

万瓦级激光-电弧复合焊接焊缝成形特性分析

梁晓梅¹, 杨义成^{1,2,3}, 黄瑞生^{1*}, 田得喜², 陈晓宇¹¹哈尔滨焊接研究院有限公司, 黑龙江 哈尔滨 150028;²北京航天新风机械设备有限公司, 北京 100039;³北京科技大学材料先进焊接与连接技术研究所, 北京 100083;

摘要 为探究万瓦级激光-MAG 复合焊接焊缝成形特性,在不同的激光功率下,对比分析了三种不同复合焊接方法在焊缝成形、等离子体形态方面的差异性及其关联性。结果表明:随着激光功率变化,焊缝的特征尺寸及波动与等离子体的特征尺寸及波动具有一定的对应关系,具体表现为:随着激光功率增加,等离子体面积及其波动都增加,焊缝熔深、熔宽及其波动均增加;当激光功率增加到 20 kW 时,等离子体面积及其波动的增量开始减小,焊缝尺寸的增量也开始减小,焊缝成形质量开始变差。激光-单丝 MAG 复合焊接方法在 20、25、30 kW 激光功率下的平均熔深增量相比 5、10、15 kW 下的减小了 71.64%。在相同的工艺参数下,与激光-单丝 MAG 复合焊接相比,激光-单丝 MAG 复合填丝焊接下的等离子体面积及其标准差显著增加,熔深减小,成形变差,而激光-双丝 MAG 复合焊接下的等离子体形态、焊缝成形变化均不明显。随着激光功率增加,不同的添丝方式体现在焊缝成形及等离子体形态等方面的差异性逐渐增强,当激光功率增加到 20 kW 时,焊缝熔深以及影响熔深的等离子体面积及其波动的增量有所减小。

关键词 激光技术; 激光-电弧复合焊接; 万瓦级激光; 焊缝成形; 等离子体形态; 送丝方式

中图分类号 TG456.7

文献标志码 A

DOI: 10.3788/CJL220679

1 引言

众所周知,激光-电弧复合焊接方法以提质增效的优势得到了良好发展^[1-3],但受激光器功率的限制,诸多机理研究均是围绕千瓦级激光-电弧复合焊接方法开展的^[4],但千瓦级激光焊接目前仍不能满足重大装备制造领域中厚板一次成形、快速成形的高效制造需求。随着高功率激光器不断涌入市场,国外已经将万瓦级激光焊接技术成熟地应用在造船、石油管道、压力容器等重要行业,有效解决了大、中厚钢板焊接时间长、变形大等焊接问题^[5-9]。目前,国外大多数报道围绕激光功率在 20 kW 以下的相关研究展开,而我国在此方面的研究起步较晚,且基本上以激光自熔焊接工艺及其相关机理为主,对于 20 kW 以上的激光-电弧复合焊接研究得相对较少。到目前为止,焊缝成形仍是制约超高功率激光-电弧复合焊接技术推广应用的难题之一^[10]。

与低功率激光相比,高功率激光的输入对热量的传输和材料间的耦合特性都会产生影响,从而使得高、低功率下的焊接出现焊缝成形、焊接缺陷、接头性能等方面的差异^[11-14]。北京工业大学的张高磊等^[15]分析了高功率光纤激光深熔焊接过程中飞溅的形成过程以及

离焦量影响下焊缝成形、金属蒸气与飞溅的关系,为抑制焊接飞溅提供了科学思路。北京工业大学的邹江林等^[16]采用超音速横向气帘抑制羽辉的上升高度,使焊接熔深提高了约 20%,焊接熔宽缩小了约 24%,焊接过程的稳定性得到了很大提高,焊缝表面成形质量得以提高。此外,万瓦级激光深熔焊接过程中产生的金属蒸气/等离子体对激光的吸收和散射作用更加剧烈,不但大幅减弱了入射激光的强度,还直接影响了小孔内外激光能量分布特征以及金属蒸气压力的变化,使熔池流动状态发生改变。这也是造成高功率激光焊接时焊接飞溅大、气孔多、成形质量差的主要原因^[17-21]。然而,万瓦级激光焊接等离子体形态与焊缝成形之间的关联性目前还未见公开报道。

本团队利用高速摄像系统采集焊接过程中的等离子体形态变化特征,并以焊缝成形为表征对象,对比了激光-单丝 MAG 复合焊接、激光-单丝 MAG 复合填丝焊接、激光-双丝 MAG 复合焊接方法在不同激光功率下的焊缝成形特点以及等离子体的形态特征,探索不同添丝方式下焊缝成形与等离子体形态变化之间的关联性,为万瓦级激光-电弧复合焊接技术的推广应用奠定基础。

收稿日期: 2022-03-18; 修回日期: 2022-05-17; 录用日期: 2022-05-25; 网络首发日期: 2022-06-07

基金项目: 国防科技基础加强计划、黑龙江省头雁行动计划-能源装备先进焊接技术创新团队项目

通信作者: *lxmeihwi@126.com

2 试 验

2.1 试验材料及设备

试验用母材为 Q235 钢板,其尺寸为 200 mm×350 mm×28 mm;选用直径为 1.2 mm 的 H08Mn2SiA 焊丝。激光器选用 IPG Photonics 公司生产的型号为 YLS-30000 的激光器,其最大输出功率为 30 kW,波长

λ 为 1.07 μm ,焦点位置处的光斑直径为 1.4 mm。试验用弧焊电源均为奥地利 Fronius 公司生产的 Kuhigerat FK 4000-R 焊接电源。使用 FastCam 高速摄像机和 I-Speed7 高速摄像机采集激光-电弧复合焊接过程的瞬态图像,主要观察飞溅和等离子体的形态变化,拍摄帧数设定为 2000 frame/s,曝光时间为 100 ns。焊接过程如图 1 所示。

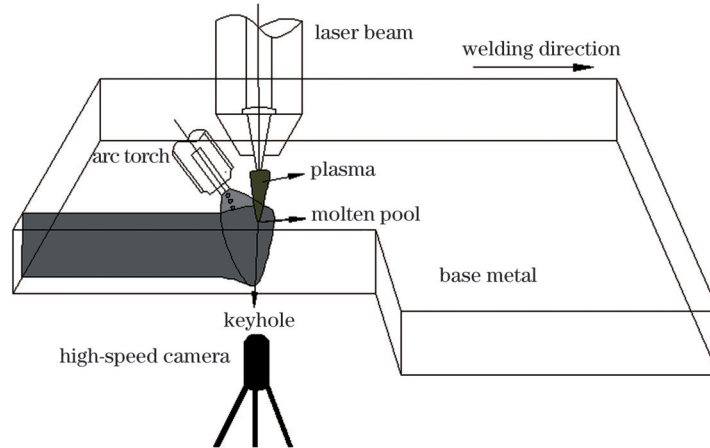


图 1 焊接过程示意图

Fig. 1 Schematic diagram of welding process

2.2 试验方法

焊接方法包括激光-单丝 MAG 复合焊接、激光-单丝 MAG 复合填丝焊接、激光-双丝 MAG 复合焊接,三种焊接方法如图 2 所示。焊接方式为平板堆焊。正式施焊

前,对试板进行机械加工,以去除其表面的氧化膜,并用酒精将表面附着的油污擦拭干净。保护气采用氩气和二氧化碳的混合气体,氩气和二氧化碳的体积配比为 4:1。试验过程中涉及的主要试验参数如表 1 所示。

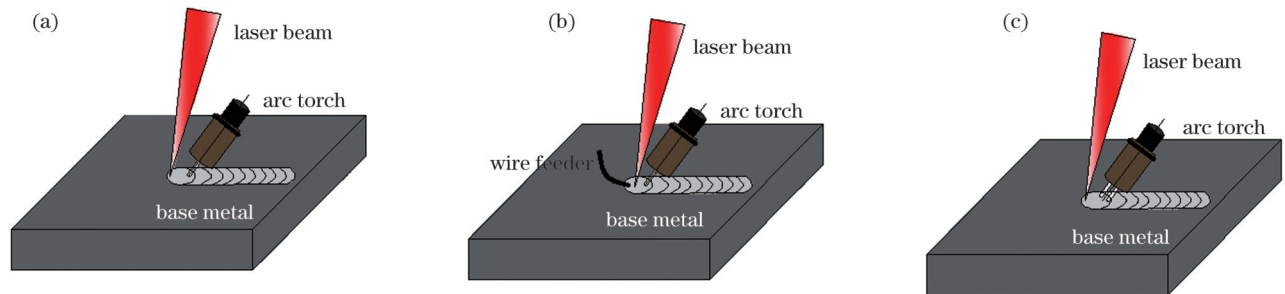


图 2 三种焊接方法简图。(a)激光-单丝 MAG 复合焊接;(b)激光-单丝 MAG 复合填丝焊接;(c)激光-双丝 MAG 复合焊接
Fig. 2 Diagrams of three welding methods. (a) Laser-MAG single-wire hybrid welding (laser-MAG-1 wire); (b) laser-MAG single-wire hybrid welding with filler wire (laser-MAG-2' wires); (c) laser-MAG double-wire hybrid welding (laser-MAG-2 wires)

表 1 焊接工艺参数

Table 1 Welding process parameters

Parameter	Value
Laser power P /kW	5-30
Welding current I /A	140
Wire extension d_1 /mm	20
Distance between wire and laser beam d_3 /mm	5
Welding speed v_1 /($\text{m}\cdot\text{min}^{-1}$)	0.8
Wire feed rate v_2 /($\text{m}\cdot\text{min}^{-1}$)	2
Gas flow Q /($\text{L}\cdot\text{min}^{-1}$)	20

焊缝尺寸的特征参数包括焊缝熔深和焊缝熔宽,其数值是通过截取稳态焊缝三处不同位置的尺寸进行平均得到的。利用 MATLAB 软件对高速摄像机拍摄的复合焊接过程的图像进行二值化处理,针对不同的研究对象通过反复试验确定合适的阈值范围,依次分别逐张提取不同复合焊接方法及焊接功率下不同时刻对应的等离子体扩散高度、面积以及等离子体飞溅的面积。焊接过程等离子体原始图像与标识图像如图 3 所示,勾勒出的红色区域表示等离子体扩散面积 S ,绿色区域为等离子体飞溅的面积 S' ,等离子体扩散的最高点与最低点之差为等离子体扩散高度 h 。

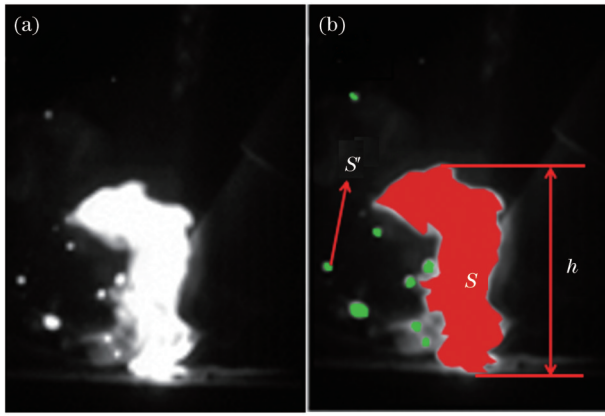


图3 等离子体形态的原始图像与标识图像。(a)原始图像；
(b)标识图像

Fig. 3 Original and mark image of plasma morphology.
(a) Original image; (b) mark image

3 试验结果与分析

3.1 激光功率对焊缝成形的影响

图4为三种焊接方法下稳态时的焊缝表面成形。可以看出,当激光功率为10 kW时,三种焊接方法的成形差别不大,焊缝均比较平整光滑,如图4(a₁)、(b₁)、(c₁)所示;当激光功率增加到20 kW时,焊缝表面成形质量较差,呈现出周期性的收缩-扩张现象,且出现了较大面积的凹坑,焊缝两侧偶有液态金属外溢现象,如图4(a₂)、(b₂)、(c₂)所示;当激光功率达到30 kW时,这种现象更加明显,两侧出现了数量较多的大颗粒飞溅,并且熔池中的液态金属直接溢出熔池,如图4(a₃)、(b₃)、(c₃)所示,此时的焊缝表面成形已很难控制。对比图4可以发现,相同激光功率下三种焊接方法的焊缝表面形貌差别不大。图5为三种焊接方法下焊接飞溅的

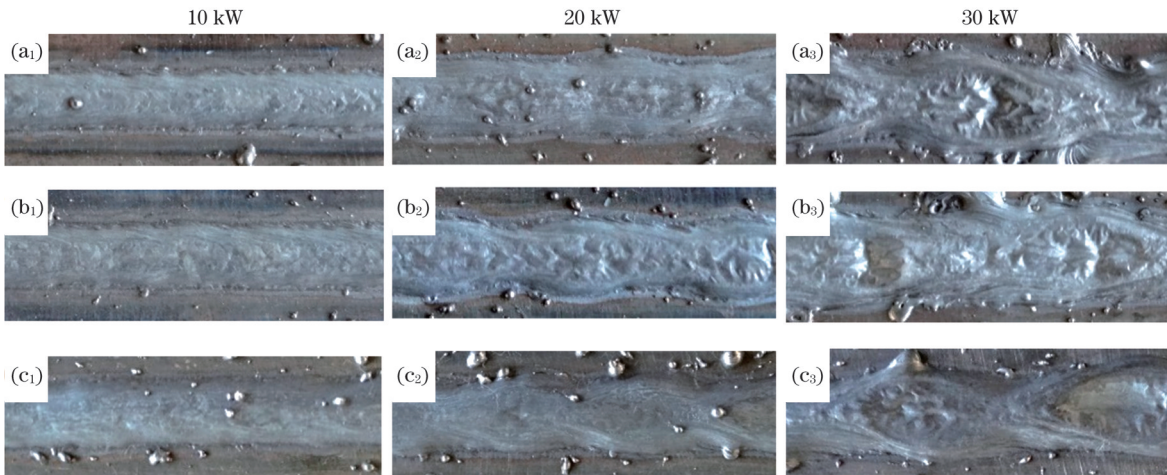


图4 激光功率对复合焊接焊缝成形的影响。(a₁)~(a₃)激光-单丝MAG复合焊接;(b₁)~(b₃)激光-双丝MAG复合焊接;
(c₁)~(c₃)激光-单丝MAG复合填丝焊接

Fig. 4 Influence of laser power on appearance of weld. (a₁)~(a₃) Laser-MAG single-wire hybrid welding; (b₁)~(b₃) laser-MAG double-wire hybrid welding; (c₁)~(c₃) laser-MAG single-wire hybrid welding with filler wire

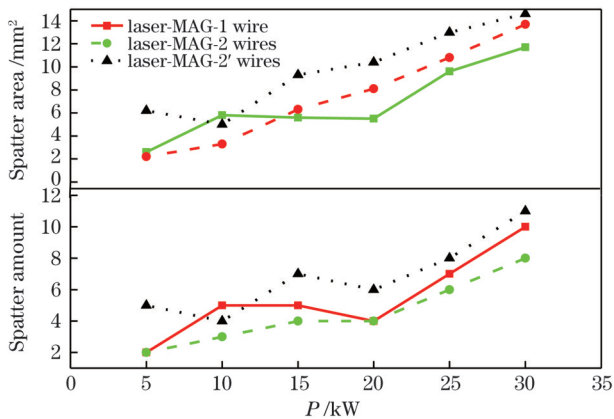


图5 激光功率对复合焊缝表面飞溅的影响

Fig. 5 Influence of laser power on spatter on weld appearance

特征参数随激光功率的变化情况。可以看出:随着激光功率增加,焊接飞溅的数量和面积均显著增加,且在相同的条件下,与激光-单丝MAG复合焊接焊缝的成

形相比,无论是加入冷丝还是加入热丝,两者的焊接飞溅数量和尺寸均增加,且冷丝的加入对焊接飞溅的影响较大。分析认为,随着激光功率增加,能量密度增加,液态金属的表面张力增大,匙孔内金属的汽化压力增大,这些都是导致成形变差、飞溅增多的根本原因,而冷丝的加入会干扰焊接过程的稳定性,因此,焊缝成形变差且产生的焊接飞溅更多。

三种焊接方法下的焊缝特征尺寸如图6(a)、(b)所示。总体来看,随着激光功率增大,焊缝熔深和熔宽均呈逐渐增大的趋势,当激光功率增加到一定值后,熔深曲线的斜率减小且整体呈“斜向上凸”的趋势,熔宽曲线的斜率增加且整体呈“斜向上凹”趋势,曲线发生弯折的位置在20 kW附近。经计算可知,激光-单丝MAG复合焊接方法在20、25、30 kW激光功率下的平均熔深增量相比5、10、15 kW下的减小了71.64%。由焊缝尺寸误差棒的长短可知,随着激光功率增加,焊缝尺寸的波

动范围增大。此外,对于激光-单丝 MAG 复合焊接来说,不论是添加冷丝还是添加热丝,都会使焊缝熔深减小、熔宽增加,而且冷丝对焊缝尺寸的影响更为明显,同时影响的差异性也随着激光功率的增加而表现得更为显著。熔深主要由激光能量决定,激光功率增加,匙孔深度增加,因此熔深随着激光功率增大而显著增加。

随着激光功率增大,热输入增加,等离子体面积增大,等离子体产生的热辐射作用增强,热输入和热辐射的综合作用使得液态金属流动加剧,焊缝熔宽显著增大。冷丝的加入会消耗一部分激光能量,从而减小激光直接作用在被焊材料上的有效值,并且焊丝的加入干扰了焊接过程的稳定性,导致焊缝成形不稳定。

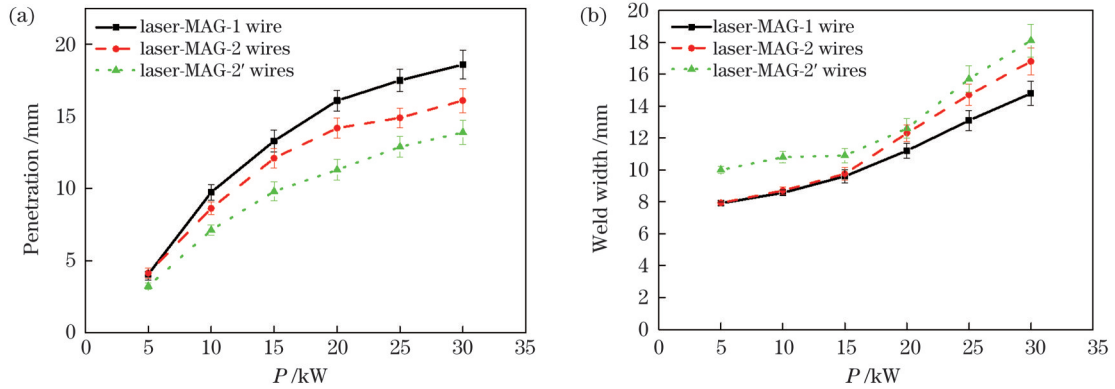


图 6 激光功率对焊缝特征尺寸的影响。(a)对熔深的影响;(b)对熔宽的影响

Fig.6 Influence of laser power on feature size of weld. (a) Effect on penetration; (b) effect on weld width

3.2 等离子体形态特征分析

图 7 为三种焊接方法下的等离子体形貌,图 8 为提取

的等离子体高度数据曲线。由图可知,随着激光功率增加,三种焊接方法下的等离子体喷射高度显著增加,且激

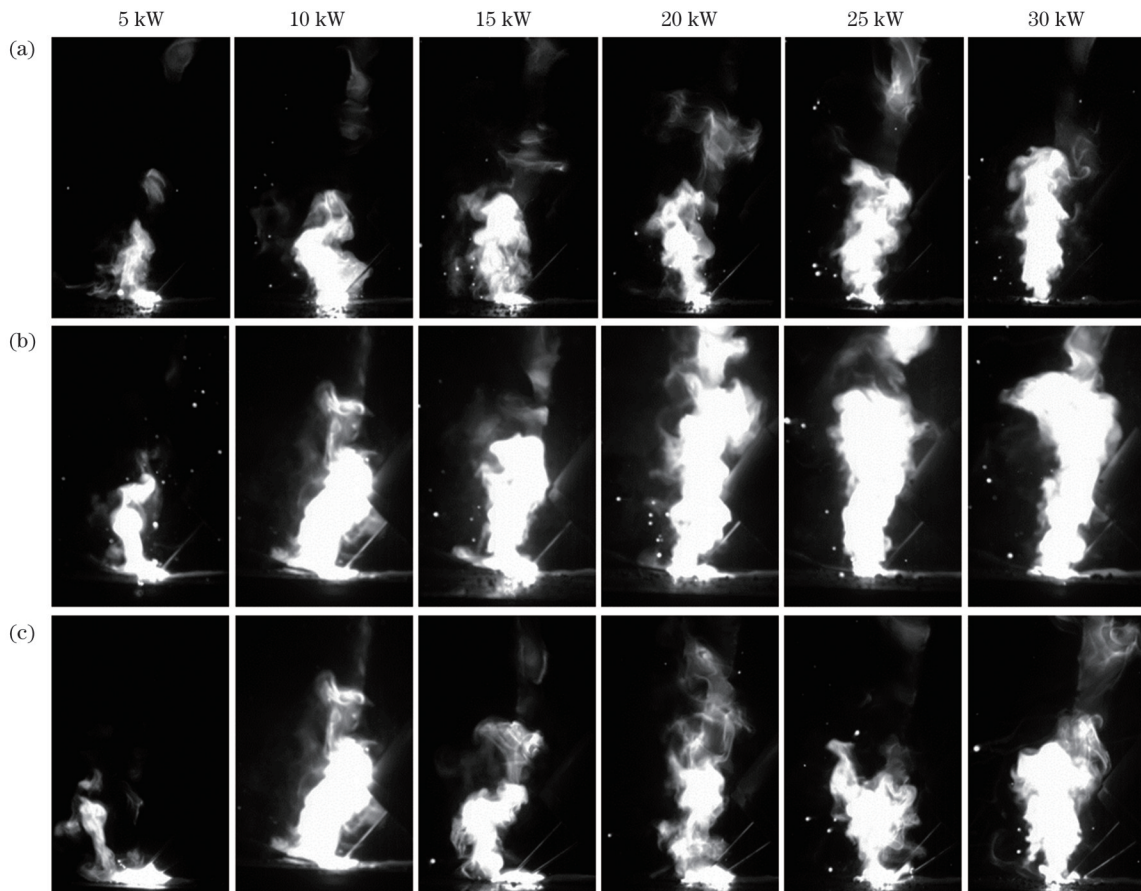


图 7 不同激光功率下的等离子体形貌。(a)激光-单丝 MAG 复合焊接;(b)激光-单丝 MAG 复合填丝焊接;(c)激光-双丝 MAG 复合焊接

Fig.7 Plasma morphologies with different laser powers. (a) Laser-MAG single-wire hybrid welding; (b) laser-MAG single-wire hybrid welding with filler wire; (c) laser-MAG double-wire hybrid welding

光-单丝 MAG 复合填丝焊接方法下的等离子体高度增加最明显,其余两种焊接方法下等离子体高度的增量较小。这是因为,随着激光功率增加,更多的金属受到高能量激光辐照后形成了大量等离子体。此外,在相同的激光功率下,与激光-单丝 MAG 复合焊接相比,不论是添加冷丝还是热丝,等离子体喷射高度均增大,相比之下,添加冷丝后的等离子体高度增加得更明显。这与 3.1 节所述焊缝尺寸、焊接飞溅变化的原因是一致的。另外,等离子体形态的差异与焊缝成形特征参数具有一定的对应关系。

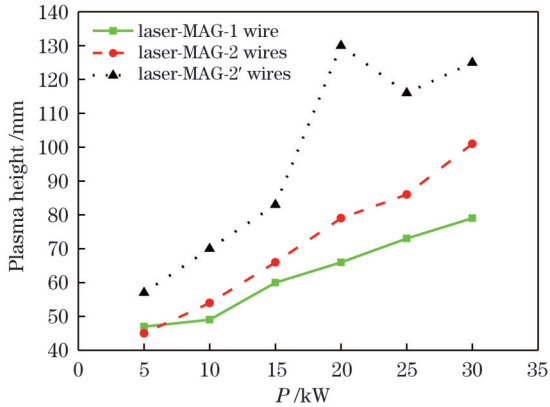


图 8 不同激光功率下的等离子体高度

Fig. 8 Plasma height with different laser powers

为了更加全面地描述等离子体的形态特征,对等离子体面积以及等离子体的波动情况进行量化处理,处理结果如图 9 所示。当激光功率分别为 5、15、20、

30 kW 时,三种焊接方法下的等离子体面积均随着时间的推进处于剧烈波动状态,等离子体面积的峰值和低谷交替出现,并且具有一定的周期性;在相同的激光功率下,激光-单丝 MAG 复合填丝焊接下的等离子体面积曲线始终处于图中的最上方,即等离子体面积最大,激光-双丝 MAG 复合焊接下的等离子体面积曲线次之,激光-单丝 MAG 复合焊接下的等离子体面积曲线始终在最下方,且后两者的等离子体面积曲线的位置相差不大。同样,激光-单丝 MAG 复合填丝焊接下的等离子体面积的离散点到平均值的距离最大(说明等离子体面积的波动最大),其余两种焊接方法下的相近,波动均较小。图 10 为三种焊接方法下等离子体面积平均值随激光功率的变化。可知:随着激光功率增加,三种焊接方法下的等离子体面积均近似呈线性增大,且激光-MAG 单丝复合填丝焊接方法下的等离子体面积曲线具有最大的斜率,即其增加的幅度最大;当激光功率增大到 20 kW 后,曲线斜率显著减小,激光-单丝 MAG 复合焊接和激光-双丝 MAG 复合焊接方法下等离子体面积曲线的斜率较小且相近。图 10 更加清晰地表明了三种焊接方法下等离子体面积与激光功率的关系。

3.3 焊缝成形与等离子体形态的关联性分析

图 11(a)、(b)、(c)分别为三种焊接方法下等离子体面积标准差、焊缝熔深波动、熔宽波动、等离子体飞溅面积标准差随激光功率的变化,各子图的上图均为等离子体面积标准差随激光功率的变化,其与等离子体面积均值随激光功率变化的趋势(图 10)相近,即:

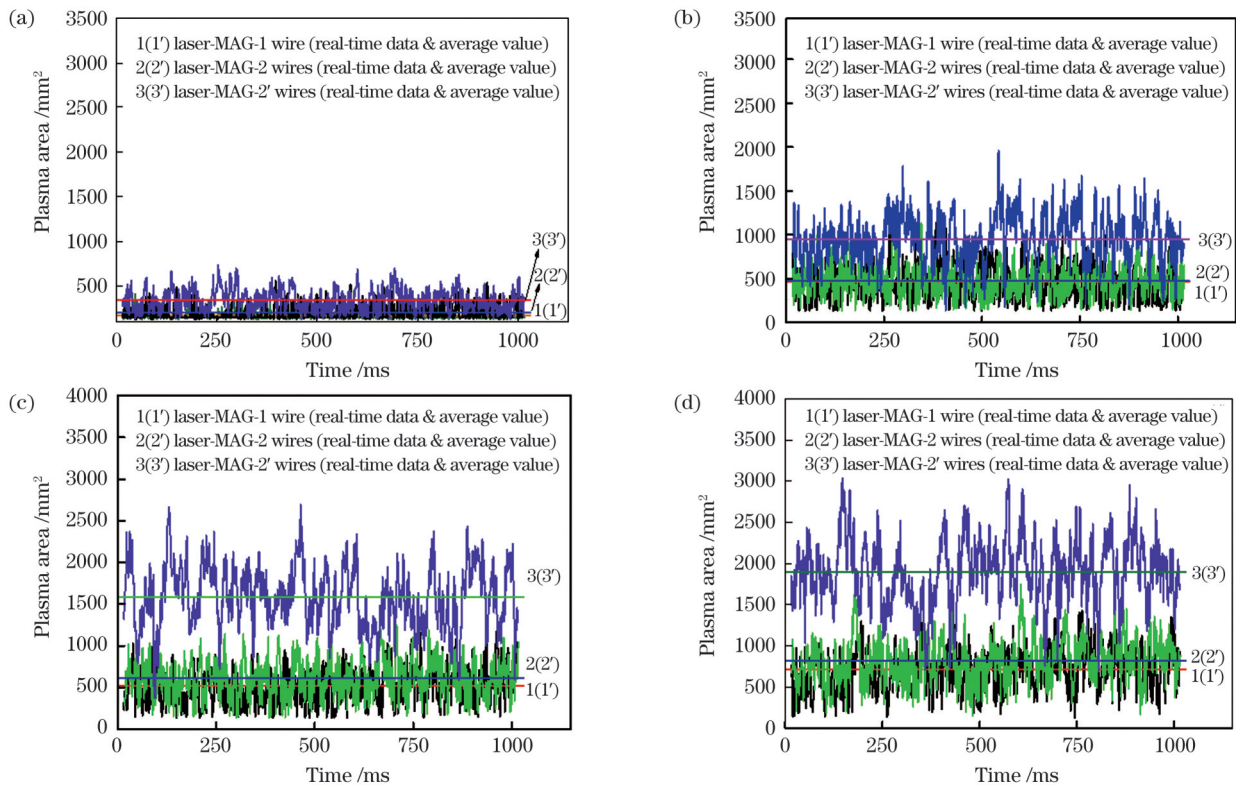


图 9 不同激光功率和焊接方法下的等离子体面积。(a) 5 kW;(b) 15 kW;(c) 20 kW;(d) 30 kW

Fig.9 Plasma area with three welding methods and different laser powers. (a) 5 kW; (b) 15 kW; (c) 20 kW; (d) 30 kW

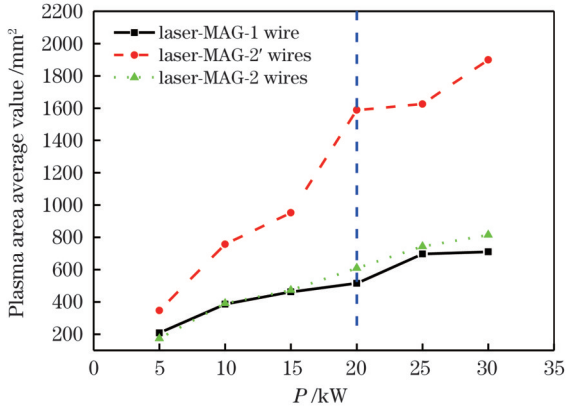


图 10 激光功率对等离子体面积均值的影响

Fig. 10 Effect of laser power on average plasma area

随着激光功率增加,等离子体面积标准差增大,且激光-MAG单丝复合填丝焊接方法下的等离子体面积标准差始终最大,而其余两种焊接方法下的等离子体面积

标准差较小且相近。对比图 11(a)中的上下两图可知,等离子体面积标准差与焊缝熔宽的波动均随激光功率的增加而增大,焊接方法对焊缝熔宽波动的影响不明显。对比图 11(b)中的上下两图可知:焊缝熔深的波动随着激光功率的增加而增大,其与等离子体面积标准差随激光功率变化的趋势相近;不同焊接方法下的熔深波动值有明显差别,在相同的激光功率下,激光-MAG单丝复合填丝焊接方法的熔深波动值最大,而其余两种焊接方法的熔深波动值相近;当激光功率增加到 20 kW 以上时,与低功率相比,熔深波动值增加的幅度变小(这与激光功率增大对等离子体形态的影响规律一致,说明等离子体面积的波动与焊缝熔深的稳定性存在一定的关联性)。由图 11(c)中的上下两图可知,与图 11(b)类似,等离子体面积标准差与等离子体飞溅面积标准差随激光功率的变化趋势接近,均随着激光功率的增加而增大,而且与焊接方法有关。

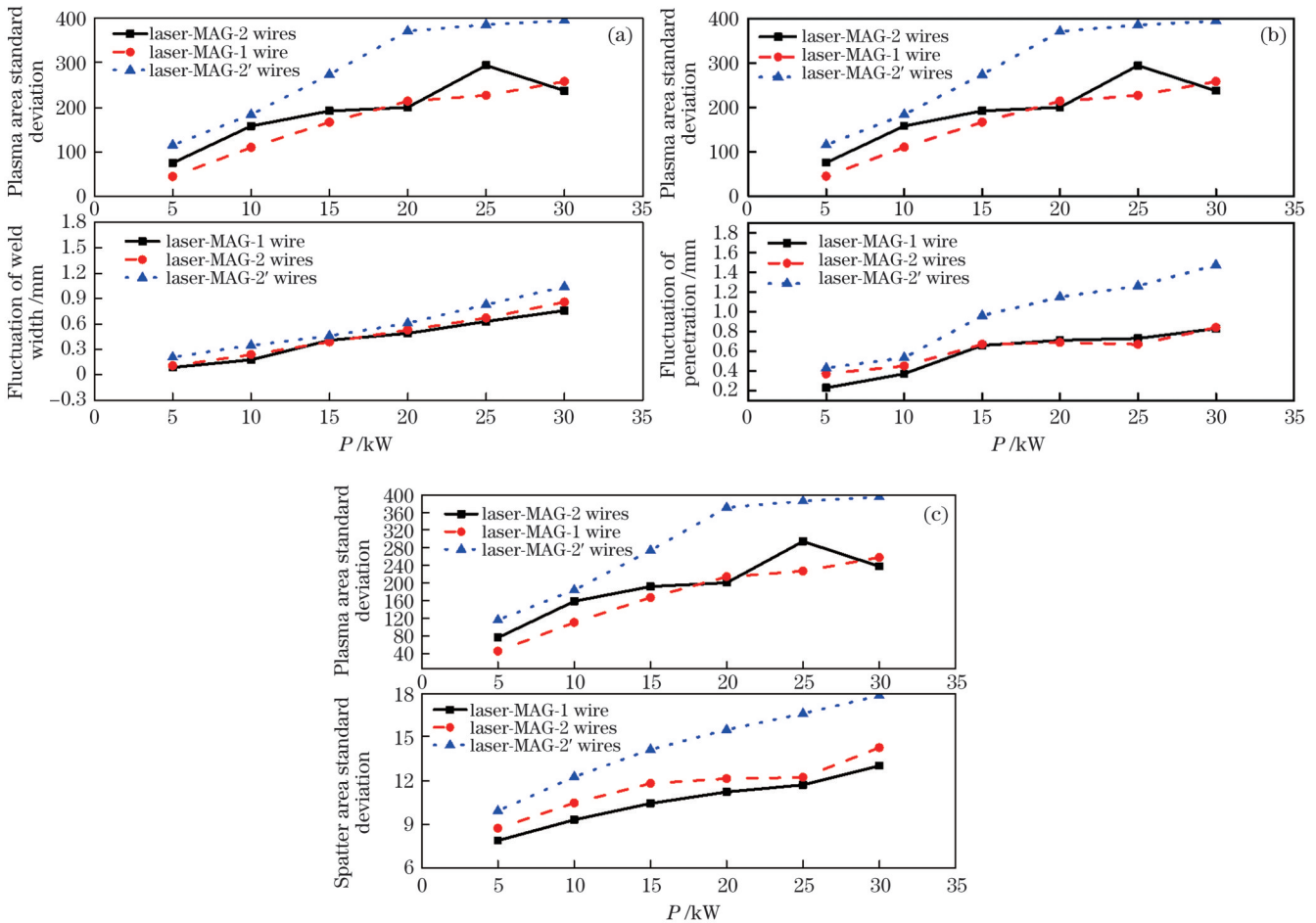


图 11 不同激光功率下等离子体形态与焊缝成形的关系。(a) 等离子体面积标准差与熔宽波动; (b) 等离子体面积标准差与熔深波动; (c) 等离子体面积标准差与飞溅面积标准差

Fig. 11 Relationship between plasma morphology and appearance of weld at different laser powers. (a) Plasma area standard deviation and weld width fluctuation; (b) plasma area standard deviation and penetration fluctuation; (c) plasma area standard deviation and spatter area standard deviation

综上所述,对于文中三种万瓦级激光-MAG 电弧复合焊接方法而言,随着激光功率增加,等离子体波动

与焊缝熔深波动、等离子体飞溅波动的变化趋势相同,焊缝熔宽波动较小。这是因为采用高功率激光焊接

时,入射方向上的等离子体浓度增加且干扰因子增多,对激光能量的衰减作用增强,直接影响焊缝熔深的大小,进而使得焊接过程的稳定性变差,最终导致焊缝表面飞溅增多、成形变差。当激光功率一定时,激光-单丝 MAG 复合焊接方法额外添加冷丝后,焊接等离子体面积及其标准差均显著增加,焊缝熔深显著减小,焊缝成形变差,而添加热丝后,等离子体形态与焊缝成形均变化不大;随着激光功率增加,填丝方式的影响效果增强。这是因为冷丝的加入损失了一部分激光能量,从而减小了焊缝熔深,并影响了焊接过程的稳定性;然而,当激光功率增加到一定值后,等离子体形态与焊缝尺寸波动曲线斜率减小。这是因为激光能量密度增加到一定值之后,激光能量损失率增加,导致其对相关特征参数的影响减弱。

4 结 论

对于三种高功率激光-MAG 复合焊接方法,无论采用哪种添丝方式,在激光能量与等离子体间的相互作用下,随着激光功率增加,等离子体面积、面积标准差及焊缝熔深、熔宽均增加;当激光功率增加到一定值后,增量有所减小,且随着激光功率增加,焊接过程稳定性变差,焊缝成形变差。

当激光功率一定时,对于激光-单丝 MAG 复合焊接,添加冷丝除了能使焊缝熔深减小外,其他的影响规律与增加激光功率的效果相同,即熔宽增加,等离子体面积及其标准差增加,焊接过程稳定性变差,焊缝成形变差;添加热丝对焊缝成形、等离子体形态的影响均不明显;随着激光功率增加,添丝方式对焊缝成形、等离子体形态影响的差异性增强。

焊缝成形的差异性与等离子体形态的变化存在一定的关联性,等离子体形态与激光功率、添丝方式有关,均遵循激光能量与等离子体间的相互作用关系,即激光入射方向上的等离子体浓度增加、稳定性变差,对激光的衰减作用、干扰作用增强,导致焊缝熔深减小、焊接飞溅增多。因此,等离子体形态的变化可以作为预判焊缝成形质量的参考依据之一。本研究对于万瓦级激光-MAG 复合焊接的理论研究与实际应用具有一定的指导意义。

参 考 文 献

- 王威,林尚扬,王旭友,等.激光-熔化极脉冲电弧复合焊接的双重导电机制[J].中国激光,2012,39(2):0203001.
Wang W, Lin S Y, Wang X Y, et al. Double electric conduction mechanism of Nd: YAG laser-pulse MAG hybrid welding[J]. Chinese Journal of Lasers, 2012, 39(2): 0203001.
- Bunaziv I, Dørum C, Nielsen S E, et al. Laser-arc hybrid welding of 12- and 15-mm thick structural steel[J]. The International Journal of Advanced Manufacturing Technology, 2020, 107(5/6): 2649-2669.
- Chen C, Shen Y P, Gao M, et al. Influence of welding angle on the weld morphology and porosity in laser-arc hybrid welding of AA2219 aluminum alloy[J]. Welding in the World, 2020, 64(3): 37-45.
- 樊丁,董丽喆,余淑荣,等.激光-电弧复合焊接的技术特点与研究进展[J].热加工工艺,2011,40(11):164-166,169.
Fan D, Dong B Z, Yu S R, et al. Technology features and progress of laser-arc hybrid welding[J]. Hot Working Technology, 2011, 40(11): 164-166, 169.
- Üstündağ Ö, Fritzsche A, Avilov V, et al. Study of gap and misalignment tolerances at hybrid laser arc welding of thick-walled steel with electromagnetic weld pool support system[J]. Procedia CIRP, 2018, 74: 757-760.
- Üstündağ Ö, Gook S, Gumenyuk A, et al. Hybrid laser arc welding of thick high-strength pipeline steels of grade X120 with adapted heat input[J]. Journal of Materials Processing Technology, 2020, 275: 116358.
- Nielsen S E. High power laser hybrid welding – challenges and perspectives[J]. Physics Procedia, 2015, 78: 24-34.
- Bunaziv I, Akselsen O M, Frostevarg J, et al. Deep penetration fiber laser-arc hybrid welding of thick HSLA steel[J]. Journal of Materials Processing Technology, 2018, 256: 216-228.
- Rethmeier M, Gook S, Lammers M, et al. Laser-hybrid welding of thick plates up to 32 mm using a 20 kW fibre laser[J]. Quarterly Journal of the Japan Welding Society, 2009, 27(2): 74s-79s.
- 凌纯,孟威.高功率光纤激光焊接研究现状及展望[J].热加工工艺,2017,46(15):15-18,24.
Ling C, Meng W. Research status and prospect of high power fiber laser welding[J]. Hot Working Technology, 2017, 46(15): 15-18, 24.
- 赵乐,曹政,邹江林,等.高功率光纤激光深熔焊接小孔的形貌特征[J].中国激光,2020,47(11):1102005.
Zhao L, Cao Z, Zou J L, et al. Keyhole morphological characteristics in high-power deep penetration fiber laser welding [J]. Chinese Journal of Lasers, 2020, 47(11): 1102005.
- 吴家洲.激光深熔焊接过程流体流动分析和传热传质机理研究[D].南昌:南昌大学,2019.
Wu J Z. Fluid flow analysis and mechanism research on heat and mass transfer during deep-penetration laser welding[D]. Nanchang: Nanchang University, 2019.
- 蔡华,肖荣诗.薄板铝合金高功率CO₂激光与光纤激光焊接飞溅特性对比分析[J].焊接学报,2013,34(2):27-30,114.
Cai H, Xiao R S. Statistic analysis on spatter characteristics in high power CO₂ laser and fiber laser welding of thin sheet aluminum alloy[J]. Transactions of the China Welding Institution, 2013, 34(2): 27-30, 114.
- 冯立晨.Q235低碳钢厚板30kW级超功率激光深熔焊接特性研究[D].哈尔滨:哈尔滨工业大学,2018.
Feng L C. Research on characteristics of deep penetration welding of thick Q235 steel plates with 30 kW level laser[D]. Harbin: Harbin Institute of Technology, 2018.
- 张高磊,孔华,邹江林,等.高功率光纤激光深熔焊接飞溅特性以及离焦量对飞溅的影响[J].中国激光,2021,48(22):2202008.
Zhang G L, Kong H, Zou J L, et al. Spatter characteristics of high-power fibre laser deep penetration welding and effect of defocus on spatter[J]. Chinese Journal of Lasers, 2021, 48(22): 2202008.
- 邹江林,李飞,牛建强,等.高功率光纤激光焊接羽辉对焊接过程的影响[J].中国激光,2014,41(6):0603005.
Zou J L, Li F, Niu J Q, et al. Effect of laser-induced plume on welding process during high power fiber laser welding[J]. Chinese Journal of Lasers, 2014, 41(6): 0603005.
- 李时春.万瓦级激光深熔焊接中金属蒸气与熔池耦合行为研究[D].长沙:湖南大学,2014.
Li S C. Study on the coupling behavior between metallic vapor and melt pool during deep penetration welding with 10-kW level laser [D]. Changsha: Hunan University, 2014.
- 李尚仁,安升辉,王春明,等.高功率激光焊接匙孔形态行为对焊缝成形及力学性能的影响[J].应用激光,2019,39(6):956-960.
Li S R, An S H, Wang C M, et al. Effect of shape and behavior of high power laser welding keyhole on weld morphology and mechanical properties[J]. Applied Laser, 2019, 39(6): 956-960.

- [19] 陈根余, 陈飞, 周聪, 等. 厚板不锈钢万瓦级激光焊接缺陷抑制研究[J]. 应用激光, 2018, 38(2): 207-214.
Chen G Y, Chen F, Zhou C, et al. Welding defect suppression of stainless steel thick plate joint by 10-kW level laser welding[J]. Applied Laser, 2018, 38(2): 207-214.
- [20] 周宇. 高功率光纤激光深熔焊接厚板的塌陷成因及其控制研究[D]. 长沙: 湖南大学, 2014.
Zhou Y. Study on the cause of surface undercut and defects control during deep penetration laser welding of the thick plate with high power fiber laser[D]. Changsha: Hunan University, 2014.
- [21] 张明军. 万瓦级光纤激光深熔焊接厚板金属蒸气行为与缺陷控制[D]. 长沙: 湖南大学, 2013.
Zhang M J. Study on the behavior of metallic vapor plume and defects control during deep penetration laser welding of thick plate using 10-kW level high power fiber laser[D]. Changsha: Hunan University, 2013.

Analysis on Characteristics of Weld Formation with 10 kW Level High Power Laser-Arc Hybrid Welding

Liang Xiaomei¹, Yang Yicheng^{1,2,3}, Huang Ruisheng^{1*}, Tian Dexi², Chen Xiaoyu¹

¹Harbin Welding Institute Limited Company, Harbin 150028, Heilongjiang China;

²Beijing Aerospace Xinfeng Machinery Equipment Limited Company, Beijing 100039, China;

³Lab of materials welding and joining, University of Science and Technology Beijing, Beijing 100083, China;

Abstract

Objective Ultrahigh-power laser welding is an important development direction for plates with medium-thickness welding. The laser-arc hybrid welding method has obvious advantages in improving the appearance, quality, and efficiency of the weld. Therefore, the 10 kW level high power laser-arc hybrid welding technology has developed rapidly. However, when the laser power reaches more than 10 kW, the vaporization behavior of the materials, the interaction between the laser beam and plasma, the stable state of the molten pool flow, the mechanism of heat transmission, and the metallurgical behavior of the weld all change to different degrees, which will affect the stability of the welding process, leading to a poor appearance of the weld and generation of weld defects, and seriously limiting the popularization and application of 10 kW laser welding. The variation in the plasma morphology during the welding process indirectly reflects the stability of the welding process. In this study, the characteristic parameters are collected, which reflect the plasma morphology and appearance of welds of three different hybrid welding methods with different laser powers: laser-MAG single-wire hybrid welding, laser-MAG single-wire hybrid welding with filler wire, and laser-MAG double-wire hybrid welding, to seek the characteristic parameters for predicting the quality of welds and providing reference values for ultrahigh-power laser-arc hybrid welding with different heat sources.

Methods Three welding methods were adopted in the present study: laser-MAG single-wire hybrid welding, laser-MAG single-wire hybrid welding with filler wire, and laser-MAG double-wire hybrid welding. The weld width and penetration were extracted when the laser power increased from 5 kW to 30 kW. Then, the plum and spatter, which were produced in the welding process and investigated by a high-speed camera, the plasma diffusion height, area, and plasma splash area with different laser powers were extracted for the three welding methods. The goal is to explore the relationship between the size of the weld and the morphological characteristics of the welding plasma for different welding methods and laser energy, which lays the foundation for 10 kW high power laser-arc hybrid welding.

Results and Discussions As shown in Figure 4, the weld face of the three welding methods becomes worse with the increase in laser power, especially when the laser power is 20 kW. The appearance of the weld changes differently, and the differences among the three welding methods are gradually highlighted. The increase in the feature size of the weld is proportional to the increase in the laser power, but the relationship is not linear. Before and after the laser power reaches 20 kW, the increase in the weld feature size decreases slightly, and concave-convex points appear in the size curve; when the power is the same, the penetration of the laser-MAG single-wire hybrid welding is small, while that of the laser-MAG single-wire hybrid with filler wire is large. The former increases slightly with an increase in laser power, whereas the latter increases significantly. The variation law of the weld width with laser power is similar to that of penetration, and the weld size curve of the laser-MAG double-wire hybrid welding method is always in the middle position, as shown in Figure 6. For the three welding methods, the plasma area and the fluctuation increase with an increase in the laser power, and the variation trend of plasma fluctuation is the same as the fluctuation of penetration and the fluctuation of plasma spatter, but the fluctuation of weld width is smaller, as shown in Figures 9 and 11.

Conclusions Three different welding methods were used to explore the regular appearance of the weld and plasma morphology with different laser powers. The results showed that when the power was increased, the plasma area and fluctuation of the three welding methods increased, and the weld width, penetration, and fluctuation values increased. When the power was increased to 20 kW, the increment in the plasma area and fluctuation decreased, the increment in the weld size decreased, the maximum increment of weld penetration for laser-MAG single-wire hybrid welding decreased by 71.64% compared with the other two welding methods, and the appearance of the weld worsened. In addition, when the power was constant, compared with laser-MAG single-wire hybrid welding, the plasma area and standard deviation increased, the penetration depth decreased, and the appearance of the weld deteriorated. When laser-MAG double-wire hybrid welding was adopted, the changes in the plasma morphology and appearance were not obvious. When the power was increased to 20 kW, the increment in the amplitude of the variation decreased. In addition, there is a correlation between the appearance of the weld and plasma morphology. The plasma morphology is related to the laser power and wire feeding mode: when the laser power increases or the filler wire is added, the plasma concentration in the incident direction of the laser increases, the stability worsens, and the attenuation and interference of the laser enhance, which leads to a decrease in penetration and an increase in the spatter. Therefore, the change in plasma shape can be used as a reference to predict the appearance quality of the weld.

Key words laser technique; laser-arc hybrid welding; 10 kW level laser; weld formation; plasma morphology; wire feeding mode