速度增大,旋转频率先减小然后维持在 500 Hz 上下并保持稳定. MAG 焊液流束摆动/旋转频率随着送丝速度的增大而增大,但在送丝速度达到 45 m/min 时,出现旋转频率减小的现象,这与送丝速度增大时焊丝刚好接触熔池表面,进而与熔池发生接触短路有关,随着送丝速度进一步增大,电弧整体潜入熔池,摆动动作受到约束,摆动幅度减小,频率增大,如图 7所示. 同时由于接触短路过程中液流束较细且大部分焊接电流在电弧中通过,所以短路过程不会

产生剧烈的液流束爆断现象,可以通过增大送丝速度使液流束与熔池接触短路,从而来控制液流束的摆动角度,获得成形良好的焊缝.

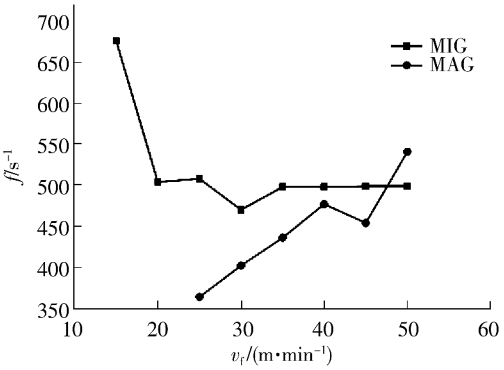


图6 GMAW焊接过程中旋转/摆动频率与送丝速度的关系

Fig. 6 Relationship between mixing rotating and swing frequency and wire feed rate in GMAW

(a)45 m/min, 490 A

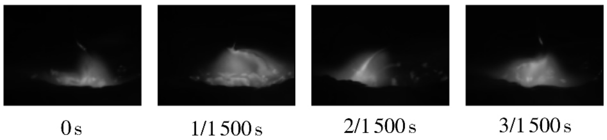
(b)50 m/min, 519 A

图7 液流束与熔池的接触短路和潜弧现象

Fig. 7 Contact short circuit and buried arc phenomenon between flow beam and weld pool

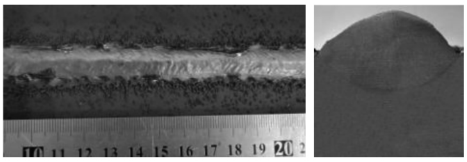
2.4 交变磁场对GMAW焊接过程的控制作用

保持上述参数不变,CO_2 流量为 4 L/min 的 MAG 焊接条件下,送丝速度为 35 m/min 时焊接电流能够达到 450 A,飞溅大,焊缝成形差,电弧、液流束形态和焊缝成形如图8所示.电弧的高速摄像结果时间间隔为 1/1 500 s,且不加磁场时电弧和液流束一旦旋转起来,方向不再改变;当外加 60 Hz 交变磁场后,电弧和液流束呈周期性正反转,且除过正反转换瞬间大幅度的摆动外,整体旋转角度变小,飞溅减少,焊缝成形改善,熔深明显增大.

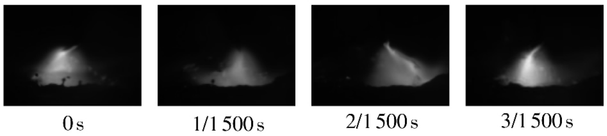


0 s 1/1 500 s 2/1 500 s 3/1 500 s

(a)不加磁场,电弧

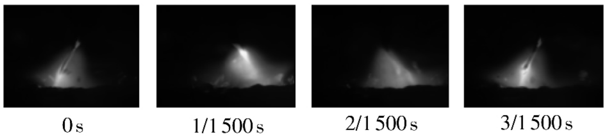


(b)不加磁场,焊缝成形



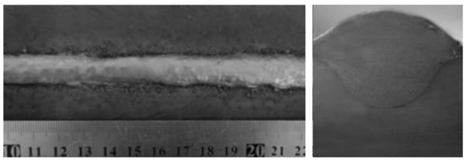
0 s 1/1 500 s 2/1 500 s 3/1 500 s

(c)外加磁场,电弧,逆时针



0 s 1/1 500 s 2/1 500 s 3/1 500 s

(d)外加磁场,电弧,顺时针



(e)外加磁场,焊缝成形

图8 外加磁场前后GMAW电弧、熔滴过渡行为及焊缝成形

Fig. 8 Arc plasma, droplet transfer behaviors and weld appearance of GMAW with or without external magnetic field

3 结论

通过对大电流GMAW焊接过程中熔滴过渡过程进行高速摄像及电流、电压信号采集,分析纯Ar保护条件下MIG和Ar与10% CO_2 混合气体保护下MAG焊接过程的区别,同时还对比了外加磁场前后MAG焊接电弧、液流束形态和焊缝成形情况,主要得到以下结论:

(1)大电流MIG焊接过程中熔滴过渡形式是旋转射流过渡;MAG则是摆动与旋转射流过渡穿插的混合过渡形式,混合气体对电弧的压缩作用是导致这一差异的主要原因;

(2)摆动过渡是导致大电流MAG焊接过程中焊接电流、电压不稳定的主要原因;

(3)大电流MIG焊接过程中液流束旋转频率随着送丝速度的增大先减小后增大,最终稳定在500 Hz上下;MAG焊接过程中则是逐渐增大,但当发生液流束与熔池表面刚好接触短路时,摆动/旋转

频率降低,进一步增大送丝速度时,频率再度升高;

(4) 外加磁场对大电流GMAW电弧和熔滴过渡行为影响明显,交变磁场能够一定程度上减小焊接飞溅并改善焊缝成形.

参考文献:

[1] LAHNSTEINER R. The T. I. M. E. process-an innovative MAG welding process [J]. Welding Review International, 1992, 11(1): 17-20.

[2] 黄健康, 何笑英, 石玗, 等. 脉冲频数对pulsed DE-GMAW焊缝成形的分析 [J]. 焊接学报, 2017, 38(6): 51-55.
HUANG Jian-kang, HE Xiao-ying, SHI Yu, et al. Study for pulse frequency and number influence on welding joint of pulsed DE-GMAW [J]. Transactions of the China Welding Institution, 2017, 38(6): 51-55.

[3] WU K, HE Z, LIANG Z, et al. The dynamic behavior of double arc interference in high-power double wire pulsed GMAW [J]. The International Journal of Advanced Manufacturing Technology, 2017, 88(9/10/11/12): 2795-2802.

[4] UEYAMA T, UEZONO T, ERA T, et al. Solution to problems of arc interruption and arc length control in tandem pulsed gas metal arc welding [J]. Science and Technology of Welding and Joining, 2009, 14(4): 305-314.

[5] ARITA M H, MORIMOTO M T, SHIGEO N, et al. Development of advanced 3-electrode MAG high-speed horizontal fillet welding process [J]. Welding in the World, 2009, 53(5/6): 35-43.

[6] YOKOTA M Y, SHIMIZU M H, SHIGEO N, et al. Development and application of the 3-electrode MAG high-speed horizontal fillet welding process [J]. Welding in the World, 2012, 56(1/2): 43-47.

[7] TANG G, CHEN H, YANG X, et al. Effects of different welding process on the electronic temperature of plasma and weld shape during laser-MIG hybrid welding of A7N01P-T4 aluminum alloy [J]. Journal of Laser Applications, 2018, 30(2): 022002-1-022002-18.

[8] 殷树言, 陈树君, 华爱兵. 单丝高熔敷率MAG焊接工艺的研究 [J]. 电焊机, 2009, 39(1): 73-76.
YIN Shu-yan, CHEN Shu-jun, HUA Ai-bing. Research on high penetration MAG welding process with single wire [J]. Electric Welding Machine, 2009, 39(1): 73-76.

[9] 华爱兵, 殷树言, 陈树君, 等. 细丝大电流MAG焊的熔滴过渡机制 [J]. 焊接学报, 2009, 30(8): 93-96.
HUA Ai-bing, YIN Shu-yan, CHEN Shu-jun, et al. Mechanics of drop transfer for high-current density MAG welding process [J]. Transactions of the China Welding Institution, 2009, 30(8): 93-96.

[10] 华爱兵, 殷树言, 陈树君, 等. 细丝大电流MAG焊接机理 [J]. 机械工程学报, 2010, 46(16): 142-147.
HUA Ai-bing, YIN Shu-yan, CHEN Shu-jun, et al. Mechanism of thin wire high current MAG welding [J]. Journal of Mechanical Engineering, 2010, 46(16): 142-147.

[11] BABA H, ERA T, UEYAMA T, et al. Single pass full penetration joining for heavy plate steel using high current GMA process [J]. Welding in the World, 2017, 61(1): 1-7.

[12] 过增元, 赵文华. 电弧和热等离子体 [M]. 北京: 科学出版社, 1986.

[13] 陈树君, 王军, 王会霞, 等. 纵向磁场作用下的旋转射流过渡的机理 [J]. 焊接学报, 2005, 26(3): 45-49, 54.
CHEN Shu-jun, WANG Jun, WANG Hui-xia, et al. Principle of rotating transfer undergoing longitudinal magnetic field control [J]. Transactions of the China Welding Institution, 2005, 26(3): 45-49, 54.

[14] 王军. 磁场控制高效MAG焊接旋转射流过渡稳定性的研究 [D]. 北京: 北京工业大学, 2003.

[15] 华爱兵, 殷树言, 陈树君, 等. 纵向磁场对MAG焊电弧及熔滴过渡的控制作用 [J]. 机械工程学报, 2010, 46(14): 95-100.
HUA Ai-bing, YIN Shu-yan, CHEN Shu-jun, et al. Behavior of arc and drop transfer of MAG welding controlled by longitudinal magnetic field [J]. Journal of Mechanical Engineering, 2010, 46(14): 95-100.

[16] 黄炜, 艾盛, 王震. MAG焊脉冲电流控制旋转喷射过渡 [J]. 焊接学报, 1996, 17(3): 145-149.
HUANG Wei, AI Sheng, WANG Zhen. Pulsed rotating-spray transfer during MAG welding [J]. Transactions of the China Welding Institution, 1996, 17(3): 145-149.

[17] 黄炜. 脉冲旋转喷射过渡的电弧行为及熔滴过渡特性的研究 [D]. 西安: 西北工业大学, 1995.

(下转第137页)

[17] 高向东,吴嘉杰. 微间隙焊缝磁光成像检测及跟踪方法[J]. 机械工程学报,2015,51(4):71-76.
GAO Xiangdong,WU Jiajie. Approach of detecting and tracking micro weld joint based on magneto optical imaging[J]. Journal of Mechanical Engineering,2015,51(4):71-76.

Weld Seam Feature Point Recognition Analysis Based on Improved Mean-shift Algorithm

GAO Xiangdong LI Yangjin LIU Xiuhang ZHANG Yanxi YOU Deyong
(Guangdong Provincial Welding Engineering Technology Research Center, Guangdong University of Technology,
Guangzhou 510006, Guangdong, China)

Abstract: A fast and accurate weld seam feature point recognition is the key of the weld seam tracking system based on structured light sensing. For the streak discontinuity caused by the deformation of structured light stripe line at the weld, tracking tests were carried on butt and lap welds of stainnless steel board, and an improved mean-shift algorithm was proposed to extract the feature point of a weld seam. Unlike the traditional algorithm, the improved algorithm eliminated the process of extracting fringe center line and fitting fringe lineand the feature points of welding seam are identified by drift. In order to prevent from back-shifting, the search direction of the algorithm was limited. To improve the running efficiency, a shifting accelerating factor was introduced. The test shows that the improved mean-shift algorithm can effectively recognize the feature point of a weld seam and saliently improve the accuracy and real-time performance.

Key words: structured light; weld feature point; mean-shift; feature point extraction

---

(上接第 131 页)

Droplet Transfer Behavior of High-current GMAW and Its Control

XIAO Lei[1,2] *FAN Ding*[1,2] *ZHENG Falei*[3] *HUANG Jiankang*[1,2] *YANG Wenyan*[1]
(1. School of Material Science and Engineering, Lanzhou University of Technology, Lanzhou 730050, Gansu, China; 2. State Key Laboratory of Advanced Processing and Recycling of Non-ferrous Metals, Lanzhou University of Technology, Lanzhou 730050, Gansu, China; 3. Central Research Institute, Zoomlion Limited Liability Company, Changsha 410000, Hunan, China)

Abstract: Single wire high-current GMAW welding methods with steady metal transfer processes has irreplaceable advantages over other high-efficiency GMAW welding methods. Based on the high-speed photography and electric signals selecting technology in metal transfer process of GMAW, the differences between MIG and MAG welding were discussed, and the impacts of current or shielding gas constitution on transfer frequency were highlighted. The results indicate that metal transfer style of high-current MIG welding is rotating spray transfer, and the rotating frequency of MIG welding decrease at first and then increase with the increase of welding current; while in the MAG welding, it becomes a mixing rotating and swing transfer style, and the rotating frequency or swing frequency increases when the flow beam contacts with the weld pool in high current condition. In addition, the external magnetic field can change the rotation direction of large current GMAW flow beam and arc, and reduce the rotation angle. This discovery provides a new idea for the research and development of high efficiency GMAW welding process with single wire over 400 A.

Key words: gas metal arc welding; droplet transfer; rotating spray transfer; swing transfer; high-speed photography