

低碳钢等离子-TIG 耦合电弧高效复合 焊接工艺性能分析

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摘 要: 针对低碳钢材料焊接效率低的问题, 提出了等离子-TIG 耦合电弧焊接方法, 通过设计集约化枪体结构促使等离子和 TIG 电弧在电磁力作用下实现稳定耦合, 优化复合焊接热源特征, 并研究了电弧形态、焊缝成形和力学性能。结果表明, 等离子-TIG 耦合电弧具有优异的深熔焊接特性, 相对于等离子和 TIG 焊接方法具有更加合理的深宽比, 且对熔滴、熔池有震荡搅拌效果, 促使晶粒细化, 并降低熔合区联生结晶倾向。使用 5 mm 厚 Q235B 钢板进行对接试验, 实现了稳定的单面焊接双面成形, 焊缝美观无缺陷且抗拉强度优于母材。

关键词: 等离子-TIG; 耦合电弧; 复合焊; 深熔焊

中图分类号: TG 456.2 **文献标识码:** A **doi:** 10.12073/j.hjxb.2019400161

0 序 言

随着当前工业制造水平和现代科技的不断提升和快速发展, 人们对于高质量、高效率的加工方法提出了更高的要求, 焊接技术作为先进制造领域的重要组成部分, 其作用和地位也越来越重要^[1]。通常情况下, 由于输入能量的限制和焊接稳定性的问题, 焊接效率的提升往往引起焊缝质量的降低^[2]。复合焊接方法的出现使得多种热源相互作用、优势互补, 在改善焊接质量的同时大幅度提升了焊接效率, 成为了近年来焊接领域的研究热点^[3-6]。

等离子弧焊接工艺 (plasma arc welding, PAW) 能量密度高、熔透能力强, 但其参数区间较窄且易出现驼峰、咬边等缺陷。钨极氩弧焊方法 (tungsten inert gas welding, TIG) 效率低、熔深浅^[7], 但其电弧稳定、成形优良。目前围绕 PAW 和 TIG 两种工艺的复合焊接方法主要包括 PAW-TIG^[8]、双面双弧焊 (double side arc welding, DSAW) 和 P+T 焊接方法^[9]。DSAW 焊接技术于 1998 年由美国肯塔基大学张裕明教授提出^[10], 该方法可获得较大深宽比

的优质焊缝, 且成本低、效率高。国内学者对该方法的小孔形成过程、电流密度、熔池流动以及温度场分布进行了系统的模拟分析^[11-13]。P+T 方法由昆山华恒焊接股份有限公司的张光新等人提出, 将等离子打底焊和随后的 TIG 填丝盖面焊通过移动滑架组装以提升生产效率, 该方法属于两种独立工艺的机械结合。上述两种方法都很好的提高了焊接生产效率和焊接质量, 但均存在焊接装备复杂, 焊接可达性差等缺陷。为此, 文中提出了 PAW-TIG 耦合电弧焊接 (P-T) 工艺, 并系统的介绍了该方法的电弧特性、电弧压力分布特征, 并通过试验加以验证, 以谋求一种优化的 PAW-TIG 复合焊接方法。

1 试验方法

试验用等离子-TIG 复合焊接设备如图 1 所示。焊接过程中等离子电弧在前, 且焊枪中心轴线与工件垂直, 与 TIG 焊枪呈 23°, 采用填丝焊接, 焊丝送丝方向与工件夹角为 25°。焊接系统由等离子电源 LORCH-V50AC/DV(主弧电源)、LORCH-Handy TIG 180DC(维弧电源)、REHM INVERTIG. PRO digital 240 AC/DC 型 TIG 电源、LORCH-CWF12 送丝机、CW-5300 型冷水机等组成。电弧图像使用 XIRIS XVC-1000 型 CCD 相机进行图像信息采集,

收稿日期: 2018-05-13

基金项目: 泰山学者青年专家支持计划 (tsqn20161062); 山东省重点研发计划 (2017GGX30132); 山东省重点研发计划 (2018GGX103032); 哈尔滨工业大学科研创新基金 (HIT.NSRIF.201707)。

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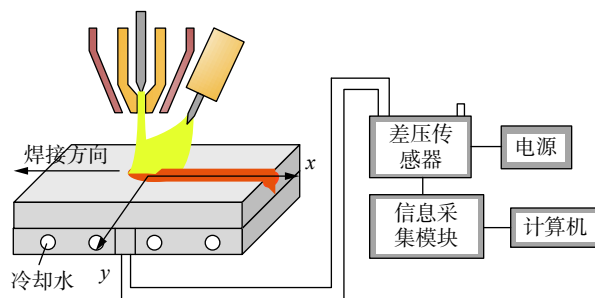


图 1 PAW-TIG 耦合电弧焊接装置示意图

Fig. 1 Schematic of PAW-TIG coupling arc welding system

使用 635 ~ 650 nm 滤光片进行滤光. 电弧压力二维分布可通过小孔法进行测量, 测量方式及后续试验系统 x, y 坐标轴如图 2 所示.

试验材料为 5 mm 厚度的 Q235B ($C \leq 0.20\%$,

图 2 焊接电弧压力测试系统中 x, y 坐标轴的确定Fig. 2 Determination of x, y coordinate axis in welding arc pressure test system

$Si \leq 0.35\%$, $Mn \leq 1.4\%$, $S \leq 0.045\%$, $P \leq 0.045\%$) 低碳钢板 (实际厚度 4.5 mm), 规格为 200 mm × 80 mm × 50 mm, 填充焊丝为 JQ-MG70S-6, 直径 1.2 mm, 焊丝的成分见表 1. 对接试验中使用工装对样板进行固定, 预留间隙 1 mm.

表 1 填充焊丝化学成分

Table 1 Elements composition of filling wire

C	Mn	Si	S	P	Ni	Cr	Mo	Cu
0.06 ~ 0.15	1.40 ~ 1.85	0.80 ~ 1.15	≤ 0.025	≤ 0.025	≤ 0.15	≤ 0.15	≤ 0.15	≤ 0.50

焊接试验结束后, 垂直于焊接方向截取金相及硬度试样. 使用 HV-1000DT 型显微硬度仪测试接头硬度, 从接头左侧母材区靠近焊缝的一点开始测试, 向右每隔 0.5 mm 测一个点, 加载时间 10 s, 载荷 0.2 gf. 根据国家标准 GB/T 2651—2008 确定焊接接头拉伸试样尺寸, 并使用 INSTRON-5967 型万能拉伸试验机测量其抗拉强度, 每组参数测试三个样品, 结果取其平均值.

2 耦合电弧复合焊接工艺

2.1 耦合电弧形态分析

P-T 复合焊工艺的典型电弧形态及焊接参数分别如图 3 和表 2 所示. 使用伪色彩增强技术将黑白图像转换为彩色图后可以直接观测到两个独立电弧在阳极附近的相互耦合. 耦合电弧与单独电弧进行对比, 具有以下特征: ①耦合后等离子弧能量更

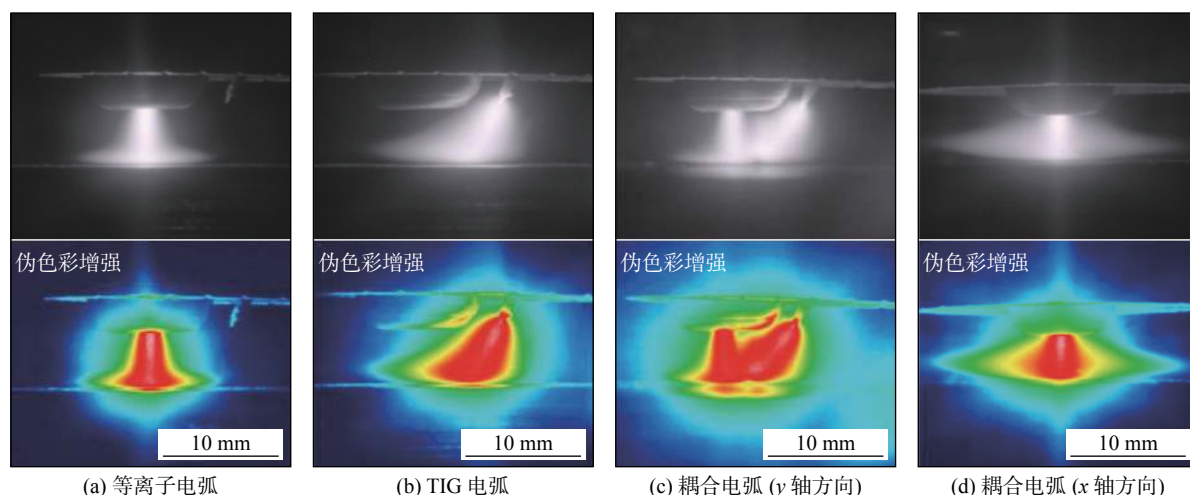


图 3 独立电弧与耦合电弧的电弧形态

Fig. 3 Arc morphology of independent and coupled arc

表 2 电弧形态采集试验工艺参数

Table 2 Process parameters of arc shape acquisition test

等离子电流 I_p/A	TIG电流 I_T/A	钨极间距 D_{PT}/mm	弧长 L/mm	等离子气流量 $Q_p/(L \cdot min^{-1})$	保护气流量 $Q_s/(L \cdot min^{-1})$
60	100	7	5	4	10

为集中, 弧柱挺直度更高; ②耦合导致等离子弧整体向 TIG 弧方向出现些许偏移和弯曲, 但整体轮廓未发生改变; ③耦合导致 TIG 电弧整体向等离子弧偏移, 偏移程度很大. 经分析产生上述现象主要是由于等离子和 TIG 焊接均为直流反接, 电弧会因为电流同向而受到洛伦兹力使得互相吸引. 同时焊枪的角度使得两电弧在下部相互接触, 进而使得洛伦兹力增强, 且由于 TIG 电弧是自由电弧, 挺直度较低, 使得其弧柱下部在力的作用下向等离子弧侧发生明显偏移, 拖拽着整个电弧向等离子弧倾斜, 并具有沿等离子弧柱爬升的趋势.

2.2 耦合电弧压力分布

由图 4 可知 (TIG 焊电流为 130 A), 在最大电弧压力均随着等离子弧电流增加的同时, 且当等离子弧电流为 40~60 A 时, 由于等离子弧挺直度高, 两电弧间洛伦兹力不足以完全形成耦合, 加上 TIG 电弧压力对小孔的分力, 此时耦合电弧最大电弧压力略大于 PAW; 当 PAW 电流大于 80 A 时, 两弧柱吸引力增大, 达到最大程度耦合, 这时两电弧的耦合电弧压力均低于相应单弧的最大电弧压力. 说明 P-T 工艺在具有类似 PAW 的良好穿孔焊接能力的同时, 又具备 TIG 焊接方法的特征.

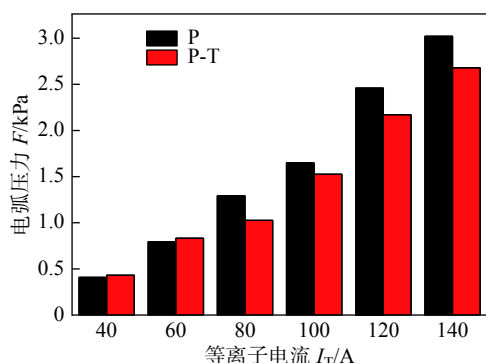


图 4 单等离子弧和耦合电弧的电弧压力对比

Fig. 4 Comparison of arc pressure between single plasma arc and coupling arc

2.3 耦合电弧复合焊接焊缝深宽比

为进一步探索 P-T 方法的焊接实用性, 在等离子电流为 100 A, TIG 电流为 160 A、送丝速度为 0.65 m/min 和焊接速度为 3 mm/s 的参数下, 设计

了不同焊接方法 (P-T; P-T-S(填丝); P(PAW); P-S; T(TIG); T-S) 下的表面堆焊试验. 根据焊缝的截面形貌中测得焊缝的熔深 D 和熔宽 B , 如图 5 所示, 根据焊缝的截面形貌中测量得出焊缝的熔深和熔宽, 可以看出同种焊接方法下填丝使得焊缝熔深下降, 同时 P-T 的焊缝远大于两单弧焊缝熔深, 与二者熔深之和相当. 因此, 这可以说明 PAW-TIG 复合焊相比于单弧焊接, 既可以显著增加熔深和焊接效率, 又可以改善深宽比、获得成形良好的焊缝.

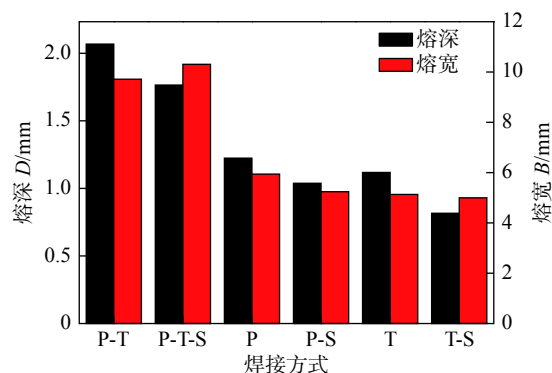


图 5 不同焊接方法下的熔深、熔宽对比

Fig. 5 Comparison of weld penetration and width under different welding methods

2.4 耦合电弧复合焊接焊缝成形

经过试验探索, 4.5 mm 厚度 Q235 板实现单面焊双面成形的工艺参数区间为: 等离子电流 150 A, TIG 电流 70~130 A. P-T 工艺 (150 A + 90 A) 参数下样品宏观成形如图 6 所示, 焊缝获得良好的正、背面成形, 焊缝横截面呈“高脚杯”状. 表明 P-T 焊接工艺横截面熔化区为一个整体, 耦合电弧仍具有 PAW 工艺的深熔穿孔能力, 同时具备良好的盖面铺展能力, 并具有宽泛的焊接参数区间.

2.5 耦合电弧熔池特性及接头组织分析

P-T 复合填丝焊的熔池侧面图像如图 7 所示. 可以看出焊丝受到复合热源加热熔化并在 PAW 侧滴落至熔池, 同时由于 PAW 压力的作用下被排挤至 TIG 电弧下方并向上攀升. 随后 TIG 弧的重力及等离子流力会对其产生向下作用力抑制其攀升; 但此时 TIG 弧仍作用于熔池, 可使得熔池内液

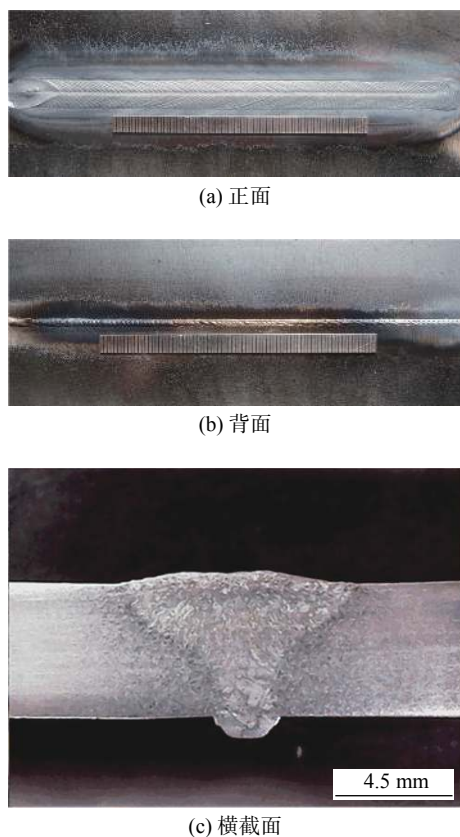


图 6 P-T 焊缝正、背面成形及横截面宏观形貌

Fig. 6 P-T Weld front and back forming and cross section macroscopic morphology

相存在时间延长,为熔池中液态金属的回流创造条件,因此熔滴过渡到熔池后,在电弧力(包括两电弧的等离子流力、电磁力、斑点力及表面张力)与重力的综合作用下,熔池内金属将一直处于振荡状态至熔池凝固.这将有利于填充焊丝中合金元素在整个熔池中的均匀化分布,改善焊缝组织性能.

由上述可知,在等离子-TIG 耦合电弧的综合作用下,熔池金属发生周期性振荡,促进填充金属与熔池金属的合金元素均匀化.在 PAW 电弧和 TIG 电弧的先后作用下,焊缝上部分熔化区先共析铁素体沿奥氏体晶界析出,晶间存在一定量的侧板条铁素体和少量的针状铁素体,如图 8a, 8b.下部分熔化区主要表现为 PAW 工艺特征,填充金属中的合金元素通过振荡方式分散到熔池中,为针状铁素体形核提供条件,主要由排列紧密的针状铁素体组成,如图 8c, 8d.

熔合区金相如图 9 所示,熔合区内先共析铁素体从熔合线沿晶间呈条状向熔化区伸展,无明显柱状晶,联生结晶现象较少.表明熔池中金属的周期性振荡可以有效抑制凝固初始阶段的焊缝偏析,降低联生结晶概率.

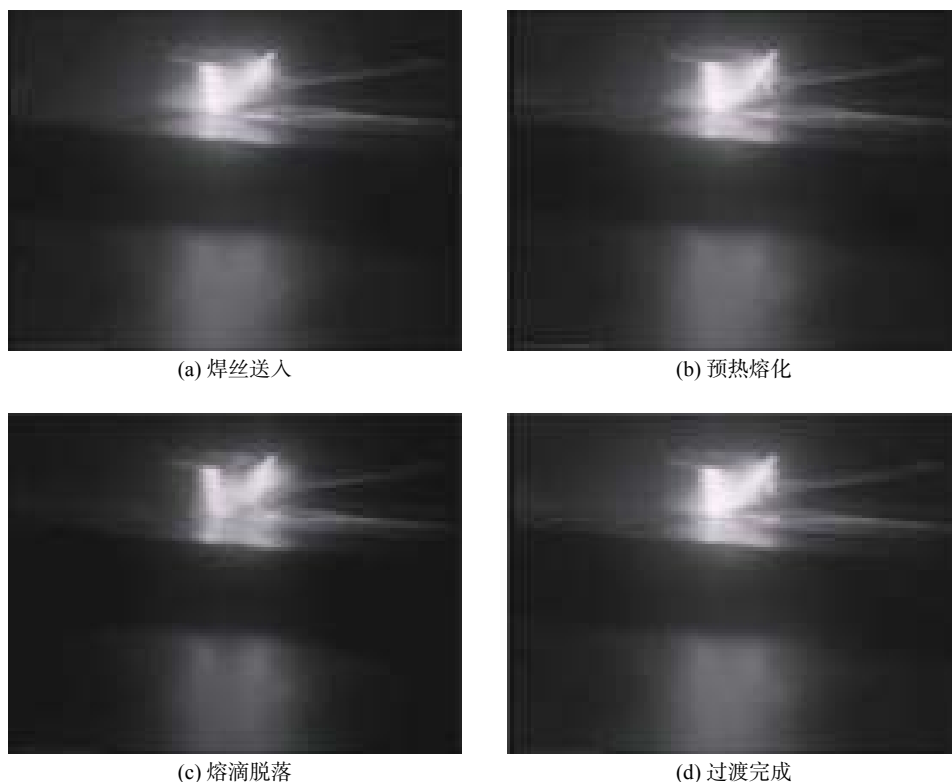


图 7 P-T 填丝焊接过程熔池状态图

Fig. 7 Weld pool state diagram of P-T filling welding process

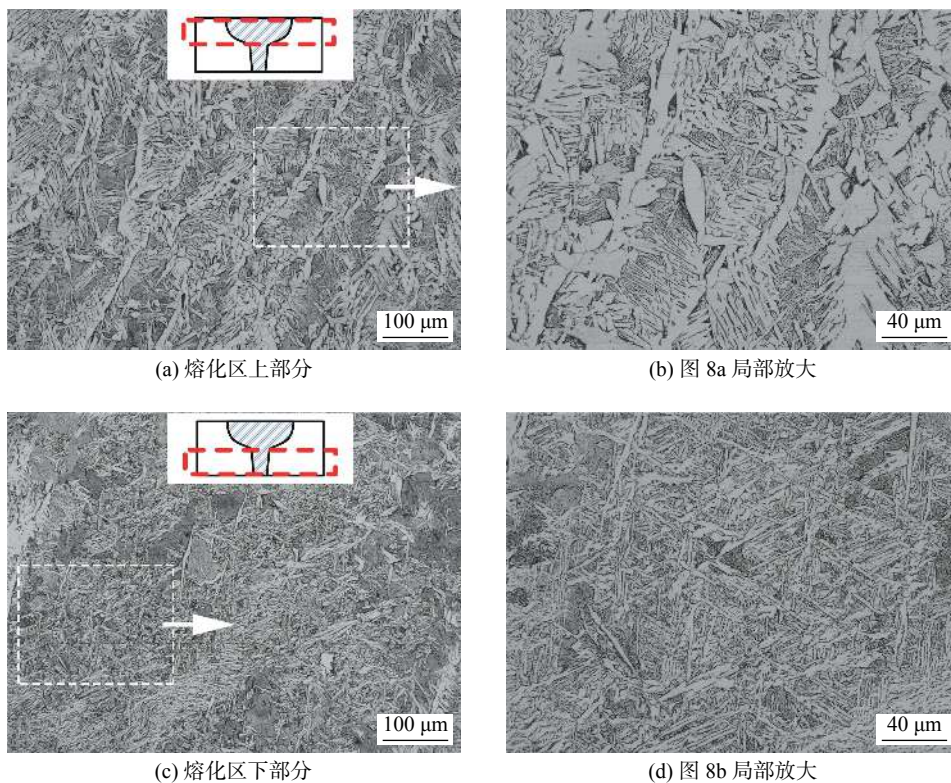


图 8 P-T 焊接焊缝区显微组织

Fig. 8 Microstructure of P-T welding weld zone

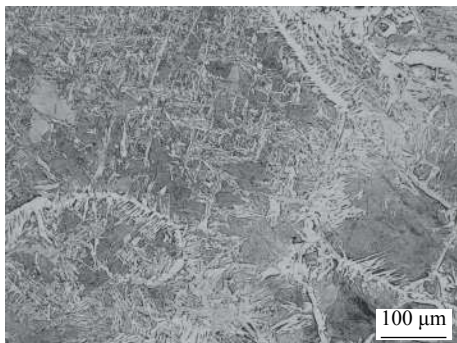


图 9 P-T 焊接熔合区显微组织

Fig. 9 Microstructure of P-T welding fusion zone

2.6 耦合电弧复合焊接接头显微硬度分析

焊缝横截面上 (P-T-U)、下部分 (P-T-D) 硬度测试结果如图 10 所示, 最高硬度分别出现在熔化区和熔合区, 峰值硬度为 234 HV. 焊缝下部分硬度较大且出现较窄平台, 主要由于其焊缝组织为针状铁素体且为等离子穿孔焊接区域.

2.7 耦合电弧复合焊接接头拉伸强度

P-T 工艺焊接拉伸试样断裂位置均在母材上 (图 11), 且抗拉强度平均可达 487 MPa. 表明焊接接头性能超过母材金属, 母材虽然碳含量高于填充焊丝, 但焊丝中的 Ni, Cr 元素含量高于母材, 可弥补

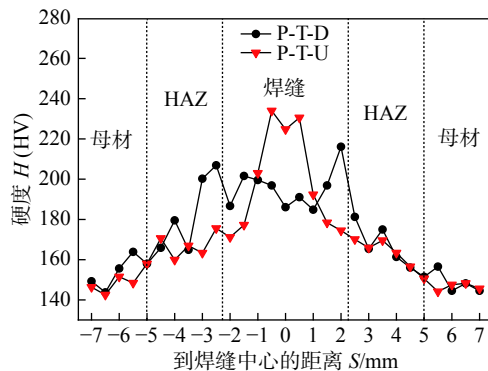


图 10 P-T 焊接接头硬度值

Fig. 10 Hardness value of P-T welding joint



图 11 P-T 拉伸试样断裂示意图

Fig. 11 Fracture diagrammatic sketch of P-T tensile samples

这一问题.同时由于熔池截面呈“高脚杯”状,焊缝较窄,热影响区小,并且熔池在耦合电弧下的周期性振荡可以细化焊缝组织、促进焊缝合金元素均匀化,故可获得超过母材力学性能的接头焊缝.

3 结 论

(1) 验证了等离子-TIG耦合电弧复合焊接工艺既具有等离子焊接技术的深熔穿孔特性,而且还有TIG焊接工艺的良好填丝盖面优势.焊接时PAW弧与TIG电弧高度耦合,并在Q235B钢板对接试验中获取的单面焊双面成形的接头,宏观成形良好,焊缝截面具有良好的深宽比.

(2) 焊缝金属截面呈“高脚杯”状,耦合电弧对熔池金属具有周期性振荡效果,促使焊缝金属组织细化,有效抑制底部熔池的联生结晶.

(3) 焊接接头的抗拉强度高于母材,P-T复合焊接工艺可以显著改善焊接可达性,提高焊接效率.

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microstructure of the high nickel ductile iron homogeneous weld is composed of fine columnar austenite dendrite, spheroidal graphite and a little intergranular carbide. With the increase of welding current, the morphology of columnar dendrite in the weld tends to be coarsening, the graphite nodularity increases, and the number of intergranular carbides increases. When the welding current is constant, with the increase of preheat temperature, the graphite morphology becomes worse, the amount of carbides precipitated increases, so the tensile strength of the joint decreases and the hardness increases. By using the high nickel ductile iron homogeneous welding electrode, along with the large welding current technology at room temperature, the microstructure and mechanical properties of the weld could be controlled effectively and the high quantity homogeneous weld with excellent machining property can be obtained.

Key words: high nickel ductile iron homogeneous welding electrode; homogeneous welding; welding current; preheat temperature

Investigation on friction stir welding process of ferritic stainless steel and mechanism of defect formation

TANG Wenshen, YANG Xinqi, LI Shengli, LI Huijun (Tianjin University, Tianjin 300354, China). pp 87-93, 111

Abstract: Friction stir welding was performed on joining T4003 ferritic stainless steel by using a tungsten rhenium (W-Re) alloy tool. The weld formation, microstructural characteristics, and mechanism of defect formation in the weld were examined. It was showed that the axial pressure of tool monotonously increased with the increasing of welding speed under different rotational speeds. Defect-free welds were successfully produced at rotational speeds of 150 and 250 r/min. However, wormhole defects were produced near the advancing side of the stir zone in the welded joints at the rotational speed of 350 r/min. This phenomenon tended to decrease with the increasing of the tool axial pressure and welding speed. A phase transformation and significantly harden occurred in the stir zone of the welded joint, and the microstructure in this region changed to very fine grains consisting of duplex structure of equiaxed ferrite and low carbon martensite. An uneven hardness distribution in the weld was observed. Moreover, a balanced-flow model of weld metal was proposed, and employed to analyze the mechanism of defect formation in the weld.

Key words: ferritic stainless steel; friction stir welding; microstructure; welding defects; formation mechanism

Analysis on welding processing properties of plasma-TIG coupling arc hybrid welding

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China; 2. Shandong Institute of Shipbuilding Technology, Weihai 264209, China; 3. Yantai CIMC Raffles Offshore Co., Ltd., Yantai 264000, China). pp 94-99

Abstract: The plasma-TIG coupling arc hybrid welding process was proposed to improve the welding efficiency of mild steel. The stable coupling arc of plasma and TIG is realized under the action of electromagnetic force by designing the intensive torch, and the welding heat source characteristics of the coupling arc have been optimized. The arc shape, weld formation and, mechanical properties are analyzed. The results showed the coupling arc still have good deep penetration welding characteristics. Compared with plasma and TIG welding method, the coupled arc has more reasonable depth-width ratio, and has the effect of shock stirring on droplet and welding pool, which promotes grain refinement and reduces the tendency of joint crystallization in fusion zone. One-side welding both sides formation could be achieved by use of the butt welding test with 5 mm thick Q235B steel plates, the weld was smooth without defects and the tensile strength was better than the base metal.

Key words: plasma-TIG; coupling arc; hybrid welding; no spatter

Microstructure based on selective laser melting and mechanical properties prediction through artificial neural net

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Abstract: Selective laser melting has been applied to fabricate 18Ni300. SEM is used to observe dendritic growth orientation and solidification structure. Artificial neural network is applied to rank the respective importance of laser power, scanning speed and scanning space for mechanical properties, while BP neural net with improved weight by genetic algorithm is applied to the prediction of tensile property. Results show that the main structure of the specimen is columnar dendritic crystals with significant epitaxial growth. The orientation of the growth is determined by the solidification condition at the bottom of the molten pool. CET can easily take place on the top of the melting pool. Meanwhile, there is transition zone in other places contributed by the thermo capillary convection. The result of the importance prediction by artificial neural network shows: They order from high to low is laser power, scanning speed and scanning space. Since the prediction results agree with the actual ones, BP neural net can effectively predict actual results. The determination coefficient $R^2 = 0.73$.