

2219/5A06 异种铝合金脉冲 VP-TIG 焊工艺

徐光霁¹, 魏耀光¹, 冉洸奇¹, 陈瑶¹, 李桓²

(1. 航空工业成都飞机工业(集团)有限责任公司, 成都, 610073;
2. 天津大学, 天津市现代连接技术重点实验室, 天津, 300072)

摘要: 为了获取最优的焊接接头性能, 采用脉冲 VP-TIG 焊方法, 对 5.5 mm 厚的 2219-T87 和 5A06-H112 异种铝合金进行单层单道对接试验, 设计了 5 种工艺参数 3 个因素水平的 $L_{27}(3^9)$ 型正交试验, 同时考虑 3 种因素间的交互作用, 分析各因素对接头抗拉强度的影响, 结果显示工艺参数对接头性能的影响从主到次依次为: 焊接速度—坡口角度—峰值电流—脉冲频率—送丝速度; 通过正交优化, 获得了理想的无缺陷焊接接头, 对优化后焊接接头的力学性能、微观组织与腐蚀性能进行试验. 结果表明, 接头断裂沿着 2219 侧熔合线附近最大应变处发生, 该位置是整个接头中硬度最低的区域, 2219 侧熔合线和焊缝耐腐蚀性最差, 是点蚀优先发生的位置.

创新点: 采用 $L_{27}(3^9)$ 型正交试验, 获得了理想的无缺陷异种铝合金脉冲 VP-TIG 焊接头, 整个接头中 2219 侧熔合线附近是断裂发生的位置, 硬度最低, 点蚀优先发生.

关键词: 正交试验; 脉冲 VP-TIG 焊; 异种铝合金; 力学性能; 腐蚀性能

中图分类号: TG 444⁺.2 **文献标识码:** A **doi:** 10.12073/j.hjxb.20230326001

0 序言

铝合金因其质量轻、比强度高、耐腐蚀性好等优点被广泛应用于航空航天、汽车制造等重要领域^[1-2]. 其中 2219 和 5A06 铝合金是应用广泛的典型代表, 2219 铝合金比强度高, 5A06 铝合金耐腐蚀性好, 两者由于性能的差异被用于不同的场合^[3-4]. 随着结构服役情况的不断提高, 为同时满足结构件高强度及耐腐蚀性的需求, 对异种铝合金焊接接头性能提出了更高要求^[5-6].

焊接接头的最终性能取决于焊接工艺参数的选择, 选择合适的工艺参数将会极大地提高接头的质量, 因此进行一系列合理的试验来确定最佳的工艺参数至关重要. 然而全面试验方法需要大量的试验次数来确定最佳工艺参数, 这很显然需要消耗大量的时间及成本^[7]. 相比于全面试验方法, 正交试验方法是从全面试验中挑选出部分有代表性的点进行试验, 并且能够利用数理统计的方法处理试验结果^[8], 因而减少了试验次数, 具有较高的效率, 得到了国内外研究学者的广泛应用^[9-10].

文中采用正交试验方法对 2219/5A06 异种铝合金脉冲变极性钨极氩弧焊 (variable polarity tungsten inert gas welding, VP-TIG) 进行工艺参数优化, 并通过试验分析优化后焊接接头组织与性能的相关性, 为异种铝合金接头性能的研究提供试验依据.

1 试验方法

母材为热处理强化的 2219-T87 铝合金和加工硬化的 5A06-H112 铝合金, 试板规格为 150 mm × 75 mm × 5.5 mm. 为了获得较高强度的焊接接头, 采用 ER2319 铝合金焊丝, 焊丝直径 1.2 mm, 母材及焊丝化学成分如表 1 所示, 焊接电源为山东奥太 WSME-315 型逆变式交直流脉冲氩弧焊机.

焊接过程中, 需保持以下工艺参数恒定不变: 基值电流 $I_b = 180$ A, 占空比 $\delta = 50\%$, 交流频率 100 Hz, 保护气体为 99.99% 纯氩气, 气体流量 15 L/min, 钨极到工件的距离为 3 mm, V 形坡口钝边 2 mm, 无根部间隙, 焊接方向垂直于轧制方向. 为了保证阴极清理的前提下, 最大程度地降低钨极的烧损, 将脉冲变极性氩弧焊机设置交流偏置 $K_i =$

表1 母材和 ER2319 焊丝化学成分

Table 1 Chemical compositions of the base material and the ER2319 welding wire

材料	Si	Fe	Cu	Mn	Mg	Zn	Ti	Zr	Al	其它
2219-T87	0.2	0.3	5.8~6.8	0.2~0.4	0.02	0.1	0.02~0.1	0.10~0.25	余量	V: 0.050 0~0.150 0
5A06-H112	0.4	0.4	0.1	0.5~0.8	5.80~6.80	0.2	0.02~0.1	-	余量	Be: 0.000 1~0.005 0
ER2319	0.2	0.3	5.8~6.8	0.2~0.4	0.20	0.1	0.10~0.20	0.10~0.25	余量	V: 0.050 0~0.150 0

10%(负半波电流/正半波电流为 1.1 时, $K_t = 10\%$), 清理比例 $K_t = -20\%$ (负半波时间/工作周期为 0.3 时, $K_t = -20\%$).

按国家标准 GB/T 228.1—2010 进行拉伸试验, 拉伸速率为 1 mm/min, 通过数字图像相关(digital image correlation, DIC) 技术测量拉伸过程中实时的应变分布云图, 采用 ZEISS Sigma 300 场发射扫描电镜、Zeiss Smart Zooms 5 超景深显微镜、SU-1510 扫描电镜观察断口形貌. 按国家标准 GB/T 2654—2008 进行显微硬度测试, 试验加载力为 4.9 N, 加载时间 15 s. 采用传统的三电极 Autolab 电化学工作站在 3.5%NaCl 溶液中进行循环电化学极化测试, 分析 2219 侧铝合金和焊缝的点蚀行为.

2 正交试验

2.1 建立正交模型

正交试验方法按以下步骤进行: ① 选因素(脉冲 VP-TIG 焊工艺参数)、定水平(工艺参数的变化范围); ② 选择合适正交表; ③ 进行正交试验, 记录质量特征值(抗拉强度); ④ 采用 Minitab 软件对试验结果进行数理统计分析; ⑤ 进行最佳参数验证试验. 脉冲 VP-TIG 焊可调工艺参数较多, 根据相关学者的研究并结合试验条件, 选择峰值电流、焊接速度、送丝速度、坡口角度、脉冲频率 5 个因素进行优化^[11], 通过观察焊缝成形以及是否全焊透, 确定工艺参数的变化范围, 如表 2 所示.

表2 因素及水平设计表

Table 2 Design table of factors and levels

编号	工艺参数(因素)	水平1	水平2	水平3
A	峰值电流 I_p /A	230.0	240.0	250.0
B	焊接速度 v / (mm·min ⁻¹)	100.0	120.0	140.0
C	送丝速度 v_s / (mm·min ⁻¹)	2.5	2.6	2.7
D	坡口角度 α / (°)	70.0	80.0	90.0
E	脉冲频率 f / Hz	1.0	2.0	3.0

根据因素和水平数选择合适的正交表, 文中正交试验中, 既需要考虑表 2 所设计的 5 因素 3 水平, 还需考虑 3 组交互作用: 峰值电流 × 焊接速度 (A × B)、峰值电流 × 送丝速度 (A × C)、峰值电流 × 坡口角度 (A × D), 并预留 1 列空白列作为随机误差列. 为了减少正交表的列数, 交互作用所占列数都设计为 1 列, 故可以选择最小正交表 $L_{27}(3^9)$ 进行工艺优化.

如表 3 所示, 正交表设计完成后, 将各列表头的因素采用表 2 编号替代, 将各列上的数字 1, 2 和 3 分别看成各因素的水平数, 就可以确定 27 组工艺参数组合方案. 交互作用和空白列虽然也占有相应列, 但对试验方案没有任何影响, 按各工艺参数的组合进行试验, 取焊后接头 3 次抗拉强度的平均值作为质量特征值.

2.2 正交试验极差分析

信噪比 (signal to noise ratio, S/N) 是衡量质量稳定性的评价指标. 为了获得接头最大的抗拉强度, 故选择望大特征的信噪比进行试验结果的极差分析, 其计算公式为

$$S/N = -10 \lg \left(\frac{1}{n} \sum_{j=1}^n \frac{1}{y_j^2} \right) \quad (1)$$

式中: n 为拉伸试验次数 (3 次); y_j 为第 j 次的抗拉强度. 计算结果如表 4 所示.

一般来说, 各因素的极差是不相等的, 这就表明各因素水平的变化对试验结果的影响是区分主次顺序的. 若极差越大, 就能够说明该因素对试验结果影响越大; 若空白列的极差比所有因素的极差大, 表明各因素之间可能存在不可忽略的交互作用.

如表 5 所示, 通过 Minitab 软件计算信噪比的极差 R . 从极差 R 的排序结果发现, 交互作用 A × C (峰值电流 × 送丝速度)、A × D (峰值电流 × 坡口角度) 对试验结果的影响最小, 因而可以忽略. 交互作用 A × B (峰值电流 × 焊接速度) 虽然排序为 5, 但是小于因素 A (峰值电流) 和 B (焊接速度) 单独变

表 3 试验方案与试验结果
Table 3 Experiment scheme and corresponding results

试验编号	A	B	A × B	C	A × C	D	A × D	E	空列	试验方案	抗拉强度 R_m /MPa
1	1	1	1	1	1	1	1	1	1	A ₁ B ₁ C ₁ D ₁ E ₁	272.05
2	1	1	1	1	2	2	2	2	2	A ₁ B ₁ C ₁ D ₂ E ₂	276.17
3	1	1	1	1	3	3	3	3	3	A ₁ B ₁ C ₁ D ₃ E ₃	276.17
4	1	2	2	2	1	1	1	2	2	A ₁ B ₂ C ₂ D ₁ E ₂	271.12
5	1	2	2	2	2	2	2	3	3	A ₁ B ₂ C ₂ D ₂ E ₃	277.58
6	1	2	2	2	3	3	3	1	1	A ₁ B ₂ C ₂ D ₃ E ₁	189.70
7	1	3	3	3	1	1	1	3	3	A ₁ B ₃ C ₃ D ₁ E ₃	299.00
8	1	3	3	3	2	2	2	1	1	A ₁ B ₃ C ₃ D ₂ E ₁	284.69
9	1	3	3	3	3	3	3	2	2	A ₁ B ₃ C ₃ D ₃ E ₂	261.00
10	2	1	2	3	1	2	3	1	2	A ₂ B ₁ C ₃ D ₂ E ₁	253.75
11	2	1	2	3	2	3	1	2	3	A ₂ B ₁ C ₃ D ₃ E ₂	246.04
12	2	1	2	3	3	1	2	3	1	A ₂ B ₁ C ₃ D ₁ E ₃	253.83
13	2	2	3	1	1	2	3	2	3	A ₂ B ₂ C ₁ D ₂ E ₂	260.60
14	2	2	3	1	2	3	1	3	1	A ₂ B ₂ C ₁ D ₃ E ₃	239.90
15	2	2	3	1	3	1	2	1	2	A ₂ B ₂ C ₁ D ₁ E ₁	277.86
16	2	3	1	2	1	2	3	3	1	A ₂ B ₃ C ₂ D ₂ E ₃	286.05
17	2	3	1	2	2	3	1	1	2	A ₂ B ₃ C ₂ D ₃ E ₁	270.42
18	2	3	1	2	3	1	2	2	3	A ₂ B ₃ C ₂ D ₁ E ₂	285.13
19	3	1	3	2	1	3	2	1	3	A ₃ B ₁ C ₂ D ₃ E ₁	260.36
20	3	1	3	2	2	1	3	2	1	A ₃ B ₁ C ₂ D ₁ E ₂	282.76
21	3	1	3	2	3	2	1	3	2	A ₃ B ₁ C ₂ D ₂ E ₃	286.95
22	3	2	1	3	1	3	2	2	1	A ₃ B ₂ C ₃ D ₃ E ₂	281.28
23	3	2	1	3	2	1	3	3	2	A ₃ B ₂ C ₃ D ₁ E ₃	282.53
24	3	2	1	3	3	2	1	1	3	A ₃ B ₂ C ₃ D ₂ E ₁	258.72
25	3	3	2	1	1	3	2	3	2	A ₃ B ₃ C ₁ D ₃ E ₃	287.49
26	3	3	2	1	2	1	3	1	3	A ₃ B ₃ C ₁ D ₁ E ₁	311.32
27	3	3	2	1	3	2	1	2	1	A ₃ B ₃ C ₁ D ₂ E ₂	302.62

表 4 抗拉强度的信噪比

Table 4 Signal to noise ratio of tensile strength

试验编号	信噪比S/N	试验编号	信噪比S/N	试验编号	信噪比S/N
1	48.69	10	48.07	19	48.24
2	48.82	11	47.81	20	48.78
3	48.78	12	48.06	21	49.16
4	48.66	13	48.32	22	48.97
5	48.85	14	47.49	23	49.00
6	45.09	15	48.87	24	48.25
7	49.51	16	49.13	25	49.16
8	49.08	17	48.64	26	49.86
9	48.33	18	49.10	27	49.62

到次的顺序依次为: B(焊接速度) — D(坡口角度) — A(峰值电流) — E(脉冲频率) — C(送丝速度).

图 1 为相对应的信噪比响应图, 结合表 5 选择最佳的试验方案组合. 正交试验选择了望大特征的信噪比, 因此从 A(峰值电流)、B(焊接速度)、C(送丝速度)、D(坡口角度)、E(脉冲频率)3 个水平中选择最大的信噪比, 得到最优工艺参数组合为 A₃B₃C₁-D₁E₃, 并不包含在已做的 27 组试验方案中, 这正体现了正交试验设计的优越性.

2.3 正交试验方差分析

极差分析清晰易懂, 但不能区分各因素水平的变化对试验结果的影响究竟是由因素的水平变化引起的, 还是由试验误差引起的, 也就是说, 无法估计试验误差的大小; 另外极差分析虽然可以确定各因素对试验结果影响的主次顺序, 但是不能提出—

化时对试验结果的影响, 因而也可以忽略. 因此文中正交试验设计中, 各因素对试验结果的影响从主

表 5 信噪比响应表
Table 5 Signal to noise ratio response table

水平	A	B	A × B	C	A × C	D	A × D	E	空列
1	48.42	48.49	48.82	48.85	48.75	48.95	48.65	48.31	48.32
2	48.39	48.17	48.35	48.40	48.70	48.81	48.79	48.71	48.74
3	49.00	49.16	48.64	48.56	48.36	48.06	48.37	48.79	48.75
极差R	0.62	0.99	0.47	0.44	0.39	0.89	0.42	0.48	0.42
排序	3.00	1.00	5.00	6.00	9.00	2.00	8.00	4.00	7.00

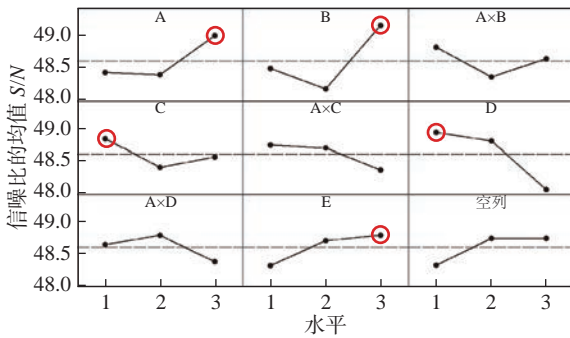


图 1 信噪比响应图

Fig. 1 Signal to noise ratio response diagram

个标准来判断各因素作用的显著程度, 因此为了弥补极差分析的缺陷, 对试验结果进行了方差分析, 表 6 为信噪比方差分析, 表中 F 值为各因素或交互作用的方差除以误差的方差; P 值表示模型及各个因素的显著水平, 系统默认值 0.05. 当 $P < 0.05$ 时, 表明该因素的变化对试验结果的影响非常显著, P 值越小影响越显著; 当 $P > 0.05$ 时, 表明该因素的变化对试验结果的影响不显著, P 值越大影响越不显著.

表 6 信噪比方差分析表

Table 6 Analysis of variance for signal-to-noise ratio

因素	自由度 m	偏差平方和 U_{SS}	方差 σ_{MS}	F 值	P 值
A	2	2.157 7	1.078 8	2.20	0.161
B	2	4.618 8	2.309 4	4.71	0.036
A × B	2	0.995 8	0.497 9	1.02	0.397
C	2	0.899 5	0.449 7	0.92	0.431
A × C	2	0.812 2	0.406 1	0.83	0.465
D	2	4.140 7	2.070 4	4.22	0.047
A × D	2	0.828 1	0.414 0	0.84	0.458
E	2	1.200 6	0.600 3	1.22	0.335
误差	10	4.903 4	0.490 3		
合计	26	20.556 9			

从信噪比方差分析表中得出, 因素 B(焊接速度) 和 D(坡口角度) 的 $P < 0.05$, 表明这 2 个因素的变化对试验结果的影响非常显著, 并发现因素 B 比因素 D 的 P 值更小, 说明了因素 B 在正交试验中对试验结果的影响是最显著的. 因素 A(峰值电流)、C(送丝速度)、E(脉冲频率) 的 $P > 0.05$, 表明这些因素对试验结果的影响并不显著, 并从 P 值的大小得知: 对试验结果的影响由大到小依次为因素 A—因素 E—因素 C. 另外, 从 3 组交互作用的 P 值都大于 0.05 得出, 正交试验中所选的交互作用可以忽略它们对试验结果的影响.

2.4 试验验证

正交试验设计最佳工艺参数组合为 $A_3B_3C_1D_1E_3$, 其具体工艺参数为: A(峰值电流 250 A), B(焊接速度 140 mm/min), C(送丝速度 2.5 m/min), D(坡口角度 70°), E(脉冲频率 3 Hz), 并不包含在已做的 27 组试验方案中, 因此将最佳方案 $A_3B_3C_1D_1E_3$ 与正交表中最好的第 26 号试验方案 $A_3B_3C_1D_1E_1$ 作对比试验. 如表 7 所示, 从 Minitab 软件预测值和实际测量值得出, 最佳方案组合的信噪比和抗拉强度都比第 26 号试验方案高, 说明正交试验设计成功优化了 2219/5A06 异种铝合金脉冲 VP-TIG 焊的工艺参数.

表 7 Minitab 预测值和实际测量值

Table 7 Minitab predicted and actual measured value

类别	试验方案	信噪比 S/N	抗拉强度 R_m/MPa
Minitab 预测值	$A_3B_3C_1D_1E_3$ (最佳)	50.33	321.21
	$A_3B_3C_1D_1E_1$ (26号)	49.85	308.92
实际测量值	$A_3B_3C_1D_1E_3$ (最佳)	50.04	317.45
	$A_3B_3C_1D_1E_1$ (26号)	49.86	311.32

图 2 为最佳工艺参数组合 $A_3B_3C_1D_1E_3$ 的焊缝宏观形貌, 从图看出焊缝成形良好, 呈明显的鱼鳞

状, 在焊缝横截面中并未发现明显的缺陷.

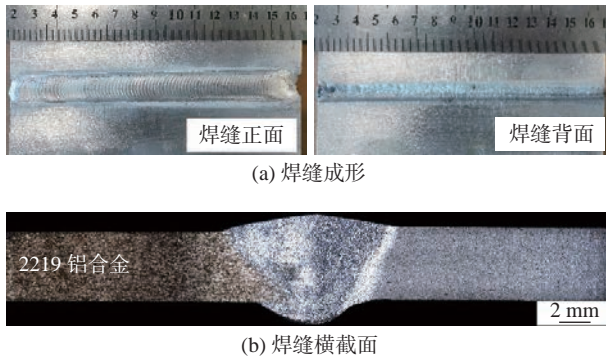


图 2 焊缝宏观形貌

Fig. 2 Macroscopic morphology of weld. (a) weld formation; (b) weld cross section

3 力学和腐蚀性能

3.1 力学性能

在焊接热循环的作用下, 焊缝区、热影响区以及熔合线附近的组织形貌、元素分布和晶体学结构均会发生改变, 这些改变会对接头力学性能产生重大影响, 因此研究优化后的 2219/5A06 异种铝合金焊接接头组织与力学性能的相关性, 解释拉伸过程中试样断裂的机理以及显微硬度的分布规律. 2219-T87 铝合金抗拉强度为 470 MPa, 断后伸长率为 15.36%; 5A06-H112 铝合金抗拉强度为 397 MPa, 断后伸长率为 15.73%; 焊后接头抗拉强度分别达到 2219 和 5A06 母材的 67.5% 和 80.0%, 断后伸长率分别达到 2219 和 5A06 母材的 27.0% 和 26.4%. 图 3 所示拉伸试验中, 试样的断裂位置发生在 2219 侧熔合线附近的区域.

图 4 为拉伸过程中焊接接头实时的应变分布云图. 从图看出, 焊接接头中的最大应变集中发生在 2219 和 5A06 侧熔合线附近的区域, 并发现

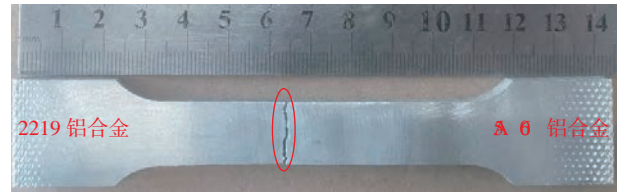


图 3 脉冲 VP-TIG 焊接头断裂位置

Fig. 3 Fracture location of pulsed VP-TIG joint

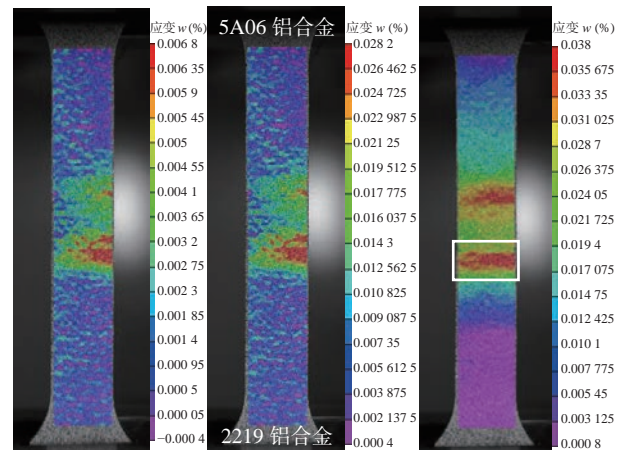


图 4 脉冲 VP-TIG 焊接头应变分布云图

Fig. 4 Strain distribution cloud diagram of pulsed VP-TIG welded joint

2219 侧熔合线附近的应变比 5A06 侧熔合线附近的应变更大、分布更密集; 随着拉伸过程的进行, 试样断裂沿着 2219 侧熔合线附近的最大应变处发生. 观察焊接接头断口横截面的微观组织, 可以更好地解释接头的失效原因. 图 5 为 2219 侧熔合线附近断裂区域的微观形态, 从图中看出, 断裂主要沿细等轴晶带和晶界发生, 由于细等轴晶带未能与 2219 侧熔合线附近热影响区侧的板条状组织和焊缝侧的粗等轴晶实现平滑过渡, 以及晶界处存在大量的呈网状连续的共晶相恶化了接头性能.

图 6 为 2219 侧熔合线附近断裂区域的第二相分布和相对应的能谱定点测量结果, 进一步阐明第

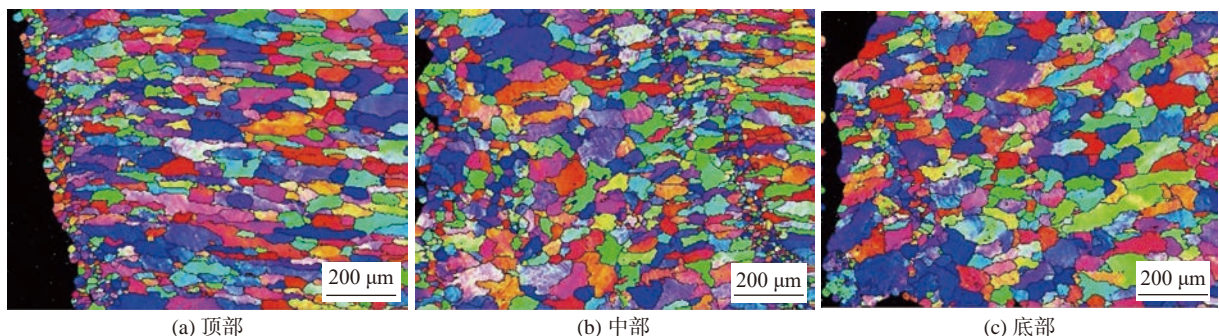


图 5 脉冲 VP-TIG 焊接头断口横截面组织

Fig. 5 Fracture cross section structure of pulsed VP-TIG welded joint. (a) top; (b) middle; (c) bottom

二相对接头断裂的影响. 结果表明, 断裂主要发生在细等轴晶带和晶界呈网状连续的 Al + Al₂Cu 共晶相处.

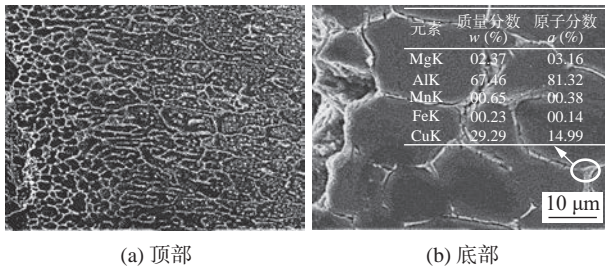


图 6 脉冲 VP-TIG 焊接接头断口横截面第二相分布
Fig. 6 Second phase distribution on the fracture cross section of pulsed VP-TIG welded joint. (a) top; (b) bottom

图 7 为焊接接头断口形貌, 将 2219 侧宏观断口分为 3 个部分: 沿厚度方向顶部①、中部②、底部③. 从图中看出, 顶部断口形貌基本全为撕裂棱, 中部和底部断口形貌还是以撕裂棱为主, 但同时又存在一些浅而平的韧窝, 底部韧窝的分布较中部多, 表明脉冲 VP-TIG 焊接接头的断裂方式主要以准解理断裂为主, 但同时存在一些塑性断裂的特征.

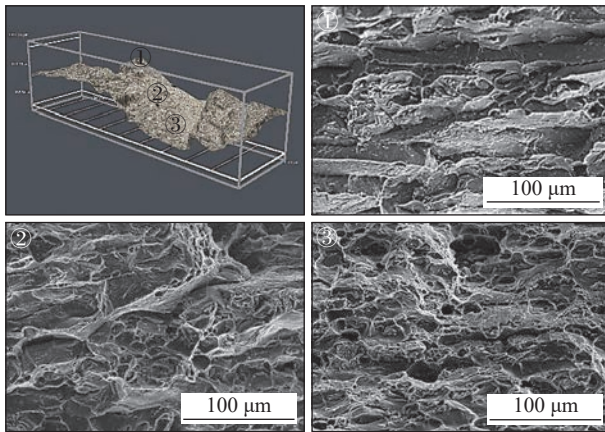


图 7 脉冲 VP-TIG 焊接接头 2219 侧断口形貌
Fig. 7 Fracture morphology of 2219 side of pulsed VP-TIG welded joint

图 8 为脉冲 VP-TIG 焊接接头不同位置的显微硬度分布和相对应的硬度分布云图, 其中位置 1-4 分别指距接头上表面的距离: 位置 1(1.25 mm)、位置 2(2.25 mm)、位置 3(3.25 mm)、位置 4(4.25 mm). 从显微硬度的分布来看, 脉冲 VP-TIG 焊接接头中 2219 和 5A06 母材的硬度值最高; 其次从母材到热影响区, 两侧接头的硬度值都呈现明显的下降趋势, 而 2219 热影响区的下降趋势更明显. 相比于热影响区, 两侧熔合线附近的硬度值更

低, 其中 2219 侧熔合线附近是整个接头中硬度值最低的区域, 这是因为从 2219 侧熔合线附近的第二相分布特征可以得出, 相比于 2219 热影响区, 由于 2219 侧熔合线附近晶粒内基本不存在颗粒状的 Al₂Cu 相, 而晶界上却分布着大量的呈网状连续的 Al + Al₂Cu 共晶组织, 导致该区域的硬度值最低、塑性差. 而对于 5A06 侧熔合线附近的区域, 由于该区域经历的峰值温度比 5A06 热影响区高, 导致加工硬化效果进一步消失, 但软化程度远小于 2219 侧熔合线附近的区域, 因此 2219 侧熔合线附近是整个接头中最薄弱的位置, 是断裂发生的位置.

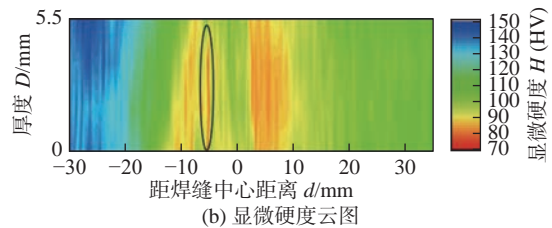
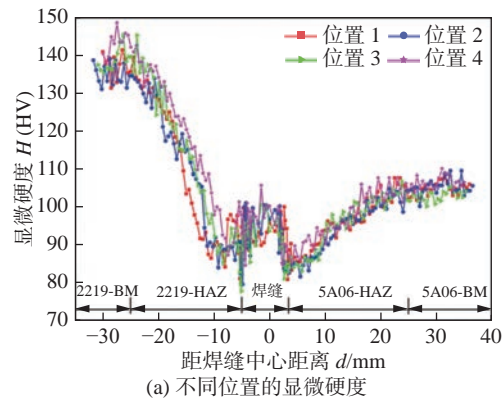


图 8 脉冲 VP-TIG 焊接接头显微硬度分布
Fig. 8 Microhardness distribution of pulsed VP-TIG welded joints. (a) microhardness at different locations; (b) microhardness cloud image

3.2 腐蚀性能

5A06 铝合金是防锈铝, 耐腐蚀性优良, 通过循环电化学极化试验, 分析焊接接头 2219 侧铝合金和焊缝的腐蚀行为. 图 9 为焊接接头 2219 侧铝合金和焊缝的循环极化曲线, 其中用黑色箭头表示扫描方向, 并标注腐蚀电位 (corrosion potential, E_{corr})、点蚀电位 (pitting potential, E_{pit})、点蚀之后重新钝化电位 (repassivation/protection, E_{prot}). 从图中看出, 焊接接头的不同区域都呈现出典型的钝化区, 该钝化区与所施加的电势无关, 直到形成钝化膜的点蚀电位 E_{pit} 为止, 从而保护了铝合金免受腐蚀.

表 8 为相对应的电化学参数值. 从表中得出,

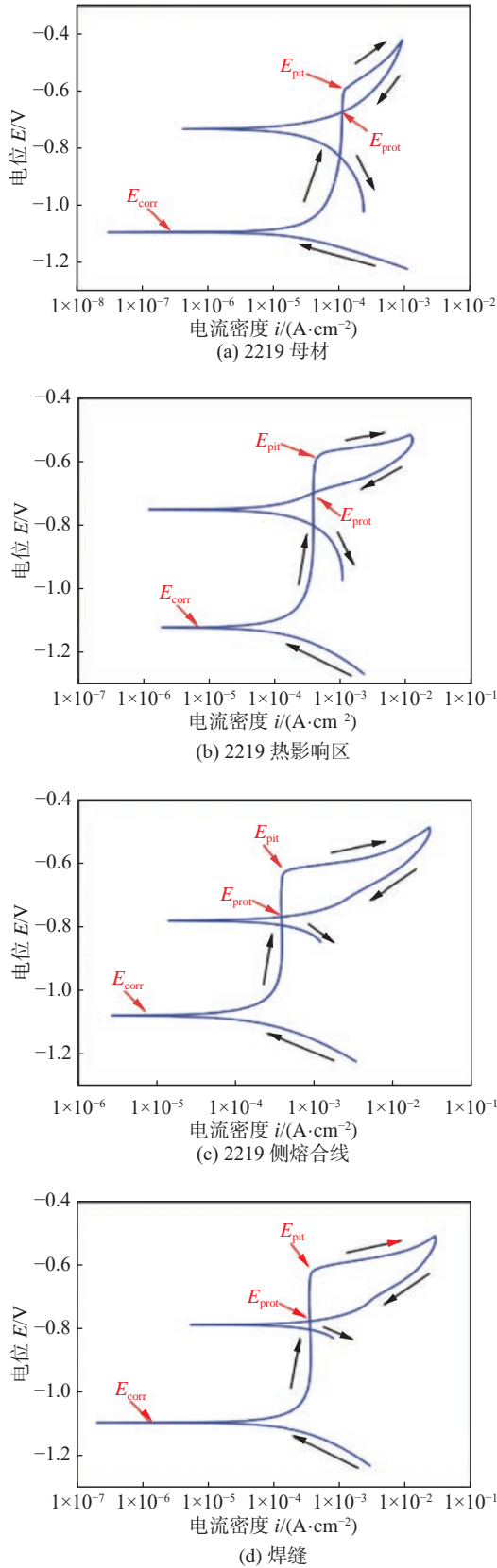


图 9 循环极化曲线

Fig. 9 Cyclic polarization curve. (a) 2219 BM; (b) 2219 HAZ; (c) 2219 side fusion line; (d) welded seam

2219 热影响区具有比 2219 母材低的自腐蚀电位和高的腐蚀电流密度, 且根据电位差 $\Delta E_1(E_{pit} - E_{prot})$ 发

现点蚀之后 2219 热影响区重新钝化的能力比母材低, 这些参数都表明热影响区由于焊接热输入的作用造成了耐蚀性降低。相比于 2219 热影响区, 由于 2219 侧熔合线附近的区域和焊缝具有更高的腐蚀电流密度, 较低的点蚀电位, 且重新钝化的能力也更弱, 因此对于焊接接头 2219 侧铝合金和焊缝, 2219 侧熔合线附近的区域和焊缝是点蚀优先发生的位置。

表 8 循环电化学极化试验结果
Table 8 Design table of factors and levels

区域	腐蚀电位 E_{corr}/V	腐蚀电流密度 $i_{corr}/(10^{-4} A \cdot cm^{-2})$	点蚀电位 E_{pit}/V	重新钝化电位 E_{prot}/V	电位差 $\Delta E_1/mV$
2219母材	-1.094	0.197	-0.599	-0.675	76
2219热影响区	-1.121	1.100	-0.588	-0.699	111
2219侧熔合线	-1.079	1.290	-0.632	-0.765	133
焊缝	-1.093	1.370	-0.627	-0.776	149

图 10 为循环电化学极化试验后的腐蚀形貌。从图中可以清晰地看出, 2219 母材的耐点蚀能力最好, 其次是 2219 热影响区, 2219 侧熔合线附近的区域和焊缝的耐点蚀性能最差, 与上述循环电化学曲线得出的结论相吻合, 并且发现 2219 侧熔合线附近的区域和焊缝发生了点蚀逐渐向晶间腐蚀的过渡, 这是因为铝合金的点蚀与第二相密切相关, Al_2Cu 相由于含有电位较高的 Cu 元素, 使其作为阴极被保护, Al_2Cu 相周围的基体产生了贫铜区, 使其作为阳极发生了腐蚀, 然而 2219 侧熔合线附近

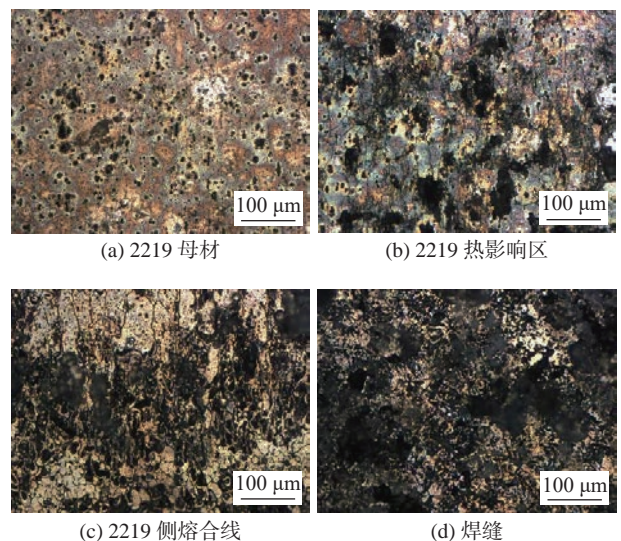


图 10 腐蚀形貌

Fig. 10 Corrosion morphology. (a) 2219 BM; (b) 2219 HAZ; (c) 2219 side fusion line; (d) welded seam

的区域和焊缝在焊接热输入作用下,晶界处存在大量的呈网状连续的 Al + Al₂Cu 共晶相,导致其耐腐蚀性降低。

4 结论

(1) 采用 L₂₇(3⁹) 正交表,最佳工艺参数组合为峰值电流 250 A、焊接速度 140 mm/min、送丝速度 2.5 m/min、坡口角度 70°、脉冲频率 3 Hz。工艺参数的变化对试验结果的影响从主到次的顺序依次为焊接速度—坡口角度—峰值电流—脉冲频率—送丝速度,其中焊接速度和坡口角度对试验结果的影响非常显著。

(2) 成功获得了无缺陷的焊接接头,接头的抗拉强度分别达到 2219 和 5A06 母材的 67.5% 和 80.0%,断后伸长率分别达到 2219 和 5A06 母材的 27.0% 和 26.4%。试样的断裂沿着 2219 侧熔合线附近的最大应变处发生,该位置是整个接头中硬度值最低的区域,接头的断裂方式主要以准解理断裂为主,同时存在一些塑性断裂的特征。

(3) 对于焊接接头 2219 侧铝合金和焊缝,2219 侧熔合线附件和焊缝区域耐蚀性最差,是点蚀优先发生的位置。

参考文献

- [1] Li H, Zou J, Yao J, *et al.* The effect of TIG welding techniques on microstructure, properties and porosity of the welded joint of 2219 aluminum alloy[J]. *Journal of Alloys and Compounds*, 2017, 727: 531 – 539.
- [2] Gao J, Yang L, Cui L, *et al.* Improving the weld formation and mechanical properties of the AA-5A06 friction pull plug welds by axial force control[J]. *Acta Metallurgica Sinica (English Letters)*, 2020, 33(6): 828 – 838.
- [3] 董晓晶,李桓,杨立军,等. 铝合金多股复合焊丝脉冲 MIG 焊接接头组织与性能分析[J]. *焊接学报*, 2019, 40(11): 61 – 67.
Dong Xiaojing, Li Huan, Yang Lijun, *et al.* Microstructure and mechanical properties of pulse MIG aluminum alloy welded joints by means of a novel multi-strands composite welding wire[J]. *Transactions of the China Welding Institution*, 2019, 40(11): 61 – 67.
- [4] 王非凡,谢聿铭,吴会强,等. 2219 铝合金 FSW 和 TIG 焊接头力学与腐蚀行为[J]. *焊接学报*, 2022, 43(6): 43 – 49.
Wang Feifan, Xie Yuming, Wu Huiqiang, *et al.* Mechanical performances and corrosion behaviors of friction stir welded and TIG welded 2219 aluminum alloy joints[J]. *Transactions of the China Welding Institution*, 2022, 43(6): 43 – 49.
- [5] 方远方,张华,窦程亮. 2A12-T4/7A09-T6 铝合金搅拌摩擦焊接接头性能分析[J]. *焊接学报*, 2020, 41(1): 86 – 90.
Fang Yuanfang, Zhang Hua, Dou Chengliang. Study on friction stir lap weld of 2A12-T4/7A09-T6 aluminum alloys[J]. *Transactions of the China Welding Institution*, 2020, 41(1): 86 – 90.
- [6] 高士康,周利,张欣盟,等. 6061-T6/7075-T6 异种铝合金搅拌摩擦焊接头组织与性能[J]. *焊接学报*, 2022, 43(6): 35 – 42.
Gao Shikang, Zhou Li, Zhang Xinmeng, *et al.* Microstructure and properties of friction stir welded joints for 6061-T6/7075-T6 dissimilar aluminum alloy[J]. *Transactions of the China Welding Institution*, 2022, 43(6): 35 – 42.
- [7] Koilraj M, Sundareswaran V, Vijayan S, *et al.* Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083—optimization of process parameters using taguchi technique[J]. *Materials & Design*, 2012, 42: 1 – 7.
- [8] 毛志伟,徐伟,周少玲,等. 基于田口方法旋转电弧焊接工艺参数优化[J]. *热加工工艺*, 2016, 45(11): 169 – 173.
Mao Zhiwei, Xu Wei, Zhou Shaoling, *et al.* Optimization of rotating arc sensor welding parameters using taguchi method[J]. *Hot Working Technology*, 2016, 45(11): 169 – 173.
- [9] Ma Z, Li Q, Ma L, *et al.* Process parameters optimization of friction stir welding of 6005A-T6 aluminum alloy using taguchi technique[J]. *Transactions of the Indian Institute of Metals*, 2019, 72(7): 1721 – 1731.
- [10] 李涛,李芳,顾勇,等. 基于田口方法的铸铝 A356 焊接工艺参数优化研究[J]. *热加工工艺*, 2016, 45(9): 43 – 47.
Li Tao, Li Fang, Gu Yong, *et al.* Study on optimization of welding process parameters for A356 cast aluminum alloy based on Taguchi method[J]. *Hot Working Technology*, 2016, 45(9): 43 – 47.
- [11] Lin Y T, Wang M C, Zhang Y, *et al.* Investigation of microstructure evolution after post-weld heat treatment and cryogenic fracture toughness of the weld metal of AA2219 VPTIG joints[J]. *Materials & Design*, 2017, 113: 54 – 59.

第一作者:徐光霁,硕士研究生;主要从事铝合金焊接的研究; Email: xgp18893918704@163.com.

通信作者:李桓,教授,博士研究生导师; Email: lihuan@tju.edu.cn.

(编辑: 郑红)

increase the number of oxides, refine the size of oxides, and ensure the toughness of CGHAZ under super large heat input.

Key words: trace element; ship plate; super large heat input; coarse grain heat affected zone

"I" shaped arc and its promotion method in Tri-Arc dual wire welding

ZHONG Pu, LI Liangyu, REN Guochun, WANG Tianqi, GUO Dongbo(Tianjin Key Laboratory of Advanced Mechatronics Equipment Technology, Tiangong University, Tianjin, 300387, China). pp 54-60

Abstract: The Tri-Arc dual wire welding achieves a high deposition rate and low heat input by redistributing the heat input through an intermediate third arc called M-Arc. The M-arc is coupled to the main arc and exhibits "I" and "μ" shapes and their mirror images throughout the dynamic cycle. In this paper, the formation mechanism of the "I"-shaped arc and the heat input regulation mechanism are investigated first. The results indicate that the "I" shape evolves from the "μ" shape, the oscillation of adhered molten droplets induces a variation in the distance between two wire ends, thereby facilitating the formation of "I" shape in the coupled arc. In this case, the M-arc does not touch the workpiece, rendering a lower heat input during welding than the "μ"-shaped arc. In order to enhance the low heat input effectiveness of the Tri-Arc dual wire welding, the alteration of the distance at two wire ends is achieved by elevating the welding torch. Simultaneously, the length of the conductive nozzle should be increased to maintaining a constant distance between the tip of the conductive nozzle and the workpiece. When the length of the conductive nozzle is increased from 30 mm to 35 mm, as the welding torch is elevated, the duration of the "I" shaped arc phase gradually extends. This extended duration effectively facilitates arc thermal distribution, consequently reducing the heat input during Tri-Arc dual wire welding. As a result, peak value of the highest temperature within the molten pool diminishes, thereby reduced the weld bead width-to-height ratios and weld penetration.

Highlights: (1) The heat input distribution mechanism of Tri-Arc dual wire welding is investigated, revealing that the coupled arc heat input is lower in "I"-shape. (2) The process of arc coupling is elucidated, confirming that the formation of the "I"-shaped arc is affected by the distance between the ends of the welding wires. (3) It is proposed and verified that reducing the distance between 2 wire ends can effectively promote the generation of

the "I"-shaped arc.

Key words: tri-arc dual wire welding; coupled arc; arc shape; arc thermal distribution; weld thermal input

Three-dimensional reconstruction of GMAW weld pool appearance based on variational stereo matching algorithm

LIANG Zhimin^{1,2}, GAO Xu¹, REN Zheng¹, WU Ziqin¹, WANG Liwei^{1,2}, WANG Dianlong^{1,2}(1. School of Material Science and Engineering, University of Science and Technology, Shijiazhuang, 050000, China; 2. Hebei Key Laboratory of Material Near-net Forming Technology, Shijiazhuang, 050000, China). pp 61-66

Abstract: In order to realize the complete three-dimensional sensing of weld pool surface morphology, a stereo vision sensing system with biprism and single camera was constructed. Aiming at the difficulty of stereo matching caused by the lack of texture in weld pool map, a globally optimized variational stereo matching algorithm was introduced. By establishing the feasibility function of energy function containing gray difference data item and spatial continuity constraint item, the dense disparity figure of weld pool surface with rich details was obtained through iterative. The results of stereo matching and three-dimensional reconstruction of the self-made non-standard concave shape show that the width error is less than 3.16% and the depth error is less than 4.82%. Based on this algorithm, the dense disparity map of weld pool surface is calculated and reconstructed under the conditions of bead on plate and V-groove butt welding with different penetration states.

Highlights: (1) A biprism stereo visual sensing system based on a single camera is constructed. (2) Disparity calculation and 3D reconstruction of the complete weld pool surface are implemented based on a variational stereo matching algorithm.

Key words: weld pool appearance; three-dimensional reconstruction; variational stereo matching algorithm; gas metal arc welding

Investigation of pulse VP-TIG welding process of 2219/5A06 dissimilar aluminum alloy

XU Guangpei¹, WEI Yaoguang¹, RAN Guangqi¹, CHEN Yao¹, LI Huan²(1. AVIC Chengdu Aircraft Industrial (Group) Co., Ltd., Chengdu, 610073, China; 2. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin University, Tianjin, 300072,

China). pp 67-74

Abstract: In order to obtain the best performance of welded joints, dissimilar aluminum alloys of 2219-T87 and 5A06-H112 with a thickness of 5.5 mm was joined by pulsed VP-TIG butt welding. The L27(3⁹) type orthogonal table with five process parameters and three levels were designed, and the interaction between three factors was considered at the same time. The influence of each factor on the tensile strength of the joints was analyzed, and the results show that the influence of the process parameters on the joint performance is in the order: welding speed > groove angle > peak current > pulse frequency > wire feeding speed. Through orthogonal optimization, an ideal defect-free welded joint was obtained. The mechanical properties, microstructure and corrosion properties of the optimized welded joint were tested. The results show that the fracture edge of the joint was near the fusion line on the 2219 side, where the strain was the largest and the hardness was the lowest. The corrosion resistance of the 2219 side fusion line and the weld area is the worst, and it is the location where pitting corrosion occurs preferentially.

Highlights: Using L27(3⁹) type orthogonal text, the ideal a defect-free dissimilar aluminum alloy pulse VP-TIG welded joints is obtained. Near the fusion line of 2219 side in the whole welded joint is the location of fracture, the area with the lowest hardness value, and the position where pitting corrosion occurs preferentially.

Key words: orthogonal experimental; plused VP-TIG welding; dissimilar aluminum alloy; mechanical property; corrosive property

Effect of microtexturing characteristics on the performance of laser welded aluminum alloy-CFRTP joints

XU Liang¹, LI Kangning¹, YANG Haifeng¹, SONG Kunlin², GU Shiwei¹(1. HWI-NICHST Welding and Engineering Innovation Center(Qingdao)Co., LTD., Qingdao, 266000, China; 2. National Invitation Center of High Speed Train at Qingdao, Qingdao, 266108, China). pp 75-81

Abstract: The effect of laser texturing on the performance of aluminium alloy-CFRTP laser welded joints was studied and the strengthening mechanism of laser texturing was analyzed. The results showed that the laser surf-sculpt could be used to build texturing on the surface of aluminium alloys to obtain well-formed and high performance aluminium alloy-CFRTP laser welded lap joints, and the joint achieved tightly embedding. With the increasing of the depth-width ratio of the laser

texturing, the molten CFRTP in the texturing was changed from fully filled to partially filled, and the joint shear properties showed a trend of first increasing and then decreased, and the joint failure mechanism was changed from hybrid fracture (adhesive failure + cohesive failure), CFRTP base material fracture to hybrid fracture. The joint performance reached its maximum when the depth-width ratio reached 1.2 to 1.6, at which point the fracture location was located in the CFRTP base material. The strengthening mechanisms of the aluminium alloy-CFRTP joint by laser texturing were enhancing mechanical embedding and the "nailing" effect of splashing.

Highlights: (1) The characteristics of laser texture and its effect on the filling effect of CFRTP were investigated. (2) Effect of laser texture characteristics on the properties and fracture mechanism of welded joints was expounded.

Key words: laser texturing; carbon fiber; composite material; laser welding

Recognition algorithm of small-diameter tube X-ray welding defect image

XIAO Yang¹, GAO Weixin^{1,2}, DENG Guohao²(1. School of Electronic Engineering, Xi'an Shiyou University, Xi'an, 710065, China; 2. Key Laboratory of Gas-Oil Logging Technology, Xi'an Shiyou University, Xi'an, 710065, China). pp 82-88

Abstract: To address the current situation of low accuracy rate of small-diameter tube welding image defect detection, by combining image feature analysis and sparse dictionary learning, a small-diameter tube welding defect detection algorithm based on image segmentation is proposed. Firstly, using two-step image segmentation way acquires the region of interest which is in small-diameter tube welding image. Secondly, the suspected defect region is obtained by extracting welding defect. Finally, we propose a mathematical model of the dictionary matrix of small-diameter tube welding defects with the objective of minimizing correlations between different types of atoms and solve it by using K-SVD algorithm. After that, the dictionary matrix is used to classify circular defects, strip defects and noise. To improve the real-time performance of the system, we use parallel programming to accelerate the image segmentation algorithm. The results show that the recognition rate of the proposed method is 0.974 for circular defects and 0.967 for strip defects, and the recognition speed is fast, which enables the effective recognition of defects in small-diameter tube welding image.