

铝合金摆动激光-MIG 复合焊接特性及气孔控制

蔡创*, 谢佳, 刘致杰, 汪汉萍, 陈辉

西南交通大学材料科学与工程学院, 材料先进技术教育部重点实验室, 四川 成都 610031

摘要 在铝合金激光-熔化极惰性气体(MIG)复合焊过程中,摆动激光的引入会增强熔滴过渡的稳定性,有效抑制焊接过程中的飞溅,改善焊缝下部激光作用区的成形,使得试板厚度方向上焊缝的尺寸均匀性增强,焊缝的气孔缺陷大大降低。当摆动圆形直径较小(为 0.2 mm)时,焊缝气孔率约为 2.4%,较常规复合焊(约为 7.8%)明显降低。常规激光-电弧复合焊匙孔底部熔池存在明显向下流动的趋势并产生局部涡流,此时在底部聚集的气泡逸出难度较大,因此有较多的气孔残留在焊缝中。当采用较小摆动幅度的激光时,匙孔开口尺寸增大,稳定性增强,并且在匙孔中部有较强的向下的熔池流动,使得熔池底部的气泡快速逸出熔池。

关键词 激光技术; 铝合金; 激光-MIG 复合焊; 摆动激光; 气孔缺陷

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1 引言

在高速列车快速发展、环境问题日益受到重视的大背景下,高速列车对车身轻量化和整体能耗降低两方面提出了更高要求。铝合金作为一种轻型材料,具有高强度、良好的耐磨性等多种优点,与高速列车轻量化的需求匹配度较高。将激光-电弧复合焊接技术应用于铝合金的焊接领域,会不可避免地出现较为严重的气孔问题,导致焊接接头强度下降。

国内外学者尝试通过引入摆动激光来解决焊接过程稳定性、焊缝成形及气孔等问题。Hao 等^[1]发现激光摆动焊的焊缝截面更加均匀,并认为焊缝搭接特性和热输入模式是影响焊缝成形的关键因素。Yamazaki 等^[2]认为激光摆动过程中的能量分布不均匀,摆动边缘处的热输入较摆动中心大,因此熔深增大。为了解决激光摆动焊过程中能量输入不均匀的问题,Kraetzsch 等^[3]研制了用以实现激光摆动过程中能量精确控制的能量调制器,避免了摆动边缘处熔深增大的现象。Wang 等^[4-5]对比了不同激光摆动模式下的铝合金焊缝,结果发现,当激光摆动模式为圆形时,焊缝熔池最稳定且无飞溅,焊缝表面质

量最好。由于摆动激光的晶粒细化作用,摆动激光焊缝的塑性比常规激光焊缝更高,但焊缝的拉伸强度差异不大。原机械科学研究院哈尔滨焊接研究所的研究人员^[6-7]同样发现采用圆形轨迹激光摆动焊接工艺时,铝合金和钛合金的焊缝气孔得到了有效抑制。Wang 等^[8]研究了直线形、圆形以及“∞”形激光摆动路径,结果发现,采用“∞”形激光摆动路径,匙孔更稳定,焊缝中的气孔最少,接头的抗拉强度高。清华大学的研究人员^[9-11]发现,在较大的焊接速度和摆动频率下,激光摆动的幅度越大,对熔池的搅拌作用越明显,焊缝中的气孔越少。Zhang 等^[12]同样发现当激光的摆动频率和摆动幅度增大到一定水平后,5XXX 铝合金焊缝内基本没有气孔存在,焊缝的拉伸强度有所提高。Fetzer 等^[13]采用 X 射线实时成像系统观察了摆动激光作用下铝合金焊接熔池的动态过程,结果发现,摆动激光对气孔的抑制作用主要与匙孔和熔池内气泡的交互作用以及熔池内液态金属的流动对熔池内气泡运动的影响有关。此外,Cho 等^[14]发现:在较低的摆动频率下,激光摆动焊可以抑制铝合金焊缝中凝固裂纹的产生,这是因为进行激光摆动焊时,焊缝中导致裂纹扩展

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通信作者: *caichuang@home.swjtu.edu.cn

的有效应力减小;但是当摆动频率大于一定数值(7.5 Hz,摆动宽度为 2 mm)后,焊接过程中熔池部分重叠,在远离焊缝中心的位置会形成连续金属液膜,从而导致裂纹产生^[15]。温鹏等^[16]采用摆动激光-冷金属过渡(CMT)技术焊接铝合金型材时发现,焊缝内气孔得到了明显改善,并且焊缝内的二次枝晶明显弱化,接头强度达到了母材的 84.22%。

综上所述,国内外学者多针对单摆动激光焊开展研究,而对铝合金激光-熔化极惰性气体(MIG)复合焊的研究较少,并且铝合金摆动激光-MIG 焊接过程的稳定性及气孔抑制机制还需进一步阐明。鉴

表 1 母材及焊丝的化学成分

Table 1 Chemical composition of base metal and welding filler wire

Material	Mass fraction / %								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A7N01P-T4	≤0.3	≤0.35	≤0.2	0.2-0.7	1.0-2.0	≤0.3	4.0-5.0	≤0.20	Bal.
ER5356	≤0.25	≤0.40	≤0.10	0.05-0.20	4.5-5.5	0.05-0.20	≤0.10	0.06-0.20	Bal.

2.2 试验设备

2.2.1 焊接及在线监测设备

采用 IPG YLR-4000 光纤激光器进行焊接试验,该激光器的最大输出功率为 4 kW,激光波长为 1.07 μm,聚焦光斑直径约为 0.25 mm。MIG 焊机为 KEMPPI Kemp Arc-450 型脉冲焊机。采用激光在前、电弧在后的复合形式,激光倾角为 20°,焊枪

于此,本课题组研究了摆动激光对 A7N01P-T4 铝合金激光-MIG 复合焊过程中熔滴过渡、焊缝成形、气孔缺陷的影响,进一步分析了匙孔稳定性及熔池流动模式对气孔的影响机制。

2 试验材料及设备

2.1 试验材料

本课题组采用 A7N01P-T4 铝合金试板和 ER5356 铝合金焊丝进行焊接试验,试板尺寸为 300 mm×150 mm×12 mm,焊丝直径为 1.2 mm,母材及焊丝的化学成分如表 1 所示。焊前采用机械打磨的方式对试板表面进行预处理。

倾角为 65°,由旁轴焊枪提供保护气体。在焊接试验过程中,热源与摄像机的位置固定不变,铝合金试板固定在滑台上水平运动。激光-MIG 复合焊接示意图如图 1 所示,主要焊接参数如表 2 所示。试验中使用高速摄像机(Photron Fastcam SA4)并配合使用背光源、对应波长的滤光片(808 nm)及若干减光片记录熔滴和激光匙孔的特征信息。在拍摄熔滴

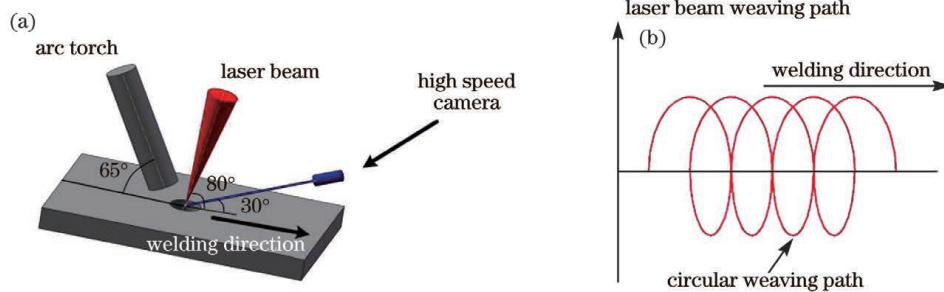


图 1 摆动激光-MIG 复合焊接示意图。(a)焊接示意图;(b)摆动扫描路径示意图

Fig. 1 Schematics of oscillating laser-MIG hybrid welding. (a) Schematic of welding; (b) schematic of oscillating scanning path

表 2 激光-MIG 复合焊接工艺参数

Table 2 Process parameters for laser-MIG hybrid welding

Parameter	Value
Laser power / W	4000
Speed of welding / (m · min ⁻¹)	1
Wire feeding speed / (m · min ⁻¹)	8.0
Laser weaving diameter / mm	0.2, 2
Laser weaving frequency / Hz	30, 50
Shielding gas flow / (L · min ⁻¹)	30

过渡时,摄像机拍摄位置与焊接方向垂直,且与试板表面成 30°夹角,采集帧率为 5000 frame/s。

2.2.2 焊缝探伤及金相设备

焊接试验结束后,采用 ERESO 65MF4 型数字式 X 射线探伤设备进行焊缝缺陷检测,并使用 ImageJ 软件计算探伤图像中焊缝的气孔率,每个工艺参数下计算一条焊缝的气孔率,并对比摆动激光对焊缝气孔率的影响。

从焊缝中心部位截取尺寸为 50 mm × 10 mm × 12 mm 的金相试样,进行粗磨、细磨和机械抛光后,使用 Keller 试剂(由 HF、HCl、HNO₃ 和 H₂O 按体积比为 2 : 3 : 5 : 90 配制而成)进行腐蚀,然后在体式显微镜 Zeiss-Stemi 2000 下拍摄焊缝的截面形貌。

2.3 匙孔及熔池流动行为的模拟

为进一步研究摆动激光对焊缝气孔缺陷的抑制机制,本课题组采用流体力学计算软件模拟了摆动激光-MIG 复合焊过程中的匙孔形态及熔池流动行为。在激光-电弧复合焊接过程中,影响传热传质的因素很多,为了保证计算精度并尽可能提高计算效率,模型作如下假设:熔化金属为不可压缩的牛顿流体,流动状态为层流;材料是各向同性材料,热物理性质除沸点外,仅取决于温度,固-液相变时金属液体的密度不发生显著变化;金属蒸气对熔池热量和动量的影响通过相关的热、力边界条件实现,在模型中不予考虑;不考虑保护气体对熔池的影响。采用双椭球+高斯体热源复合热源模型,热源方程分别为

$$q_f = \frac{6\sqrt{3}f_f Q}{\pi^{3/2}ab_f c} \exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{b_f^2} - \frac{3z^2}{c^2}\right), \quad (1)$$

$$q_r = \frac{6\sqrt{3}f_r Q}{\pi^{3/2}ab_r c} \exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{b_r^2} - \frac{3z^2}{c^2}\right), \quad (2)$$

$$q_{laser} = \frac{9Q_{laser}}{\pi R_0 H (1 - e^3)} \exp\left[\frac{-9(x^2 + y^2)}{\lg(H/z)}\right], \quad (3)$$

式中: Q 表示电弧功率; f_f 和 f_r 分别表示双椭球热源前、后部分的热流分布系数; a 、 b_f 、 b_r 和 c 分别表示双椭球热源的尺寸; Q_{laser} 表示激光功率; H 表示小孔深度; R_0 表示表面激光热源作用的半径。

模型的固-液界面采用焓-孔隙技术进行处理,气-液自由界面采用 VOF (Volume of Fluid) 方法进行追踪,描述熔池和小孔传热以及流体流动的控制方程包括连续性方程、能量守恒和动量守恒方程^[17-18]。其中,连续性方程为

$$\rho \nabla \cdot \mathbf{v} = 0, \quad (4)$$

能量方程为

$$\frac{\partial h}{\partial t} + \mathbf{v} \cdot \nabla h = \frac{1}{\rho} \nabla \cdot (k \nabla T) + \dot{h}_s, \quad (5)$$

动量方程为

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{v}) - K \mathbf{v} + \mathbf{G} + \mathbf{S}_m, \quad (6)$$

式中: ρ 表示密度; \mathbf{v} 表示速度矢量; h 表示总焓焓;

t 表示时间; k 表示热导率; T 表示温度; \dot{h}_s 表示能量源项引起的焓源项; P 表示压力; μ 表示黏度; K 表示混合相模型 Carman-Kozeny 系数; \mathbf{G} 表示重力加速度; \mathbf{S}_m 表示动量源项。

根据 VOF 方程,通过流体的体积分数可以计算、确定自由表面单元,并最终计算得到自由表面的轮廓。VOF 方程^[18-19]为

$$\frac{\partial F}{\partial t} + \nabla \cdot \mathbf{v} F = 0, \quad (7)$$

式中: F 表示各相的体积分数。

激光深熔焊过程中形成小孔的蒸气反作用力的方程为^[20]

$$P_r = \frac{AB_0}{\sqrt{T_w}} \exp\left(-\frac{m_a H_v}{N_a k_b T_w}\right), \quad (8)$$

式中: A 表示与环境压强有关的计算系数; B_0 表示蒸发常数; T_w 表示小孔壁的表面温度; m_a 表示原子质量; H_v 表示蒸发潜热; N_a 和 k_b 分别表示阿伏伽德罗常数和玻尔兹曼常数。

熔池的上表面为自由界面,该表面上除了有激光和电弧复合热源的热作用外,还有热量的对流和辐射,以及金属的散热,具体方程如(9)式所示^[17,19];试板其他壁面与环境仅考虑辐射和对流的综合散热。

$$-k \frac{\partial T}{\partial t} = q_L + q_A - \alpha(T - T_0) - \epsilon k_b (T^4 - T_0^4) - q_{evap}, \quad (9)$$

式中: q_L 和 q_A 分别表示激光和电弧提供的热量; α 表示热对流系数; ϵ 表示热辐射系数; q_{evap} 表示工件因蒸发而散失的热量; T_0 表示环境温度。

按照以上模型设置,得到了焊缝横截面的模拟结果。如图 2 所示(图中红色区域表示模拟熔池区域),模拟结果与实际焊接焊缝成形尺寸吻合较好,

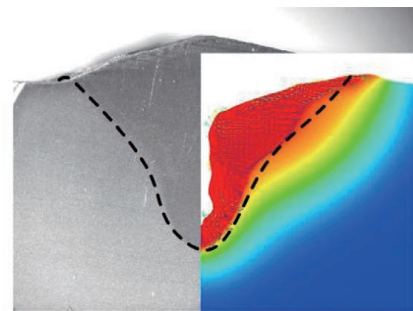


图 2 焊缝横截面模拟结果与实际焊接结果对比(摆动频率为 30 Hz,摆动圆形直径为 0.2 mm)

Fig. 2 Weld seam cross-section comparison of numerical and experimental results (weaving frequency of 30 Hz, weaving diameter of 0.2 mm)

但需要说明的是,本文模型并未考虑激光-电弧复合焊接过程中的熔滴过渡,因此模拟结果中的焊缝余高与实际焊接结果有一定差别。本文重点研究摆动激光作用下的匙孔、熔池行为以及摆动激光对焊缝气孔缺陷的影响,在后续工作中将继续在模型中加入熔滴的影响。

3 分析与讨论

3.1 摆动激光对熔滴过渡过程中飞溅的影响

图 3 所示为铝合金激光-MIG 复合焊过程中的熔滴过渡图片,可以看出:未加激光摆动时,铝合金激光-MIG 复合焊过程出现了较多飞溅,熔滴形状非常不规则,如图 3(a)所示;采用摆动激光-MIG 复合焊时(其他参数与未加激光摆动复合焊参数相同,摆动激光频率为 20 Hz,摆动圆形直径为 4 mm),因激光作用在不同位置,熔滴过渡明显变得更加平稳,熔滴呈规整的水滴形,飞溅得到了有效抑制,如图 3(b)和图 3(c)所示。结合匙孔的受力进行分析:当激光未摆动时,熔滴在下落过程中受匙孔中金属

蒸气作用力的影响,而在铝合金激光焊接过程中,高能密度激光作用于金属材料表面使金属材料大量蒸发形成等离子体,等离子体的衰减作用使激光能量的传输存在波动性,匙孔的稳定性会受到影响。同时,在铝合金焊接过程中,匙孔前壁下部易形成凸台,激光束经凸台反射到匙孔后壁,激光能量的输入会导致局部匙孔坍塌^[21-22],金属蒸气作用力发生剧烈变化,金属蒸气作用力的波动性导致熔滴受力失稳,增大了熔滴在下落过程中的不稳定性。而当采用摆动激光进行复合焊接时,如图 3(b)和图 3(c)所示,随着匙孔位置到熔滴距离的增加,小孔对熔滴的作用减弱^[23],金属蒸气作用力对熔滴的影响也随之减弱,电弧作用力成为熔滴过渡的主要作用力,此时熔滴过渡主要受电弧控制,熔滴过渡的稳定性增强。此外,有学者研究发现:增大激光的扫描幅值后,激光与电弧之间的相互作用增强,电弧的导电性增强,从而有助于熔滴的快速熔化,熔滴尺寸减小;并且,激光作用于不同位置时,由于激光和焊丝相对位置的变化,出现了颗粒过渡和短路过渡交替出现的情况^[23]。

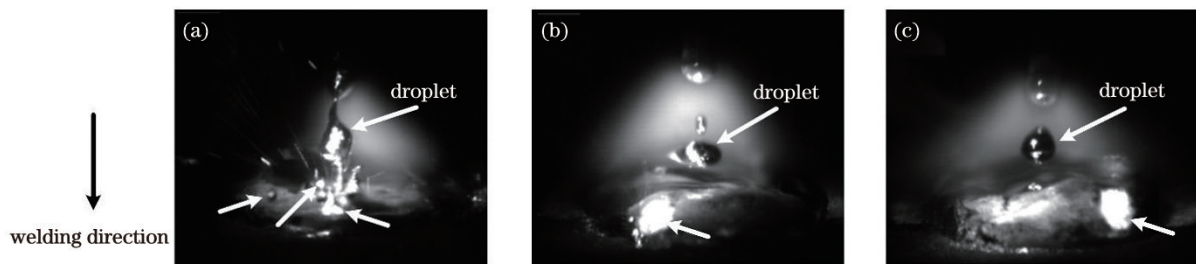


图 3 铝合金激光-MIG 复合焊过程中的熔滴过渡。(a) 激光未摆动;(b)(c) 同一摆动参数下,激光摆动至不同位置
Fig. 3 Droplet transfer during laser-MIG hybrid welding of aluminum alloy. (a) Non-weaving laser; (b)(c) weaving laser at different positions with the same weaving parameter

3.2 摆动激光对焊缝截面形状的影响

图 4 所示为摆动激光-MIG 复合焊缝与常规非摆动复合焊缝横截面的对比图。表 3 所示为不同摆动参数时焊缝熔深的测量值。图 4(a)是常规激光-

MIG 复合焊缝的横截面形貌,测得焊缝熔深约为 5.6 mm。整体来看,摆动激光-MIG 复合焊缝与常规非摆动复合焊缝横截面形貌相比没有发生根本性改变,只是伴随着摆动频率和摆动圆形直径的变

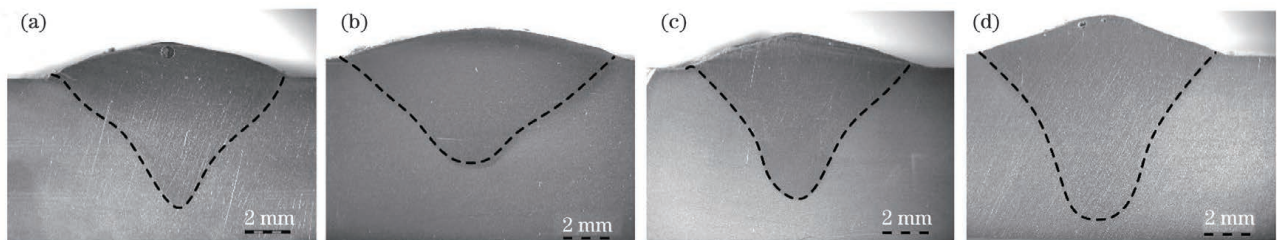


图 4 铝合金激光-MIG 复合焊缝的横截面。(a) 激光未摆动;(b) 摆动频率 30 Hz,摆动圆形直径 2 mm;(c) 摆动频率 30 Hz,摆动圆形直径 0.2 mm;(d) 摆动频率 50 Hz,摆动圆形直径 0.2 mm

Fig. 4 Weld seam cross-section of laser-MIG hybrid welded aluminum alloys. (a) Non-weaving laser; (b) weaving frequency of 30 Hz, weaving diameter of 2 mm; (c) weaving frequency of 30 Hz, weaving diameter of 0.2 mm; (d) weaving frequency of 50 Hz, weaving diameter of 0.2 mm

表 3 不同摆动激光参数下的焊缝熔深
Table 3 Weld penetration depth at different weaving laser parameters

No.	Laser weaving frequency /Hz	Laser weaving diameter /mm	Weld penetration depth /mm
a	Non-weaving	Non-weaving	5.6
b	30	2.0	4.6
c	30	0.2	5.7
d	50	0.2	6.8

化,熔宽、熔深、激光作用区域的面积对应发生了一定改变。图 4(b)是当摆动频率为 30 Hz、摆动圆形直径为 2 mm 时,摆动激光-MIG 复合焊缝的横截面形貌,可以看出,焊缝熔深有所减小,约为 4.6 mm,表面熔宽有所增大,焊缝下部激光作用区宽度有所增大。这是由于摆动激光的直径较大,相对而言,激光作用不够集中。当摆动圆形直径较小(为 0.2 mm)时,在不同的摆动频率(30 Hz 和 50 Hz)下,焊缝成形质量发生了明显变化:当摆动频率为 30 Hz 时,焊缝表面熔宽及熔深变化不明显,焊缝熔深约为 5.7 mm,如图 4(c)所示;当摆动频率为 50 Hz 时,焊缝熔宽变化不明显,熔深和未摆动、摆动频率较小时相比有所增大,达到了最大值(约为 6.8 mm),焊缝下部激光作用区宽度有所增大,如图 4(d)所示。

可以看出,摆动激光的应用可以有效改善焊缝下部激光作用区的成形质量。一方面,当摆动幅值较小而摆动频率较大时,焊缝熔深有所增大,这主要是因为,在激光摆动过程中,能量在局部聚集,匙孔的尺寸有所增大,稳定性有所增强,匙孔尺寸增大允许激光以更多角度进入匙孔,由于摆动激光不是垂直作用于匙孔,因此夹角越小激光反射现象越明显,反射次数的增多提高了激光的总热输入量,即匙孔对激光能量吸收的非涅耳吸收效应有所增强^[21],从而使焊缝的熔深有所增大。有学者通过计算发现,当摆动幅值较小时,增大摆动频率可使热源能量分布更加集中,且中心位置的能量强度最大^[5]。另一方

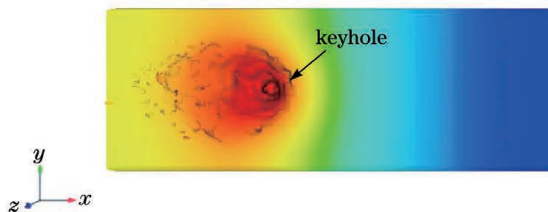


图 6 铝合金激光-MIG 复合焊熔池的上表面形貌(激光未摆动)

Fig. 6 Upper surface of molten pool during laser-MIG hybrid welding process(non-weaving laser)

面,在激光复合焊过程中,焊缝上部电弧作用区和下部激光作用区的尺寸差异减小,如图 4(d)所示,这有助于改善焊接接头中的应力水平。

3.3 摆动激光对焊缝气孔的影响机制

3.3.1 激光摆动对焊缝气孔率的影响

铝合金摆动激光-MIG 复合焊缝与常规非摆动复合焊缝中的气孔分布及焊缝气孔率对比如图 5 所示。可以看出,采用摆动激光可以有效降低焊缝气孔率。对于常规激光-MIG 复合焊,焊缝气孔率约为 7.8%,如图 5(a)所示。当摆动频率为 30 Hz、摆动圆形直径为 2 mm 时,焊缝气孔率为 3.1%,如图 5(b)所示;当摆动圆形直径较小(为 0.2 mm)时,焊缝气孔率进一步降低,约为 2.4%,如图 5(c)所示。下面将通过焊接过程中的匙孔及流场行为分析摆动激光对焊缝气孔的抑制机制。

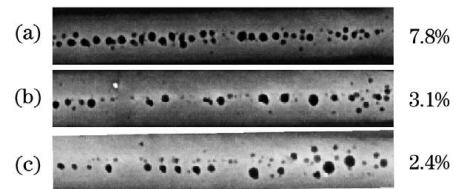


图 5 铝合金激光-MIG 复合焊缝中的气孔分布。(a) 激光未摆动;(b) 摆动频率 30 Hz,摆动圆形直径 2 mm;(c) 摆动频率 30 Hz,摆动圆形直径 0.2 mm

Fig. 5 Porosity distribution of laser-MIG hybrid weld seam of aluminum alloy. (a) Non-weaving laser; (b) weaving frequency of 30 Hz, weaving diameter of 2 mm; (c) weaving frequency of 30 Hz, weaving diameter of 0.2 mm

3.3.2 激光摆动对复合焊接熔池上表面形貌的影响

图 6~8 分别为激光未摆动、摆动圆形直径为 0.2 mm 和摆动圆形直径为 2 mm 时,铝合金激光-MIG 复合焊熔池上表面(图中红色区域)的形貌,可以看出,相对于激光未摆动,激光摆动后,熔池区域有所增大,并且随着摆动幅值的增大而进一步增大。观察匙孔开口可以发现,激光摆动后,匙孔的开口尺寸有所增大;当激光摆动圆形直径为 0.2 mm 时,匙孔直径比激光未摆动时增大了约 37%。这

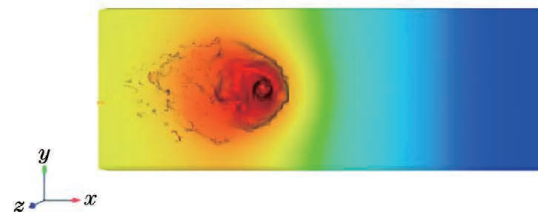


图 6 铝合金激光-MIG 复合焊熔池的上表面形貌(激光未摆动)

Fig. 6 Upper surface of molten pool during laser-MIG hybrid welding process(non-weaving laser)

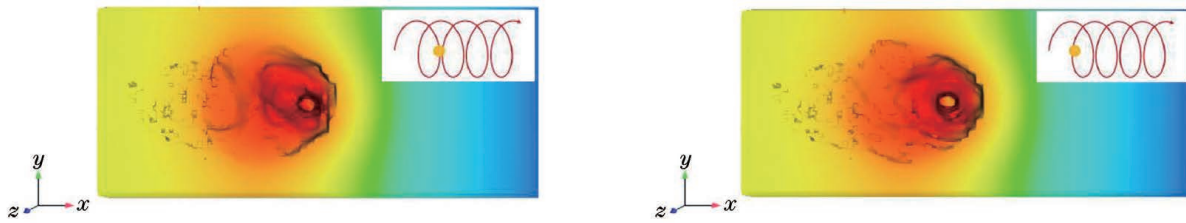


图 7 铝合金激光-MIG 复合焊熔池的上表面形貌(摆动圆形直径 0.2 mm)

Fig. 7 Upper surface of molten pool during laser-MIG hybrid welding process (weaving diameter of 0.2 mm)

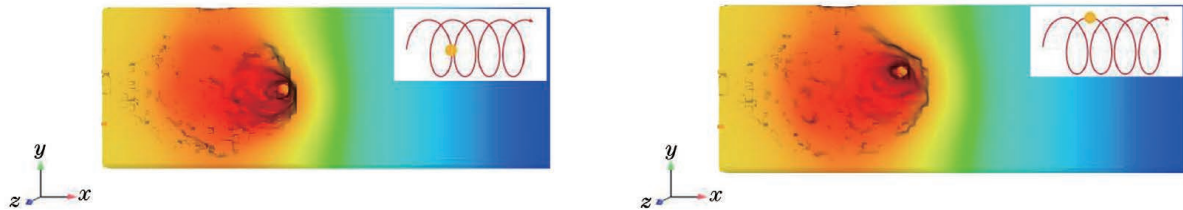


图 8 铝合金激光-MIG 复合焊熔池的上表面形貌(摆动圆形直径 2 mm)

Fig. 8 Upper surface of molten pool during laser-MIG hybrid welding process (weaving diameter of 2 mm)

是因为摆动圆形直径较小时,激光能量在局部聚集,使得匙孔尺寸增大。当摆动幅值较大时,由于在焊接过程中激光作用区域相对比较较大,匙孔前部熔化区域较小,匙孔前部熔池的流动对匙孔底部及后部的影响不明显。

3.3.3 激光摆动对复合焊接熔池纵截面形貌的影响

图 9 所示为焊接过程中焊缝的纵剖面图。可以看出:相对于激光未摆动,当摆动圆形直径为 0.2 mm 时,纵截面上匙孔的深度增大了约 18%,如

图 9(b)所示;当摆动圆形直径为 2 mm 时,由于激光作用区域较大,匙孔的深度没有明显增大,如图 9(c)所示。另外,相对于激光未摆动,采用摆动激光焊接时,熔池纵向长度尺寸有所增大(摆动圆形直径为 0.2 mm 和 2 mm 时,熔池纵向长度分别增大了约 15% 和 31%),即激光作用区域都有不同程度的增加。熔池尺寸增大意味着熔池凝固需要更多的时间,这也为气泡的逸出提供了更加有利的条件。

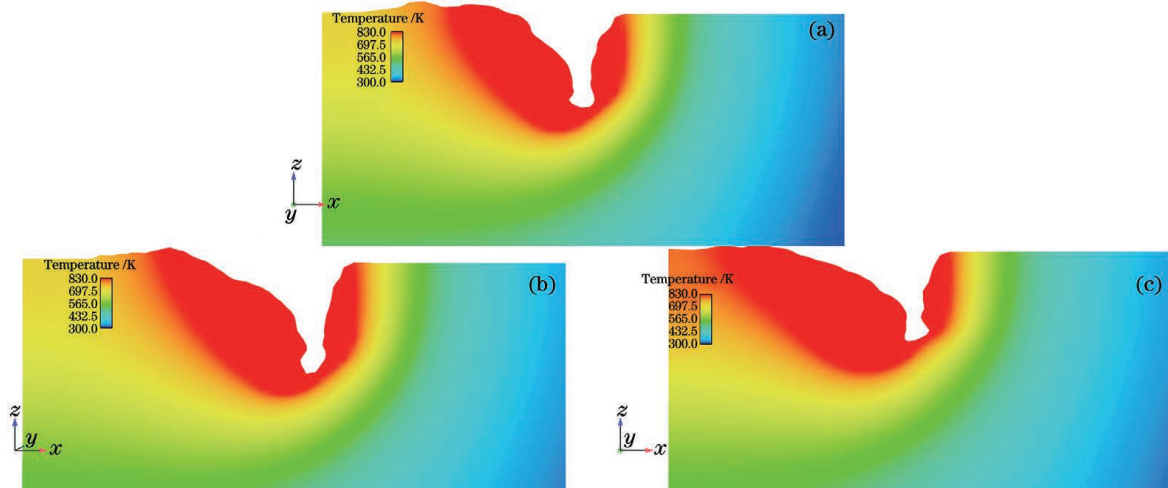


图 9 铝合金激光-MIG 复合焊熔池的纵截面形貌。(a) 激光未摆动;(b) 摆动圆形直径 0.2 mm;(c) 摆动圆形直径 2 mm

Fig. 9 Longitudinal section of molten pool during laser-MIG hybrid welding process. (a) Non-weaving laser; (b) weaving diameter of 0.2 mm; (c) weaving diameter of 2 mm

3.3.4 熔池流动模式对焊缝气孔的影响机制

焊缝中气孔缺陷的产生主要由焊接过程中匙孔的稳定性和熔池的流动模式决定。上述研究发现,激光的摆动有助于增强匙孔的稳定性,减少匙孔底

部气泡的产生。下面针对匙孔的稳定性、熔池的流动模式以及焊缝气孔缺陷的影响机制展开讨论。

提取模拟结果中不同焊接参数下的匙孔深度数据,得到匙孔深度波动曲线,如图 10 所示。整体来

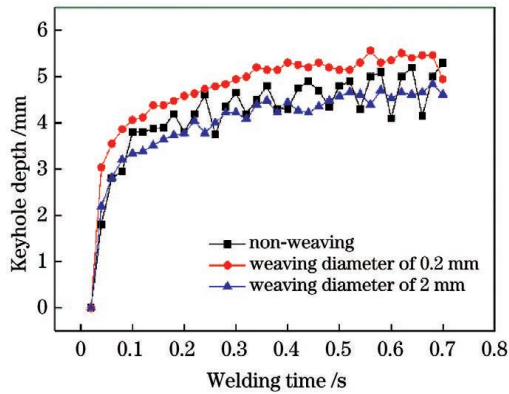


图 10 焊接过程中匙孔深度的变化曲线

Fig. 10 Keyhole depth evolution curves during welding

看,与激光未摆动相比,激光摆动后匙孔的波动幅度均较小,说明摆动激光的加入可以改善匙孔的稳

定性。

截取焊缝纵截面观察不同激光作用模式下熔池的流动模式,结果如图 11 所示。当激光未摆动时,如图 11(a)所示,熔池的流动主要集中在匙孔前壁和匙孔底部。其中:在匙孔前壁部分的熔池中,液态金属有较强的向下流动的趋势;高能量密度激光导致金属气化,受金属蒸气反作用力的影响,匙孔底部熔池产生了明显向下的流动趋势,如图 11(a)中的流速矢量箭头所示;在匙孔后部熔池的底部产生了明显的局部涡流,这种流动模式易使匙孔底部产生的气泡在熔池底部聚集,不利于气泡的快速逸出。总结以上两处熔池的主要流动现象可以发现,它们均会导致气泡向熔池底部运动,增加了气泡逸出熔池的难度,最终使焊缝中更易出现较多气孔缺陷。

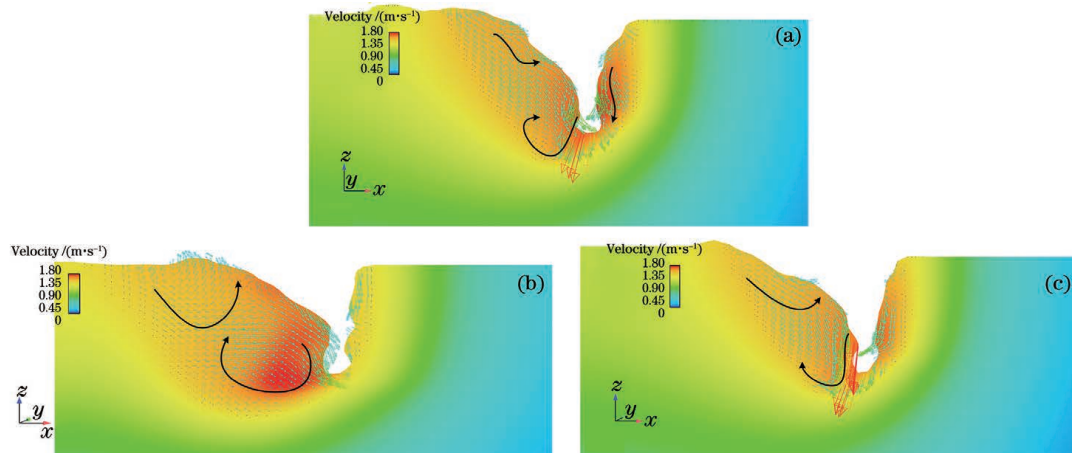


图 11 铝合金激光-MIG 复合焊熔池的纵截面流场分布。(a) 激光未摆动;(b) 摆动圆形直径 0.2 mm;(c) 摆动圆形直径 2 mm

Fig. 11 Molten pool flow field on longitudinal section during laser-MIG hybrid welding process. (a) Non-weaving laser; (b) weaving diameter of 0.2 mm; (c) weaving diameter of 2 mm

当激光以较小的摆动直径进行摆动时,匙孔在局部区域内的摆动使熔池流动产生了明显的变化,如图 11(b)所示,熔池在纵截面上的最大流速出现在匙孔后壁中部,如图中流速矢量箭头所示,流速达到了约 1.8 m/s,高于激光未摆动时纵截面上的最大流速值;熔池中部的剧烈流动会加速熔池中下部的流动,使匙孔底部可能出现的气泡快速移动至熔池的上部,从而在上部熔池流动的作用下(如图 11 熔池上部流速矢量箭头所示)快速逸出熔池。当激光以较大的摆动直径进行摆动时,由于匙孔的摆动区域比较大,熔池体积明显变大,并且熔池的流动更加平稳,如图 11(c)所示,熔池流动速度低于 1 m/s,熔池的流动模式与摆动圆形直径较小时的流动模式相似(有利于熔池中的气泡逸出熔池),熔池尺寸变大,焊缝的凝固时间变长,气泡有更多的时间逸出熔

池;但从另一方面来看,熔池流速的减小也会增加气泡的逸出时间。此外,激光摆动区域增大也会使能量有所分散,焊缝的熔深有所减小。因此,为保证焊缝熔深以及改善气孔缺陷,需要采用较小的摆动圆形直径。

4 结 论

本课题组通过引入摆动激光来抑制铝合金激光-电弧复合焊缝中的气孔,探究了摆动激光对焊接过程稳定性、焊缝成形质量和气孔缺陷分布规律的影响。

1) 采用摆动激光进行复合焊接时,由于匙孔位置到熔滴有一定的距离,削弱了金属蒸气作用力对熔滴的影响,因而熔滴过渡受电弧控制的影响更明显,稳定性也得以增强。

2) 摆动激光的引入可以有效改善焊缝下部激光作用区的成形。当摆动圆形直径为 0.2 mm、摆动频率为 50 Hz 时,焊缝熔深达到了最大值,约为 6.8 mm,高于激光未摆动时的 5.6 mm;焊缝上部电弧作用区和下部激光作用区的尺寸差异减小,焊缝的整体均匀性增强。

3) 引入摆动激光可以有效降低焊缝的气孔率,当摆动圆形直径较小(为 0.2 mm)时,焊缝气孔率约为 2.4%,较常规复合焊(约为 7.8%)明显降低。这是因为摆动圆形直径较小时,匙孔的开口尺寸增大、稳定性增强,并且在匙孔中部有较强的向下的熔池流动,使得熔池底部的气泡可以快速逸出熔池。

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Welding Characteristics and Porosity Control of Weaving Laser-MIG Hybrid Welding of Aluminum Alloys

Cai Chuang^{*}, Xie Jia, Liu Zhijie, Wang Hanping, Chen Hui

Key Laboratory of Advanced Technologies of Materials, Ministry of Education, School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, China

Abstract

Objective Aluminum alloys are widely used in high-speed train manufacturing industry owing to their lightweight, high strength, and good wear resistance. Compared with conventional metal inert gas (MIG) welding, laser-MIG hybrid welding has great application prospects for the welding of aluminum alloys because this welding technology exhibits deeper penetration depth, higher welding speed, better gap and misalignment adaptability, and smaller welding residual stress and distortion. However, the suppression of porosity defect in the weld seam is one of the main problems for laser-MIG hybrid welding of aluminum alloys and needs further investigation. Currently, several studies have focused on the suppression of porosity defect using different methods, including optimization of the position and energy ratio of laser and arc sources, optimization of assist gas or welding shielding gas, welding under subatmospheric pressure, and welding with the weaving laser beam. However, previous studies on weaving laser welding were focused on single laser welding. Few studies have discussed the effects of weaving laser on the porosity defect of laser-MIG hybrid welded joints. In this study, the laser-MIG hybrid welding experiments of A7N01P-T4 aluminum alloys with different weaving diameters and frequencies were performed. The influences of weaving diameter and frequency on the droplet transfer behavior, weld formation, and weld porosity defect were investigated. Furthermore, the mechanism of porosity defect suppression was presented.

Methods In this study, the A7N01P-T4 aluminum alloys with a thickness of 12 mm and ER5356 filler wire with a diameter of 1.2 mm were used. A 4-kW laser (IPG YLS-4000) and an arc welding machine (Kemp Arc-450) were used for the bead-on-plate laser-MIG hybrid welding experiments. A laser-leading hybrid welding with a circle-mode weaving laser was adopted during the welding process. The welding parameters are as follows: laser power of 4 kW, welding speed of 1 m/min, wire-feeding speed of 8.0 m/min, laser-weaving diameters of 0.2 and 2 mm, and laser-weaving frequencies of 30 and 50 Hz. A high-speed video (Photron Fastcam SA4) with a frame rate of 5000 frame/s was used to monitor the effect of weaving laser on the droplet transfer behavior. The porosity defects of the weld seams were observed using the digital X-ray detected machine (ERESCO 65MF4). The porosity ratio of the weld was measured using the ImageJ software. Furthermore, the mechanism of the porosity suppression was presented by discussing the keyhole and molten pool behaviors characterized by numerical simulation.

Results and Discussions According to the images obtained from high-speed video, the spatters of the droplet during the traditional laser-MIG hybrid welding process could be efficiently suppressed using a weaving laser. The stability of the droplet transfer was improved. The weld penetration depth decreased with the increase of the weaving diameter. The weld penetration depth increased with the decrease of the weaving frequency. Large weaving frequency (Fig. 4) was used to obtain more concentrated energy distribution and high intensity of energy. The size of the keyhole opening was enlarged using the high-weaving frequency such that more laser energy could be absorbed. The porosity defects of the weld were suppressed efficiently. While the laser-weaving diameter was 0.2 mm, the weld porosity ratio was $\sim 2.4\%$, which was efficiently reduced compared with $\sim 7.8\%$ weld porosity ratio of the conventional hybrid welding. The numerical simulation results showed that the size of the keyhole opening increased by 37% with a weaving diameter of 0.2 mm compared with that of the traditional laser-MIG hybrid welding (Figs. 6 and 7). The longitudinal lengths of the molten pool increased by 15% and 31% with the weaving diameters of 0.2 and 2 mm, respectively. The porosity defect in the weld seam was related to the keyhole stability and molten flow behavior. Compared with traditional welding, the fluctuation of the predicted keyhole depth was smaller (Fig. 10), which was beneficial for the suppression of bubbles formed during the welding process. Additionally, the fluid flowed downward at the middle of the keyhole rear, which was beneficial for the escape of bubbles from the molten pool while applying the weaving laser (Fig. 11). Consequently, the porosity defects were significantly suppressed during the weaving laser-MIG hybrid welding process.

Conclusions During the laser-MIG hybrid welding process of aluminum alloys, the welding spatters can be suppressed and the stability of the droplet transfer can be improved by applying the weaving laser. The weld formation of the laser zone is improved, and a more uniform weld seam along the direction of the sample thickness can be obtained. Besides, the porosity defects of the weld are suppressed efficiently. When the laser-weaving diameter is 0.2 mm, the weld porosity ratio is $\sim 2.4\%$, which is efficiently reduced compared with $\sim 7.8\%$ weld porosity ratio of the conventional hybrid welding. In the conventional laser-MIG hybrid welding, the bubbles generated at the bottom of the keyhole cannot escape from the molten pool because the fluid flows downward under the keyhole, and the vortex is formed. Consequently, more porosity defects are formed. A weaving laser with small weaving diameter is applied, the keyhole with a large size is formed and its stability is improved. Besides, the fluid flows downward at the middle of the keyhole rear, which is beneficial for the escape of bubbles from the molten pool.

Key words laser technique; aluminum alloys; laser-MIG hybrid welding; weaving laser; porosity defect

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