激光—电弧复合焊接咬边缺陷分析及抑制方法

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摘　要：为了提高激光—电弧复合焊接的可靠性，对复合焊接咬边缺陷成形机理及抑制方法进行了研究。结果表明，激光能够提高复合焊接的临界咬边速度，最高可达电弧焊接的 5 倍。在激光—电弧相互作用下，复合焊接存在两种抑制咬边的机理。一种是改变焊趾处固、液、气三相的表面张力状况，形成指向熔池外部的合力。另一种是通过提高熔池内温度梯度和热输入来增加熔池内由内向外的流动速度和时间，使熔化金属能够流向并填充焊趾，这种抑制机理作用更为显著。试验确定了复合焊接临界咬边速度的经验公式和电弧电压的合理调节范围。

关键词：激光焊接；复合焊接；咬边；临界咬边速度
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0　序　　言

激光—电弧复合焊接能够充分结合激光焊接和电弧焊接的优点，具备焊接熔深更大、焊接效率更高、焊缝质量更好等优点，已经成为人们关注的焦点，并开始应用于某些关键领域[1,2]。相对于单热源焊接，激光—电弧复合焊接能够通过两热源间的相互作用有效抑制和改善单热源焊接中的常见缺陷，如咬边、烧穿及气孔等，显著提高焊缝质量。但是，当焊接参数不当时，复合焊接仍然难以避免焊缝缺陷的形成。如何消除这些缺陷来提高焊件的可靠程度是确保激光—电弧复合焊接工艺走出试验研究阶段，进入工业应用的首要前提。因此，系统研究激光—电弧复合焊接焊缝缺陷的成形机理及其抑制方法具有重要的工程意义，并能进一步加深对激光—电弧复合焊接的理解程度。

现阶段尽管已经有少量研究[3,4]对此有所涉及，但仍然缺乏深入系统的研究和探讨。针对这一情况，作者采用低碳钢对 CO_2 激光—MIG（metal inert gas）复合焊接中的重要缺陷——咬边进行了详细研究，通过试验得到了不同激光和电弧能量配比下的临界咬边速度，并对其成形机理及抑制方法进行了探讨，旨在进一步提高该工艺的研究深度，为其工业应用提供可靠的试验依据。

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1　试验方法

试验采用 Rofin TR050 5 kW 快轴流 CO_2 激光器和 Panasonic 脉冲 MIG 焊机进行复合焊接。图 1 为试验装置示意图。激光束模式为 TEM_{01}，聚焦距离为 286.5 mm，光斑直径为 6 mm。

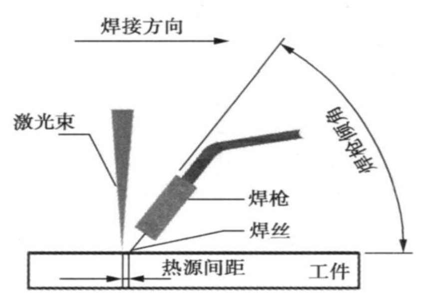


图 1　CO_2 激光－MAG 复合焊接示意图
Fig. 1　Schematic setup of CO_2 laser-MIG hybrid welding

激光束和电弧焊枪的位置参数为热源间距（焊丝尖端到激光束轴线的距离）2 mm，焊枪倾角 60°，焊丝伸出长度 11 mm，激光离焦量为零，保护气体为 He－Ar 混合气体。激光功率的变化范围为 1.5～4.5 kW，焊接电流的变化范围为 90～210 A。

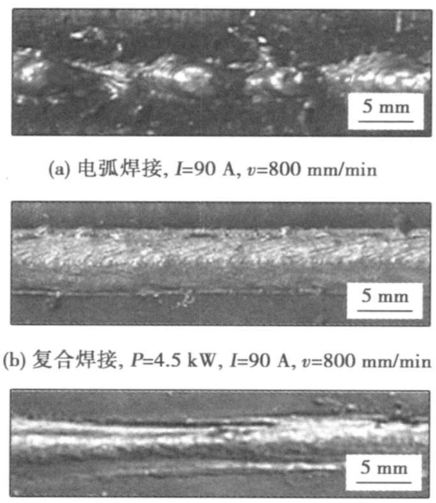
试验材料为 Q235 钢板，尺寸为 100 mm × 50 mm，厚度为 4 mm 和 5 mm。焊丝为神钢 M51－T，直径为 ϕ1.0 mm。咬边临界速度确定试验采用平板

堆焊，其余采用平板对接焊。焊接完成后，按照标准工序制备试样，并采用 4%硝酸酒精溶液腐蚀焊缝。

2　试验结果与讨论

2.1　复合焊接咬边成形机理

咬边是指在焊接接头中沿着焊趾的母材部位上被烧熔而熔敷金属未完全覆盖形成的焊缝缺陷，是焊接中较为严重的表面缺陷，容易造成应力集中，严重时会引起焊缝开裂，在高速电弧焊接中较难克服[5]。在激光—电弧复合焊接中，激光的加入能够增加电弧稳定性，减小咬边出现的倾向或者提高出现咬边的临界速度(临界咬边速度)。如图 2a 所示，在单独电弧焊接速度过大的情况下焊缝出现驼峰现象，形成咬边。相反，如图 2b 所示，复合焊接能够有效克服这一现象，获得成形平滑的焊缝。但当焊接速度增大至一定程度时，复合焊接焊缝仍然会出现明显的咬边缺陷，如图 2c 所示。



(a) 电弧焊接, I=90 A, v=800 mm/min

(b) 复合焊接, P=4.5 kW, I=90 A, v=800 mm/min

(c) 复合焊接, P=1.5 kW, I=90 A, v=2 000 mm/min

图 2　电弧焊接及复合焊接的焊缝表面形貌

Fig. 2　Weld appearances for arc welding and hybrid welding

咬边的成形机理与焊缝表面固、液、气三相界面张力密切相关。通常情况下，如果不考虑电弧压力，从静力学角度考虑，稳定状态下电弧平板焊接熔化金属的形状可由图 3 所示的二维模型来分析[6]，在熔池边缘的固、液、气三相交界点处的表面张力合力为

$$s = s_{sg} - (s_{sl} + s_{gl}\cos\theta) \tag{1}$$

式中：θ 为固液界面接触角；s_{sg} 为固气表面张力系数；s_{sl} 为固液表面张力系数；s_{gl} 为气液表面张力系数。由式(1)可知，$s = 0$，合力刚好达到平衡，是不发生咬边的临界情况；$s > 0$，合力指向熔池外部，不发生咬边情况；$s < 0$，合力指向熔池内部，熔池金属将向内部聚拢并形成咬边。采用这种咬边模型，文献[6] 认为在电弧焊接中消除咬边，应采用三种方式，即减小接触角、减小熔宽和增加熔敷量。

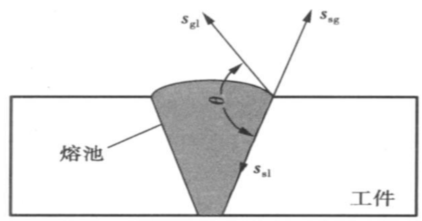


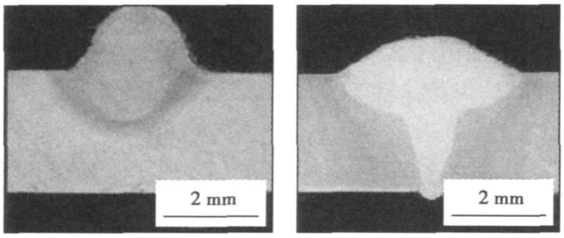
图 3　电弧焊接咬边缺陷的二维模型

Fig. 3　2-D model of undercut in arc welding

在复合焊接中，激光和电弧之间存在强烈的相互作用[1,7]。通过这种相互作用，电弧更加稳定并受到压缩[8]，电弧弧柱直径缩小，试验能观察到同样的物理现象。这种变化能够在增强电弧稳定性的同时提高能量利用效率，减少电弧在焊接过程中因漂移、能量发散而造成的飞溅，间接增加了焊丝熔敷量。单对电弧来说，电弧收缩后，其作用在工件上的有效宽度减小，相当于缩小了电弧单独作用的范围(或者电弧单独作用形成的熔宽)。从而有助于减小复合焊接焊缝形成咬边的倾向。

此外，在焊接熔池内存在强烈的由表面张力驱动的液态金属流动。通常情况下，低碳钢焊接熔池内的液态金属流动表现为由内向外的流动[5,9]，焊缝金属能够通过这种流动向焊缝边缘铺展，防止焊缝咬边的形成。但是对电弧焊接来说，当焊接速度过大时，熔池液态金属凝固过快，缺乏充足的时间流至焊趾并填补母材熔缺部位，容易形成咬边。当激光加入后，复合焊接的热输入增加，在相同或更大的焊接速度下，熔化金属的凝固速度降低，有更充足的时间流至焊趾；另一方面，熔池中心，即激光“小孔”内金属等离子体温度可高达 20 000 K[10]，远高于常规 MIG 焊接熔池中心的温度，约 6 000 K，从而复合焊接熔池具备更高的温度梯度。

这意味复合焊接熔池内的表面张力梯度更大，熔化金属具备更快的流速[11]。也就是说，熔化的焊丝金属能够在更短的时间内通过熔池流动流向并填充焊趾以抑制咬边。这种作用机理也能够通过如图 4 所示的焊缝形貌得到证明，复合焊接焊缝熔宽比电弧焊接焊缝更宽、余高更低的现象。



(a) 电弧焊接，I=120 A，v=600 mm/min　　(b) 复合焊接，P=4.5 kW，I=120 A，v=1 200 mm/min

图 4　电弧焊和复合焊焊缝形貌对比

Fig. 4　Weld shapes of arc welding and hybrid welding

上述分析表明，复合焊接分别在焊缝焊趾处和熔池内部存在两种不同的咬边抑制机理。首先，在激光—电弧相互作用下电弧受到压缩，稳定性增强，间接提高了焊缝金属的熔敷量及其有效作用宽度。最终改变了焊趾处固、液、气三相的表面张力状况并抑制咬边的形成。其次，通过激光—电弧相互作用及两者能量在熔池内的相互叠加，熔池内表面张力梯度增加，流速加快，焊缝金属由熔池中心流向焊缝边缘的时间更充分，最终使更多焊缝金属运动至焊趾处，填充焊趾并消除咬边。

实际上，在焊接电流一定的情况下因飞溅减少而添加的熔敷量相对有限，作者以前的工艺研究[12]中也证明复合焊接焊缝熔宽高于电弧焊接焊缝；另一方面，如图 5 所示，复合焊接临界咬边速度远高于电弧焊接，约为电弧焊接的 3 ~6 倍。显然，仅靠焊趾处因熔敷量和电弧有效作用宽度而造成的表面张力状态的微弱变化并不足以造成临界咬边速度如此大的变化。因此，由表面张力驱动的熔池内部流动抑制咬边的方式相对来说更为有效。

2.2　临界咬边速度

图5 为试验测得的激光—电弧参数对复合焊接临界咬边速度 v_c 的影响规律。由图可见，在设定焊接电流条件下，增加激光功率能显著提高复合焊接临界咬边速度。当激光功率为 4.5 kW 时，复合焊接临界咬边速度高达 5 000 mm/min，约为电弧焊接的 5 倍。临界咬边速度和焊接电流呈线性关系。对图 5 中的试验参数线性拟和后得到以下关系式（I 以 A 为单位），即

$$v_c = -30 + 5.8I,\ P = 0 \tag{2}$$

$$v_c = 1\,000 + 7.3I,\ P = 1.5\ \text{kW} \tag{3}$$

$$v_c = 1\,735 + 11.2I,\ P = 2.5\ \text{kW} \tag{4}$$

$$v_c = 2\,166 + 11.8I,\ P = 3.5\ \text{kW} \tag{5}$$

$$v_c = 2\,585 + 11.5I,\ P = 4.5\ \text{kW} \tag{6}$$

对比式(2) ~式(6)发现以 2.5 kW 为界，图 5 中

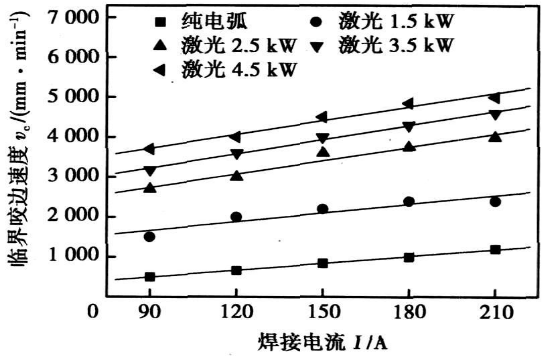


图 5　激光—电弧复合焊接的咬边临界速度

Fig. 5　Critical laser-arc hybrid welding speed of undercut

的曲线斜率可以分为两个相对接近的部分。这是因为在试验条件下，激光小孔和光致等离子体在 $P \geqslant$ 2.5 kW 时才开始稳定形成[11]，并使熔池中心温度迅速增加，激光—电弧相互作用急剧增强，其对电弧的稳定和压缩作用急剧增加，最终提高临界咬边速度随电流变化的斜率。此外，式(2) ~式(6)中的临界咬边速度截距随激光功率的增加而增加，将其二次拟合后可得到如图 6 所示的二次曲线及关系式。该关系中，X 表示激光功率 P，Y 表示截距 x。

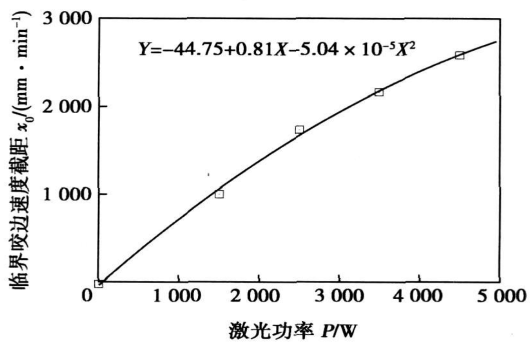


图 6　激光功率和临界咬边速度截距的关系

Fig. 6　Relationship between laser power and critical speed for undercut

将式(2) ~式(6)中的斜率以激光功率 2.5 kW 为界平均后，结合图 6 中的二次关系式可得到临界咬边速度经验公式（P 以 W 为单位），即

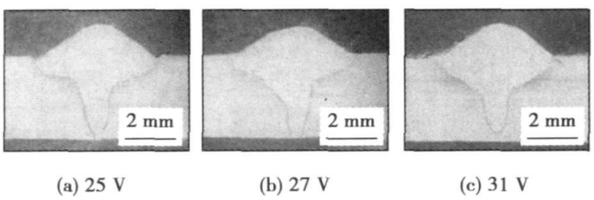
$$v_c = -44.75 + 0.81P - 5.04 \times 10^{-5} P^2 + 11.5I,\quad P \geqslant 2.5\ \text{kW} \tag{7}$$

$$v_c = -44.75 + 0.81P - 5.04 \times 10^{-5} P^2 + 6.65I,\quad P < 2.5\ \text{kW} \tag{8}$$

2.3　电弧电压的影响

试验同时发现在复合焊接中，当电弧电压略高

于常规电弧电压(单独MIG 电弧焊接在稳定可靠焊接时的设定电压)时可以减小咬边出现的倾向。如图7a 所示,在常规电弧电压下,即使焊接速度仅为 1 000 mm/min,焊趾处仍有咬边出现。增加电弧电压后,咬边消失,如图 7b 所示。电压增加过大时,咬边虽得到抑制,但焊接熔深减小,如图 7c 所示。这是因为电弧电压过低时,电弧力增加,其对熔池的“挖掘”作用增强,不利于熔化金属向焊缝四周的铺展。电压过高时,电弧弧长过长,能量散失增加,其有效作用面积降低,致使激光消耗过多的能量来维持电弧稳定,减弱其小孔效应,降低焊接熔深[7]。试验表明相对于常规电压设定值,电压增加值在 2~3 V 时能在抑制咬边的同时保证复合焊接熔深不减小。



焊接工艺参数为 P=4.5 kW, I=120 A, v=1 000 mm/min

图 7 电弧电压对复合焊接咬边的改善

Fig. 7 Effect of arc voltage on hybrid weld undercut

3 结 论

(1) 激光能够提高复合焊接工艺的临界咬边速度。激光功率越高,复合焊接临界咬边速度越大。

(2) 在激光—电弧相互作用下,复合焊接存在两种抑制咬边的机理。一种是改变焊趾处固、液、气三相的表面张力状况,形成指向熔池外部的合力。另一种是提高和增加熔池内部液态金属由内向外的流动速度和时间,使熔化金属能够流向并填充焊趾,相对来说,这种抑制机理作用更为显著。

(3) 试验得到了复合焊接临界咬边速度经验公式,对工艺参数的选取有一定指导意义。

(4) 试验结果表明,相对于常规电弧电压设定值,其增加值在 2~3 V 左右能够在抑制咬边的同时保证复合焊接熔深不减小。

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tensile plastic strain in the weld metal is $A\alpha_l (T_m - T_r) - (R_{rt} - R_{rc}) / E$.

Key words: welding stress and strain; hypothesis of plain section; compressive plastic strain; tensile plastic strain

Influence of TIG dressing on fatigue property of 10Ni5CrMoV steel welded joints XUE Gang, WANG Renfu (Luoyang Ship Material Research Institute, Luoyang 471039, Henan, China). p77—80

Abstract: The fatigue tests were taken on the large angle welded joints of 10Ni5CrMoV steel with and without tangsten inert gas welding(TIG) dressing treatment on the toe. The fatigue life, the relation of load and stroke and the fatigue crack initiation at the same loading condition were analyzed comparatively. The welding residual stress was also measured. The stress field and the strain field of welded joints with and without TIG dressing treatment were calculated by the finite element method. The results indicate that the TIG dressing treatment can improve the fatigue property of the large angle welded joints of 10Ni5CrMoV steel. The fatigue life of the welded joints is increased 34% by TIG dressing on the toe at the same loading condition. The primary cause is that the TIG dressing treatment can improve the weld geometry and reduce the stress concentration on the weld toe. So the stress value in the toe is reduced at the same loading condition and the fatigue ability of the welded joints is increased.

Key words: TIG dressing; 10Ni5CrMoV steel; welded joint; fatigue property

Effect of double-wire narrow gap GMA welding parametars on weld appearance ZHAO Bo, FAN Chenglei, YANG Chunli, ZHANG Liangfeng (1. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p81—84

Abstracts: The influences of three parameters which are space between wire and edge, space between two wires and angle between two wires on weld appearance were studied in double-wire narrow gap welding with one pool by procedure experiments. The results show that the increase of space between wire and edge can make sidewall penetration and saucer shape of weld surface increase. When the arrangement of wires became parallel, sidewall penetration and saucer shape of weld surface increased to the maximum value. When space between wires increased, sidewall penetration and saucer shape of weld surface increased firstly and then decreased, and finally arrived at peak value when the space between wires is 5—10 mm under the co-action of arc and molten pool energy. But when there was no finger penetration, the three procedure parameters mentioned had little influence on weld penetration. There was lack of fusion of weld bottom when I-shape groove was adopted, and adjusting the three parameters could not eliminate the phenomenon of non-fusion.

Key words: narrow gap welding; twin-wire welding; weld formation

Mechanism and remedy of undercut formation during laser-arc hybrid welding GAO Ming, ZENG Xiaoyan, HU Qianwu, YAN Jun (Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China). p85—88

Abstract: To enhance the reliability of laser-arc hybrid welding, undercut formation and its remedy mechanisms during this process were discussed. The results demonstrated that laser can increase undercut critical speed of hybrid welding, which reaches 5 times than that of arc welding with appropriate welding parameters. Two undercut remedying mechanism resulted from laser-arc interaction were found during hybrid welding. The one is the surface tension state of three phases (solid, liquid and gas) at weld toe is changed by laser-arc synergic effects and form a resultant force pointing to the outside of molten pool. The other is the enhancement of flow speed and time of molten metal flowing from pool center to outer by the increasing of heat input and temperature gradient in molten pool. This faster flow drives molten metal to weld toe and avoid undercut, which is the main mechanism for restraining undercut. Furthermore, the experiential formula to undercut critical speed of hybrid welding and the optimal adjusting range of arc voltage were also obtained.

Key words: laser welding; hybrid welding; undercut; critical speed

Numerical simulation of welding residual stress for longitudinal straight weld seam for aluminum alloy thin-wall cylinder

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Abstract: Numerical simulation of TIG welding of thin wall aluminum cylinder by thermo-elastic-plasic FEM was conducted. Based on the generation of analysis model, the values and distribution on the whole cylinder for quasi-steady temperature field and residual stress field were described quantitatively. Experiments were performed to verify the residual stress. It can be drawn that during welding there exits high temperature at the centre of heat source and its vicinity where temperature gradient keeps greater. The longitudinal residual stress in weld seam and its HAZ are tensile, its maximum is in the cross-section at the center of weld length and reached 138 MPa. The maximum compressed transverse residual stress was on the both sides of weld seam. The tensile and compressive region of longitudinal residual stress changed alternately at the circumference of cylinder. The residual stress of the welded Al cylinder has been measured by stress-release method, and excellent agreement between the measured value and calculated value is shown.

Key words: numerical simulation; temperature field; residual stress; stress measurement

Laser welding of new type austenite heat-resistant steel HR3C for ultra supercritical boilers WU Shikai[1], YANG Wuxiong[1], XIAO Rongshi[1], QI Anfang[2], LI Zhongjie[2] (1. Institute of Laser En-