

不锈钢/碳钢 TIG 焊熔池表面流动行为

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摘 要: 为研究异种钢在钨极惰性气体保护焊过程中的熔池表面流动行为, 以粒子示踪法为基础, 通过激光熔池表面反射的方法, 对 304 不锈钢/Q235 碳钢、316L 不锈钢/Q235 碳钢焊接过程中熔池表面液态金属的流动行为进行了研究, 分析了熔池表面示踪粒子的运动趋势, 并以此为依据计算了熔池表面液态金属的流动速度. 结果表明, 在不锈钢/碳钢的 TIG 焊过程中, 熔池表面的液态金属存在从不锈钢侧流向碳钢侧的流动行为. 其中, 示踪粒子在 304 不锈钢/Q235 碳钢的焊接熔池表面平均流动速度约为 25.3 mm/s, 在 316L 不锈钢/Q235 碳钢的焊接熔池表面平均流动速度约为 21.6 mm/s.

关键词: 异种钢焊接; 粒子示踪; 熔池表面流动行为; 表面流速

中图分类号: TG 444 **文献标识码:** A **doi:** 10.12073/j.hjxb.2019400203

0 序 言

钨极惰性气体保护焊 (tungsten inert gas, TIG) 技术因具有成本低、效率高、易操作等优点而被广泛应用, 同时焊接过程的熔池行为会直接影响焊缝的成形与焊接质量, 因此, 众多学者从不同角度对 TIG 焊过程熔池行为进行了研究, 主要对熔池流动形式、流动机理等问题开展了试验与数值分析^[1-3].

张瑞华等人^[4]采用钨粒子示踪法研究了 TIG 焊与活性剂钨极氩弧焊的熔池流动行为, 结果表明活性剂改变了熔池流动方向并加快了流动速度, 强烈的熔池流体向内对流是熔深增加的主要原因. 李冬杰等人^[5]以钨颗粒为示踪粒子, 利用钨板隔开熔池中心与边缘区域, 对比了传统 TIG 焊与双层气流保护焊接的熔池表面流动, 证明了传统 TIG 焊在熔池表面产生外向对流, 双层气体保护焊接在熔池表面产生内向对流. Zhao 等人^[6]根据机器视觉理论建立了熔池表面三维重构方法, 在高速摄像头前增加立体适配器, 从不同视点获得同一帧中的两幅图像, 通过两幅图像重建熔池表面, 由此获得了熔池表面的三维速度场. 在数值模拟方面, 主要通过对熔池的受力情况的仿真模拟来分析熔池的流动行为^[7-10]. 陆善平等人^[11]通过电弧模型与熔池模型的耦合数值模拟, 发现氩弧焊下熔

池表面的流动主要受到表面张力与气体剪切力的影响. 赵明等人^[12]利用完备的熔透熔池上、下表面变形方程, 计算了熔池流场的动态演变, 提高了熔池形状尺寸与上下表面变形的数值计算精度. Ko 等人^[13]通过建立定点 TIG 焊模型, 分析了电弧压力、电磁力与表面张力对熔池流动的作用, 认为熔池中的循环对流模式主要是由电磁力与表面张力梯度产生的, 且受到熔池振荡过程中垂直速度分量的影响.

当前对 TIG 焊熔池的研究, 大多是针对同种金属的焊接, 对异种金属的焊接研究较少, 特别是针对异种金属焊接熔池行为的研究才起步, 使得其正成为研究的重点. 因此, 利用可避免弧光干扰的激光熔池表面镜面反射的方法, 通过获取熔池表面示踪粒子的运动轨迹, 研究 304 不锈钢/Q235 碳钢、316L 不锈钢/Q235 碳钢异种金属焊接时熔池表面的流动行为, 能为异种金属焊接过程中熔池行为研究提供理论基础.

1 试验方法

为了研究异种钢 TIG 焊的熔池表面流动行为, 在前期研究的基础上^[14], 搭建如图 1 所示试验观测系统. 观测系统由激光发生器、TIG 焊枪、成像屏、610 nm ± 10 nm 滤光片与 CCD 工业相机组成. 其主要原理是利用熔池表面具有的反射特性, 将面积略大于熔池表面的激光束投射于熔池表面, 经熔池

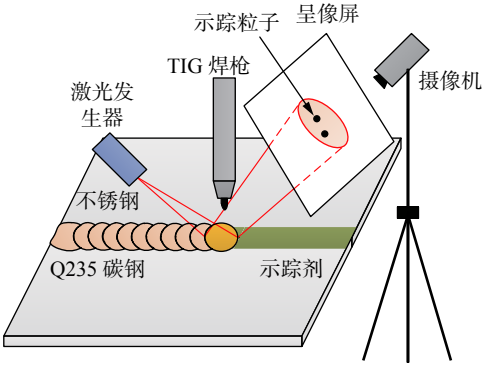
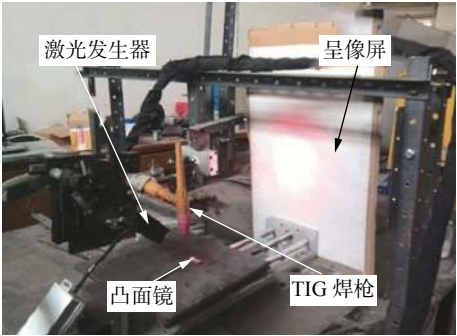


图 1 试验系统示意图

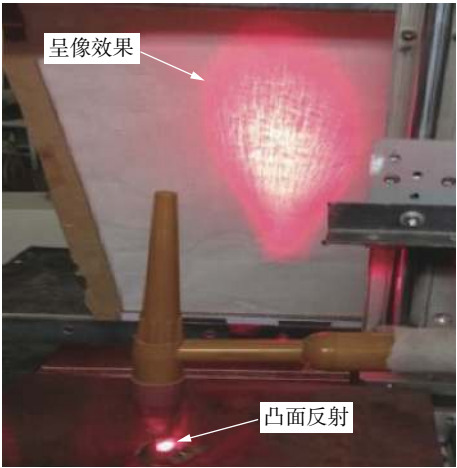
Fig. 1 Schematic diagram of the test system

表面镜面反射后激光反射至成像屏,通过 CCD 工业相机采集成像屏上的图像信息,从而避免电弧的强弧光干扰,以此来观察示踪粒子在熔池表面的运动行为. 在焊接过程中,提前置于焊道上的示踪剂 Al_2N_3 漂浮于熔池表面且以固态团簇即示踪粒子的形式存在,其镜面反射效果并不明显,与熔池表面的反射形成明显对比. 这样可清晰地观测示踪粒子在熔池表面随着熔池表面流动的运动情况. 图 2 为试验系统的实物及测量观测效果.

试验选用 304 不锈钢、316L 不锈钢分别与 Q235 碳钢进行对焊,其成分列表如表 1 所示. 材料成分的不同导致了材料在焊接过程中熔池的状态出现很大不同,为验证观测系统在基材熔池上的可行性,采用 304 不锈钢进行了 TIG 熔池的观测. 选用厚度为 3 mm 的基材,在路径表面均匀铺展示踪剂,掩盖基材的金属光泽. CCD 摄像机的记录速率为 35 帧/秒. 考虑到焊接过程中电弧对熔池表面会



(a) 试验系统实物图



(b) 系统测量观测效果

图 2 熔池镜面反射成像系统

Fig. 2 Mirror reflection imaging system of molten pool

产生较大影响,采用脉冲 TIG 进行焊接. 一方面,较高的峰值电流有着较大的热输入,获得较大的熔池,但强弧光易对观察造成干扰;而在基值电流时,弧光弱且熔池表面平静,此时观察效果较好,因此,提取基值电流下熔池表面成像结果来分析熔池表面的流动行为. 焊接工艺参数如表 2 所示.

表 1 基材的化学成分 (质量分数, %)

Table 1 Chemical compositions of base material

材料	C	Si	Mn	P	S	Ni	Cr
304不锈钢	≤ 0.08	≤ 1.00	≤ 2.00	≤ 0.035	≤ 0.030	≤ 8.0 ~ 11.0	≤ 17.0 ~ 19.0
316L不锈钢	≤ 0.08	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.030	≤ 12.0 ~ 14.0	≤ 16.0 ~ 18.0
Q235碳钢	≤ 0.18	0.30	0.35 ~ 0.8	0.040	0.040	—	—

表 2 焊接工艺参数

Table 2 Welding parameters

板厚 δ /mm	基值电流 I /A	峰值电流 $I_{\max}$ /A	占空比	焊接电压 U/V	焊接速度 $v/(\text{cm}\cdot\text{min}^{-1})$	弧长 L/mm	焊枪倾角 $\alpha/^\circ$	气体流量 $Q/(\text{L}\cdot\text{min}^{-1})$
3	40	90	1:9	10	20	3	90	15

图 3 为基值电流下 304 不锈钢熔池表面反射在屏幕上的成像结果. 将图像进行二次处理,以提

高色差,并将示踪粒子所在位置进行标定.由图3可看出 304 不锈钢的熔池特征明显,其形貌近似为

椭圆,且示踪粒子的运动轨迹大致为从熔池中心向边缘移动.

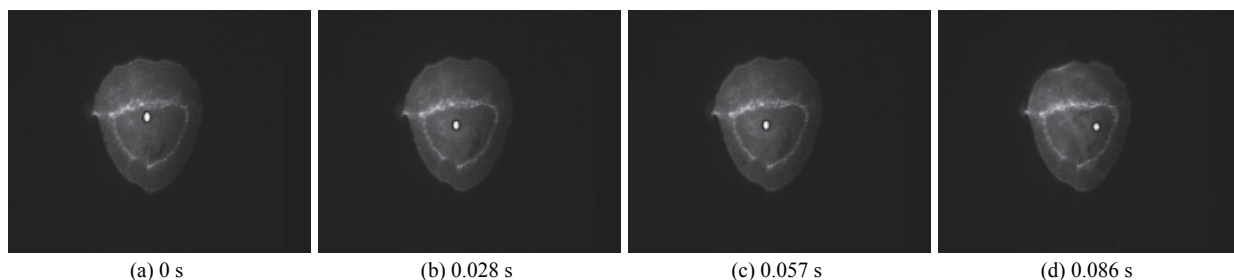


图 3 304 不锈钢熔池表面反射成像结果

Fig. 3 Reflection imaging results of 304 stainless steel molten pool surface

2 异种金属焊熔池表面流动分析

在相同焊接参数下分别将 304 不锈钢/Q235 碳钢、316L 不锈钢/Q235 碳钢进行对焊,并采用建

立的试验系统对熔池表面成像进行记录.图4分别为两种不锈钢与碳钢对焊后的宏观形貌,可以看到焊缝成形良好,表明在焊接过程中熔池形成比较稳定.

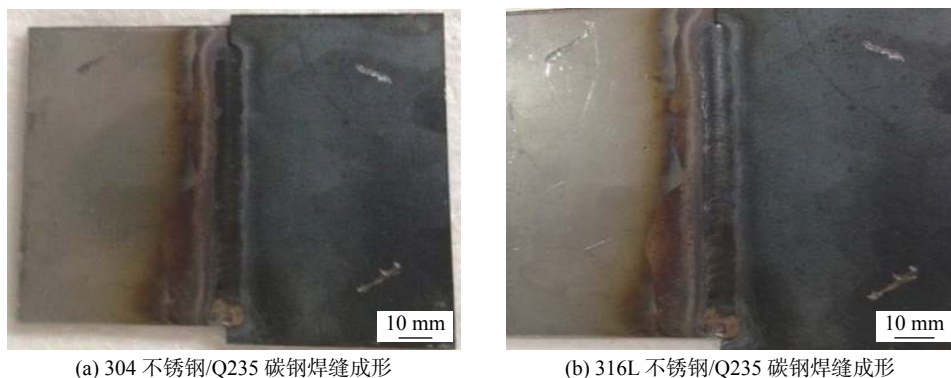


图 4 不同种不锈钢/Q235 碳钢焊缝成形

Fig. 4 Weld formation of different kinds of stainless steel/Q235 carbon steel

2.1 304 不锈钢/Q235 碳钢熔池表面流动行为

图5为屏幕上的图像所反映的熔池形貌,为便于观察,将示踪粒子标记为白色.可以看出熔池边缘呈现出不规则形状,由于基值电流持续时间较

短,热源移动速度较慢,此时间段内熔池边缘的融化与凝固变化较小,因此熔池边缘可看作准稳态,示踪粒子在熔池内的移动速度不受熔池移动的影响.同时,根据不同种类材料的熔池边缘的成形特点可判定焊缝中心.

图6为一典型观测系统记录的基值电流条件下 304 不锈钢/Q235 碳钢对焊过程中 0.086 s 内熔池的变化信息,可清晰地显示连续 4 帧图像内示踪粒子在熔池中的运动情况.

为了更好地研究示踪粒子的运动情况,将像素为 1280×960 的熔池图像进行示踪粒子的像素坐标定位,并在坐标系内按序依次相连,即可得到 0.12 s 内示踪粒子的运动轨迹,如图7所示.根据图7中结果可知,示踪粒子由熔池前端沿着 304 不锈钢侧向熔池后端运动,且有向 Q235 钢侧运动的

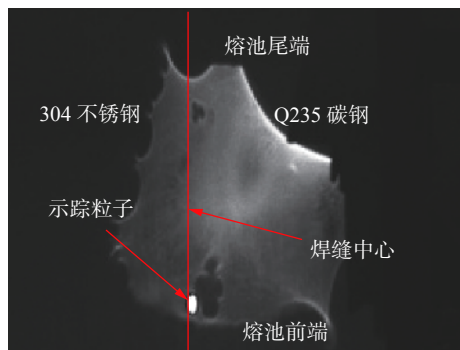


图 5 304 不锈钢/Q235 碳钢焊接熔池成像信息

Fig. 5 Imaging information of molten pool for 304 stainless steel/Q235 carbon steel

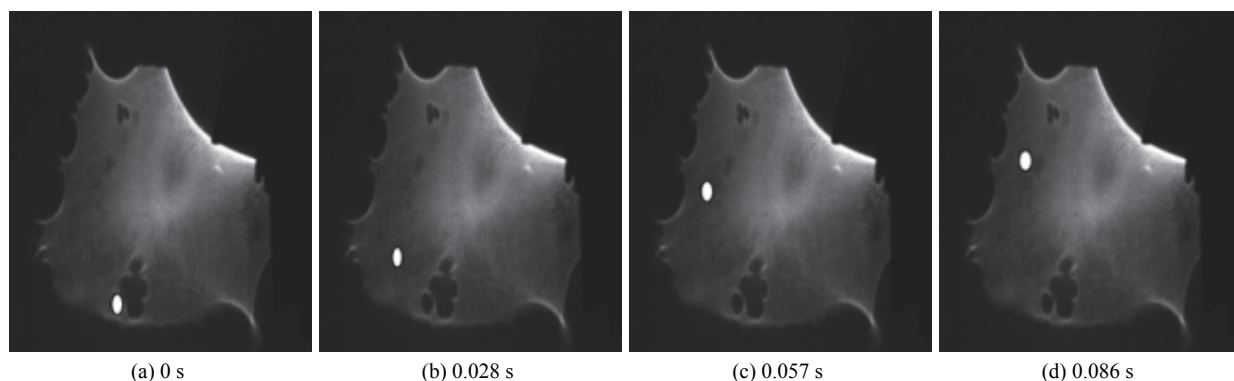


图 6 不同时刻下 304 不锈钢/Q235 碳钢焊接熔池成像结果

Fig. 6 Imaging results of welding pool of 304 stainless steel/Q235 carbon steel at different times

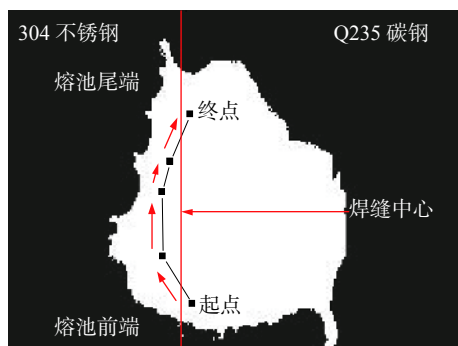


图 7 0.12 s 内示踪粒子在熔池内的运动轨迹

Fig. 7 Trajectories of the tracer particles in the molten pool in 0.12 s

趋势.

为分析 304 不锈钢/Q235 碳钢对焊过程中熔池表面的流动行为特征, 分别对四个时间段熔池表面的示踪粒子运动轨迹采用前期研究得到的算法^[13] 进行处理, 结果如图 8 所示. 由图 8 中可知, 示踪粒子在熔池表面的运动具有明显的特征, 都是从熔池前端进入熔池, 并向熔池后端移动, 且都由 304 不锈钢侧向 Q235 碳钢侧移动. 这表明熔池表面的流动是由前端向后端, 由不锈钢侧向碳钢侧进行的.

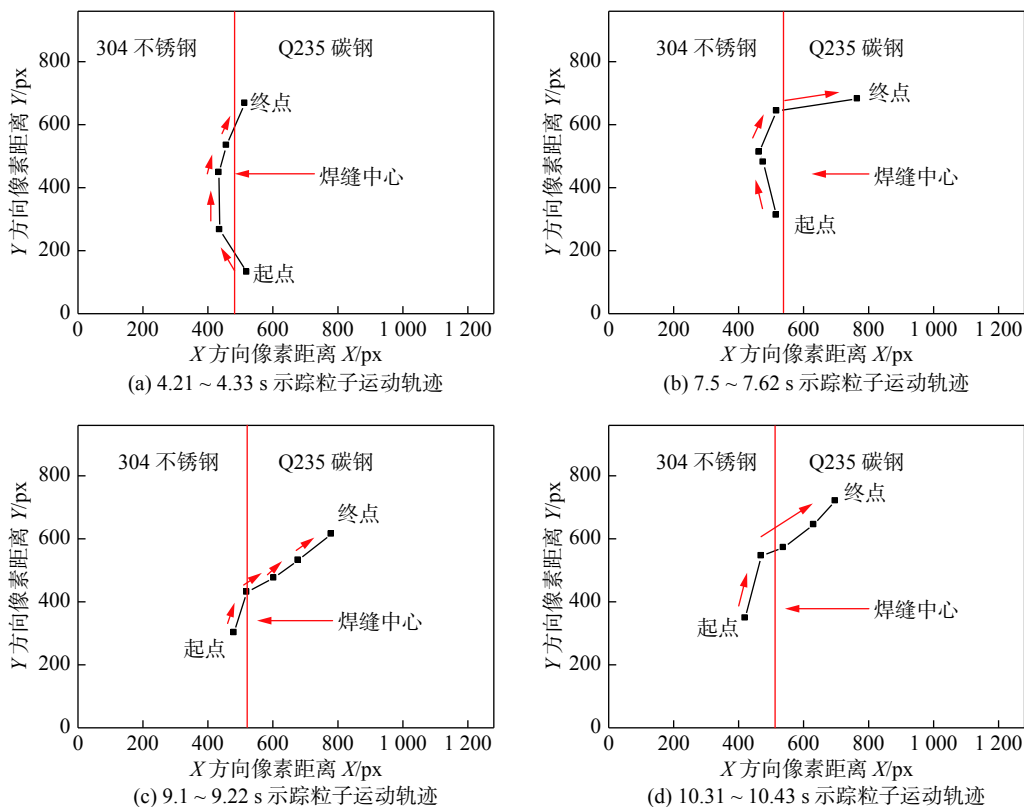


图 8 不同时间段内示踪粒子的像素运动轨迹

Fig. 8 Pixel motion trajectories of tracer particles in different time periods

2.2 316L 不锈钢/Q235 碳钢熔池表面流动行为

图 9 为观测系统记录的 316L 不锈钢与 Q235 碳钢对焊时的熔池形貌, 白色圆点为示踪粒子. 图 10 为基值电流条件下 0.086 s 内熔池的连续变化信息, 经过分帧处理后可清晰地显示连续 4 帧图像内示踪粒子在熔池中的运动情况.

图 11 所示为 0.12 s 内示踪粒子的运动轨迹. 根据示踪粒子运动轨迹可知, 示踪粒子由熔池中部沿着 316L 不锈钢侧向熔池前端运动, 且有从 316L 不锈钢侧向 Q235 钢侧运动的趋势.

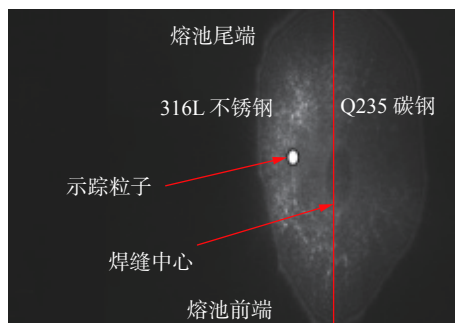


图 9 316L 不锈钢/Q235 碳钢焊接熔池成像信息
Fig. 9 Imaging information of molten pool for 316L stainless steel/Q235 carbon steel

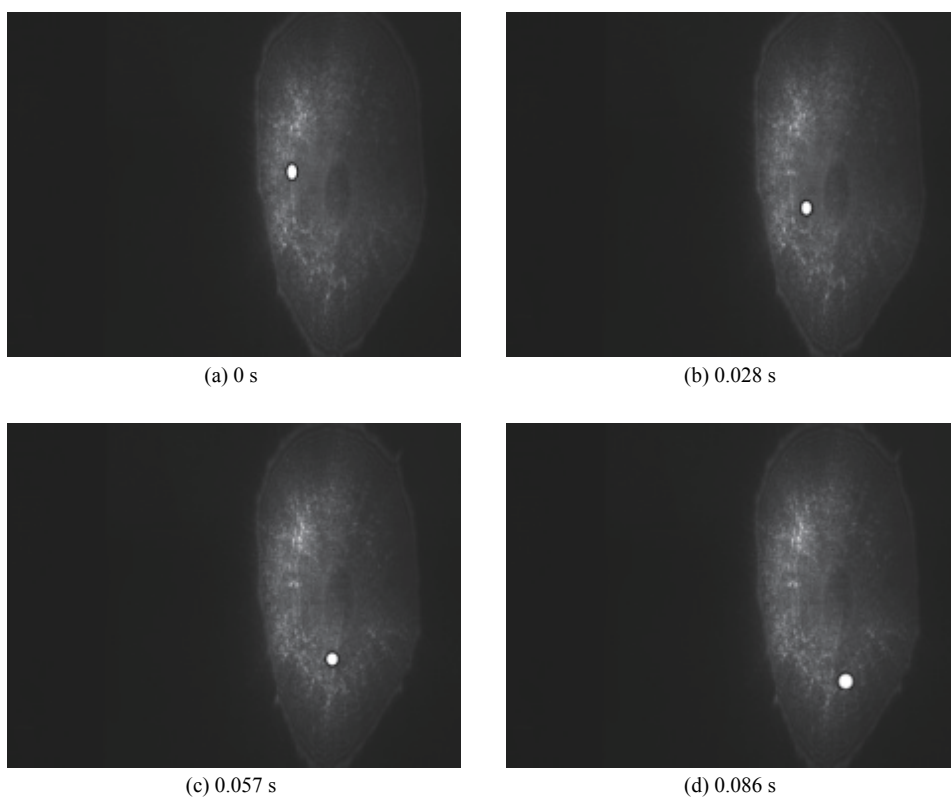


图 10 不同时刻下 316L 不锈钢/Q235 碳钢焊接熔池成像结果

Fig. 10 Imaging results of welding pool of 316L stainless steel/Q235 carbon steel at different times

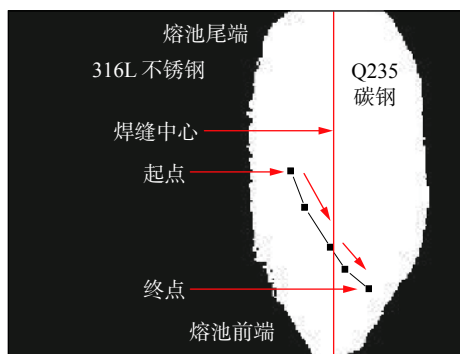


图 11 0.12 s 内示踪粒子在熔池内的运动轨迹

Fig. 11 Trajectories of the tracer particles in the molten pool in 0.12 s

分别对四个典型的连续时间段内熔池表面的示踪粒子运动轨迹进行处理, 结果如图 12 所示. 由图 12 结果可知, 示踪粒子在熔池表面都是从熔池中部进入熔池, 并向熔池前端移动, 且都由 316L 不锈钢侧向 Q235 碳钢侧移动. 表明熔池表面的流动是由中部向前端, 由 316L 不锈钢侧向 Q235 碳钢侧进行的.

2.3 流场速度计算

为进一步研究异种钢对接焊的熔池表面流速, 采用前期研究得到的算法^[14], 利用示踪粒子在不同时刻的像素坐标获得粒子在 1280×960 分辨率的

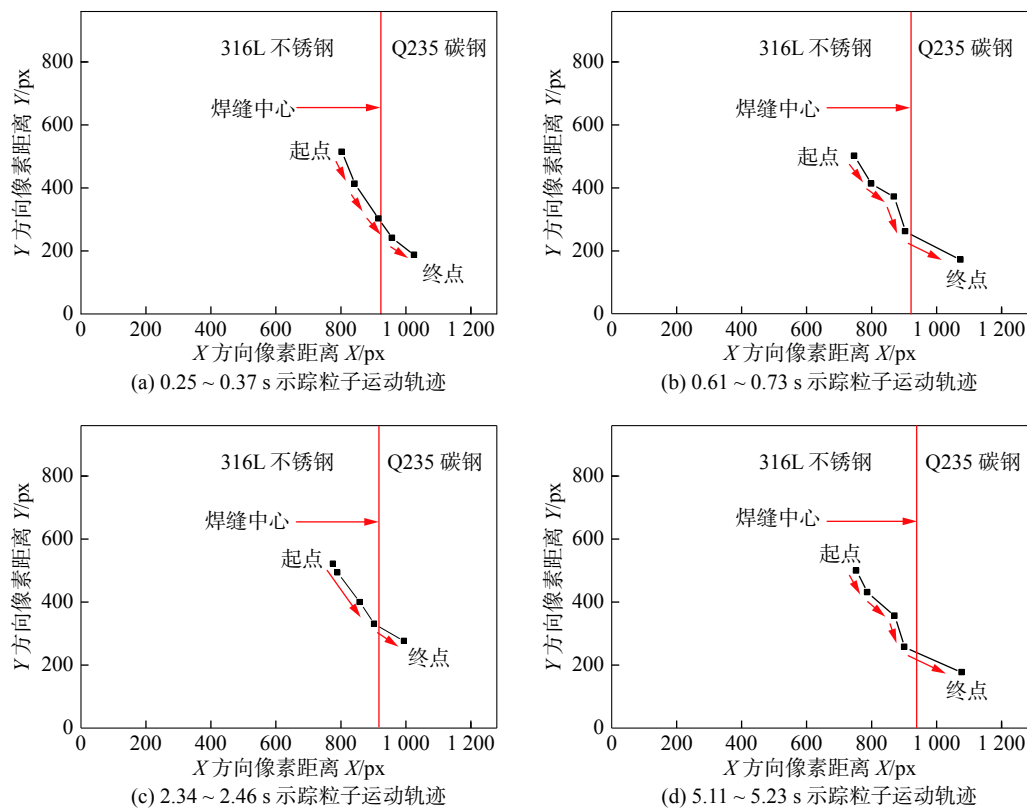


图 12 不同时间段内示踪粒子的像素运动轨迹

Fig. 12 Pixel motion trajectories of tracer particles in different time periods

图像内相邻位置间的运动距离,由此来计算各时间段内示踪粒子的运动速度.表 3 与表 4 分别为 304 不锈钢/Q235 碳钢、316L 不锈钢/Q235 碳钢对焊时示踪粒子在不同运动轨迹下的运动像素距离及其对应的流动速度.

表 3 304 不锈钢/Q235 碳钢示踪粒子运动速度

Table 3 Motion velocity of tracer particles in 304 stainless steel/Q235 carbon steel

序号	图像内运动距离S/px	流动速率v/(mm·s ⁻¹)
1	732.456	24.3
2	864.253	27.2
3	694.475	23.6
4	760.264	26.9

表 4 316L 不锈钢/Q235 碳钢示踪粒子运动速度

Table 4 Motion velocity of tracer particles in 316L stainless steel/Q235 carbon steel

序号	图像内运动距离S/px	流动速率v/(mm·s ⁻¹)
1	500.275	21.6
2	543.256	22.4
3	463.952	19.3
4	563.426	23.2

分别对表 3 与表 4 中的流动速度求平均值,可得到 304 不锈钢/Q235 碳钢的熔池表面流动平均速度为 25.3 mm/s,316L 不锈钢/Q235 碳钢的熔池表面流动平均速度为 21.6 mm/s.同文献 [15] 所测量得到的熔池表面液态金属流动速度进行对比,可初步确定不锈钢/碳钢异种焊接过程中熔池表面的流动速度为 20 mm/s 的量级.

3 试验分析与讨论

已有的研究表明普通的 Q235 碳钢 TIG 焊熔池流动是由中间流向熔池边缘的;而对于有一定氧化膜的 304 不锈钢来说,通常是由熔池边缘流向熔池中心,并认为是表面张力温度梯度所导致的转变.造成熔池流动转变的本质,如图 13 所示^[16].

对于不锈钢/碳钢的异种金属焊接来说,可用图 14 来解释试验中所观测到的熔池表面的流动行为.不锈钢由于负的表面张力温度梯度系数作用,使得熔化的不锈钢由熔池边缘向中心线流动,而对于 Q235 碳钢侧,由表面张力温度梯度系数可知,碳钢侧熔池边缘的表面张力大,使得液态金属由熔池中心流向边缘.同时,由于马兰戈尼力^[17]的存在,

使得熔池中液态金属不严格从不锈钢侧向碳钢侧流动。

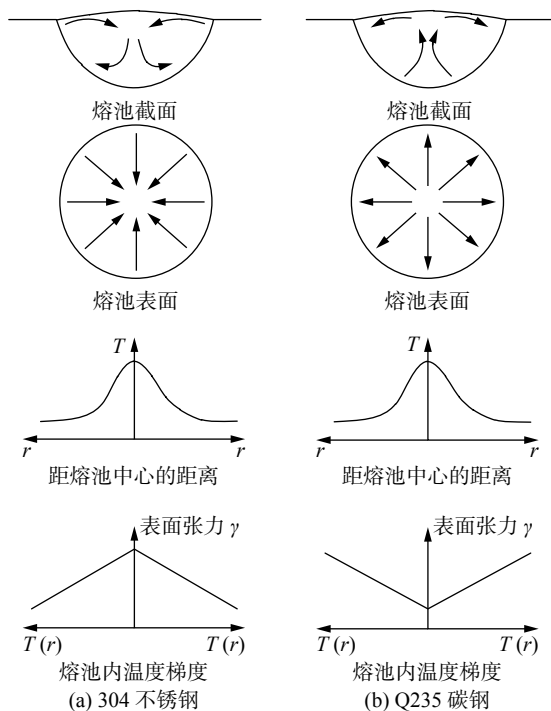


图 13 304 不锈钢与 Q235 碳钢的 TIG 焊熔池流动行为
Fig. 13 Flow behavior of molten pool in TIG welding of 304 stainless steel and Q235 carbon steel

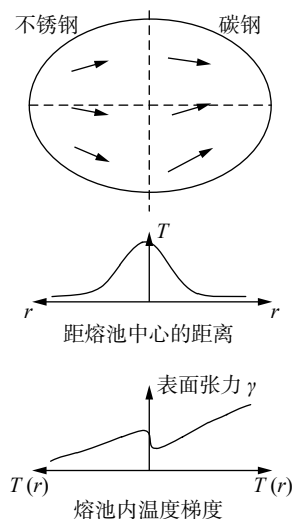


图 14 不锈钢/碳钢熔池表面流动机制
Fig. 14 Flow mechanism of molten pool surface in stainless steel/carbon steel

4 结 论

(1) 在异种钢焊接过程中, 可以通过示踪粒子的运动轨迹判断熔池表面的流动行为。不同种类的不锈钢与 Q235 碳钢进行焊接, 熔池的流动趋势不

同, 这是由材料的性能所决定的。

(2) 不锈钢/碳钢异种材料 TIG 焊时, 熔池表面流动是从不锈钢侧流向碳钢侧, 且示踪粒子在 304 不锈钢/Q235 碳钢焊接的熔池表面平均流动速度约为 25.3 mm/s, 在 316L 不锈钢/Q235 碳钢焊接的熔池表面平均流动速度约为 21.6 mm/s。

(3) 对不锈钢/碳钢的异种金属焊, 熔池表面的流动由熔池表面张力温度梯度决定, 并受到温度、焊速、马兰戈尼力等因素的影响, 使熔池内液态金属的流动变得更为复杂。

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Relationship between thermal process and microstructure during additive manufacturing of double-electrode gas metal arc welding

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Abstract: Wire arc additive manufacture of ER304L stainless steel was studied using double electrode micro-plasma arc welding. The effect of different bypass current and stacking sequence on the microstructure and properties of 304 stainless steel stacking samples were analyzed by microstructure observation and microhardness test. Combining with the thermal cycle curve measured in the process of additive manufacturing. The results show that when the bypass current is increased, the dendrite arm spacing of the stacking sample decreased firstly and then increased during additive manufacturing of double electrode micro-plasma arc welding. Meanwhile, the effect of stacking sequence on microstructure was that the different direction of heat dissipation led to the change of dendrite growth direction. The microhardness decreased slowly along the direction of stack height. And with the increase of the bypass current, the hardness increases firstly and then decreases. The stacking order had no obvious effect on the hardness.

Key words: arc additive manufacture; double electrode micro-plasma; microstructure; thermal process

Forming regularity of aluminum alloy formed by laser induced MIG arc additive manufacturing

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Abstract: In order to research the influence of various parameters on the forming dimension of thin-walled structural parts in the process of laser induced MIG arc additive manufacturing of aluminum alloys, this paper used the quadratic general rotation combination method to design orthogonal test samples, and established the process parameters (arc current I , stacking velocity v , interlayer temperature T , laser power P) and the size prediction model of the stable area of the thin-walled wall through quadratic regression equations.

And the influences of individual process parameters on the forming of the test piece were studied. It was found that the model prediction effect was good. When the arc current exceeded 106 A, the order of influence of parameters on the layer width from large to small were arc current, interlayer temperature, stacking speed, and laser power. The order of influence of parameters on layer height from large to small were arc current, stacking speed, interlayer temperature, laser power.

Key words: laser induced arc; additive manufacturing; forming size; orthogonal test

Ti/Al dissimilar metals fabricated by cold metal transfer additive manufacturing

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Abstract: Dissimilar alloys component was fabricated using TC4 and ER2319 wires by direct/variable polarity cold metal transfer. Microstructure and mechanical properties of Ti/Al component were analyzed by optical microscope, scanning electron microscope, transmission electron microscopy, energy dispersive X-ray spectrometer, nanoindentation, microhardness test and tensile test. The results shown that minute Ti alloy was melted when Al alloy was deposited on the surface of Ti alloy. Ti atoms diffused to liquid Al alloy and the long strip TiAl_3 phases were formed with difference length. The reaction layer about 10 μm in thickness was formed at the Ti/Al interface. The reaction layer near the Ti alloy side was continuous. The reaction layer near the Al alloy was long strip or block shape. The microhardness of reaction layer was between Al alloy and Ti alloy. The maximum tensile strength of the component was 111 MPa. Fracture occurred in the Ti/Al reaction layer for all samples.

Key words: Ti alloy; Al alloy; additive manufacturing; cold metal transfer

Flow behavior of stainless steel/carbon steel TIG welding pool surface

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Engineering, Lanzhou University of Technology, Lanzhou 730050, China). pp 18-25

Abstract: In order to study the flow behavior of molten pool surface in the process of dissimilar steel gas tungsten arc welding, based on the particle tracing method, the flow behavior of the molten pool surface during the welding process of 304 stainless steel /Q235 carbon steel and 316L stainless steel /Q235 carbon steels were studied by the laser reflection on the molten pool surface. The movement trend of tracer particles on the molten pool surface was analyzed, and the flown velocity of molten metal on the molten pool surface was calculated. The results shown that the liquid metal flows from the stainless steel side to the carbon steel side during the TIG welding process, and the average flow velocity of tracer particles on the molten pool surface of 304 stainless steel /Q235 carbon steel was about 25.3 mm/s, and the average flow velocity of tracer particles on the surface of 316L stainless steel /Q235 carbon steel was about 21.6 mm/s.

Key words: dissimilar steel welding; particle tracing; flow behavior of molten pool surface; surface velocity

Interface behavior and mechanical properties of Ti/Cu dissimilar metals welding by electron beam GUO Shun¹, LUO Tianyuan², PENG Yong¹, ZHOU Qi¹, ZHU Jun³ (1. Nanjing University of Science and Technology, Nanjing 210094, China; 2. CRRC Changchun Railway Vehicles Co., Ltd., Changchun 130000, China; 3. Nanjing Institute of Technology, Nanjing 211167, China). pp 26-32

Abstract: In order to obtain high-strength dissimilar metals joints of T2 copper and Ti-6Al-4V titanium alloy, electron beam welding was used to carry out experiments, and the interfacial microstructure and mechanical properties of the joints were analyzed. Based on the Ti/Cu welding-brazing process, the remelting temperature field of intermetallic compounds layer at the Ti/Cu bonding interface was constructed by secondary composite welding on the Ti side of high melting point, and then the remelting modification of Ti/Cu intermetallic compounds layer was realized. By temperature field simulation of FEM and detection of SEM, XRD, the results shown that a high temperature of about 1 000 °C at the interface was formed by remelting welding at titanium side, leading to local remelting of intermetallic compound layer. In the process of solidification, due to the direction of heat dissipation and the redistribution of elements, the formation sequence of the phase was changed, the diffusion distance of titanium atoms was reduced and TiCu with high hardness was transformed to Ti₂Cu. The phase structure was optimized and finally the strength of the welded joints improved.

Key words: electron beam welding; titanium alloy; in-

termetallic compounds; microstructure

Comparative study on load voltage-ampere characteristic and seam quality of CO₂ arc welding ZHAI Peizhuo¹, XUE Songbai¹, SUN Zijian², CHEN Tao¹, CHEN Weizhong² (1. Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China; 2. Kunshan Huaheng Welding Co., Ltd., Kunshan 215347, China). pp 33-37

Abstract: In the short-circuiting transfer process of CO₂ arc welding, the concept of load voltage-ampere characteristic curve and single cycle load voltage-ampere characteristic curve were put forward in view of the dynamic characteristic behavior of "power-arc-liquid bridge" system, which integrated the expression of different references. Under same welding conditions and parameters, the difference of load voltage-ampere characteristic curve among three welding machines were studied and their welding seam qualities were compared. The results shown that if the load voltage-ampere characteristic curve was closer to the origin of coordinate, welding spatter degree would be smaller. Additionally, the better repeatability of the curve was, the more stable welding process and the more beautiful welding seam would be. However, if the area enclosed by curves was too large, the possibility of welding defects, such as incomplete fusion and asymmetry of welding seam, would increase.

Key words: voltage-current curve; short-circuiting transfer; welding seam quality

Microstructures and mechanical properties of welding joint of Q235/1Cr18Ni9Ti dissimilar steel with ultra-narrow-gap welding ZHENG Shaoxian¹, LI Yenan¹, SHI Wei², ZHAO Xilong¹ (1. Lanzhou Jiaotong University, Lanzhou 730070, China; 2. Lanzhou LS Test Technology Co., Ltd., Lanzhou 730314, China). pp 38-43

Abstract: Dissimilar steels with thick wall welded by ultra-narrow-gap welding have some extra advantages in increasing welding efficiency, reducing production costs, improving mechanical properties of joint. In the paper, microstructures and mechanical properties of welding joint of Q235/1Cr18Ni9Ti dissimilar steels with ultra-narrow-gap welding were studied. The results indicated that welding pool of backing weld solidified with the FA solidification mode, and solidification microstructures were made of fine equiaxed grains of austenites and a few dendritic ferrites. Welding pool of filling bead and cover pass near the transition region of fusion solidified with the AF solidification mode, solidification microstructures are made of cellular austenites and ferrites between cellular austenites, welding pool of filling bead and cover pass far away from the transition region of fusion can solidify with the FA solidification mode, and solidification microstructures were made of columnar dendrite of austenites and a few skeleton ferrites. Ultra-narrow-gap welding joint of