

15-5PH 钢 K-TIG 焊熔池流动行为分析

冯涛¹, 吕祚翔², 刘俊¹, 段琮¹

(1. 中国石油大学(华东), 青岛, 266580;

2. 中国石化催化剂有限公司长岭分公司, 湖南 岳阳, 414012)

摘要: 采用 K-TIG 焊实现 15-5PH 钢中厚板的焊接, 并借助示踪法研究 K-TIG 焊熔池的流动行为. 结果表明, K-TIG 穿孔型焊接时, 焊缝上部为马兰戈尼对流圈, 下部为表面张力与洛伦兹力导致的对流圈, 两个对流圈中间为过渡区. 示踪法表明, 熔池上部和下部 W 元素呈弧形分布于对流圈外围, 而在过渡区中 W 元素未出现明显形状. 熔池下方对流圈 EDS 分析结果表明, 熔池下方的熔融金属以内旋方式流动. 熔池流动计算及试验结果均表明, 熔池上部和下部流动剧烈, 但是中间层流动加速度很小, 且随着焊接热输入的增大, 中间层流动加速度有降低的趋势, 中间层晶粒有长大趋势.

创新点: (1) 通过试验和计算, 发现在 K-TIG 穿孔型焊接过程中, 熔池分成 3 个区域. 其中熔池中部区域熔融液体流动速度缓慢.

(2) 通过熔池形状进行表征分析, 发现在熔池中部, 熔融金属流动的加速度较小, 且随着热输入的增加, 流动加速度有降低的趋势.

关键词: 15-5PH 钢; K-TIG 焊; 示踪法; 熔池流动加速度

中图分类号: TG 406

文献标识码: A

doi: 10.12073/j.hjxb.20201015002

0 序言

15-5PH 钢因含有 Cr, Cu, Nb, Al, Ti 等合金元素而具有良好耐腐蚀性, 且这些合金元素可形成沉淀相和金属间化合物, 使母材具有良好的力学性能, 可满足航天航空、海洋和核工业等各种恶劣环境的使用要求, 其中厚板常被应用于机翼梁, 高压阀门, 汽轮机压缩机叶片等^[1-4]. 目前对 15-5PH 钢的研究主要集中于热处理方面^[5-7], 对其焊接性的研究多采用等离子弧焊接、TIG 焊等 4 mm 以下的薄板焊接^[8-10].

为了提高 15-5PH 钢中厚板的焊接质量和焊接效率, 扩大 15-5PH 钢中厚板的应用, 选取 8 mm 厚

的 15-5PH 板材为研究对象, 选用 K-TIG 焊接方法, 并借助示踪法研究了 K-TIG 焊接熔池的流动行为, 建立了 15-5PH 钢 K-TIG 焊熔池的流体动力学数学模型, 计算了焊接熔池不同区域熔融金属流动的加速度.

1 试验方法

试验所用的 15-5PH 钢的化学成分见表 1, 试验采用 I 形坡口, 单面焊双面成形, 钨极直径 10 mm, 钨极尖端夹角 60°, 钨极距母材 2 mm, 焊接电压 21.7 V, 氩气为保护气体, 焊缝正面氩气流量 20 L/min, 背面保护气体流量 15 L/min, 试验的其它焊接参数见表 2.

表 1 15-5PH 不锈钢化学成分 (质量分数, %)

Table 1 Chemical constituents of 15-5PH

C	Si	Cr	Ni	P	S	Cu	Nb
0.07	1	14.2	4.8	0.040	0.030	2.86	0.25

示踪法试验中, 在 15-5PH 钢板正面钻取直径 2 mm, 深度 4 mm 的孔, 在孔中埋入直径为 2 ~

表 2 15-5PH 钢 K-TIG 焊接参数

Table 2 Welding parameters of 15-5PH stainless steel

试验 编号	焊接电流 I/A	焊接速度 $v/(mm \cdot s^{-1})$	焊接热输入 $E/(kJ \cdot cm^{-1})$
T ₁	570	6	20.6
T ₂	540	5	23.4
T ₃	570	5	24.7

10 μm 的钨粉。焊后在小孔位置取样,用 Fry 试剂腐蚀后观察其形貌,并对其进行 EDS 面扫描,观察钨元素的分布。

2 试验结果及分析

2.1 焊缝示踪试验结果

焊缝宏观形貌见图 1。由图 1 可见,焊缝横截面呈现明显的 3 个区域,分别为表面张力驱动的马兰戈尼对流圈 a^[11],洛伦兹力和表面张力共同驱动的对流圈 c,以及中间的过渡区域 b^[12]。分别对 3 个区域进行 EDS 扫描,通过 W 元素的分布,推断熔池中熔融金属的运动方式如图 2 所示。

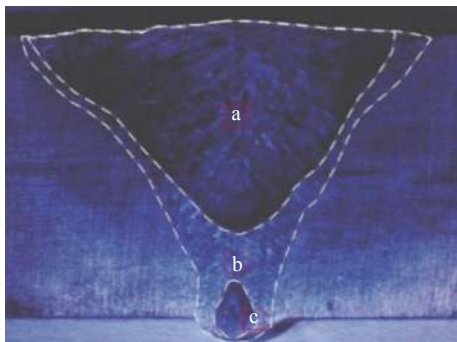


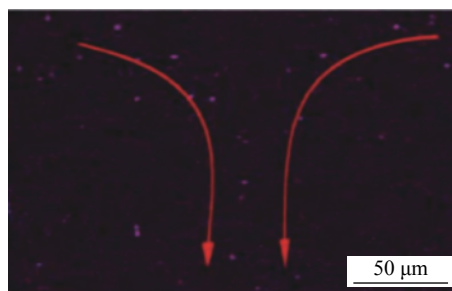
图 1 示踪法焊缝宏观横截面

Fig. 1 Weld macro cross section of trace method

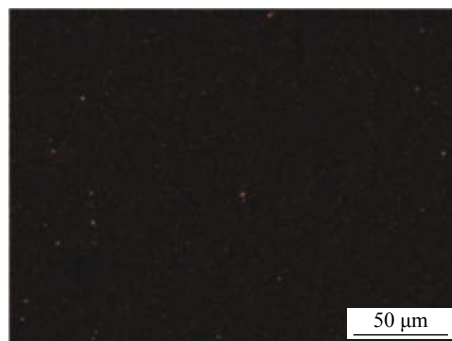
由图 2a 可见,在熔池上部对流圈中, W 元素呈弧形分布,这是因为 W 元素密度远大于 Fe,在离心力的作用下,分布于对流圈的外围。由图 2b 可见在中间过渡层中, W 元素呈现明显的形状,而非均匀的分布在焊缝中。由图 2c 可见在熔池下部对流圈中, W 元素也呈弧形分布在流圈外围。

为确定焊缝熔池各部分熔融金属的流动方向,对焊缝组织的生长方向和 W 元素浓度分布差异性来进行分析。

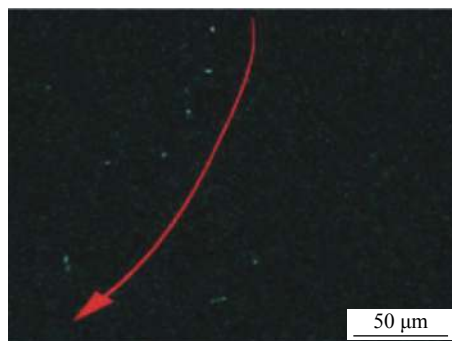
图 3 为焊后接头的宏观金相。由图 3 可见,在 A 区域马兰戈尼对流圈外围,树枝晶并未垂直熔合线向焊缝中心生长,而是呈现弧形,这与熔融金属在凝固过程中,受到了对流圈涡流运动的影响。中



(a) a 区 W 元素分布



(b) b 区 W 元素分布



(c) c 区 W 元素分布

图 2 焊缝不同区域 W 元素分布

Fig. 2 Distribution of tungsten in different regions of weld. (a) a zone; (b) b zone; (c) c zone

心等轴晶为分界线,将左右两个对流圈分开。在 B 区域,树枝晶沿着过冷方向较笔直的向中心线生长,这说明该区域在凝固过程中,熔融金属运动速度缓慢。在 C 区域,树枝晶同样受涡流运动的影响而呈弧状。

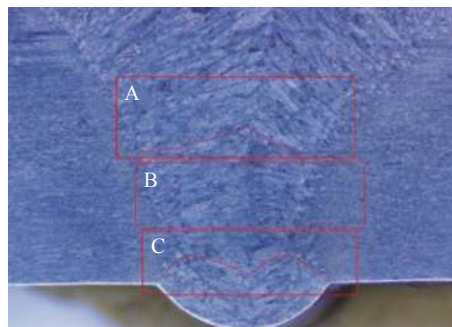


图 3 宏观焊缝组织生长方向

Fig. 3 Microstructure growth direction of macro weld

对熔池下方对流圈中的 4 个典型位置进行 EDS 成分扫描, 位置选择如图 4 所示, W 元素浓度分布见图 5。

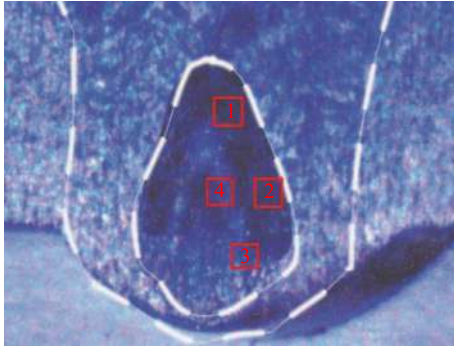


图 4 熔池下方对流圈 EDS 扫描

Fig. 4 EDS scanning of convection zone under the molten pool

由图 5 可见, 位置 1, 2, 3, 4 的 W 元素含量分别为 0.4%, 0.7%, 0.5%, 0.3%。在测试区域中, W 元素沿顺时针方向由 1 点运动至 2 点。由于熔池降温迅速, 熔融金属粘性增加, W 元素由 3 点运动到 4 点变得困难, 导致由 3 点到 4 点 W 元素含量逐渐下降。由此推断, 在熔池下部对流区, 熔融金属以内旋方式流动。

2.2 15-5PH 钢 K-TIG 焊熔池流动模型的建立

上下对流圈与中间层的速度存在差异, 通过计算焊缝不同区域熔融金属加速度的大小, 判断其运动状态。为简化计算, 做如下假设。

(1) 在考虑流体粘性作用下, 建立的熔池流动性模型如图 6 所示, 忽略因流圈形状不规则导致的能量损失。试验测量结果如图 7 所示。

(2) 电弧完全穿透板材, 形成小孔型焊接过程。

(3) 流体体积在运动过程中, 不会随着温度、压力等因素而发生改变, 为不可压缩的非牛顿流体。

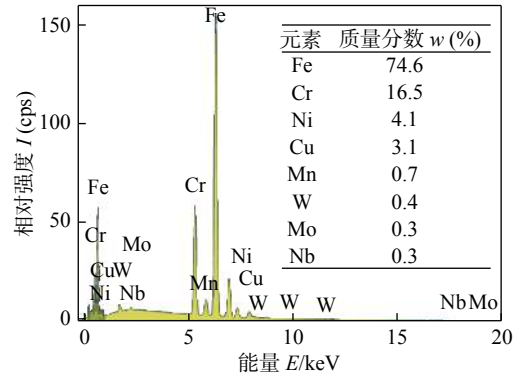
(4) 熔池中上下两个对流圈可以通过中间层完整的传递能量与速度, 不发生损耗。

$$u \frac{\partial u}{\partial x} + \omega \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{1}{\rho} \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} - \rho \overline{u' \omega'} \right) \quad (1)$$

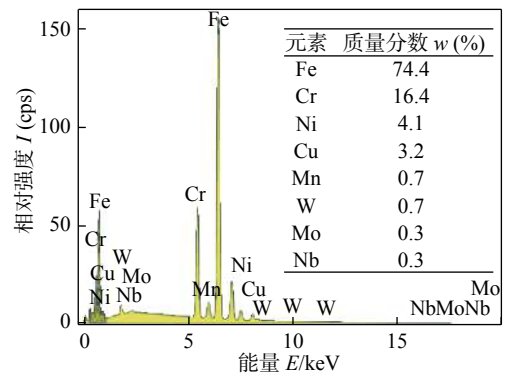
$$\frac{\partial u}{\partial x} + \frac{\partial \omega}{\partial z} = 0 \quad (2)$$

$$\frac{\partial P}{\partial z} = 0 \quad (3)$$

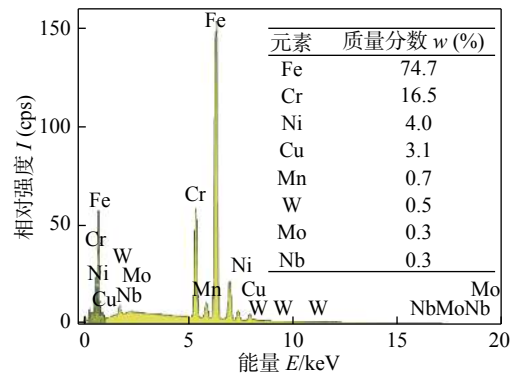
式中: $u \frac{\partial u}{\partial x} + \omega \frac{\partial u}{\partial z}$ 为剪切层的加速度; l 为剪切层长度; δ 为剪切层厚度; u 为 x 方向运动速度; ω 为 z 方向的运动速度; ρ 为液体密度; μ 为液体粘度; P 为熔融金属受到的作用力; $\rho \overline{u' \omega'}$ 为雷诺切应力。



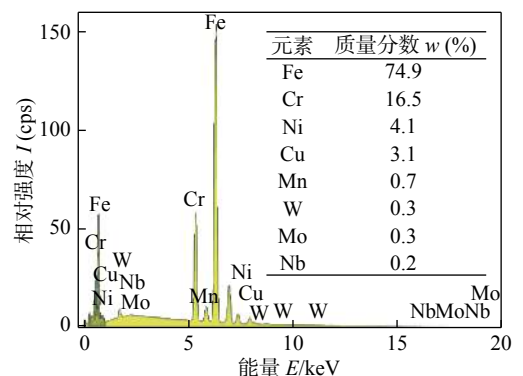
(a) 位置 1 的 W 含量



(b) 位置 2 的 W 含量



(c) 位置 3 的 W 含量



(d) 位置 4 的 W 含量

图 5 焊缝下方对流圈不同位置钨元素含量扫描

Fig. 5 Scanning of tungsten content in different positions. (a) spot 1; (b) spot 2; (c) spot 3; (d) spot 4

由式 (1)~式 (3) 可推导出薄剪切层公式 (4)。在层流中雷诺切应力 $\rho \overline{u' \omega'}$ 忽略不计。将边界层

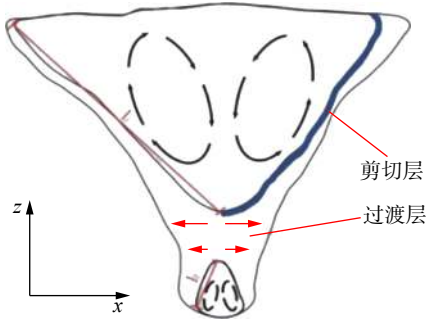


图 6 K-TIG 焊熔池流动模型

Fig. 6 K-TIG molten pool flow model

厚度 δ (式 (5)) 和运动学粘性系数 ν (式 (6)) 代入式 (4), 整理后得到式 (7)。

$$u \frac{\partial u}{\partial x} + \omega \frac{\partial u}{\partial z} = u \frac{du}{dx} + \frac{1}{\rho} \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} - \rho u' \omega' \right) \quad (4)$$

$$\delta = 5.3 \left(\frac{\nu x}{u} \right)^{0.5} \quad (5)$$

$$\nu = \frac{\mu}{\rho} \quad (6)$$

$$u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} = \frac{u^2}{l} + \frac{1}{\rho} \frac{\partial}{\partial \delta} \left(\mu \frac{u}{\delta} \right) \quad (7)$$

由于无法直接测量出对流圈熔融金属的流动速度, 所以将 S KOU 与 Heiple C R^[7-8] 通过模拟的方法得出的对流圈速度为 $1 \times 10^3 \text{ mm/s}$ 的量级带入式 (7), 同时, 为简化计算, 用边界层的参数 l 和 δ 替换 x 和 z , 可得到熔池对流圈粘性剪切层的加速度, 即

$$u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} = \frac{\mu^2}{l} - \frac{1}{\rho} \frac{\mu u}{\left(5.3 \frac{\rho l}{\mu u} \right)^2} \quad (8)$$

通过粘性剪切层, 上下两个对流圈分别对中间层产生了作用力, 将纳维-斯托克斯方程 (式 (9)) 对 x, y, z 轴分别列方程并写成标量形式如式 (10) ~ 式 (12)。

$$\frac{d\vec{v}}{dt} = \vec{F} - \rho \nabla P + \nu \nabla^2 \vec{V} \quad (9)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = F_x - \frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \nabla^2 u \quad (10)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = F_y - \frac{1}{\rho} \frac{\partial P}{\partial y} + \nu \nabla^2 v \quad (11)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = F_z - \frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \nabla^2 w \quad (12)$$

在满足如下情况, 可推导出式 (13) ~ 式 (15)。

(1) 流体在 (x, z) 平面上 x 轴作定常运动, $u \neq 0, v = w = 0$ 。

(2) 不考虑 y 方向的作用力, 即 $F_y = 0$ 。

(3) 熔融金属在 x 轴方向运动的加速度 $\frac{\partial u}{\partial t} \neq 0$

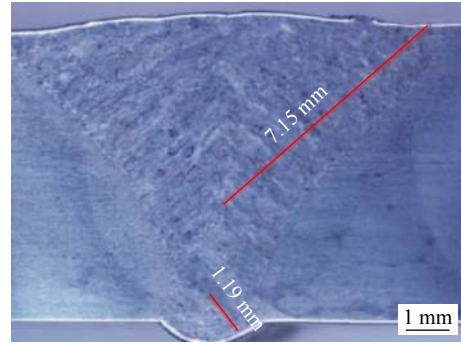
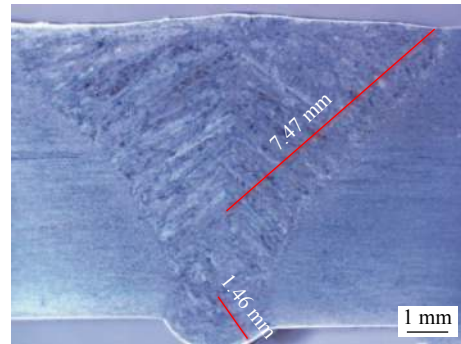
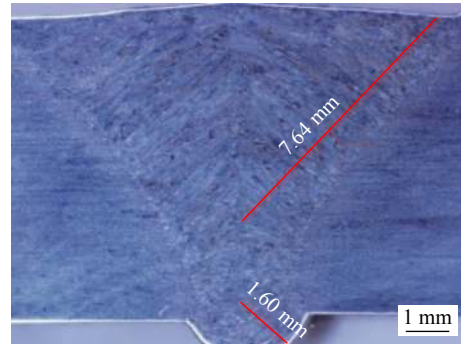
(a) $E = 20.6 \text{ kJ/cm}$ (b) $E = 23.4 \text{ kJ/cm}$ (c) $E = 24.7 \text{ kJ/cm}$

图 7 不同焊接热输入下焊接接头的剪切层长度

Fig. 7 Shear layer length of welded joint under different welding heat input. (a) $E = 20.6 \text{ kJ/cm}$; (b) $E = 23.4 \text{ kJ/cm}$; (c) $E = 24.7 \text{ kJ/cm}$

$$\frac{\partial u}{\partial t} = F_{12} - F_3 - \frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \nabla^2 u \quad (13)$$

$$0 = -\frac{1}{\rho} \frac{\partial P}{\partial y} \quad (14)$$

$$0 = -g - \frac{1}{\rho} \frac{\partial P}{\partial z} \quad (15)$$

将式 (14) 和式 (15) 代入式 (13), 可得到中间过渡层的运动加速度, 即

$$\frac{\partial u}{\partial t} = \rho \left[\frac{\mu^2}{l_1} - \frac{1}{\rho} \frac{\mu u_1}{\left(5.3 \frac{\rho l_1}{\mu u_1} \right)^2} - \frac{\mu^2}{l_2} - \frac{1}{\rho} \frac{\mu u_2}{\left(5.3 \frac{\rho l_2}{\mu u_2} \right)^2} \right] + \nu \nabla^2 u - \frac{1}{\rho} \frac{\partial (-\rho g z + P_1(x))}{\partial x} \quad (16)$$

将测得的上方对流圈边界长度 l_1 、下方对流圈边界长度 l_2 及速度 u_1 与 u_2 带入式 (8) 和式 (16), 可以得到上对流圈、下对流圈及中间过渡层的加速度大小 (表 3). 测量不同热输入下焊接接头的剪切层长度, 如图 8 所示, 得到 T_1 , T_2 , T_3 的上方对流圈的剪切层长度 l_1 分为 7.15, 7.47, 7.64 mm, 下方对流圈的剪切层长度 l_2 分别为 1.19, 1.46,

1.6 mm, 上下两个对流圈的剪切层长度都随着焊接热输入的增加而增加. 由表 3 可得, 随热输入增加, 中间层的加速度逐渐降低, 中间层的搅拌作用减弱. 不同参数下, 焊缝中间过渡区的微观组织如图 8 所示. 由图 8 可见随焊接热输入的增加, 焊缝中间层的加速度减小, 熔融金属运动变缓, 中间层晶粒逐渐增大.

表 3 焊接热输入对中间过渡层的影响

Table 3 Effect of welding heat input on middle layer

试验 编号	上方对流圈边界层长度 l_1/mm	下方对流圈边界层长度 l_2/mm	上方对流圈边界层加速度 $a_1/(\text{m}\cdot\text{s}^{-2})$	下方对流圈边界层加速度 $a_2/(\text{m}\cdot\text{s}^{-2})$	中间过渡层加速度 $a_3/(\text{m}\cdot\text{s}^{-2})$
T_1	7.15	1.19	139	840	0.058
T_2	7.47	1.46	134	746	0.049
T_3	7.64	1.6	130	625	0.044

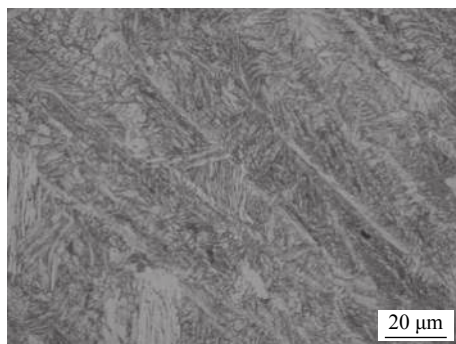
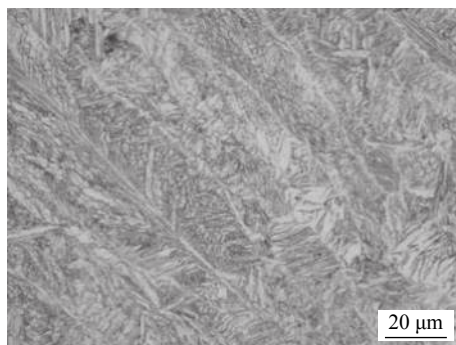
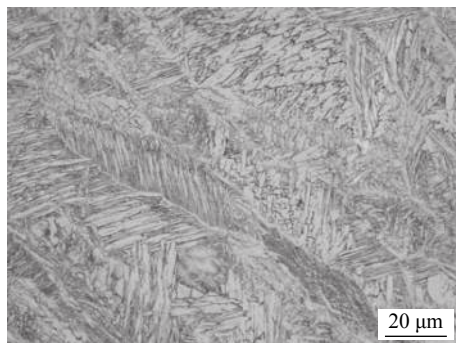
(a) T_1 (b) T_2 (c) T_3

图 8 焊缝中间过渡区的微观组织

Fig. 8 Dendrite structure in the middle transition zone of the weld. (a) T_1 ; (b) T_2 ; (c) T_3

3 结论

(1) 采用 K-TIG 穿孔型焊接实现 15-5PH 钢中厚板的焊接, 焊后焊缝上部和下部均为以内旋方式流动的对流圈, 两个对流圈之间为中间过渡区. 焊缝上部和下部的对流圈外围, 树状晶呈现弧形生长. 中心等轴晶作为分界线, 将左右两个对流圈分开. 而在中间过渡区中, 树枝晶沿着过冷方向中心线生长.

(2) 示踪法试验表明, W 元素呈弧形分布于上下两个对流圈外围, 而在过渡区中 W 元素未呈现明显形状. 对熔池下方对流圈进行 EDS 分析, 结果表明, W 元素含量分别为 0.4%, 0.7%, 0.5%, 0.3%. 根据 W 元素浓度分布判断, 在熔池下部区域中, W 元素以顺时针内旋方式进行运动.

(3) T_1 , T_2 , T_3 的上方对流圈的剪切层长度 l_1 分为 7.15, 7.47, 7.64 mm, 下方对流圈的剪切层长度 l_2 分别为 1.19, 1.46, 1.6 mm, 其上下两个对流圈的剪切层长度都随着焊接热输入的增加而增加, 但熔池流动加速度降低. 中间层熔池流动的加速度随着热输入的增加, 由 0.058 m/s^2 下降为 0.044 m/s^2 , 同时晶粒有长大趋势.

参考文献

- [1] 刘海涛, 司超阳, 霍登平, 等. 激光熔覆修复 15-5PH 不锈钢的拉伸性能及组织研究 [J]. 航空制造技术, 2017(10): 86–90.
Liu Haitao, Si Chaoyang, Huo Dengping, et al. Study on tensile

- property and microstructure of laser cladding repaired of 15-5PH stainless steel[J]. *Aeronautical Manufacturing Technology*, 2017(10): 86 – 90.
- [2] Nong X D, Zhou X L, Li J H, *et al.* Selective laser melting and heat treatment of precipitation hardening stainless steel with a refined microstructure and excellent mechanical properties[J]. *Scripta Materialia*, 2020, 178: 7 – 12.
- [3] Dallas Roberts, Yi Zhang, Indrajit Charit, *et al.* A comparative study of microstructure and high-temperature mechanical properties of 15-5 PH stainless steel processed via additive manufacturing and traditional manufacturing[J]. *Progress in Additive Manufacturing*. 2018, 3(3): 183-190.
- [4] 闫成龙. 庞巴迪 Q400 飞机垂尾方向舵安装接头孔的精加工方法 [J]. *现代制造技术与装备*, 2020, 56(9): 150 – 151.
Yan Chenglong. The finish machining method for the installation joint holes of the aviation Q400 bombardier vertical rudder[J]. *Modern Manufacturing Technology and Equipment*, 2020, 56(9): 150 – 151.
- [5] Abdelshehid M, Mahmodieh K, Mori K, *et al.* On the correlation between fracture toughness and precipitation hardening heat treatments in 15-5PH stainless steel[J]. *Engineering Failure Analysis*, 2007, 14(4): 626 – 631.
- [6] 华小珍, 魏振伟, 刘智勇, 等. 固溶处理对 15-5PH 不锈钢马氏体相变的影响 [J]. *金属热处理*, 2011(8): 67 – 70.
Hua Xiaozhen, Wei Zhenwei, Liu Zhiyong, *et al.* Effect of solution treatment on martensitic transformation of 15-5PH stainless steel[J]. *Heat Treatment of Metals*, 2011(8): 67 – 70.
- [7] 特日格乐, 张玉妥. 15-5PH 不锈钢 CCT 曲线与固溶冷却方式研究 [J]. *沈阳理工大学学报*, 2020, 39(4): 21 – 24,30.
TE Rigele, Zhang Yutuo. Research of the CCT curve and solution cooling method of 15-5PH stainless steel[J]. *Journal of Shenyang Ligong University*, 2020, 39(4): 21 – 24,30.
- [8] Jing Zhang, Bin Hu, Yi Zhang, *et al.* Comparison of virgin and re-used 15-5 PH stainless steel powders for laser powder bed fusion process[J]. *Progress in Additive Manufacturing*, 2018, 3(1–2): 11 – 14.
- [9] Zhenyu Fei, Zengxi Pan, Dominic Cuiuri, *et al.* Effect of heat input on weld formation and tensile properties in keyhole mode TIG welding process[J]. *Metals*, 2019, 9(12): 1 – 10.
- [10] ZuMing Liu, ShiYu Chen, Xin Yuan, *et al.* Magnetic-enhanced keyhole TIG welding process[J]. *The International Journal of Advanced Manufacturing Technology*, 2018, 99(1–4): 275 – 285.
- [11] 罗震, 解龔, 崔霜林. 基于三维重构技术的 K-TIG 熔池流动表征 [J]. *天津大学学报: 自然科学与工程技术版*, 2018, 51(326): 79 – 83.
Luo Zhen, Xie Yan, Cui Shuanglin. Morphology characterization of molten pool flow behavior during K-TIG welding based on 3D reconstruction techniques[J]. *Journal of Tianjin University (Science and Technology)*, 2018, 51(326): 79 – 83.
- [12] Liu X, Wu X, Han E H. Electrochemical and surface analytical investigation of the effects of Zn concentrations on characteristics of oxide films on 304 stainless steel in borated and lithiated high temperature water[J]. *Electrochimica Acta*, 2013, 108: 554 – 565.

第一作者: 冯涛, 博士, 副教授; 主要从事特种材料的焊接及材料的表面改性; Email: ft_210750@163.com.

(编辑: 张基隆)

appears in the short circuit phase. When the DC connection is reversed, the repulsion of droplets becomes the main spatter in peak stage.

Key words: self-shielded flux cored wire; CMT; droplet transfer; welding spatter

Welding processes and microstructures of weld bead of Zr-Sn-Nb-Fe-Cr and Zr-Nb-Fe zirconium alloy ZHONG Jianwei, AN Junjing, DING Huaibo, SHENG Guofu, FENG Liang (CGNPC Uranium Resources Co., Ltd., Beijing, 100029, China). pp 82-90

Abstract: Zr-1.0Sn-0.50Nb-0.50Fe-0.14Cr and Zr-Nb-Fe alloys were the two new developed zirconium alloys which used in fuel assembly. In this paper, different welding parameters of the Zr-1.0Sn-0.50Nb-0.50Fe-0.14Cr guide thimble welded to Zr-1.30Nb-0.30Fe tab by using pressure resistance spot welding method were studied. The mechanical properties and microstructures of the optimum welding parameters of the weld bead were studied. The result showed that the shear strength and nugget size increased as the welding current increased and the welding force decreased. The Failure mode of the weld bead changed from junction surface fracture to button fracture as the welding current increased. The welding current was the key factors on the mechanical properties and microstructure. As the increasing of the electrode force, the welding shearing strength and the diameter of the welding core size decreased. Under the imbalance express cooling, the fusion zone consists of a mixture of α -Zr and β -Zr phases among which lamellar structure. The fine $\text{Fe}_2(\text{Nb}_{0.35}, \text{Zr}_{0.65})$ and $\text{Fe}_2(\text{Nb}_{0.3}, \text{Zr}_{0.7})$ second phases particles were precipitated inter and intergranular in the grains, so the mechanical and anti-water corrosion properties were improved.

Highlights: (1) The spot welding of the new kind zirconium alloys independently developed in China was studied.
(2) Study the welding process parameters of welded joints.
(3) The precipitates in welded joints and their effects on joint properties were analyzed.

Key words: zirconium alloys; resistance welding; micro-structure

Analysis of flow behavior in K-TIG molten pool of 15-5PH steel FENG Tao¹, LV Zuoxiang², LIU Jun¹, DUAN Qiong¹

(1. China University of Petroleum, Qingdao 266580, China; 2. Changling Branch of Sinopec Catalyst Co., Ltd., Hunan, Yueyang 414012, China). pp 91-96

Abstract: K-TIG was used to weld 15-5PH plate. Tracing technique was used to analysis K-TIG molten pool flow behavior. The welding beam consisted of three parts: the upper part was the marangoni convection circle produced by surface tension, the lower part was the convective circle produced by the interaction of surface tension and lorentz force, and the transition zone between the upper and lower convection circles. The trace method indicated that the W elements in the upper and lower parts of the molten pool were distributed in an arc shape around the convective zone, but the W element was no obvious shape in the transition zone. EDS analysis was carried out on the flow ring under the molten pool, and the results showed that the molten metal under the molten pool flowed by internal rotation. The results of calculation and test show that the upper and lower parts of the molten pool flowed violently, but the flow velocity of the middle layer was small. With the increase of welding heat input, the flow velocity of the middle layer had a tendency to decrease, and the grain size of the intermediate layer tended to grow.

Highlights: (1) Through test and calculation, it is found that the weld pool is divided into three areas in the process of k-tig through-hole welding. The flow velocity of molten liquid in the middle of molten pool is slow.
(2) Through the characterization analysis of the shape of the molten pool, it is found that the acceleration of molten metal flow is small in the middle of the molten pool, and the flow acceleration tends to decrease with the increase of heat input.

Key words: 15-5PH steel; K-TIG; tracer method; molten pool flow acceleration