

镁合金铸件氦-氩保护 TIG 焊修复工艺

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摘要: 镁合金因其较高的比强度而在诸多领域发挥重要的减重作用, 且多为铸造构件, 但镁合金铸件的缺陷问题成为制造瓶颈. 对镁合金铸件修复工艺进行研究, 采用非熔化极惰性气体保护焊 (TIG 焊) 探究此工艺下不同保护气体对 TIG 焊修复焊道的成形、组织特征及性能的影响, 并通过不同氦-氩含量的保护气体下 TIG 焊电弧形态及电弧电压的研究, 分析氦气含量对修复焊道熔深的影响. 结果表明, 调整镁合金铸件 TIG 焊修复工艺保护气体中的氦气比例, 会改善焊道形貌; 增加保护气体中的氦气比例, 将有效提高焊道熔深和深宽比; 保护气体中氦气含量的改变对修复焊道组织、硬度无显著影响. 模拟缺陷修复试验结果表明, 镁合金铸件氦-氩保护 TIG 修复工艺可以满足铸件浅层缺陷修复需求, 增加保护气体中氦气含量可提高熔深, 提高此工艺的适用性.

创新点: (1) 通过改变保护气体中氦气含量改善镁合金铸件氦-氩保护 TIG 焊修复焊道形貌.

(2) 设计模拟缺陷修复试验, 验证了氦-氩保护 TIG 焊修复工艺的可行性.

关键词: 镁合金铸件; 缺陷修复; 氦气; 电弧特性

中图分类号: TG 444.2

文献标识码: A

doi: 10.12073/j.hjxb.20201223001

0 序言

镁合金具有密度小、比强度高、电磁屏蔽性好等特点, 在航空、航天、汽车等领域得到越来越广泛的应用. 但是镁合金室温下塑性较差, 难以加工成形, 主要以铸件的形式获得应用^[1-3]. 铸造过程中难以避免产生缺陷, 是目前镁合金铸件工程应用中必须要解决的问题, 所以对镁合金铸件进行缺陷修复具有必要性. 现在的普遍做法是将缺陷通过机械加工方法去除后进行熔覆修复, 再按设计要求尺寸进行加工修整^[4-6], 修复成本高、效率低, 且在反复熔覆过程中容易再次产生缺陷. 针对焊接缺陷 (如裂纹) 修复工艺的研究表明, 采用不填丝 TIG 焊修复的方法可以直接修复一定深度范围内的缺陷, 省去了缺陷去除和修复后加工修整的工艺流程, 具有工艺简单、使用方便、价格低廉等优点^[7]. 采用不填丝 TIG 焊工艺可以实现一些浅层缺陷的修复, 在镁合金铸件修复中有一定的应用价值, 有必要针对镁合金铸件 TIG 焊修复工艺开展研究.

保护气体成分会影响 TIG 焊电弧特性、焊道成形, 通常采用氩气作为 TIG 焊的保护气体, 而在 TIG 焊的氩气保护气体中加入氦气是增加焊道熔深的有效方法^[8-10]. 文中将不填丝 TIG 焊修复工艺应用于镁合金铸件缺陷修复中, 研究保护气体中氦气含量对 TIG 焊电弧特性、熔深、焊道成形的影响, 并进行了不同保护气体下不填丝 TIG 焊修复镁合金铸件模拟缺陷的修复试验, 拟重点阐明氦-氩保护 TIG 焊对浅层缺陷能力的影响.

1 试验方法

采用 Master TIG MLSTM3003 型交流焊接电源. 试件材料为 AZ91D 镁合金铸件, 尺寸为 200 mm × 100 mm × 10 mm. 焊接工艺参数如表 1 所示, 保护气体为氦-氩, 氦气含量分别为 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, 100%. 对不同氦气含量下焊道成形、组织及硬度进行测试. 为探讨氦气含量对焊道成形的作用, 试验采用 Phantom V311-32G 型高速摄像机进行电弧形态采集, 采集频率为 1 000 帧/s, 曝光时间 4 μm; 采用计算机外接数据采集卡进行电弧电压采集.

为了模拟镁合金铸件气孔、裂纹等孔洞类缺

表 1 焊接工艺参数
Table 1 Welding process parameters

焊接电流 <i>I</i> /A	焊接速度 <i>v</i> /(mm·s ⁻¹)	电弧长度 <i>a</i> /mm	保护气体流量 <i>Q</i> /(L·min ⁻¹)	钨极伸出长度 <i>l</i> /mm
160	4	1.5	14	11

陷、线状缺陷,在试板中加工一定深度的凹槽,并在凹槽底部钻取孔洞.图 1 为模拟缺陷的示意图,采用线切割的方法切出宽度 w 为 2 mm、深度 H 的凹槽,在凹槽底部钻孔径为 1 mm、深度 h 的孔.将槽块放回凹槽中,即在槽块下的孔形成内部孔洞类缺陷,槽块与凹槽侧界面即作为近表面线性缺陷.通过试验研究不同保护气体下 TIG 焊修复对缺陷的

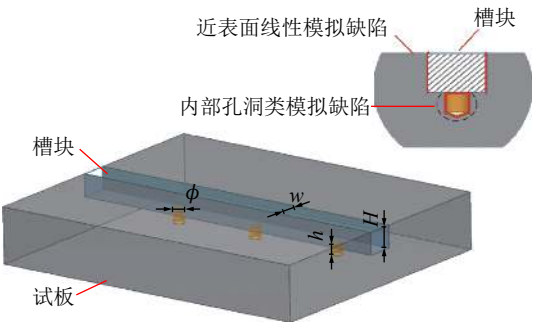


图 1 模拟缺陷设计示意图
Fig. 1 Simulated defect schematic

修复情况.修复完成后,在钻孔位置沿垂直焊道方向进行切割,观察缺陷修复情况.

2 试验结果与分析

2.1 保护气体对焊道形貌的影响

图 2 为不同的氦气含量下焊道形貌.随着保护气体中氦气含量增加,焊道形貌质量先提高后降低,在氦气含量为 50% 时焊道表面光滑,在其它氦气含量下焊道表面存在不同程度的鱼鳞纹.分析认为,不同氦气含量下焊道表面形貌的变化是由于电弧阴极清理作用的差异、电弧等离子流力的变化、熔池金属流动性的改变等因素造成.

2.2 保护气体对焊道熔深熔宽的影响

对不同氦气含量下焊道截面进行切割、磨抛及腐蚀,得到焊道截面的宏观形貌,并测量焊道熔深、熔宽.图 3 为焊道宏观金相.图 4 为熔深、深宽比

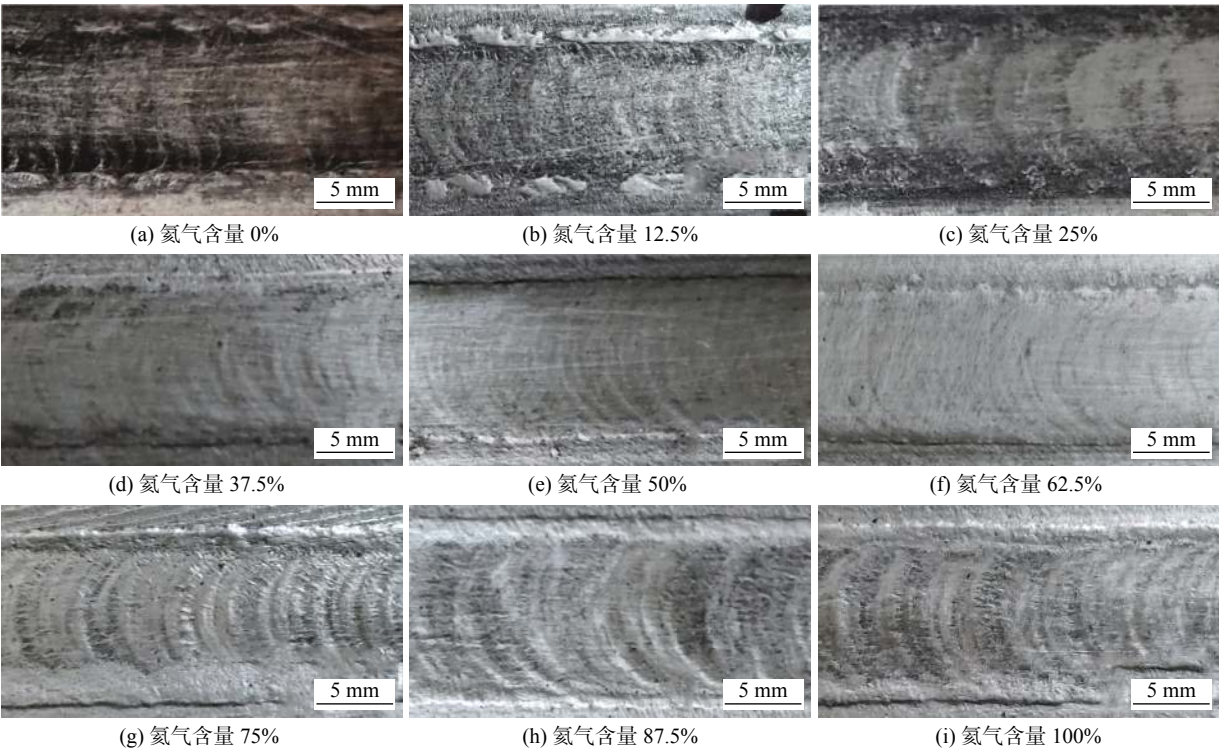


图 2 不同氦气含量的焊道形貌

Fig. 2 Weld appearance of different helium content. (a) helium content 0%; (b) helium content 12.5%; (c) helium content 25%; (d) helium content 37.5%; (e) helium content 50%; (f) helium content 62.5%; (g) helium content 75%; (h) helium content 87.5%; (i) helium content 100%

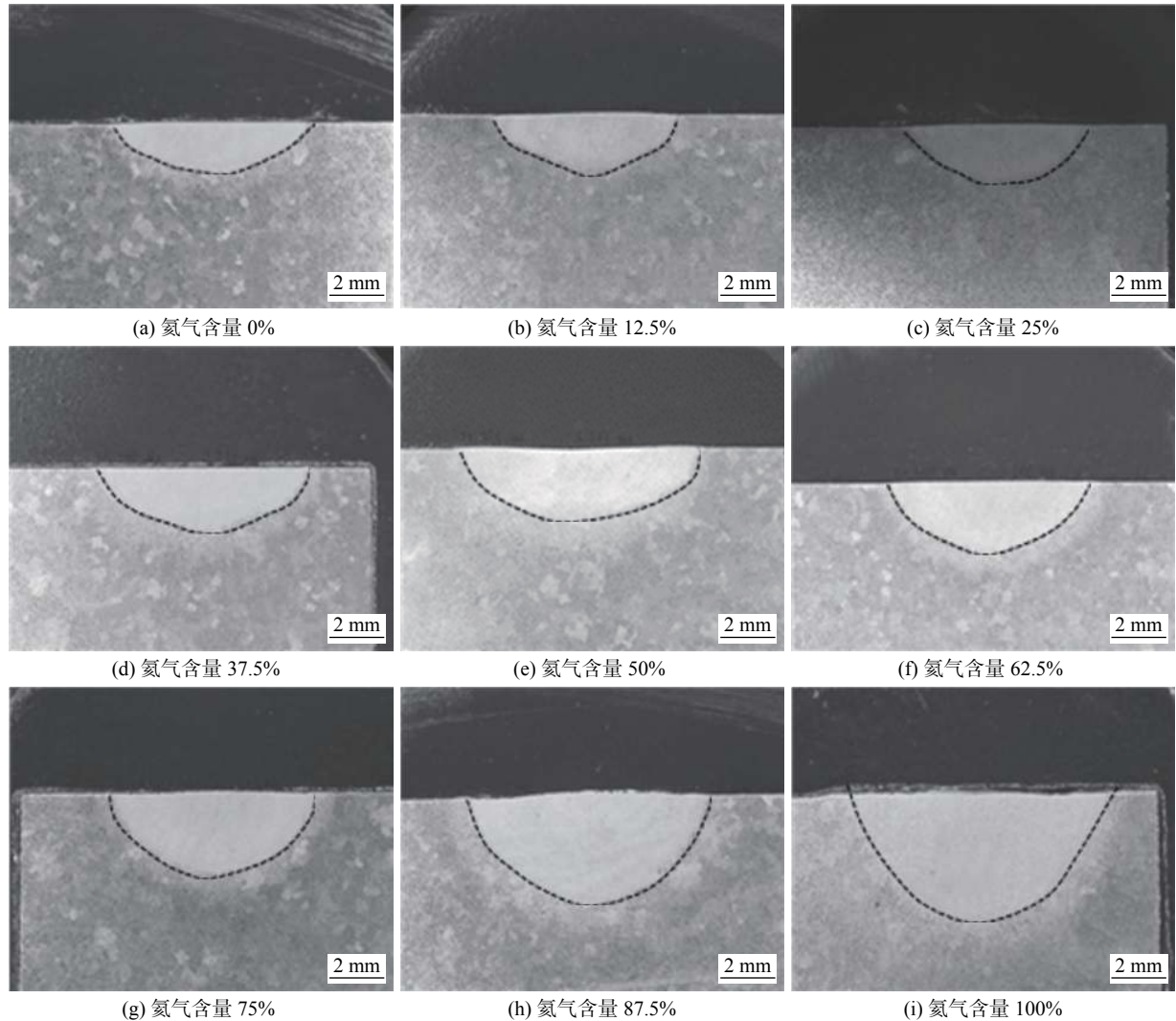


图 3 焊道宏观形貌

Fig. 3 Macroscopic metallographic of weld. (a) helium content 0%; (b) helium content 12.5%; (c) helium content 25%; (d) helium content 37.5%; (e) helium content 50%; (f) helium content 62.5%; (g) helium content 75%; (h) helium content 87.5%; (i) helium content 100%

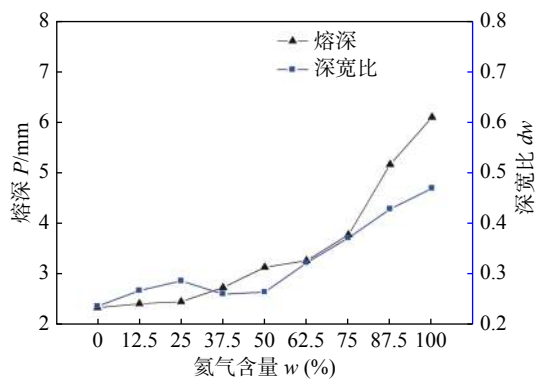


图 4 焊道熔深、深宽比与氦气含量关系曲线

Fig. 4 Relationship between weld penetration, penetration-to-width ratio and helium content

与氦气含量关系曲线. 从图 3 可知, 在 He-Ar 保护气体 TIG 焊修复焊道截面上均未出现气孔、裂纹等缺陷. 随着保护气体中氦气含量增加, 焊道熔深增

加, 且焊道深宽比呈现与熔深相似的增大趋势. 氦气含量从 0 增加至 100%, 焊道熔深从 2.3 mm 增长至 6.1 mm, 提高 2.6 倍, 深宽比从 0.23 增长至 0.47, 提高 1.98 倍. 当氦气含量超过 50% 时, 焊道熔深和深宽比大幅提高.

2.3 焊道组织特征

图 5 为不同氦气含量下焊道和部分熔化区组织. 图 5a 为保护气体 100% 氦气时焊道至母材区域的微观组织. 铸态 AZ91D 母材为典型铸态组织, 组织晶粒粗大, 在 α -Mg 基体上分布网状 β -Mg₁₇Al₁₂ 相. 焊道受高温热作用熔化后, 在较快的冷却速度下, 形成细小的等轴晶, 晶界析出连续的 β -Mg₁₇Al₁₂ 相. 在母材与焊道之间的区域, 其温度处于材料的固相线和液相线之间, 属于部分熔化区 (PMZ), 冷却过程中重新析出大量 β -Mg₁₇Al₁₂ 相. 对比不同氦

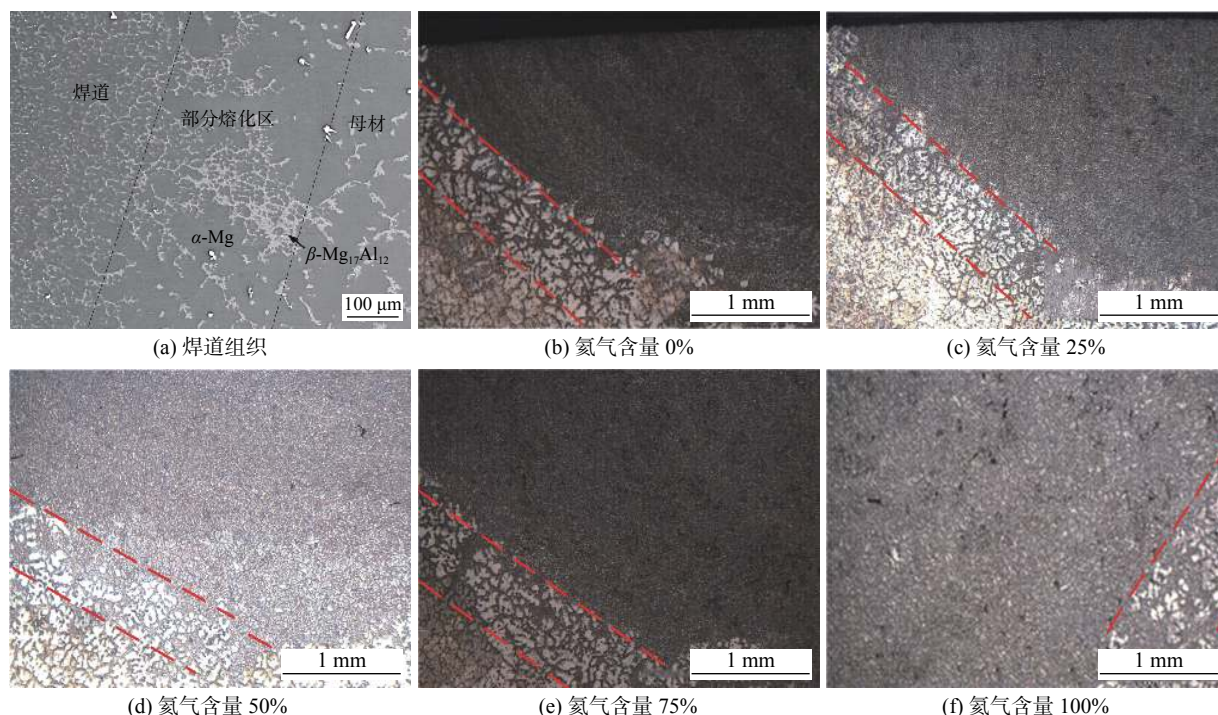


图 5 焊道和部分熔化区组织

Fig. 5 Microstructure of weld and PMZ. (a) microstructure of weld; (b) helium content 0%; (c) helium content 25%; (d) helium content 50%; (e) helium content 75%; (f) helium content 100%

气比例下 TIG 焊道的微观组织, 没有发现组织特征及相的变化. 图 5b~图 5f 为在不同氦气含量下的焊道部分熔化区组织. 对部分熔化区宽度进行测量, 随着保护气体中氦气比例的增加, 部分熔化区的宽度有小幅增加.

2.4 焊道硬度分析

为探讨氦气含量对焊道性能的影响, 测量不同氦气下得到焊道硬度, 对焊道截面中心取硬度测量点, 首点位置距焊道表面 0.5 mm, 每隔 0.5 mm 取一测量点, 取点范围由焊道表面至母材处. 图 6 为氦气含量为 50% 时硬度测试点示意图, 每组数据最后一个硬度数据为母材硬度, 由于不同试样熔深不

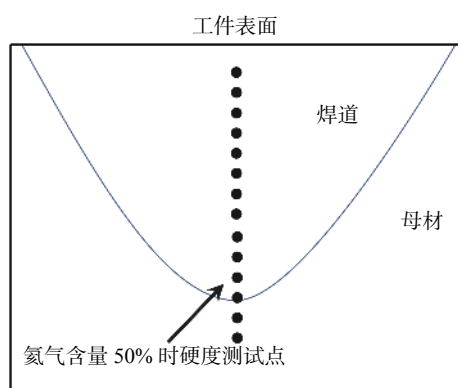


图 6 硬度测试点

Fig. 6 Hardness test point

同, 取点数量也有变化. 图 7 为焊道的硬度测试结果. 不同氦气含量下 TIG 焊道试样上的硬度差别较小, 而同一焊道试样上近表面处的晶粒更为细小, 靠近上表面的硬度较焊道中心较高, 但焊道区整体硬度没有明显的变化. 由于镁合金铸件试件组织粗大, 母材处硬度低于焊缝处硬度. 不同氦气含量对焊道硬度不会产生显著影响. 即在保护气体中加入氦气成分可以有效增加熔深, 且不会降低焊道力学性能.

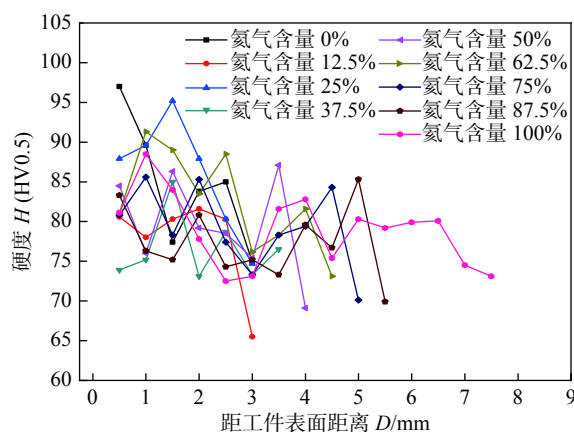


图 7 焊道硬度测量结果

Fig. 7 Hardness measurement results

2.5 电弧特性分析

焊接时焊枪不动, 试板随行走机构移动, 相机

固定于一指定位置对不同氦气含量保护气体下焊接电弧进行拍摄. 由于试验使用交流焊接, 所以分为正半波与负半波, 正半波时期电弧能量主要作用于母材, 负半波时期电弧主要发挥氧化层清理作

用. 所得稳定正半波电弧图像如图8所示. 图9为电弧形态示意图. 在保护气体为纯氩气时, 焊接电弧形态如图9a所示. 随着氦气含量增加, 焊接电弧形态逐渐变为图9b的形态.

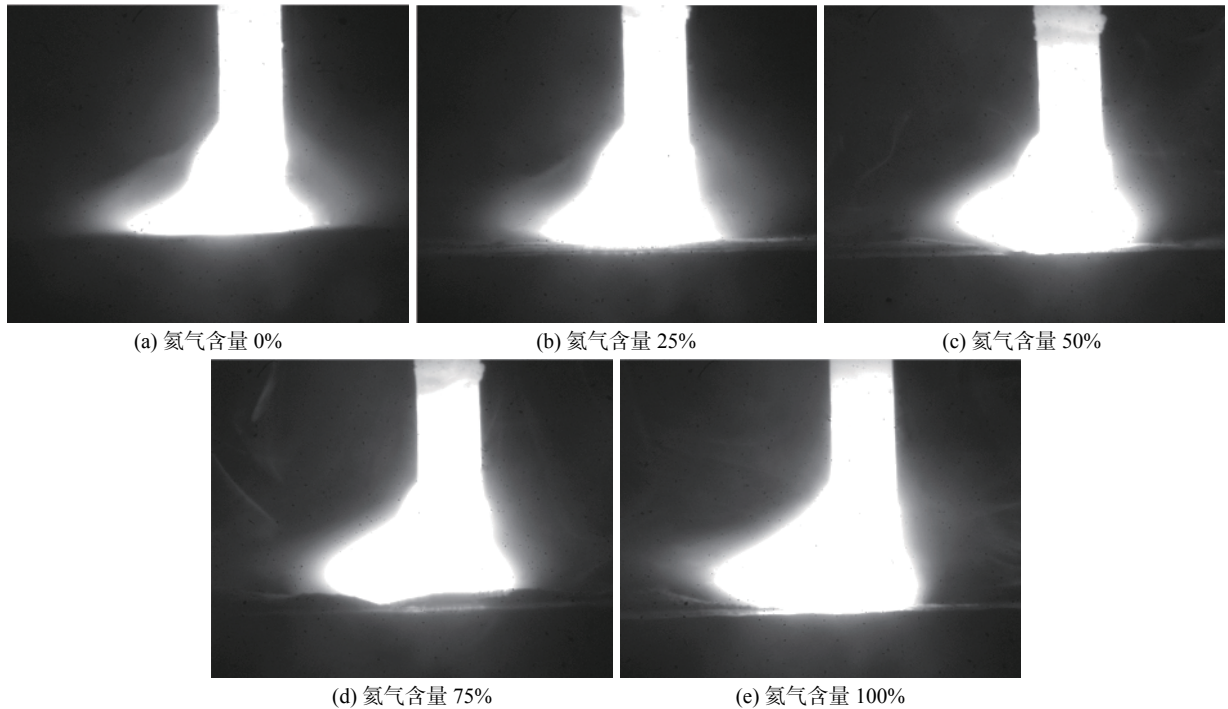


图8 不同氦气含量保护气下电弧形态

Fig. 8 Arc shape with different helium content. (a) helium content 0%; (b) helium content 25%; (c) helium content 50%; (d) helium content 75%; (e) helium content 100%

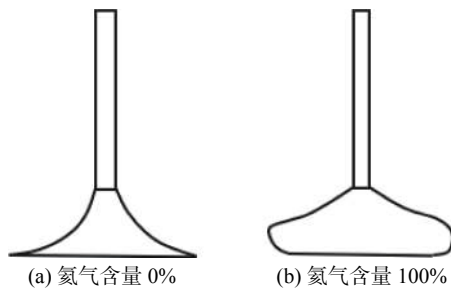


图9 电弧形态示意图

Fig. 9 Schematic diagram of arc shape. (a) helium content 0%; (b) helium content 100%

随着氦气含量的增加, 电弧中间段发生了一定程度的扩张, 而在试件表面区域则发生收缩. 不同保护气体下电弧形态的变化是保护气体不同比热、电导率、热导率及粘度等物理特性的变化引起的综合效应^[11]. 在相同的焊接电流下, 增加保护气体中氦气比例, 试件表面附近电弧收缩, 提高了试件表面区域电弧电流密度, 有助于提高焊道熔深及深宽比.

图10为电弧电压与氦气含量关系曲线. 图中数据为测量电弧稳定后多个周期数据的平均结果.

由于AZ91D镁合金板发射电子能力与高温钨极不同, 所以测得正半波电压与负半波电压绝对值不同.

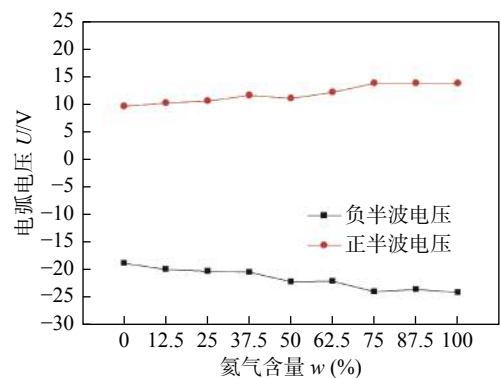


图10 电弧电压与氦气含量关系曲线

Fig. 10 Curve for arc voltage and helium content

随着保护气体中氦气含量增加, 正半波电压及负半波电压绝对值都有所增长, 当氦气含量高于50%时, 电压增长速率加大. 氦气的热导率较高, 使得氦气和周围环境的热量交换更为迅速, 对电弧起到了一定的冷却效果, 电弧将会收缩以减小散热面

积, 电弧能量密度增大; 另一方面, 氦原子的电离电压远高于氩气, 所以在保护气体中加入氦气需要电源提供更高的电场使保护气体电离, 电压增大. 而当氦气含量小于 50% 时, 电弧电离主要以低电离电压的氩气为主, 保护气体中的氦气主要起了冷却作用、收缩电弧, 电压升高; 而随着氦气含量的增加, 氦气参与电弧电离, 电弧电压快速升高.

综合以上分析, 在保护气体中添加氦气成分, 一方面提高了电弧电压, 提高热输入, 增加焊道熔深; 另一方面, 试件附近的氦弧形态较氩弧形态更加拘束, 减小了电弧在试件表面的作用半径, 进一步提高了焊道深宽比.

2.6 模拟缺陷修复试验与分析

按照图 1 加工试件, 并按照表 1 中的焊接工艺参数进行孔洞类和裂纹类的模拟缺陷的修复, 检验不同保护气体下 TIG 焊修复铸造镁合金缺陷的能力. 采用氩气作为 TIG 焊保护气体, 凹槽深度为 1 mm, 凹槽底部钻孔深度为 2, 3 mm 试件; 采用氦气作为 TIG 焊保护气体, 焊接凹槽深度为 3 mm, 凹槽内分别钻深度为 2, 3 mm 试件. 模拟缺陷修复焊道宏观形貌如图 11 ~ 图 12 所示.

在相同的焊接工艺参数下, 不同的保护气体会

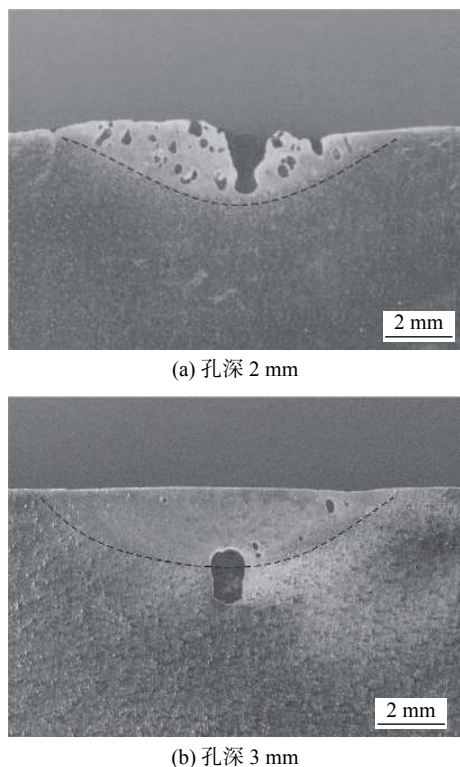


图 11 凹槽深度 1 mm 时模拟缺陷修复

Fig. 11 Simulated defect repair of groove depth 1 mm. (a) hole depth 2 mm; (b) hole depth 3 mm

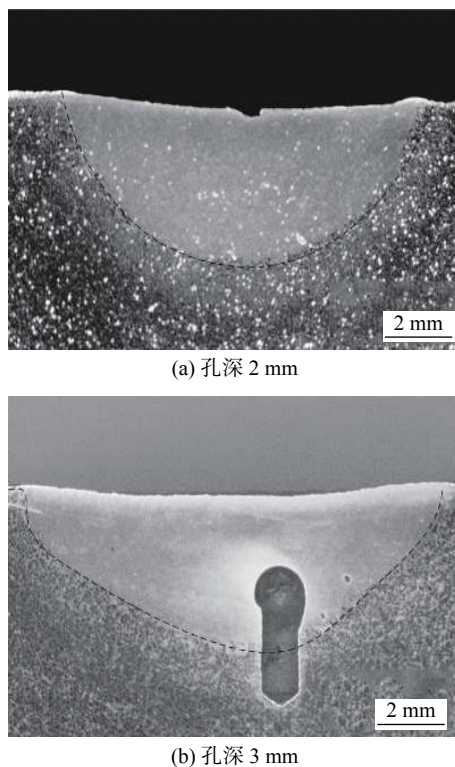


图 12 凹槽深度 3 mm 时模拟缺陷修复

Fig. 12 Simulated defect repair of groove depth 3 mm. (a) hole depth 2 mm; (b) hole depth 3 mm

给修复能力带来较大的差异. 采用氩气保护的修复工艺不能满足凹槽深度为 1 mm、钻孔深度 2, 3 mm 的条件下的修复需求; 采用氦气保护的修复工艺下, 基本可以满足凹槽深度为 3 mm、钻孔深度为 2 mm 的修复需求, 而无法当钻孔深度为 3 mm 时的修复需求. 在该试验条件下, 可修复深度约为 5 mm 范围内的缺陷. 当焊道熔深超过缺陷深度时, TIG 不填丝修复工艺可以满足缺陷的修复需求, 而保护气体中氦气含量增加带来的焊道熔深增加, 提高了 TIG 不填丝修复工艺的适用性.

3 结论

(1) 在保护气体中增加氦气含量可有效增加镁合金铸件焊道熔深及深宽比, 镁合金铸件 100% 氦气保护气体下 TIG 焊修复焊道较 100% 氩气保护气体下, 焊道熔深从 2.3 mm 增加至 6.1 mm, 提高 2.6 倍.

(2) 增加保护气体中氦气含量使镁合金铸件 TIG 焊电弧电压得到较大的提高, 并减小了电弧作用于试件表面上的半径, 增加了能量密度, 对焊道成形产生显著影响.

(3) 模拟缺陷修复试验表明, 采用 TIG 焊不填丝修复工艺可在约 5 mm 深度范围内满足镁合金铸件缺陷修复需求。

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(编辑: 戴红)

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(编辑: 戴红)

from 3.5 kW to 4.0 kW.

Highlights: (1) A hybrid heat source model combined with double ellipsoid heat source and three-dimensional conical heat source was established for hybrid laser-MIG welding of medium-thickness X80 pipeline steel plates. Welding temperature field and residual stress field of hybrid laser-MIG welding process were numerically simulated using the established heat source model.

(2) Welding parameters for hybrid laser-MIG welding can be optimized based on analysis of microstructures and residual stress in the hybrid welded joints with different laser powers.

Key words: laser arc hybrid welding; combined heat source model; microstructure; temperature field; residual stress

Repair process of magnesium alloy casting by He-Ar mixed gas TIG welding CHEN Yi¹, GUO Longtao², QI Tongfu¹, YANG Chunli¹ (1. State Key Laboratory of Modern Welding Production Technology, Harbin Institute of Technology, Harbin, 150001, China; 2. Amperex Technology Limited, Ningde, 352100, China). pp 35-41

Abstract: Magnesium alloy plays an important role in weight-loss because of its high specific strength, most of magnesium alloy components are casting. The defects of magnesium alloy castings become a manufacturing bottleneck issue. The repair process of magnesium alloy castings by tungsten inert gas (TIG) welding was studied, the effects of protect gas on the form, microstructure and properties of TIG repair beads were examined. The effects of helium content on the penetrations of welding beads were analyzed through the arc shape and arc voltage of TIG welding under different helium content. The results showed that the form of the weld bead could be improved by changing the helium content, the penetration and the penetration to width ratio could be improved by increasing the helium content, with no obvious effect on the microstructure and the hardness. The results of the simulating defect repair experiments showed that, the He-Ar mixed gas TIG welding repair process could repair shallow defects of magnesium alloy castings, increasing the helium content in the protect gas could increase the penetration and the suitability of this repair process.

Highlights: (1) The penetration of the He-Ar mixed gas TIG welding repair bead was regulated by changing the helium content in the protect gas.

(2) The feasibility of the He-Ar mixed gas TIG welding repair process was verified by simulated defect repair experiments.

Key words: magnesium casting; defects repair; helium; arc

characteristics

TiB₂-based ceramics/42CrMo alloy layered gradient material mechanical test and structure design LU Mingyuan, HAN Baohong, HE Wanheng, ZHAO Zhongmin (Shijiazhuang Campus of Army Engineering College, Shijiazhuang, 050003, China). pp 42-48,73

Abstract: Based on the previous supergravity field synthesis gradient materials, a TiB₂-based ceramic /42CrMo graded material with continuous gradient content of TiB₂-TiC-Fe has been preparated. XRD, SEM, hardness test and three-point bending strength test on the materials are conducted. And electrical measuring method is used to obtain ceramic substrate part of elasticity modulus. The elastic modulus of the intermediate transition zone is fitted. Finally, an analytical method is used to calculate the stress-strain distribution of the graded material. The results show that the ceramic/alloy phase boundary changes in a continuous gradient, and the hardness decreases in a gradient from ceramic to metal. Three point bending test found that the type of material has similar to the metal plastic deformation features. Therefore, obvious failure delay behavior appears. The elastic modulus of pure ceramic is about 560 GPa. The variation form of elastic modulus in the intermediate transition zone is closer to trigonometric function. The calculated stress indicates that the damage occurs from the bottom of the metal, and then the crack spreads to the top of the ceramic, which is consistent with the experimental phenomenon of this type of material.

Highlights: (1) The elastic modulus of gradient material is calculated by parameter fitting method.

(2) The stress distribution of gradient material is calculated by mathematical analysis method and the structure of the material is optimized.

Key words: graded materials; mechanical properties; damage failure; strain measurement

PBGA solder joint fatigue under temperature cycling, random vibration and combined vibration and thermal cycling loading conditions AN Tong^{1,2}, CHEN Xiaoxuan^{1,2}, QIN Fei^{1,2}, DAI Yanwei^{1,2}, GONG Yanpeng^{1,2} (1. Institute of Electronics Packaging Technology and Reliability, Beijing University of Technology, Beijing, 100124, China; 2. Beijing Key Laboratory of Advanced Manufacturing Technology, Beijing University of Technology, Beijing, 100124, China). pp 49-54

Abstract: In this paper, temperature cycling, random