

## 2219 铝合金高频耦合脉冲 TIG 焊接工艺

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**摘 要:** 对 2219 铝合金采用高频耦合脉冲 TIG 的焊接工艺研究, 结果表明, 采用特殊交流以及叠加高频脉冲可以有效的细化组织, 消除气孔和减少裂纹等冶金缺陷, 显著改善和提高铝合金接头性能。在此基础上研究了单层焊和双层焊对接头性能的影响, 对双层焊每一层的工艺参数做了优化, 对接头各微区采用了晶粒度的定量分析与对比, 提出了通过控制热循环对接头“控性”的方法, 使接头微观组织趋于均匀, 是提高接头综合力学性能的一个新思路, 在工程上具有适用性。

**关键词:** 2219 铝合金; 高频耦合; 脉冲 TIG; 接头力学性能; 晶粒度评定

**中图分类号:** TG 444 **文献标识码:** A **文章编号:** 0253-360X(2015)05-0017-04

### 0 序 言

目前 2219 铝合金正逐步运用到航天、航空领域, 相对于 2014 铝合金, 它具有焊接性好, 热裂倾向低, 断裂韧度高的特点。但是采用变极性 TIG 焊, 它还是存在很多问题, 依然易产生气孔、裂纹等缺陷, 在实际工程中接头性能并不理想。其问题集中在两个方面, 一是尽量减少接头冶金损伤; 二是对接头热循环的精度控制, 因此研究新的 TIG 焊接工艺成为关键。采用高频耦合脉冲 TIG 焊则有效的改善了 2219 铝合金焊接问题, 达到了细化焊缝组织, 消除气孔缺陷, 接头性能也显著提高。但是由于该铝合金的特殊用途, 接头性能还有待进一步提高, 特别是接头塑性, 它通常以铝合金焊接接头的断后伸长率来表征<sup>[1,2]</sup>。

在焊缝的对焊中, 一般采用单层焊和双层焊, 单层焊焊接效率高, 同时也获得相对较小的热影响区宽度, 传统理论上热影响区的缩小对接头性能提高有利, 但是通过扩大热影响区, 即把热影响区向母材方向移动, 这样可以减小熔合区附近集中承载应力, 也可以使熔合区附近的软化区尽量向母材方向转移, 这对接头性能的提高特别是塑性提高具有重要作用。双层焊由于进行了两次焊接, 所以热影响区也进一步扩大, 同时, 第二层对第一层所具有的热处理效果也会更进一步提高接头性能。双层焊并不是简单的焊两次, 合理的控制打底层和盖面层的工艺

参数才能得到最佳接头性能。对 2219 铝合金进行高频耦合脉冲 TIG 焊接, 通过接头力学性能、金相组织评定及显微硬度等检测分析, 探讨提高 2219 铝合金接头性能焊接工艺。

### 1 试验方法

高频耦合脉冲 TIG 焊接系统示意图如图 1 所示, 它是由脉冲 TIG 焊机和配套使用的高频电源组成, 采用氩气为保护气体, 焊枪垂直沿着焊接方向运动实现对焊焊接。

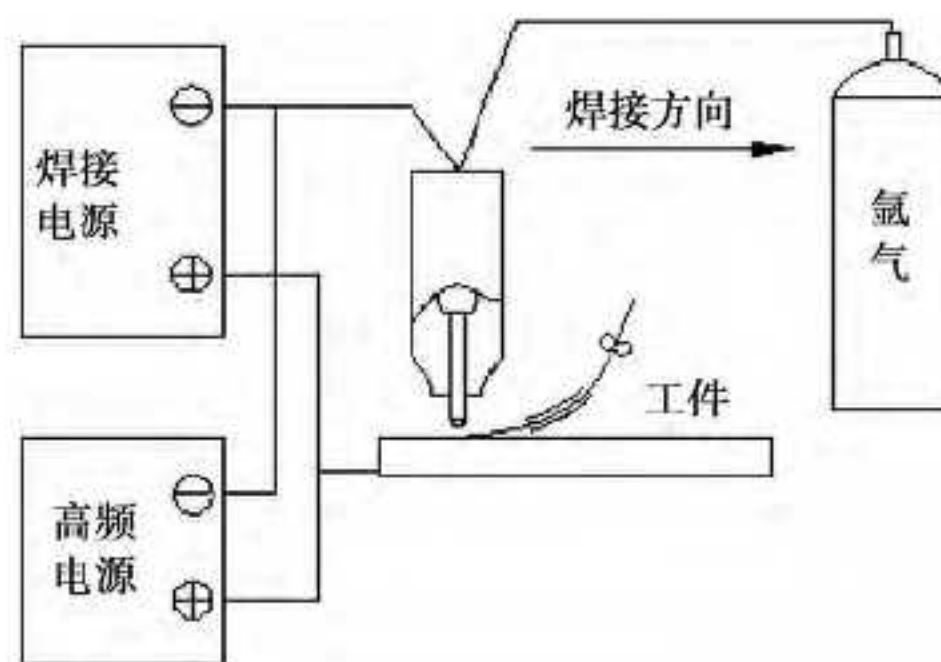


图 1 焊接系统示意图

Fig. 1 Schematic diagram of welding system

2219 铝合金焊接试板尺寸选择 300 mm × 150 mm × 5 mm, 开 1 mm × 1 mm 小坡口作为导丝槽, 焊丝选择  $\phi 1.6$  mm 2325 焊丝, 母材和焊丝的化学成分如表 1 所示。

在开始焊接前要对试板表面进行脱脂和去氧化膜处理, 并合理装夹, 保护气流量设为 12 L/min。焊接电源选择输出特殊交流波形, 如图 2a, 高频电源

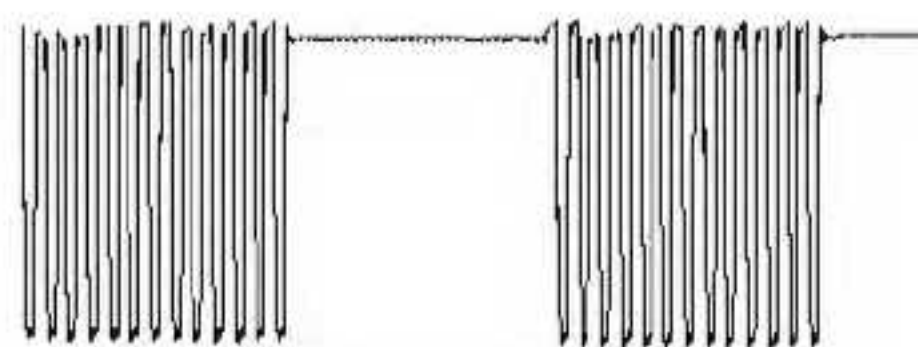
表 1 2219 母材和 2325 焊丝成分(质量分数, %)

Table 1 Chemical compositions of 2219 and 2325

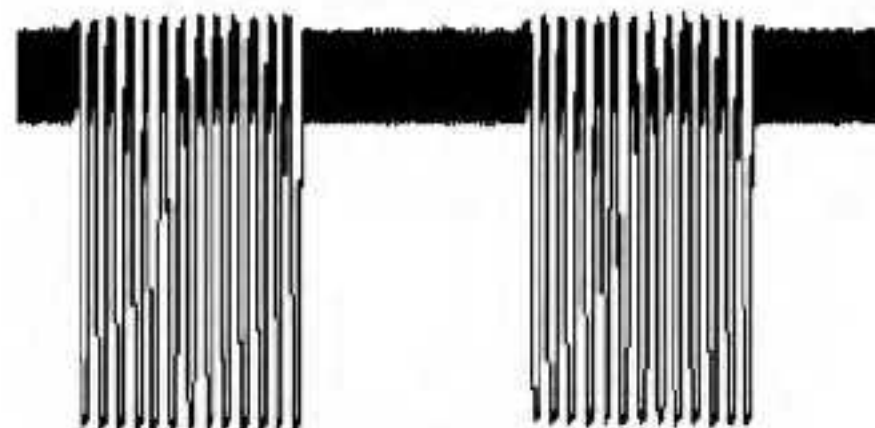
|      | Cu      | Mg      | Mn      | Fe    | Si     | Al |
|------|---------|---------|---------|-------|--------|----|
| 2219 | 5.8~6.8 | ≤0.02   | 0.3     | ≤0.30 | ≤0.022 | —  |
| 2325 | 3.6~4.2 | 1.0~1.5 | 0.5~0.7 | 0.06  | 0.06   | —  |

输出高频脉冲波形, 实际焊接电流波形为高频耦合脉冲波形, 如图 2b 所示。然后分别进行单层焊和双层焊, 单层焊工艺参数选择如表 2 所示。对于双层焊存在如何确定每一层的工艺参数, 才能达到接头性能最佳。打底层一般决定了焊缝强度, 盖面层对晶粒大小、热影响区宽度和组织均匀性具有关键作用。盖面层的厚度对两层接触处气孔的逸出会有影响, 也会影响焊缝力学性能特别是塑性。每一层的焊接速度同样不同程度的影响着接头性能。选择两种双层焊工艺参数见表 2 所示, 进行对比分析。最后, 对以上三种焊接工艺参数进行试验分析, 找出提

高接头性能特别是接头塑性的最佳工艺参数, 实现对焊接接头的“控形与控性”。



(a) 特殊交流波形



(b) 高频耦合脉冲电流波形

图 2 电流波形

Fig. 2 Current waveform

表 2 单层焊和双层焊工艺参数

Table 2 Welding parameters for single-layer and double-layer

|        |     | 恒流    | 峰值      | 频率     | 焊接速度                    | 送丝速度                     | 高频峰值    |
|--------|-----|-------|---------|--------|-------------------------|--------------------------|---------|
|        |     | $I/A$ | $I_m/A$ | $f/Hz$ | $v/(mm \cdot min^{-1})$ | $v_c/(m \cdot min^{-1})$ | $I_a/A$ |
| 单层焊    | —   | 272   | 272     | 4      | 300                     | 2.50                     | 80      |
| 双层同速焊  | 打底层 | 165   | 165     | 3      | 160                     | 0.56                     | 80      |
|        | 盖面层 | 165   | 165     | 3      | 160                     | 0.65                     | 80      |
| 双层不同速焊 | 打底层 | 265   | 265     | 4      | 300                     | 0.91                     | 100     |
|        | 盖面层 | 180   | 180     | 3      | 150                     | 0.63                     | 100     |

## 2 试验结果

### 2.1 接头截面总体形貌

用显微镜观察截面, 对三种不同工艺下的焊缝成型总体形貌进行分析, 特别是双层焊时每个焊层填丝量以及层与层之间气孔情况。三组工艺下的接头截面形貌如图 3 所示。



(a) 单层焊

(b) 双层同速焊

(c) 双层不同速焊

图 3 接头截面总体形貌

Fig. 3 Cross-section shape of joint

#### 2.1.1 接头焊层填丝量

单层焊接头截面形貌是采用一次焊接成型, 送

丝速度选择 2.5 m/min。双层同速焊的两层都采用较低的焊速, 然后送丝量是盖面层大于打底层。双层不同速焊采用打底层快速焊接, 焊丝填充量控制在打底层焊后正面焊缝低于试件平面不超过 1 mm; 盖面层低速焊接, 焊丝填充量控制在盖面层焊后正面焊缝高于试件平面不超过 1 mm。

#### 2.1.2 层间气孔

从图 3 总体形貌可以看出, 由于采用了高频耦合脉冲 TIG 焊接工艺方法, 不管单层焊焊缝还是双层焊的每一层焊缝都几乎没有微气孔出现。但是, 在双层同速焊中层与层之间出现了气孔, 而双层不同速焊中层与层之间没有气孔。这是因为第一层和第二层焊缝金属交汇处是气孔出现率较高区域, 通过控制填丝量有利于气孔溢出。对双层焊采用不同速焊是一种对接头最终组织与性能的调控手段。

### 2.2 微观组织分析

不同焊接工艺下的焊缝区微观组织如图 4, 金相观察选择在焊缝区第一层区域。可以看出焊缝区晶体形态都是以等轴晶为主, 焊缝组织以  $\alpha(Al)$  固

溶体为基体,在基体内分布着许多颗粒较小的  $\theta$  ( $\text{CuAl}_2$ ) 相,起到强化基体的作用。在基体晶界和枝

晶间分布着大量的  $\alpha(\text{Al}) + \theta(\text{CuAl}_2)$  共晶相,共晶相呈网络状连续分布<sup>[4]</sup>。

从表3可以看出焊缝区晶粒度大小为双层同速焊 > 双层不同速焊 > 单层焊,这是因为随着热输入的减小,也就是焊接速度的提高,晶粒也会变小,细化晶粒有利于强度的提高。双层不同速焊的晶粒度之所以与单层焊不同,是因为它为打底层,还会受到盖面层的热输入影响,会使晶粒略有长大。双层不同速焊与双层同速焊相比,双层同速焊晶粒整体会上会偏大,这会影响力学性能。从焊缝区晶粒面积均方差来看,双层不同速焊晶粒也更均匀。

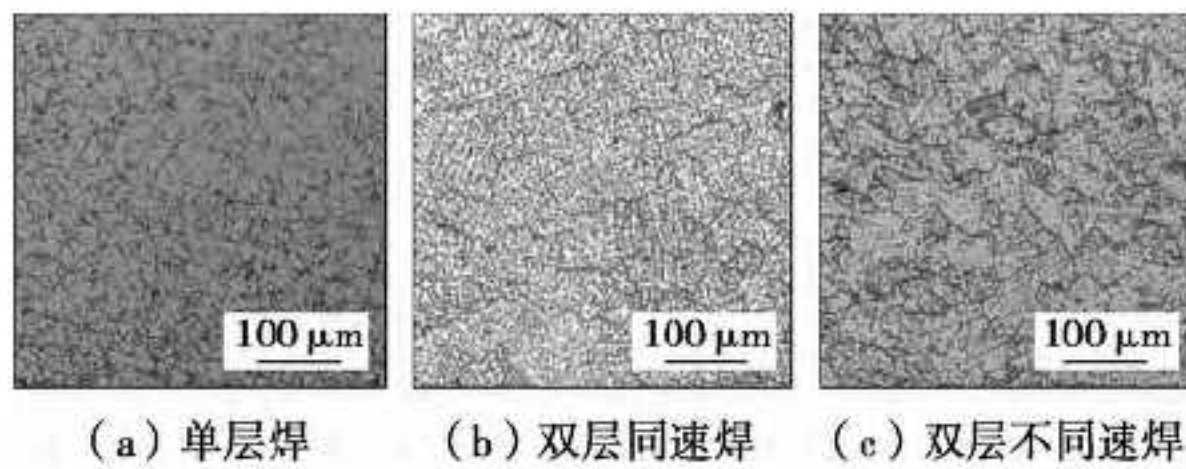


图4 焊缝区微观组织

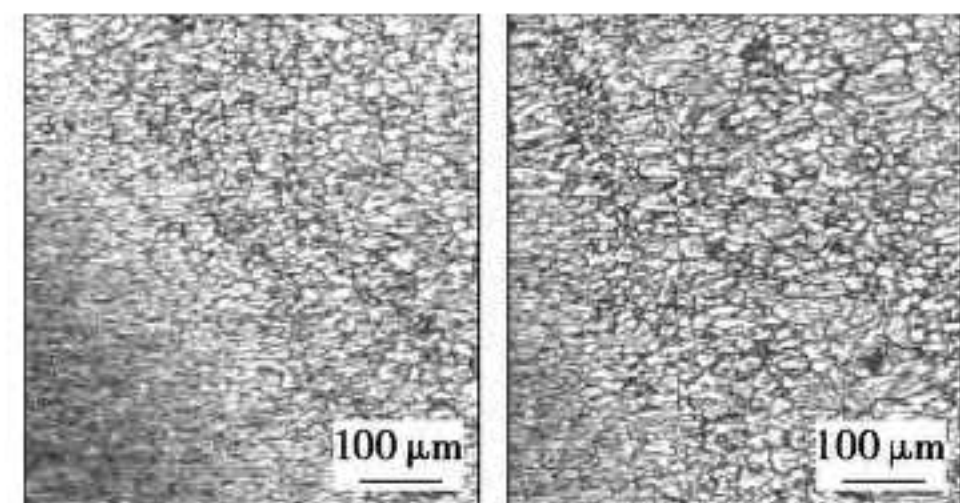
Fig. 4 Microstructure of weld zone

表3 焊缝区晶粒度评定

Table 3 Grain size evaluation of weld zone

| 规范     | 晶粒面积平均值 $S/\mu\text{m}^2$ | 晶粒面积均方差 $\sigma/\mu\text{m}$ | 晶粒大小平均截距 $d/\mu\text{m}$ | 晶粒大小平均级别 |
|--------|---------------------------|------------------------------|--------------------------|----------|
| 单层焊    | 476.3                     | 3 125.0                      | 23.8                     | 7.4 级    |
| 双层同速焊  | 832.4                     | 2 021.0                      | 48.4                     | 5.8 级    |
| 双层不同速焊 | 769.7                     | 1 095.3                      | 39.7                     | 6.3 级    |

图5和表4为单层焊和双层焊熔合区微观组织及晶粒度对比,两种的晶粒大小相差不大,但从熔合区晶粒面积均方差可以看出单层焊晶粒尺度差异相对较大,双层焊晶粒尺寸较均匀,这是因为双层焊经历了两次热循环,对熔合区附近组织均匀化产生影响。另外,双层焊的晶界共晶相要窄于单层焊的晶界,过多的晶界析出量会降低晶粒之间的结合力,熔合区附近又是接头的最薄弱环节,所以提高熔合区微观特征有利于2219固溶强化铝合金接头性能的提高。



(a) 单层焊 (b) 双层焊

图5 熔合区微观组织

Fig. 5 Microstructure of fusion-line zone

表4 熔合区晶粒度评定

Table 4 Grain size evaluation of fusion-line zone

|       | 晶粒面积平均值 $S/\mu\text{m}^2$ | 晶粒面积均方差 $\sigma/\mu\text{m}$ | 晶粒大小平均截距 $d/\mu\text{m}$ | 晶粒大小平均级别 |
|-------|---------------------------|------------------------------|--------------------------|----------|
| 单层焊   | 320.5                     | 605.6                        | 23.5                     | 7.5 级    |
| 双层同速焊 | 410.6                     | 437.8                        | 26.2                     | 7.2 级    |

### 2.3 显微硬度分析

铝合金表面硬度较小,所以测量采用维氏硬度,试验载荷 100 g,保持时间 15 s。测试范围从焊缝中心开始,依次经过熔合区、热影响区和母材,测试点在  $1/2$  板厚处。三种工艺参数下的显微硬度曲线如图6所示。可以看出整体上硬度最大的是双层不同速焊接,硬度变化也相对其它两种较均匀。热影响区宽度最大的是双层同速焊,最小的是单层焊,热影响区的宽度反应了熔合线附近受到的热输入大小,双层不同速焊熔合线附近热输入介于两者之间。三种工艺参数的熔合线位置离焊缝中心大致相同,可

以看出此处双层同速焊硬度值最大,但是在单层焊和双层同速焊熔合线附近的硬度值仍小于左右两侧,这容易形成相对软化区,造成应力集中,不利于接头性能,特别是塑性的提高。而双层不同速焊在熔合线附近的硬度是不断增加的,成功的阻止了此处软化区的形成。

### 2.4 力学性能分析

2219 铝合金不同工艺下焊接接头和母材的力学性能见表5。可以看出双层焊要比单层焊的力学性能好,不仅接头强度有所提高,更重要的是断后伸长率显著增加。双层焊中不同速焊要好于同速焊,特

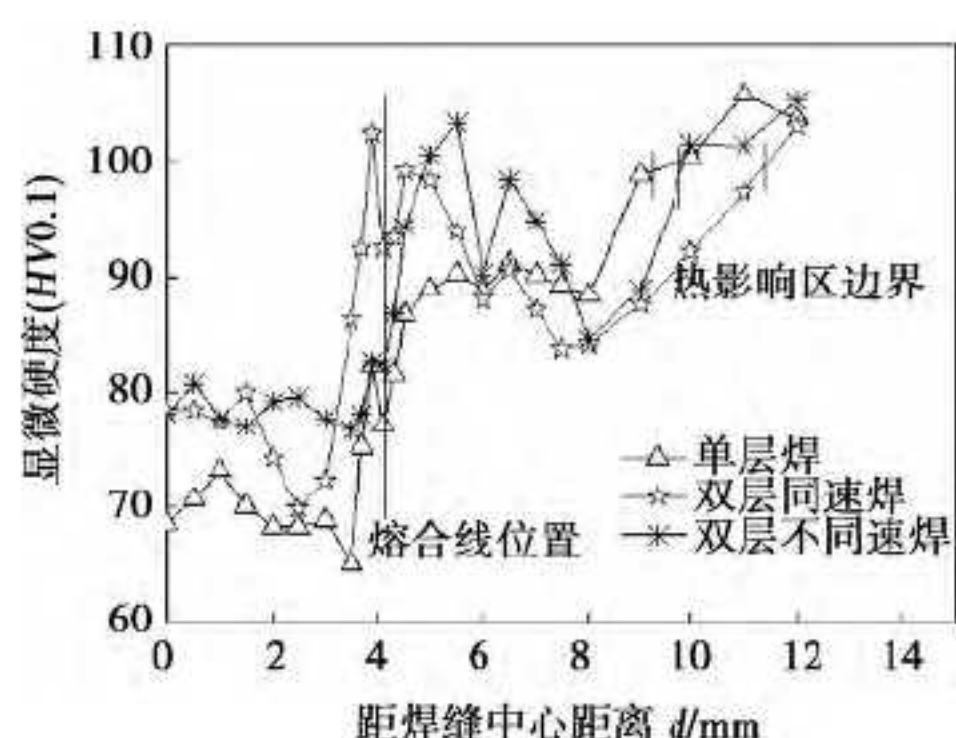


图 6 不同工艺参数显微硬度曲线

Fig. 6 Microhardness curves of joints under different welding conditions

别是断后伸长率的进一步提高, 双层不同速焊强度达到了母材的 67.8%, 断后伸长率达到了母材的 47.4%, 这说明精确控制每一层的热输入量, 设置合理工艺参数才能够得到最佳的接头性能。

表 5 焊接接头和母材金属的力学性能

Table 5 Mechanical properties of welded joints

| 焊接工艺   | 抗拉强度 $R_m$ /MPa | 断后伸长率 $A$ (%) |
|--------|-----------------|---------------|
| 单层焊    | 285             | 3.8           |
| 双层同速焊  | 290             | 4.3           |
| 双层不同速焊 | 305             | 5.5           |
| 母材     | 450             | 11.6          |

### 3 结 论

(1) 高频耦合脉冲 TIG 焊工艺是通过在特殊交流上叠加高频能量产生电磁搅拌作用, 具有促进结晶与晶粒细化、加速熔池内气体逸出、减少铝合金焊

接接头冶金缺陷等效果。在文中试验条件下获得的 2219 铝合金接头性能优于目前的变极性 TIG 焊。

(2) 采用单面双层焊, 层间气孔出现的概率较高。在工艺上要增加第一层的填丝量, 减少第二层填丝量, 会有利于层间气孔的逸出, 也是对第一层焊缝的“控性”处理。经过优化的两次热循环, 提高了接头组织均匀性, 降低了应力水平, 显著提高了接头的综合力学性能。

(3) 在焊缝微观组织分析中, 通过对晶粒大小以及均匀性做出定量分析, 有助于建立焊接热循环与组织状态之间的联系, 从而为接头性能的分析提供了一种新的认识途径。

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**High frequency energy coupling pulsed TIG welding process on 2219 aluminum alloy** LI Xian<sup>1</sup>, SONG Yonglun<sup>1</sup>, LU Zhenyang<sup>1</sup>, SUN Yujuan<sup>1</sup> (College of Mechanical Engineering & Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China). pp 17 - 20

**Abstract:** A study on 2219 aluminum alloy welding using high frequency energy coupling pulsed TIG welding process are carried out. It shows that using a special AC with the high-frequency pulse current can refine the microstructure of weld, eliminate pores and reduce cracks and other defects effectively, and also can improve the properties of the aluminum alloy joint significantly. The properties of single-layer joint and double-layer joint were investigated and compared by means of quantitative analysis of grain size. The paper proposed a way to reach "controllable joint property" by thermal cycles controlling, which makes the joint microstructure more homogeneous. It is a new way to improve the comprehensive mechanical properties of joint and therefore has applicability in engineering.

**Key words:** 2219 aluminum alloy; high frequency energy coupling; pulsed TIG; joint properties; grain size evaluation

**Formation quality analysis and parameters optimization of laser hot wire repair welding** WEN Peng<sup>1,2</sup>, FENG Zhenhua<sup>1</sup>, WANG Gang<sup>1,2</sup>, ZHENG Shiqing<sup>1</sup> (1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. The State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China). pp 21 - 24

**Abstract:** Laser welding with hot wire addition can precisely control the heat input and therefore it can efficiently clad the metal, which is suitable for surface repairing. There are few reports on the analysis and optimization of weld formation quality of laser hot wire multi-pass repair welding. Based on RSM (response surface methodology), laser power, scanning speed, wire feed rate and overlap ratio were selected as process variables, while surface flatness, dilution rate and incomplete fusion ratio as response parameters. The results indicated that the surface flatness, the dilution rate and the incomplete fusion ratio had a quadratic relation with these variables. Meanwhile, an optimal cladding layer with no incomplete fusion, low dilution rate and good surface flatness was obtained by appropriately reducing the wire feed rate, and increasing the laser power, the scanning speed and the overlap ratio. By using overlap contour, multiple responses were comprehensively optimized according to the specific requirement of formation quality.

**Key words:** laser hot wire welding; multi-pass repairing; response surface methodology; formation quality; parameters optimization

**Numerical simulation on temperature and stress fields of laser clad Ni-based coating** LI Meiyun<sup>1</sup>, HAN Bin<sup>1</sup>, CAI Chunbo<sup>1</sup>, WANG Yong<sup>1</sup>, SONG Lixin<sup>2</sup> (1. College of Electromechanical Engineering, China University of Petroleum, Qingdao 266580, China; 2. Offshore Oil Engineering (Qingdao) Co., Ltd., Qingdao 266520, China). pp 25 - 28, 32

**Abstract:** In this paper, the software SYSWELD was used to simulate the single track and overlapped laser cladding

process. The results show that the molten pool undergoes a rapid heating and cooling process with high superheat degree during the laser cladding. During the single track laser cladding, the peak temperature of the center point on the molten pool surface is highest, reaching 2 589 °C. In addition, the peak temperature decreases as the distance is far away from the molten pool center. After the single track laser cladding, the cladding coating is in the tensile stress status and the maximum value locates at the interface between the cladding coating and the matrix, while the heat affected zone is in compressive stress. During the laser overlapped cladding process, the first cladding layer experiences tensile stress, but the tensile stress value decreases obviously and the maximum stress locates at the heat affected zone. Furthermore, because of the preheating from the first track to the second one, the peak temperatures of the points on the second cladding coating are higher than those of the single track. The maximum tensile stress appears at the bottom of the cladding coating while the heat affected zone is in compressive stress.

**Key words:** laser cladding; Ni-based coating; numerical simulation; temperature field; stress field

**Weld defect detection using line-focusing ultrasonic method**

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**Abstract:** Defect signals collected using conventional TOFD (time of flight diffraction) ultrasonic method is often weak in amplitude because of the low energy of diffracted sound field. In order to improve the testing sensitivity, a new ultrasonic TOFD detection method using line-focusing probe is put forward. Based on geometrical acoustics theory, a line-focusing wedge was designed according to the desired refraction angle of the spindle acoustic field and the focus depth. Through the testing of an aluminum alloy block containing artificial defects, the sensitivity of the proposed method was studied. Through the testing of several friction stir welded aluminum alloy pieces, the advantage of the proposed method was verified. The result shows that the testing sensitivity of the line-focusing ultrasound TOFD method is higher than the conventional method. In the collected D-scan image using the proposed method, the contrast between the defect and background image is sharp, and the image edge can also be kept well. The new method has the advantages in the improvement of defect resolution and the increase of defect detection rate, as well as the reduction of residual error rate, which contribute to a great application prospect.

**Key words:** TOFD; defect detection; testing sensitivity

**Analysis on multidirectional joint tensile properties for dual laser-beam bilaterally synchronous welding joint of aluminum-lithium alloy**

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