电场提高激光-TIG 复合焊熔深的机制

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摘 要：通过对比电场对单激光和单 TIG 焊接电弧在镁合金板材上堆焊熔深的影响，分析了外加电场对激光-TIG 复合焊熔深的影响机制. 同时通过研究在不同激光功率、不同 TIG 电流强度下电场的作用效果，对该机制进行了验证. 结果表明，外加电场对激光-TIG 复合焊熔深的作用是通过对激光小孔内等离子中带电粒子运动的控制来实现的. 外加电场使小孔内电子向小孔底部运动时，可以增加焊接熔深；激光功率越大，外加电场增加熔深效果越明显；增大 TIG 焊接电流，削弱外加电场对熔深的增加作用.

关键词：激光-TIG 复合焊；等离子体；电场；焊接熔深
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0 序 言

作为稳定焊接过程和提高焊接质量的有效手段，电、磁场辅助焊接具有广阔的应用前景. 近几十年来，国内外焊接界针对磁场作用于 TIG 焊进行了大量研究. 1971 年 Tseng 等人[1] 第一次深入研究了在 TIG 焊时电磁搅拌对微观组织和性能的影响. 随后国内外开始对外加磁场 TIG 焊开展广泛研究. 华爱兵等人[2] 利用外加横向旋转磁场对 TIG 焊焊缝成形进行了研究，适当的磁参数下，焊缝成形得到了改善. 常云龙等人[3] 利用外加纵向磁场对 TIG 电弧形态进行了研究. 结果表明，在外加纵向磁场的作用下，TIG 电弧发生了明显的收缩，激磁电流一定，激磁频率越高，电弧收缩越明显. 最近十年，激光焊得到了良好的发展并取得了广泛的应用，很多学者针对激光焊的不足，提出外加电、磁场辅助激光焊的新思路. 杨德才等人[4] 认为外加磁场辅助激光焊时，熔深的增加存在一个最佳值，同时，外加磁场对熔深的影响取决于等离子体中电子在磁场中的漂移半径和漂移速度. Tse 等人[5] 运用外加电场对 CO_2 激光焊中产生的等离子体进行了控制，试验条件下，适当的参数，熔深最大增加 8%. 然而，针对电场辅助激光-电弧复合焊的研究却鲜见报道. 而电场辅助焊接技术操作简单，具有广泛的应用前景，所以展开这方面的研究非常有现实意义.

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与单一激光焊、电弧焊相比，激光-电弧复合焊是一种先进的连接技术，它综合了 2 种热源各自的优势，在改善激光焊桥联性的同时，进一步提高了焊接效率[6]. 而低功率脉冲 YAG 激光-TIG 复合焊在保持以往激光-电弧复合焊技术优点的同时，通过降低激光功率、提高电弧能量，达到降低成本、节约能源的目的[7,8].

文中设计了一种极性、极间电压、极间距离可调的直流电场装置，并将此电场装置应用于低功率 YAG 激光-TIG 复合热源焊中，以 AZ31B 变形镁合金为试验材料，分析了外加电场对激光-TIG 复合焊熔深影响的机制，并通过研究激光功率和 TIG 电流对电场作用效果的影响，对该机制进行了验证.

1 试验方法

试验采用尺寸为 100 mm×100 mm 的 AZ31B 变形镁合金板材，进行平板堆焊，板材的厚度为 5 mm，其化学成分如表 1 所示.

表 1 AZ31B 变形镁合金板材的化学成分(质量分数，%)
Table 1 Chemical compositions of base metal

Al	Zn	Mn	Si	Mg
3.00	0.90	0.31	0.02	余量

试验所用装置如图 1 所示，采用低功率 YAG 激光-TIG 复合热源作为焊接热源. 其中，激光由一台 YAG: Nd 脉冲固体激光器产生，最大平均功率为

500 W,聚焦镜焦距为 150 mm,焦点控制在试件表面以下 1 mm; TIG 焊机最大输出电流为 300 A,试验均采用直流正接方式,即工件为正极、钨极为负极. 两热源采用旁轴方式复合,钨极尖端与激光轴线之间的距离(D_{LA}) 为 1 mm; 钨极高度为 1 mm,钨极与激光器焊枪夹角为 45°. 保护气体采用纯度为 99.99% 的氩气,流速为 12 L/min,焊接速度为 1 000 mm/min. 焊接时沿焊接方向电弧在前,激光在后. 外加电场装置用一台电压连续可调(0 ~ 220 V) 并且可以调换极性的直流电源提供电压,采用尺寸为 20 mm × 20 mm 的薄铜片和针状铜柱为电极. 铜片置于焊接母材上方 10 mm 处,并开有一个 2 mm 直径小孔,激光束通过该孔作用到母材表面; 针状铜电极置于焊接母材下方正对激光光斑位置,与焊接母材间距为 1 mm,被空气隔开. 文中定义当针状铜电极为正极,铜板电极为负极时,电场为正; 反之电场为负.

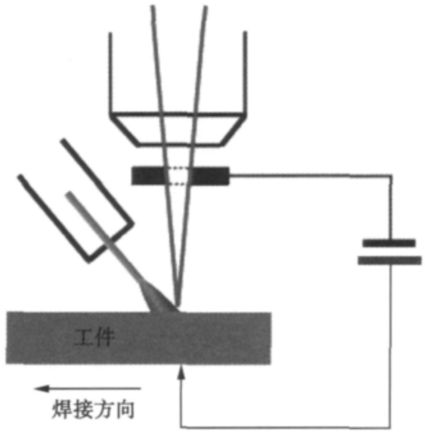

图 1 电场施加方式示意图

Fig. 1 Sketch of electric field adding device

焊接试验前,AZ31B 变形镁合金板材经砂纸打磨,再用丙酮清洗去除表面氧化膜和油脂. 焊后,截取焊缝纵截面和横截面,采用腐蚀液(5% HCl + 95% 乙醇) 对其腐蚀,对加电场区域和未加电场区域焊接熔深进行比较、分析. 熔深数值选取同一焊缝 6 个不同位置测量后所得数据的平均值.

2 试验结果与分析

2.1 电场对焊接熔深的作用

为了研究外加电场对单激光、单电弧以及激光-TIG 复合焊熔深的影响,分别对这 3 种焊接方式进行了外加电场的堆焊试验,并对焊接得到的焊缝进行了纵剖观察. 试验中针状铜极为外加电场正极,铜片为负极,激光功率为 350 W,TIG 焊电流为 100 A. 试验结果如图 2 所示.

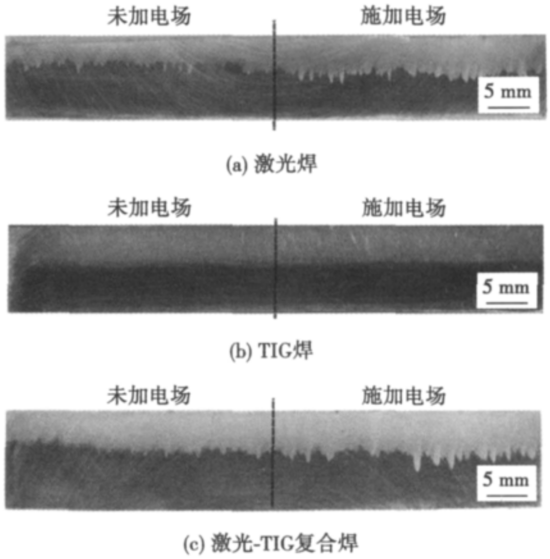

图 2 外加电场对 3 种焊接方式熔深的影响

Fig. 2 Influence of additional electric field on welding penetration depths formed by three different welding methods

结果表明,施加正向电场时,单激光焊的熔深增加; 单 TIG 焊的熔深在施加电场前后基本没有变化,表明电场对单 TIG 焊的电弧熔透能力作用较小; 在激光-TIG 复合焊过程中,电场的施加在一定程度上使焊接熔深增加,但其作用效果弱于对单激光焊的作用效果,同时具有脉冲激光作用特征的间断性尖细熔深形貌出现频率增大.

2.2 作用机制分析

众所周知,在激光 - 电弧复合热源焊过程中,激光可以在母材上形成小孔. 由于激光的高能量密度的特性,小孔内会存在高温高密度的金属等离子体. 在外加电场的作用下,等离子体中的带电粒子会发生定向加速运动. 在激光 - 电弧复合焊条件下,施加外部电场时,小孔内电场分布如图 3 所示. 小孔内电场由 TIG 钨极和母材之间电场(E_1) 以及外加电场(E_2) 复合而成. 在单激光焊过程中,外加正电场时,小孔内等离子体某一位置的电子(如图 3 中 e 点所示) 受到指向小孔底部力的作用,电子在电场中获得能量,加速向小孔底部运动,与液态金属作用,动能转变成热能,增加焊接熔透能力. 在复合焊过程中,小孔内增加了 TIG 电弧电场,由于电场矢量叠加性,电子加速运动方向发生偏转,由向小孔底部运动转为一定程度的斜向侧壁运动,其偏转程度取决

于 2 个电场的各自强度．电弧电场强度越大，电子偏转力越大，电子对熔深增加的作用效果越弱．而在单 TIG 焊接过程中，由于焊接电源本身对焊接电流的自动控制、调整功能，因此当外加电场作用于电弧空间时，焊接电源通过调节电弧两端电压，可以维持焊接电流保持不变或在一个很小的范围内波动，导致外加电场对单 TIG 焊电弧的熔深作用不明显．

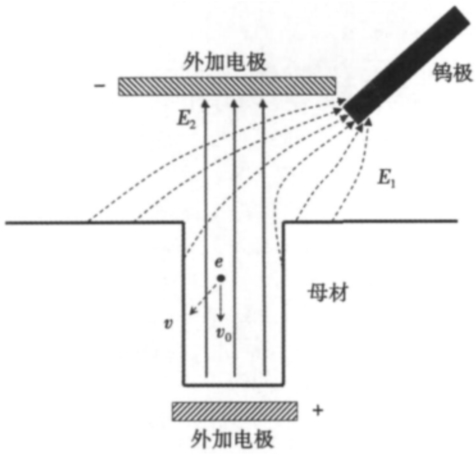

图 3　正向电场作用下小孔内电子运动示意图

Fig. 3　Sketch of electron motion under effect of additional electric field with positive direction

2.3　电场方向对复合焊熔深的影响

为了验证上述提出的电场对复合焊熔深的影响机制，将外加电场的方向改变，同时保持其它焊接工艺参数不变．试验所用激光功率为 350 W，TIG 焊电流为 90 A，试验结果如图 4 所示．

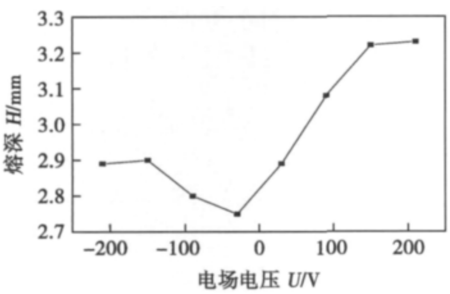

图 4　电场方向对熔深的影响

Fig. 4　Influence of electric field direction on welding penetration depth

由图 4 可以看出，在外加正电场作用下，激光-TIG 复合焊熔深增加较明显，在此焊接工艺参数条件下，熔深增加可达到 20%；负电压下电场作用效果不明显．这说明外加电场的方向对复合热源焊接熔深影响较大，当外加电场与 TIG 电弧电场具有同向分量时，电场对焊接熔深起到增强作用．根据第 2.2 节关于电场作用机制的分析，当外加正电场时，小孔等离子体中电子加速运动方向指向小孔底部．电场强度增大，电子动能增加较大，熔深增加程度较大．当电场方向相反时，电子向相反方向运动，而正离子（Ar 离子、Mg 离子）向小孔底部运动，但正离子在电场中获得的动能远远小于电子[9]，因此反向电场对焊接熔深的增加效果不明显．

2.4　小孔内电子密度对电场作用效果的影响

通过改变激光功率 P 来改变激光-TIG 复合焊过程中激光小孔内电子密度，研究在不同电子密度下电场对熔深的作用．试验中激光功率分别为 150，250，350 W，TIG 焊电流均为 100 A，电场正方向，其它工艺参数保持不变，试验结果如图 5 所示．可以看出，随着电场电压增大，焊接熔深整体呈上升趋势．由前面的机制分析可知，随着电场强度的增加，电子获得的动能增大，熔深增加．同时由图 5 还可看出，激光功率越大时，熔深增加的程度越大，即电场作用效果越明显．这是由于较大的激光功率在小孔内形成的激光等离子体密度较大，电子数量较多，这些电子从外加电场中获得的总能量较大，因此熔深增加的程度较大．

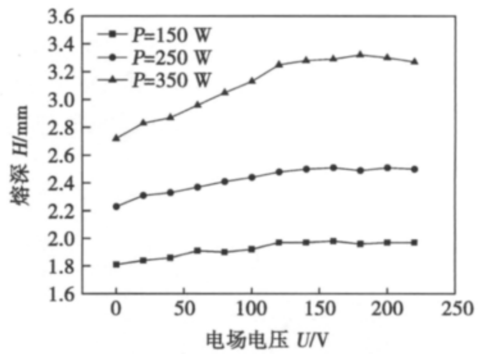

图 5　激光功率对电场作用效果的影响

Fig. 5　Influence of laser power on electric field

2.5　TIG 焊电流对电场作用效果的影响

为了考察在激光-TIG 复合热源焊过程中，TIG 焊电弧对电场作用效果的影响，进行了以下试验．试验中激光功率为 350 W，施加正向电场，TIG 焊电流分别为 80，100，120 A，其它工艺参数保持不变，试验结果见图 6．由图 6 可见，在不同 TIG 焊电流强度下，外加正电场对复合焊的熔深均有增加效果，且随着电场强度增大熔深均呈上升趋势．但随着电流的增大，外加电场对焊接熔深增加的效果减弱．根据前面提出的模型，当 TIG 焊电流强度较大时，电弧电压升高，在激光小孔内由 TIG 焊电弧产生的电场

分量增大，电子向小孔侧壁偏转运动趋势增大，造成熔深增加的效果减弱.

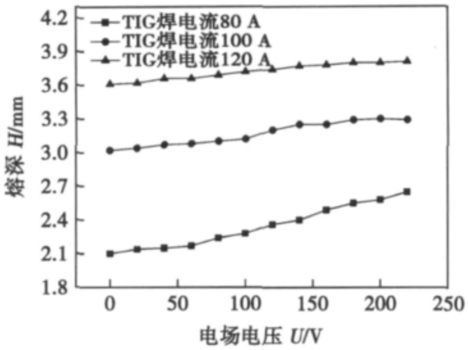

图6　TIG焊电流对电场作用效果的影响

Fig. 6　Influence of TIG current on additional electric field

3　结　　论

(1) 外加电场对激光-TIG复合焊熔深增加的作用是通过对激光小孔内等离子中带电粒子运动的控制来实现的. 通过施加正向电场，使小孔内电子向小孔底部运动，将从电场中获得的能量转化为热能传递给母材，可以增加焊接熔深; 而施加反向电场，熔深增加效果不明显.

(2) 增大激光功率可以提高小孔内等离子的密度，大量的电子可以从电场中获得更大的动能，有利于焊接熔深的提高; 提高TIG焊电弧的电流会削弱电场对熔深增加的效果.

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tiation. It was found that the Weibull stress for all specimens is almost identical under the same fracture probability when the interface fracture initiation occurs for different crack-size specimens. Moreover, the interface fracture behavior of one type of specimens with crack can be predicted from the test results of the other type of pre-crack specimens based on the local approach, and the predicted results have a good agreement with the test results. It showed that the local approach not only can be used to describe the interface fracture behavior, but also can be used in the integrity evaluation for interface between different materials.

Key words: coating; interface fracture; local approach; weibull stress

Welding residual stress in T-joint after TIG dressing and its relief

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Abstract: The welding temperature field in T-joint P355NL1 steel plates was measured by using an infrared thermography, and the welding thermal cycle curves were obtained, which have good agreement with the simulation results. The residual stress in T-joint plates was measured by blind-hole method after MAG welding, TIG dressing and heat treatment. The residual stress in T-joint plates was calculated according to the simulated welding temperature field, and the calculated results correspond with the experiment results. The results showed that the method of TIG dressing could lower the residual stress in seam center area to some extent, but the residual stress in remelted area increased. However, the overall heat treatment can effectively relieve residual stress caused by TIG dressing, but there is still partial residual stress in joint.

Key words: TIG dressing; residual stress; overall heat treating; FEM

Analysis on microstructure of particles reinforced Fe-based layers by plasma spray welding

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Abstract: The WC reinforced Fe-based alloy composite coatings were prepared on the surface of 45 steel by back feeding equipment of plasma spray welding. Scanning electron microscopy (SEM), X-ray diffraction (XRD) and energy diffraction spectrum (EDS) were used to analyze the microstructures and compositions of the coatings. The results show that WC particles are mainly distributed on the top of the coating, and less in the middle and bottom of coating. There are planar crystal, celluler crystal, dendritic crystal and equiaxed crystal from the interface of coating/substrate to the top of the coating. The surface of the coatings has a microstructure consisting of WC, $Fe_{23}B_6$, $Cr_{23}C_6$, Cr_7C_3, SiC, W_2B_5 and FeW_2B_2. The WC particles have dissolution in the spraying process. The dissolution at the top of the coating is higher. The hardness increases from the matrix to the surface of coatings, which is up to 2218 HV.

Key words: plasma spray welding; WC particles reinforced; dissolution; back feeding

Influences of Nd: YAG laser + CMT arc hybrid horizontal welding parameters on weld shape

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Abstract: The cross-section appearance characteristics of Nd: YAG laser + CMT arc hybrid horizontal welding on 304 stainless steel was evaluated by the welding weld cross-sectional images. The influence of welding parameters on weld cross-section appearance in Nd: YAG laser + CMT arc hybrid horizontal welding were studied. The results indicated that there is a great influence of weld parameters on the weld cross-section shape in YAG laser + CMT arc hybrid horizontal welding. The addition of Nd: YAG laser into CMT arc welding can significantly improve the composite weld and CMT weld penetration in hybrid welded joint. By appropriate welding parameters (the small laser-wire distance, large laser power, the low welding speed, appropriate defocusing distance and low or high CMT power), the mechanical overlay of the weld pool and dislocation of the weld cross-section can be avoided, and the good weld appearance can be obtained.

Key words: laser welding; hybrid horizontal welding; CMT horizontal welding; weld cross-section shape

Mechanism of enhancing effect of electric field on penetration depth of laser-TIG hybrid welding

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Abstract: The mechanism of the effect of additional electric field on welding penetration depth in laser-TIG hybrid welding was analyzed by comparing with electric field effect on single laser welding and single TIG welding. Meanwhile, the mechanism is verified by the investigation on the effect of electric field at different laser powers and TIG welding currents. Results show that the electric field has influence on the weld penetration depth of laser-TIG welding by controlling the motion of the charges in the plasma in the laser keyhole. The penetration depth can be enhanced when the electrons are forced to move to the bottom of the laser keyhole. The higher laser poweris, the more obvious the enhancing effect of electric fieldis. When the TIG current increases, the effect of electric field is depressed.

Key words: laser-TIG hybrid welding; plasma; electric field; weld penetration

Low power laser-TIG arc hybrid welding of thin magnesium alloy plate

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Abstract: Low-power pulsed Nd: YAG laser-TIG hybrid welding process of 2 mm AZ31B magnesium alloy plate was studied. The experiments results showed that the energy cooperation between laser and arc will have influence on the weld appearance