铝合金激光深熔焊气孔形成机理与控制技术

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摘 要：观察了铝合金激光深熔焊气孔的分布特征和形貌特征，深入分析了气孔的形成机理，研究了双光点能量分布的激光对铝合金激光深熔焊气孔的控制效果. 结果表明，铝合金激光深熔焊焊缝中存在分布特征和形貌特征不同的两类气孔，即冶金类气孔和工艺类气孔. 冶金类气孔的形成与氢在熔池中的析出、聚集与合并有关，而工艺类气孔产生的根本原因是焊接过程中匙孔的瞬间失稳. 采用双光点能量分布的激光焊接铝合金可以扩大匙孔张口和根部直径，改善匙孔壁的波动状态，增强匙孔的稳定性，从而减少工艺类气孔的产生，但对冶金类气孔没有明显影响.

关键词：激光深熔焊；气孔；双光点；铝合金
中图分类号：TG46.7 文献标识码：A 文章编号：0253—360X(2009)01—0060—03

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0 序 言

聚焦激光作为一种高能量密度热源用于焊接与传统弧焊方法相比具有许多优势. 然而，在激光深熔焊模式下，由于材料物性、装配条件以及等离子体波动等因素的干扰，往往导致焊缝根部出现气孔，尤其在未焊透和临界焊透条件下[1,2]. 文献[3]利用X射线成像装置对铝合金激光深熔焊气孔的产生过程进行了实时观察，发现大量气泡周期性地产生于匙孔根部，但没有对激光深熔焊气孔的形成机理与控制技术做更深入的研究. 文中观察了铝合金激光深熔焊气孔的分布特征和形貌特征，深入分析了气孔的形成机理，研究了双光点能量分布的激光对铝合金激光深熔焊气孔的控制效果.

1 试验方法

试验材料采用 5083 铝合金，其化学成分如表 1 所示[4]. 焊接试板采用金属清洗液除去材料表面油污，并用 5%HF＋10%HNO_3＋H_2O（余量）除去材料表面氧化膜，焊前用丙酮擦拭焊接区表面. 焊接过程中采用氩气作为熔池保护气.

表 1 5083 铝合金的化学成分（质量分数，%）

Table 1 Chemical composition of 5083 aluminum alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.40	0.40	0.10	0.40～1.0	4.0～4.9	0.05～0.25	0.25	0.15	余量

试验采用激光器为 Trumpf 灯泵浦 YAG 激光器，其最大输出功率为 3 kW. 焊接头采用 HIGHYAG 双光点激光焊接头，如图 1 所示. 激光通过光纤传输，经双光点焊接头中焦距为 150 mm 的透镜聚焦能够获得焦斑直径为 0.45 mm 的激光光斑. 调整双光点焊接头中楔形镜的位置可以获得两个位向和距离均可调的、焦斑直径为 0.45 mm 的激光光斑，即可实现单光点和双光点激光焊接. 填丝焊时采用 PLANETICS 推拉式送丝机构填加焊丝. 焊接过程中工作台静止，由六轴机械手带动激光器相对运动实现.

针对单光点和双光点激光焊接（包括不填丝和填丝）工艺，预定离焦量为 0 mm，激光功率为 3 kW，根据板面堆焊焊缝的熔透性和表面质量确定最佳焊接速度，并以此焊接工艺参数进行对接焊. 双光点激光焊接时，预定双光点的功率配比为 50∶50，双光点距离为 0.27 mm，光点位向与焊接方向的关系如

收稿日期：2008—02—28

图 2 所示. 填丝焊时,填丝方向与焊接方向相反, 且与激光方向间夹角为 30°,填丝速度为1.5 m/min. 为减小反射光对激光器和外光路光学元件的损害, 焊接头中轴线逆着焊接方向偏转 10°.

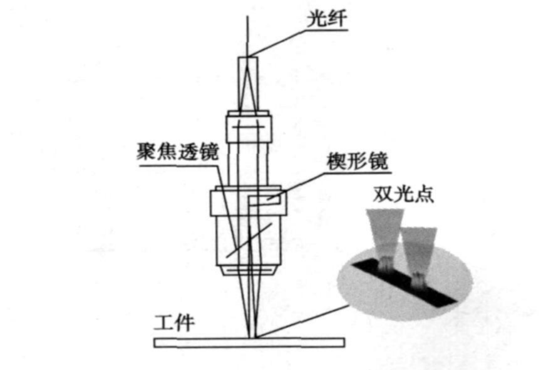
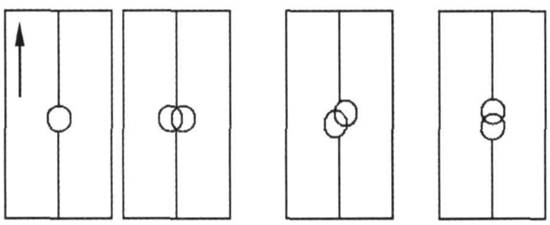


图 1　双光点激光焊接原理
Fig. 1　Principle of twin spot laser welding



(a) 单光点 (b) 并行双光点 (c) 45° 位向双光点 (d) 列行双光点

图 2　光点位向与焊接方向的关系
Fig. 2　Relationship between spot rotation and welding direction

2　试验结果与分析

2.1　气孔分布特征

图 3 为焊缝 X 射线检测形貌. 可以看出, 激光焊接铝合金焊缝中容易产生较多数量的气孔. 气孔体积大小不一,其中较大体积的气孔多分布于焊缝中心, 而较小体积的气孔则分布于焊缝及其两侧的熔合区内.

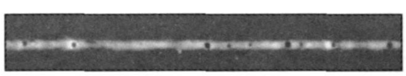


图 3　典型焊缝 X 射线检测形貌
Fig. 3　Radiograph of typical weld

2.2　气孔形貌特征

图 4 为焊缝横截面上气孔扫描电镜形貌. 可以看出, 激光焊接铝合金焊缝中存在形貌特征不同的两类气孔. 图 4a 所示气孔呈规则的椭球形, 体积一般较小, 气孔内壁较光滑. 图 4b 所示气孔形状不规

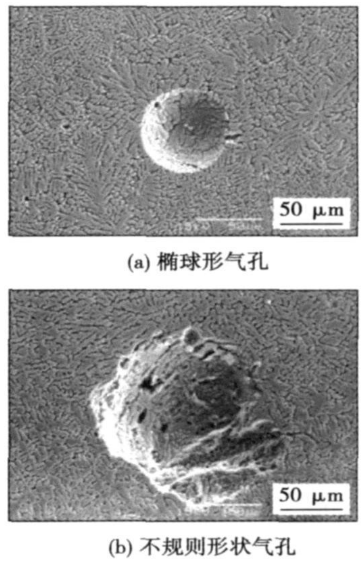


图 4　气孔扫描电镜形貌
Fig. 4　SEM of porosities in weld

则, 体积一般较大, 气孔内壁较粗糙, 呈涡流状.

2.3　气孔形成机理

文献[3]研究表明, 激光焊接铝合金焊缝中小气孔的产生主要与氢在熔池中的析出有关. 另外, 多个小气孔也可能通过聚集、合并等方式形成体积较大的气孔. 这类气孔的产生主要是焊接冶金因素造成的, 因此称之为冶金类气孔. 通过焊前对焊接材料表面进行严格的化学或物理清理以及焊接过程中加强对焊接熔池的保护等措施可以减少冶金类气孔的产生. 焊缝中大气孔的产生主要与激光匙孔焊接模式有关, 因此称之为工艺类气孔. 文中重点分析工艺类气孔的形成机理.

众所周知, 激光焊接时, 如果作用于母材金属的激光功率密度足够高(对 YAG 激光, 功率密度需达到 10^6 W/cm^2 以上), 母材金属将迅速熔化、汽化和电离, 并在金属蒸气和等离子体压力作用下产生一个沿焊接厚度方向渐细的匙孔. 匙孔周围被熔池液体金属所包围, 并在金属蒸气和等离子体压力、熔池液体金属重力和表面张力等因素共同作用下力图维持稳定. 然而实际上, 匙孔在各种变化的热学和力学因素作用下始终处于不稳定的波动状态.

文献[4]利用 X 射线成像装置对铝合金激光焊接过程中匙孔的波动和气孔的产生过程进行了实时观察. 观察发现, 激光能量并不是均匀地作用在整个匙孔上, 而是非常集中地作用于匙孔前壁的某一局部位置, 并造成局部材料的汽化. 当激光集中加热位置位于匙孔前壁的上部时, 由于匙孔上部直径比较大, 材料汽化产生的金属蒸气和等离子体比较容易喷发出去. 但是当激光集中加热位置移动到匙孔根部时, 由

于匙孔根部直径非常小,金属蒸气和等离子体更不容易喷发出去,并且匙孔壁对激光能量存在聚焦效应,使得匙孔根部材料的汽化膨胀尤为剧烈. 匙孔根部前壁材料的剧烈汽化膨胀将对匙孔后壁对应位置产生巨大的冲击,使匙孔后壁局部向熔池内部凹陷. 周围熔池液体金属在重力和表面张力作用下塌陷, 导致匙孔根部瞬间失稳,并将匙孔根部的金属蒸气、焊接保护气及少量侵入匙孔的空气等卷入熔池形成气泡. 这类气泡体积一般较大,并且由于铝合金流动性较好,因此少数气泡可以随液体金属流动迁移而逸出熔池. 但是由于激光焊接速度较快,大多数气泡一般来不及逸出熔池即被迅速冷却凝固的金属包围,并在焊缝中心附近形成气孔. 熔池金属凝固前气泡在熔池中剧烈的翻滚迁移使气孔内壁呈涡流状.

金属蒸气和等离子体的周期性波动也是造成匙孔不稳定的重要因素. 金属蒸气和等离子体的周期性波动使匙孔吸收的激光能量发生周期性变化,匙孔壁液体金属的表面张力也随之发生变化. 匙孔壁将在表面张力周期性变化作用下发生波动,并有可能在最小直径处封闭,导致匙孔瞬间失稳,并将匙孔内部的气体卷入熔池,最终形成气孔.

以上分析表明,工艺类气孔产生的根本原因是激光焊接过程中匙孔的瞬间失稳.为了减少或消除工艺类气孔,必须保证焊接过程中匙孔的稳定.

2.4 双光点能量分布的激光对气孔的影响

图5是对单光点和双光点激光焊接铝合金焊缝(长度为300 mm)中不同直径气孔数量的统计结果. 从统计结果可以看出,与单光点激光焊接相比,双光点激光焊接铝合金可以显著减少焊缝中直径在0.6 mm以上的大气孔(主要为工艺类气孔)的数量,但对焊缝中直径在0.4 mm以下的小气孔(主要为冶金类气孔)数量的影响不明显. 研究表明,双光点激光焊接的光点位向对焊缝中工艺类气孔的数量有较大的影响. 列行双光点焊接工艺类气孔数量较少,并行双光点焊接工艺类气孔数量较多,45°双光点位向焊接介于前两者之间. 填丝焊时,焊丝熔滴过渡将削弱匙孔稳定性,因而增大工艺类气孔产生的倾向. 但采用双光点激光焊接仍可使焊缝中工艺类气孔的数量明显减少.

以上试验结果表明,采用双光点能量分布的激光焊接铝合金在稳定焊接匙孔和控制工艺类气孔数量方面具有明显效果. 主要原因在于,双光点激光各自产生的匙孔叠加在一起,使匙孔张口和根部直径得到扩大,匙孔壁的波动状态也得到改善,一方面匙孔前壁材料汽化面积增大,削弱了材料汽化对匙孔后壁的局部冲击,金属蒸气和等离子体更容易从匙孔张口喷发出去,另一方面金属蒸气和等离子体的周期性波动不易造成匙孔壁的封闭,增强了匙孔的稳定性,从而减少了工艺类气孔的产生.

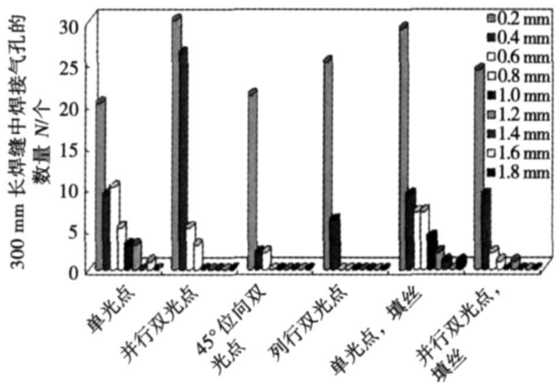


图 5 300 mm 长焊缝中不同直径气孔数量统计结果
Fig. 5 Number of porosities with different diameters in weld of 300 mm length

3 结 论

(1) 铝合金激光深熔焊焊缝中存在分布特征和形貌特征不同的两类气孔,即冶金类气孔和工艺类气孔.

(2) 冶金类气孔的形成与氢在熔池中的析出、聚集与合并有关,而工艺类气孔产生的根本原因是焊接过程中匙孔的瞬间失稳.

(3) 采用双光点能量分布的激光焊接铝合金可以扩大匙孔张口和根部直径,改善匙孔壁的波动状态,增强匙孔的稳定性,从而减少工艺类气孔的产生,但对冶金类气孔没有明显影响.

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lyre commended.

Key words: laser cladding; multiple linear regression; genetic neural network; prediction of the form; comparative analysis

Effect of gallium on microstructure and properties of Ag-Cu-Zn filler metal LU Fangyan[1], XUE Songbai[1], LAI Zhongmin[1,2], ZHANG liang[1], GU Liyong[3], GU Wenhua[3] (1. Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; 2. Jiangsu University of Science and Technology, Zhenjiang 212003, Jiangsu, China; 3. Changshu Huayin Filler Metals Co. Ltd., Changshu 215513, Jiangsu, China). p55—59

Abstract: Melting temperature, spreadability, microstructures of silver filler metal with different content of gallium, and the mechanical properties of brazed joints were studied respectively. Results show that adding gallium can decrease the melting temperature, improve the spreadability of the silver filler metal, and the microstructure of the silver filler metal was refined significantly. Using copper and brass plates as base metal, brazing with flame method, the mechanical properties of the joints brazed with lap joint and butt joint were tested and analyzed at the same time. Results indicate that the fracture position of two kinds of brazed joints happened on the base metal, except for the lap joint of brass, which shows better mechanical properties of the joints brazed with the silver filler metal bearing gallium; For the lap joint of brass, the tensile strength gradually strengthened with the increasing of gallium content, and the optimum content of Ga cowsing best comprehensive properties of the AgCuZn filler metal is about 3.0%.

Key words: silver filler metal; melting temperature; spreadability; microstructure; mechanical properties;

Porosity formation mechanisms and controlling technique for laser penetration welding of aluminum alloy GONG Shuili[1], YAO Wei[1], Steve Shi[2] (1. National Key Laboratory for High Energy Density Beam Processing Technology, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China; 2. TWI Ltd, Cambridge CB1 6AL, United Kingdom). p60—62

Abstract: The distribution and appearance characteristics of porosities in laser penetrated weld of aluminum alloy were observed, the formation mechanisms of porosities were analyzed in detail, and the influences of twin-spot laser energy distribution on porosities were investigated. It showed that there are two kinds of porosities, metallurgical and technologic porosities, in laser penetrated weld of aluminum alloy. The formation of metallurgical porosities is related to the separation, congregation and incorporation of hydrogen in the weld pool, while instantaneous instability of its keyhole is an essential reason for the occurrence of technologic porosities. Twin spot laser energy distribution can enlarge diameters of the opening and the root of its keyhole, improve fluctuating conditions of the wall of its keyhole, increase stability, and consequently decrease technologic porosities in number; but it has no obvious influence on metallurgical porosities.

Key words: laser penetration welding; porosity; twin spot; aluminum alloy

Development of duplex stainless steel flux-cored wire GDQA2205 LI Wei, LI Zhuoxin, LI Guodong, LI Hui (Department of Material Science and Engineering, Beijing University of Technology Beijing 100124, China). p63—67

Abstract: The developed wires were used for gas metal arc welding. The chemical composition, microstructure, tensile strength and corrosive pitting rate of weld bead and Rockwell hardness, bend strength and impact toughness of welded joint were investigated. The microstructure of weld metal was analyzed by metalloscope. The impact fracture was analyzed by scanning electron microscope, and inclusions of impact fracture were analyzed by energy spectrometer. Experiment results indicated that it was effective to add rational nickel and MnN in the wire to accelerate austenite formation. The influence factors of pitting corrosion resistance and impact ductility were studied. It had been found that, besides chemical constitution, the uniform distribution of duplex phases in the weld metal could improve pitting corrosion resistance. Elements Mn, Ni, Cr etc. were the assurance of welded joint impact ductility.

Key words: duplex stainless steel; flux-cored wire; weld; joint performance

Image processing of weld seam based on beamlet transform DENG Shuangcheng[1], JIANG Lipei[1], JIAO Xiangdong[1], XUE Long[1], DENG Xiaobin[2] (1. Opto-Mechatronic Equipment Technology Beijing Area Major Laboratory, Beijing Institute of Petrochemical Technology, Beijing 102617, China; 2. Beijing Spacecrafts, China Academy of Space Technology, Beijing 100080, China). p68—72

Abstract: A novel algorithm based on beamlet transform for detecting weld seam edges was presented. Taking into account of some special characteristics of welding image processing, an orientation-thresholding step as well as a two-scan method to the standard beamlet-based line detection algorithm were introduced. Experiments are conducted to detect weld seam edges in noisy weld seam images to test the anti-noising performance of the algorithm. The result of experiments show that the algorithm is capable of directly extracting weld seam edges from highly noisy weld seam images without any pre-processing or post-processing steps, showing its high efficiency and prominent anti-noising performance. The two-scan method is particularly helpful when coping with low SNR weld seam images.

Key words: beamlet transform; weld seam; imogemage processing; line detection

Relation of welding speed and heat input at aluminum alloy friction stir welding YAN Keng, LEI Yanping, ZHANG Zhen, FANG Yuan, WANG Luzao (Provincial key Lab of Advanced Welding Technology, Jiangsu University of Science and Technology,