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铝合金激光—电弧双面焊接头特征分析

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摘 要：采用激光—电弧双面焊工艺进行铝合金焊接试验，发现该工艺不仅可以获得稳定可靠的焊接过程与美观的焊缝成形，还可以有效地增加接头熔深和降低焊接成本。主要研究了焊接参数对双面焊接头特征的影响。结果表明，激光功率增加时，双面焊两侧的熔宽都以同样的趋势增大；焊接电流增大时，电弧侧熔宽的增加趋势明显大于激光侧；增加激光功率或提高焊接电流都会引起焊缝最小熔宽的增大，且焊缝最小熔宽的深度也发生一定的变化。随焊接速度的提高，激光侧的深宽比增加，而电弧侧的深宽比减小。

关键词：激光—电弧双面焊；铝合金；接头特征
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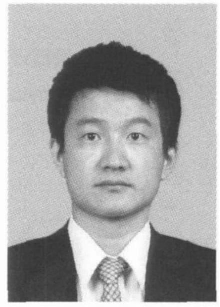

苗玉刚

0 序 言

在焊接生产中，如何提高产品质量和焊接生产效率，降低焊接成本，一直是广大焊接工作者所关注的问题。例如，在中厚壁金属结构制造中，电弧焊是广泛被采用的焊接方法之一[1]，但由于电弧的熔透能力所限，母材往往需要单面或双面开坡口，进行多道焊[1-3]。这种工艺会带来一系列问题，开坡口需要占用大量机时和人力，降低了生产效率，提高了产品制造成本；填充坡口需要消耗大量的焊接材料；多道焊容易出现夹杂、熔合不良和热影响区过大等问题，焊接质量得不到保证[2,3]。这些问题随板厚的增加变得更加严重，因此提高电弧的熔透能力和焊接质量成为焊接领域的一个难题[2]。

激光焊由于具有功率密度高、同等热输入量时熔深大、热影响区窄、焊接变形小、焊接速度快和易于实现自动化等优点，在焊接生产中具有很大的应用潜力。但是利用激光束来焊接铝合金时，由于铝合金对激光的反射率高、导热快等特性，常需要采用较大功率的激光器进行焊接，造成焊接成本过高，且在激光焊接铝合金厚板时也易出现稳定性差、气孔、裂纹、下塌等焊接缺陷[4,5]。

作者利用激光—电弧双面焊工艺(laser-arc double sides welding，LADSW)对铝合金进行了焊接试验，结果发现该工艺除了具有显著增加熔深、提高电弧的熔透能力和材料对激光的吸收率、减少焊接缺陷、降低焊接成本、提高焊接生产率等技术优势外，还具有改善焊缝成形、提高接头质量等优势。由于激光—电弧双面焊的接头形状与常规的单面焊的差别较大，且接头形状对接头的组织和力学性能影响较大。因此，对双面焊的接头形状进行研究有着重要的理论意义和工程应用价值。

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1 试验材料和试验方法

1.1 试验材料

试验材料为4 mm厚5A06铝合金板，其材料的化学成分如表1所示。

表1 5A06的化学成分(质量分数，%)
Table 1 Chemical composition of 5A06 aluminium alloy

Mg	Mn	Fe	Si	Al
6～6.8	0.5～0.8	≤0.4	≤0.4	余量

1.2 试验方法

利用3 kW的CO_2激光器和逆变氩弧焊机共同组成双面焊的热源，在自制的立焊行走机构上进行铝合金激光—电弧双面焊工艺试验。双面焊过程中，两热源同时对称加热工件，立焊行走机构带动工件运动，如图1所示。

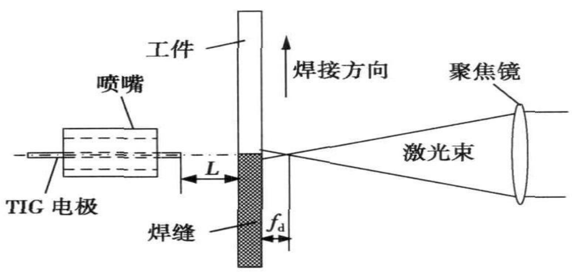

图 1 双面焊试验装置示意图

Fig 1 Schematic diagram of LADSW

2 结果和讨论

2.1 焊缝成形和熔透条件

图2 为相同条件下,单电弧、单激光及激光—电弧双面焊的接头形貌。

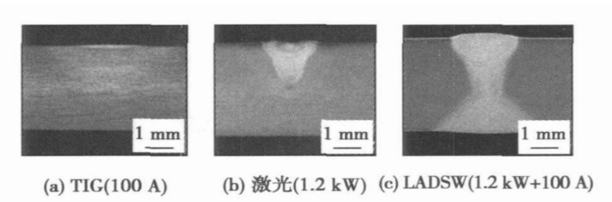

图 2 三种焊接方法的接头形貌(v= 1.0 m/min)

Fig. 2 Cross-section of three methods(v= 1. 0 m/min)

从图 2 可以看出,100 A 电流,1.0 m/min 的焊接速度下进行 TIG 电弧焊时,工件基本没有熔化(图 2a);1.2 kW 激光单独焊接时,焊缝的熔深较浅(图 2b);双面焊在激光与电弧共同作用下,两侧的焊缝熔深都得到了显著增加,实现了在小功率激光条件下的 4 mm 厚 5A06 铝合金的全熔透焊接。

为保证双面焊工件的使用性能,必须保证双面焊接头的完全熔透。在大量试验基础上,总结双面焊熔透的工艺条件,如表 2 所示。从表 2 可知,当焊接速度(≤1.0 m/min)较低时,保证双面焊熔透所需的焊接电流和激光功率都较低;随着焊接速度的提高,为保证工件的完全熔透,双面焊所需的激光功率和焊接电流都要进行相应的增大。

表 2 双面焊熔透的工艺条件

Table 2 Parameters of full pentration in LADSW

焊接速度 v/(m·min^{-1})	焊接电流 I/A	激光功率 P/W	电弧长度 L/mm	离焦量 f_d/mm
≤1.0	≥80	≥1 000	2.0~4.0	≤±1.0
1.0~2.0	≥150	≥1 500	2.0~4.0	≤±1.0

2.2 接头形状特征量定义

图 3 为熔透条件下,单激光、单电弧及激光—电弧双面焊的典型的接头形状。

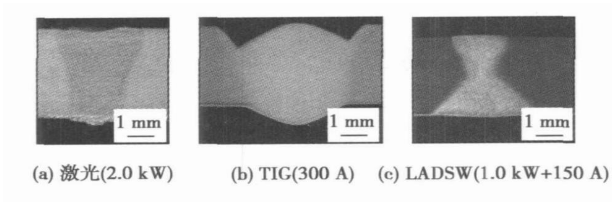

图 3 单面焊和双面焊的接头成形(v= 1.0 m/min)

Fig 3 Joint appearance of single-side and LADSW (v= 1. 0 m/min)

从图 3 可以看出,双面焊与单面焊接头形状的最大区别在于,双热源在工件两侧同时对称加热工件,在接头中部存在一个最小熔宽,而最小熔宽的大小和深度决定了其熔透程度,进而影响接头的组织和力学性能。为表征这种形式的接头,对双面焊的接头特征进行了定义,如图 4 所示。其中,W_l,W_a 分别为激光和电弧侧的焊缝熔宽;W_m 为焊缝中部的最小熔宽;h 为最小熔宽至激光侧的距离;h_l,h_a 分别为激光和电弧侧熔深。

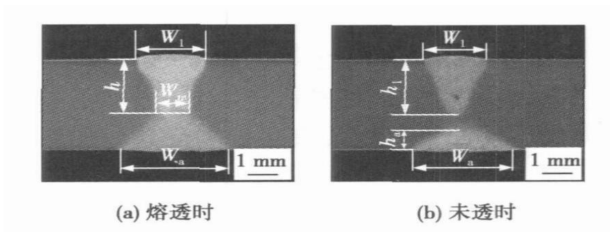

图 4 双面焊的接头特征量定义

Fig. 4 Definition of cross-section in LADSW

2.3 接头熔宽特征

图 5,图 6 分别为其它条件相同,激光功率或焊接电流不同时的典型接头形状。图 7 为两热源能量匹配对双面焊熔宽的影响。可以看出,随着激光功

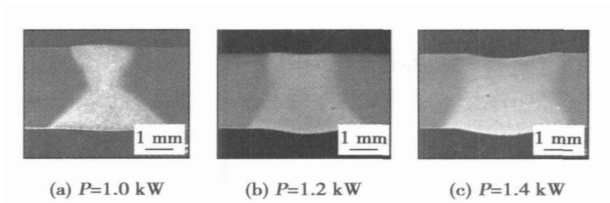

图 5 不同激光功率时典型的接头形状(I= 150 A)

Fig 5 Joints appearance of different laser powers(I= 150 A)

率的增加，激光与电弧侧的熔宽都增大，且增大趋势基本一致。随着焊接电流的增大，电流侧熔宽的增加趋势要大于激光侧的。这可能与激光和电弧的能量密度及其熔透能力不同有关。

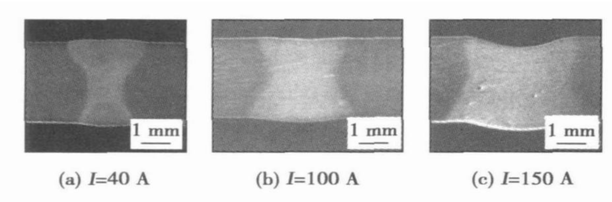

图 6　不同焊接电流时典型的接头形状（P= 1.5 kW）

Fig. 6　Joints appearance of different welding currents (P= 1.5 kW)

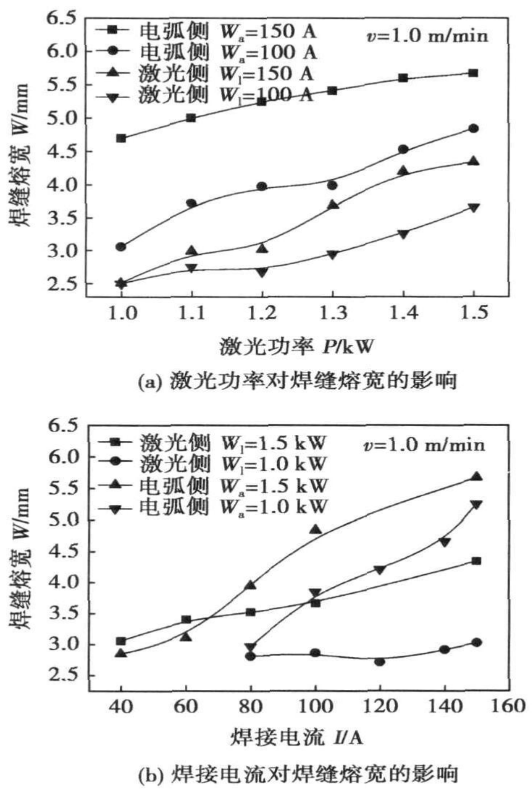

图 7　两热源能量匹配对双面焊熔宽的影响

Fig. 7　Relation of power ratio and weld width

2.4　接头最小熔宽特征

图 8 为两热源能量匹配对接头最小熔宽特征的影响。

可以看出，无论是增加激光功率，还是增大焊接电流，焊缝中部的最小熔宽都增加，接头的熔透程度增大，且两者的增加趋势基本一致。当焊接热输入较小（如电流较小或激光功率较小）时，焊缝最小熔宽的深度略有波动；当焊接热输入达到一定程度后，

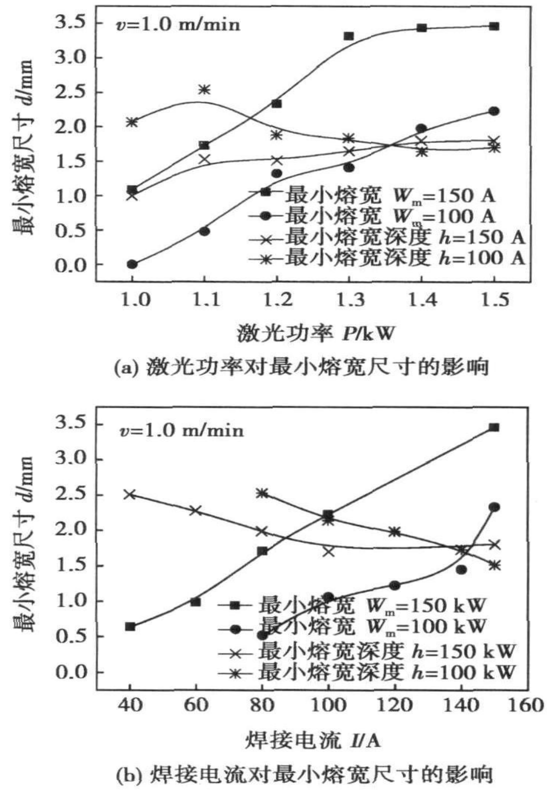

图 8　两热源能量匹配对接头最小熔宽特征影响

Fig. 8　Relation of power ratio and minimum width

如激光功率（$P \geqslant 1.3$ kW）或焊接电流（$I \geqslant 120$ A）较大时，最小熔宽的深度基本保持不变，即焊缝最小熔宽的位置与两热源的能量配比及其绝对值无关。这可能是由于焊接热输入较大时，两热源形成稳定的同一熔池（图 5b 和图 6b）后，改变能量配比对焊缝最小熔宽深度的影响不大。

2.5　接头深宽比特征

进一步在未熔透条件下，研究了焊接速度及其导致的散热条件变化对双面焊两侧的焊缝成形及其深宽比的影响。图 9 为其它条件相同，焊接速度不同时典型的焊缝成形。图 10 为焊接速度与焊缝尺寸的关系。可以看出，随着焊接速度的提高，双面焊

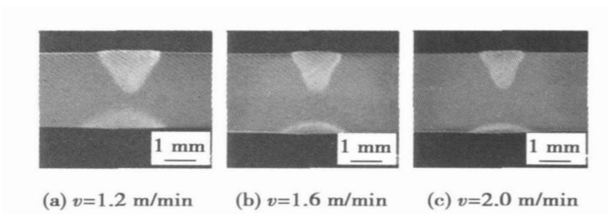

图 9　不同焊接速度的接头形状（1.2 kW+ 100 A）

Fig. 9　Joints appearance of different welding rates (1.2 kW+ 100 A)

两侧的熔宽和熔深都减小。从图 10b 可知，激光侧的深宽比随焊接速度的提高而增大，而电弧侧深宽比随焊接速度的提高而减小；当焊接速度提高到一定程度（$v \geq 1.6$ m/min）后，激光和电弧侧的深宽比基本保持不变。

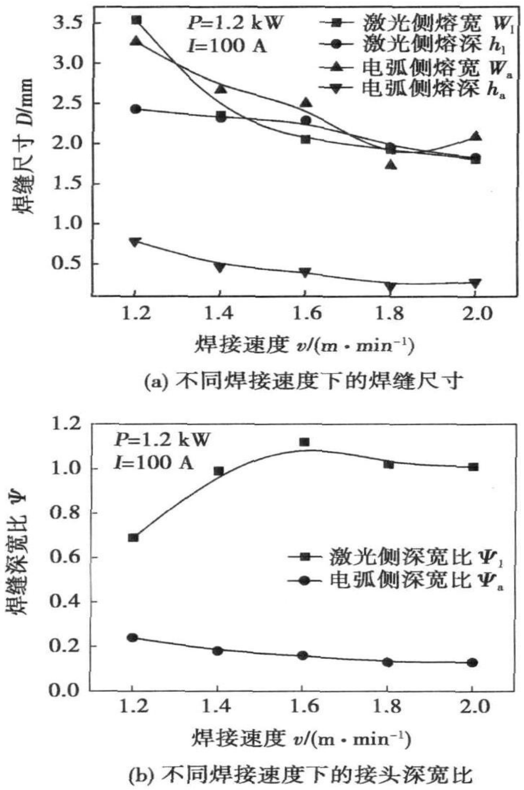

图 10 焊接速度与焊缝尺寸的关系

Fig. 10 Relation of welding rate and weld dimension

分析认为，这是由于激光和电弧的能量密度不同引起的。激光焊的能量密度高，主要依靠"匙孔"进行焊接[6]，焊接速度提高后，材料的横向热扩散条件变差，有利于形成深宽比大的焊缝，而焊接速度较高时，双面热源的能量相互增强作用变小，又不利于接头深宽比的增大；而电弧热源的能量密度要小得多，主要依靠电弧热来加热工件，焊接速度提高后，激光和电弧的相互作用变小，电弧热源的能量利用率降低，电弧的稳定性也变差，从而导致了其接头深宽比的减小。

3 结 论

（1）随激光功率的增加，激光和电弧两侧的熔宽都增大且两者增加的幅度基本相同；提高焊接电流，两侧的熔宽也随之增大，但电弧侧熔宽增加的幅度更大。

（2）增加激光功率或提高焊接电流都会造成焊缝最小熔宽的增加，最小熔宽的深度也发生一定的变化，当焊接热输入达到一定程度后，即双面焊形成稳定的同一熔池后，改变两种热源的能量配比对最小熔宽的深度影响就比较微弱。

（3）随着焊接速度提高，双面焊两侧的熔宽和熔深都减小，激光侧的深宽比随焊接速度的提高而增大，而电弧侧的深宽比随焊接速度的提高而减小；当焊接速度提高到一定程度后（$v \geq 1.6$ m/min），焊接速度对焊缝深宽比的影响变得不明显。

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to ensure the accuracy of sampled arc voltage in arc voltage sampling circuit. The test shows that the two circuits are simple, reliable and easy to operate and play an important role in increasing anti-interference characteristic of control circuit.

Key words: anti-interference; circuit design; photoisolator; filtering

Volt-ampere characteristic of plasma arc in air plasma spraying

YANG Hui, WANG Liang (The Second Artillery Engineering College, Xi' an 710025, China). p77—80

Abstract: The volt-ampere characteristics deciding the electric arc power, which affect the fusion of the spraying powder and then influence the quality of coatings, are affected by many factors including gas species, gas flow rates, the nozzle' s aperture and compression angle. So the factors influencing the volt-ampere characteristics were studied. The results showed that the arc voltage is increased with the primary gas flow rates in some range. The secondary gas flow rates have an important effect on the electric arc voltage. The influence of nitrogen on the arc voltage is more than argon when they are chose as the primary gas in plasma spraying. The arc voltage is decreased with the increase of the nozzle' s compression angle and the decrease of the nozzle' s aperture when the length of the nozzle is unvarying.

Key words: plasma arc; volt-ampere characteristic; air plasma spraying; nozzle

Analysis of stress intensity for dimple jacket

ZHANG Guodong, LI Zheng, ZHOU Changyu (College of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 210009, China). p81—84

Abstract: Due to the complexity of loading case in dimple jacket weld, the problem of leakage is always happened in weld, which is induced by cracks in weld. Welding residual stress is one of the main affected factors. By the finite element analysis code ABAQUS and the function of coupling process between heat and stress, the methods of plug welding and fillet welding were simulated for 304 stainless steel dimple jacket and the distribution of welding residual stress was obtained. The results indicated that the residual stress of plug welding was higher than the residual stress of fillet welding in weld. The much higher residual stress was produced by plug welding in the hole of dimple jacket, and the residual stress of first dimple jacket hole was affected greatly after the second hole had been welded. But the affection was little when the method of fillet welding was applied. Intensity calculation for plug welding and fillet welding was carried out, and the results shown that loading bearing capacity of fillet welding is better. The research results provided theory base for the analysis design and controlling welding cracks of dimple jacket.

Key words: dimple jacket; fillet welding; plug welding; welding residual stress; finite element analysis

Joint characteristics of laser-arc double sides welding for aluminum alloy

MIAO Yugang, LI Liqun, CHEN Yanbin, WU Lin (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p85—88

Abstract: A novel technology of laser-arc double sides welding for aluminum alloys was explored. The stability welding process and better appearances can be obtained in double sides welding, except of deeper penetration, higher efficiency and lower cost. The effect of welding parameters on the characteristics of the joints was investigated systemically. The results showed that with the increase of laser powers, the weld width of both laser side and arc side became broadened, and the degree of an increase of the widths of both laser side and arc side was almost consistent. With the increase of currents, the widths of both laser side and arc side will be enlarged, and the extent of an increase of the width of arc side was more obvious than that of laser side. Whether laser powers or arc currents are augmented, the minimum widths of cross-sections will rise. Moreover, the depth of minimum width will fluctuate with the alteration of heat input. If the heat input increases to some extent, the depth of minimum width is invariant. With the increase of welding rates, the width and depth of double sides welding will fall, and results in the increase of depth-width ratio in laser welding and the reduction of depth-width ratio in arc welding.

Key words: laser-arc double sides welding; aluminum alloys; characteristics of joints

Structure and performance of LF6/TA2 diffusion bonded joint

YAO Wei, WU Aiping, ZOU Guisheng, REN Jialie (Key Laboratory for Advanced Materials Processing Technology of Ministry of Education, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China). p89—92, 96

Abstract: Structure and performance of the Ti/Al diffusion bonded joint was studied by means of scanning electron microscopy, X-ray diffractometry and shear strength measurement. The results showed that the highest joint strength was 83 MPa. When the bonding temperature reached 525 ℃, the diffusion reaction occurred, and $Al_{18}Ti_2Mg_3$ was the unique product from the diffusion reaction. Meanwhile, the joint strength depended on the percentage of solution metallurgical combination area and new phase zone, and it increased with the accretion of solution area but decreased with the accretion of new phase zone. Although interdiffusion of Al and Ti proceeded in the bonding process, Mg did not diffuse to TA2. The results also showed the new phase layer grew in accordance with the linear law.

Key words: diffusion bonding; diffusion reaction; joint structure

Influence of chromium and boron on wettability of nickel-based high temperature filler metal on C_f/SiC ceramic matrix composite

ZHANG Yong[1], ZHANG Guoqing[1], HE Zhiyong[2], FENG