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中国激光

# 摆动工艺对钛合金窄间隙激光填丝焊缝成形及气孔率的影响

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**摘要** 本文探索了光束摆动对 TC4 钛合金窄间隙激光填丝焊缝成形和气孔率的影响。研究结果表明，无摆动时，焊缝表面起伏不连续，横截面窄而深，增加光束摆动之后，表面成形连续均匀，横截面相对变得宽而浅。当采用垂直或圆形摆动方式，摆动幅度为 1.5～2 mm，摆动频率在 20～100 Hz 之间时，获得了焊缝表面和横截面成形良好的焊接接头。当采用圆形摆动，摆幅为 2 mm，摆动频率在 100～200 Hz 之间时，获得的焊缝无明显气孔。采用该工艺进行了 20 mm 厚 TC4 钛合金窄间隙激光填丝焊接，焊接接头呈银白色，焊缝均匀连续，接头拉伸性能测试表明，其最大抗拉强度达 930 MPa，接头强度与母材等强，断裂方式为韧性断裂，拉伸试样断裂在母材。

**关键词** 激光技术；光束摆动；钛合金；焊缝成形；气孔率

**中图分类号** TG456.7 **文献标志码** A **doi**：10.3788/CJL202148.0602111

## 1 引 言

钛合金具有低密度、高比强度、优良的耐腐蚀性能等特点[1-2]，被誉为铁和铝之后的第三金属，作为一种优良的结构材料，在航空航天、海洋工程、医学等领域中得到了广泛应用[3-4]，且厚板钛合金的需求越来越大。目前厚板钛合金主要采用窄间隙非熔化极稀有气体保护电弧(TIG)焊接和电子束焊接。然而，窄间隙 TIG 焊接存在热输入大、间隙大、易出现侧壁未熔合等问题；电子束焊接则局限于设备昂贵、工件形状尺寸受限等缺点，影响其推广应用。

窄间隙激光填丝焊接热输入小、焊接速度快、热影响区小、变形小，兼备了激光焊接和窄间隙坡口的优势，在厚板焊接中具有巨大优势[5-6]。但是侧壁未熔合和气孔是目前窄间隙激光填丝焊接工艺存在的突出问题，文献[7-12]提出光束摆动，通过往复摆动反复重熔部分焊缝，加大熔池的流动与搅拌，束流的偏转增加单位面积热输入，减小深宽比，达到改善成形和抑制气孔的作用。自 21 世纪初，国内外学者就开始进行了窄间隙摆动激光焊接的研究，Cai 等[13-14]开发了窄间隙激光摆动焊接工艺，进行了 150 mm 厚度的碳钢窄间隙焊接，接头成形良好，气孔率符合标准；邹吉鹏等[15]实现了 130 mm 厚 5A06 铝合金的窄间隙扫描激光焊接，在摆幅大于 1 mm，高频摆动下得到了气孔率低于 1%，无明显缺陷的优质焊接接头。而目前在国内外，多数学者着重于研究激光功率、焊接速度、离焦量等参数对钛合金焊接质量的影响，在摆动工艺方面研究内容较少，鲜有报道。

本文在 20 mm 厚 TC4 钛合金板上进行了大量的摆动工艺试验探索，研究了摆动方式、摆动幅度、摆动频率等对坡口间隙为 3.2 mm 的 TC4 钛合金单道激光填丝焊缝成形及气孔率的影响，在优化工艺后实现了 20 mm 厚 TC4 钛合金窄间隙摆动激光填丝焊接。

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## 2　试　　验

### 2.1　试验材料

试验所用材料为 20 mm 厚退火态 TC4(Ti-6Al-4V)钛合金,所用焊丝为 TC3(Ti-5Al-4V)实心焊丝,直径为 1.2 mm。母材与焊丝成分如表 1 所示。焊前对试板进行打磨和酸洗,酸洗溶液采用体积分数为 5%HF+30%$HNO_3$+$H_2O$,去除表面油污和氧化物,水洗清除酸液后烘干备用。

表 1　母材及焊丝的化学成分(质量分数,%)

Table 1　Chemical composition of base metal and filler metal (mass fraction, %)

| Element | Ti | Al | V | Fe | N | O | H |
|---|---|---|---|---|---|---|---|
| TC4 | Bal. | 6.30 | 4.11 | 0.018 | 0.007 | 0.14 | 0.001 |
| TC3 | Bal. | 4.75 | 3.82 | 0.044 | 0.006 | 0.18 | 0.001 |

### 2.2　试验方法

焊接试验采用 IPG 公司生产的 YLS-30000-S4 光纤激光器,激光头 FLW D50W 最大输出功率为 12 kW。试验中采用的光束摆动方式除无摆动以外有三种,分别是线性、圆形和无穷形摆动,线性摆动方向垂直于焊接方向,本文中称为垂直摆动,如图 1 所示。焊接过程由 KUKA 机器人控制运动完成。

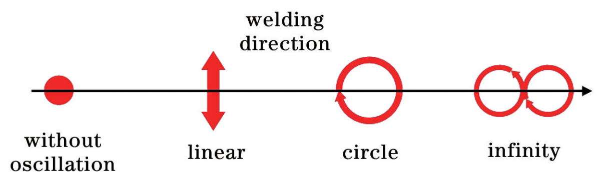



图 1　光束摆动方式

Fig. 1　Wobble modes of laser beam

单道窄间隙摆动工艺试验所用坡口如图 2 所示,焊接过程中采用自制保护气罩后置保护,如图 3 所示,由于窄间隙坡口的约束作用,保护气很容易排

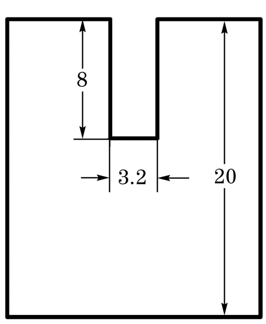



图 2　TC4 窄间隙激光焊接坡口尺寸

Fig. 2　Groove dimension of narrow gap laser welding for TC4 titanium alloy

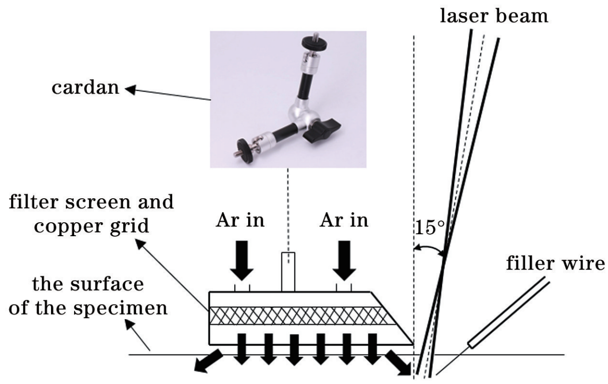



图 3　保护气罩示意图

Fig. 3　Diagram of protective atmosphere mask

除间隙里的空气,并且气罩与万向节连接,便于调节气罩位置及保护区域。在焊接打底层时附加背保护气,保护气体均采用体积分数为 99.99% 的氩气。在施焊前提前通氩气,排除工件表面和背部周围的空气;焊接完成后继续通氩气,使正反面的焊缝高温区域在冷却过程中依然得到保护。经试验调试确定,在保护气流量为 15 L/min 时,得到保护良好的银白色焊缝。

窄间隙单道摆动焊接工艺试验完成后,经 X 射线检测,再从试板上取样研磨抛光,用 kroll 试剂(体积分数为 1~3%HF+2~6%$HNO_3$ 水溶液)腐蚀,在显微镜下观察焊缝截面,测量得到熔宽与熔深等数据,并对焊缝成形系数及气孔率进行计算,然后对上述试验数据进行优化,对 20 mmTC4 钛合金平板进行窄间隙激光填丝焊接验证,并对得到的焊接接头进行 X 射线检测和拉伸性能测试。

## 3　试验结果与分析

### 3.1　摆动工艺对焊缝成形的影响

经前序工艺试验验证,在窄间隙单道填丝焊接时采用激光功率为 3 kW、焊接速度为 0.6 m/min、送丝速度为 3 m/min 的焊接参数,能得到成形好、气孔率较低的焊缝,本文旨在通过光束摆动来进一步改善成形和降低气孔率,仅对摆动工艺进行调整,在摆动频率为 60 Hz、摆幅为 2 mm 的基础上变动,具体按摆动方式、摆动幅度和摆动频率分为三个组别进行试验。试验后得到焊缝表面成形以及焊缝横截面形貌,如表 2~4 所示。

表 2 为不同摆动方式下焊缝的表面成形和横截面形貌,原始坡口尺寸如横截面虚线所示。可以看出,无摆动时焊缝表面起伏不平,连续性及稳定性较差,横截面深度方向上形成较深的匙孔,呈丁字形;

表 2　摆动方式对焊缝成形的影响

Table 2　Effect of oscillation modes on weld formation

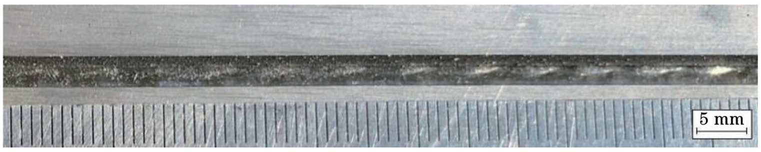
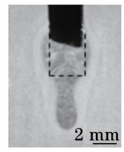
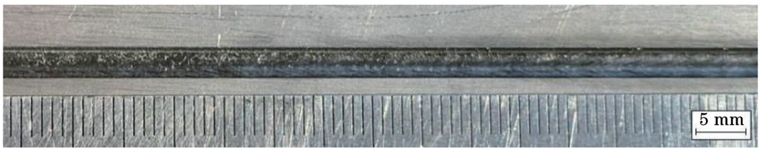
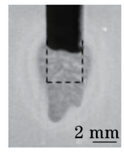
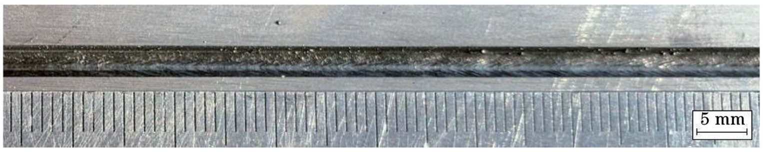
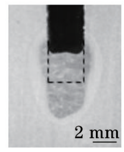
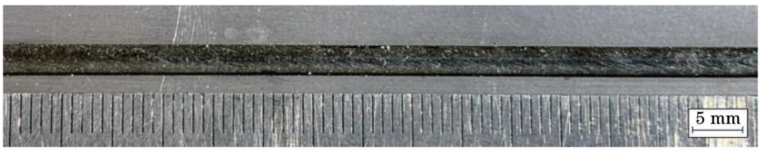
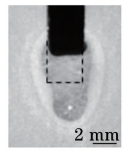
| Oscillation mode | Appearance | Cross section |
| --- | --- | --- |
| Without oscillation |  |  |
| Linear |  |  |
| Circle |  |  |
| Infinity |  |  |

表 3　摆动幅度对焊缝成形的影响

Table 3　Effect of oscillation amplitude on weld formation

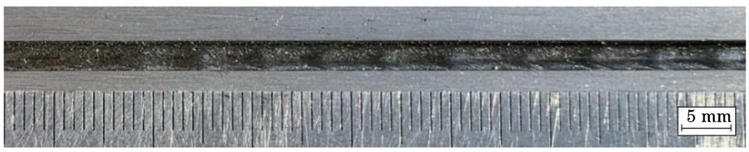
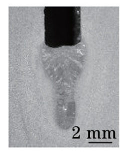
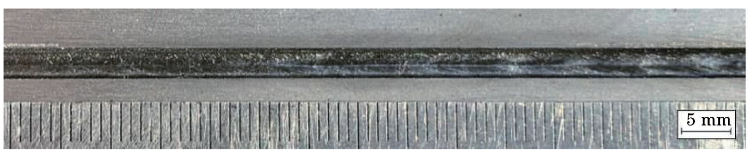
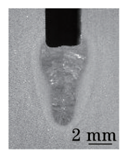
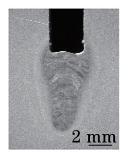
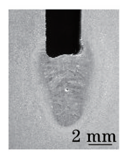
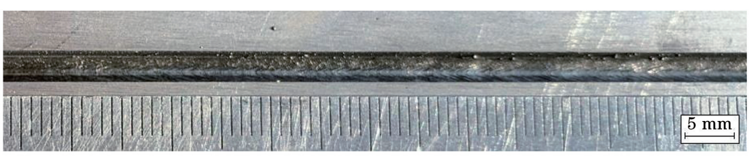
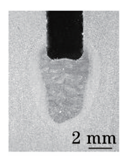
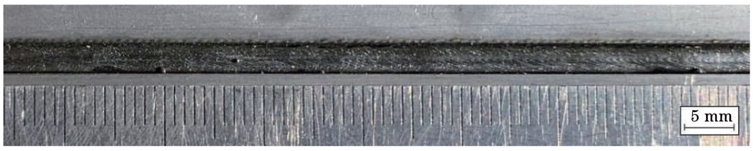
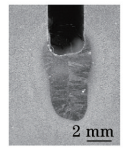
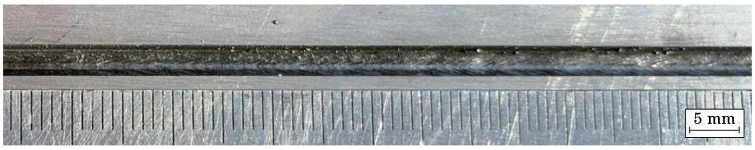
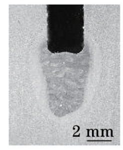
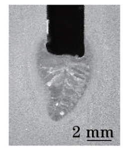
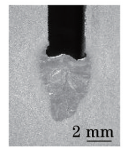
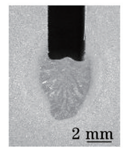
| Oscillation amplitude /mm | Appearance | Cross section |
| --- | --- | --- |
| 0.2 |  |  |
| 0.6 |  |  |
| 1.0 |  |  |
| 1.5 |  |  |
| 2.0 |  |  |

表 4　摆动频率对焊缝成形的影响

Table 4　Effect of oscillation frequency on weld formation

| Oscillation frequency /Hz | Appearance | Cross section |
| --- | --- | --- |
| 20 |  |  |
| 60 |  |  |
| 100 |  |  |
| 150 |  |  |
| 200 |  |  |

增加光束摆动之后，小孔稳定性增强，熔池尺寸增大，熔池金属的铺展性提高，焊缝表面成形得到改善，连续均匀，熔池面积增大，向两侧铺展，熔宽增加；焊缝横截面成形也由长条的丁字形变为梨形，侧壁熔合更好。

在圆形摆动、频率为 60 Hz 的工艺下，表 3 反映了摆动幅度对焊缝成形的影响。摆动幅度的大小主要影响激光能量的分布状态、匙孔形状尺寸以及熔池的尺寸。当摆幅为 0.2～0.6 mm 时，焊缝表面成形不均匀且不连续；当摆幅为 1～2 mm 时，焊缝表面成形连续性和均匀性较好。从横截面来看，摆幅为 0.2～1 mm 时，焊缝在深度方向上能量集中于中部，仍体现为长条的丁字形，此时表现为熔深大，熔宽较小；当摆幅为 1.5～2 mm 时，焊缝横截面呈梨形，熔深减小，熔池在横向得到铺展，侧壁熔合更为良好。

在圆形摆动、摆幅为 2 mm 的工艺下，表 4 反映了不同摆动频率对焊缝成形的影响。摆动频率决定了单位时间内光束对熔池搅动的程度和光束在垂直于焊接方向上的停留时间，从而影响熔池的铺展和气孔的生成及上浮，高频振荡光束能够改变焊接温度场分布和熔池流动状态，进而改善焊缝成形。当摆动频率为 20～100 Hz 时，焊缝表面成形均匀连续、平滑，横截面上焊缝呈梨形；当频率为 150～200 Hz 时，焊缝中部出现棱状凸起，横截面表现为两侧侧壁略微下凹，这种现象在多层焊接时容易造成后续焊道出现侧壁未熔合。分析认为熔池在激光光束的高频率扫描作用下，还未来得及向侧壁铺展就被带到熔池中心位置，从而在焊缝中部容易出现棱状凸起的现象。

图 4 为不同摆动工艺下熔宽 $B$、熔深 $H$ 及焊缝成形系数($B/H$)的关系曲线。在窄间隙焊接中，为确保不出现侧壁和根部未熔合缺陷，一般采用较大的焊缝成形系数，即较大的熔宽和较小的熔深。一方面，熔池可以向两侧铺展更多，侧壁熔合更好；另一方面，熔深较小时，气孔较容易上浮，可以达到减小气孔率的目的。由图 4(a)可以看出，无摆动情况下熔深较大、熔宽较小，无论光束以何种方式进行摆动，在单位时间和单位面积上的激光能量密度均较低，能量不再集中于中部，而向两侧分散，导致熔深

变小、熔宽增加。图 4(b)反映了随着摆动幅度在一定范围内增加,熔深略有减小,熔宽变化不大,此时激光能量的分布受激光功率、摆动频率和离焦量的影响较大。而在不同摆动频率下,熔宽和熔深变化较小。

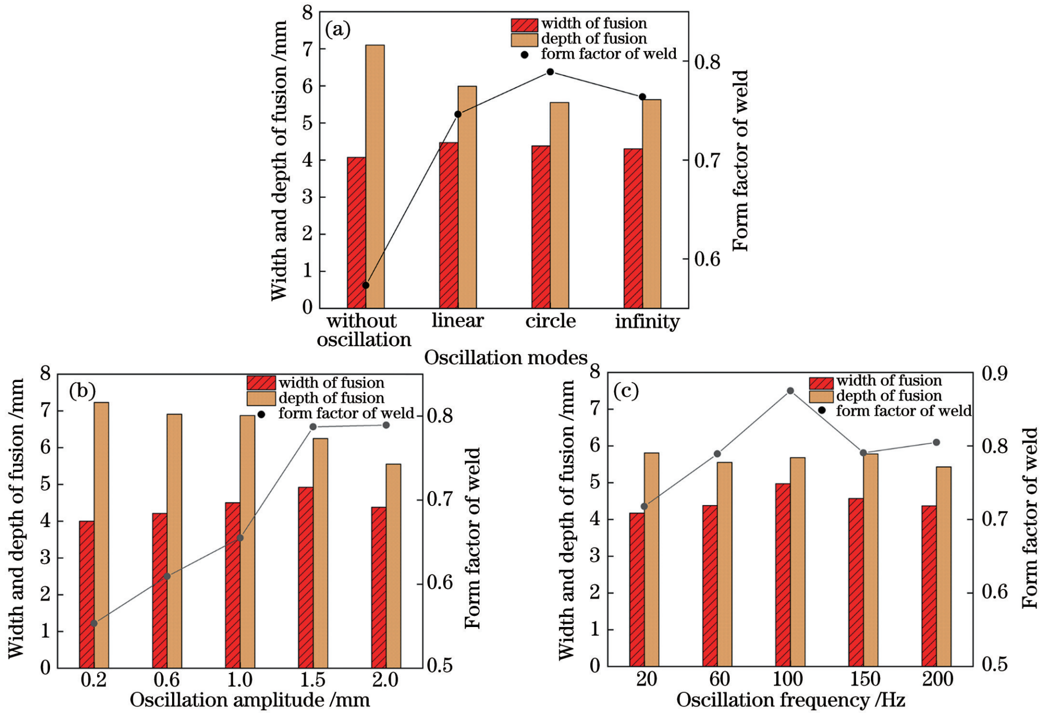



图 4 摆动工艺对熔宽、熔深及焊缝成形系数的影响。(a)摆动方式;(b)摆动幅度;(c)摆动频率

Fig. 4 Effect of oscillation parameters on width and depth of fusion and form factor of weld. (a) Oscillation modes; (b) oscillation amplitude; (c) oscillation frequency

### 3.2 摆动工艺对单道焊缝气孔率的影响

焊接完成后对每道焊缝进行 X 射线检测气孔含量,计算单道焊缝中气孔总面积与焊缝纵截面面积比值,两者的比值即为单道焊缝的气孔率。分别计算不同摆动方式、摆动幅度、摆动频率下的气孔率,计算结果如图 5 所示。

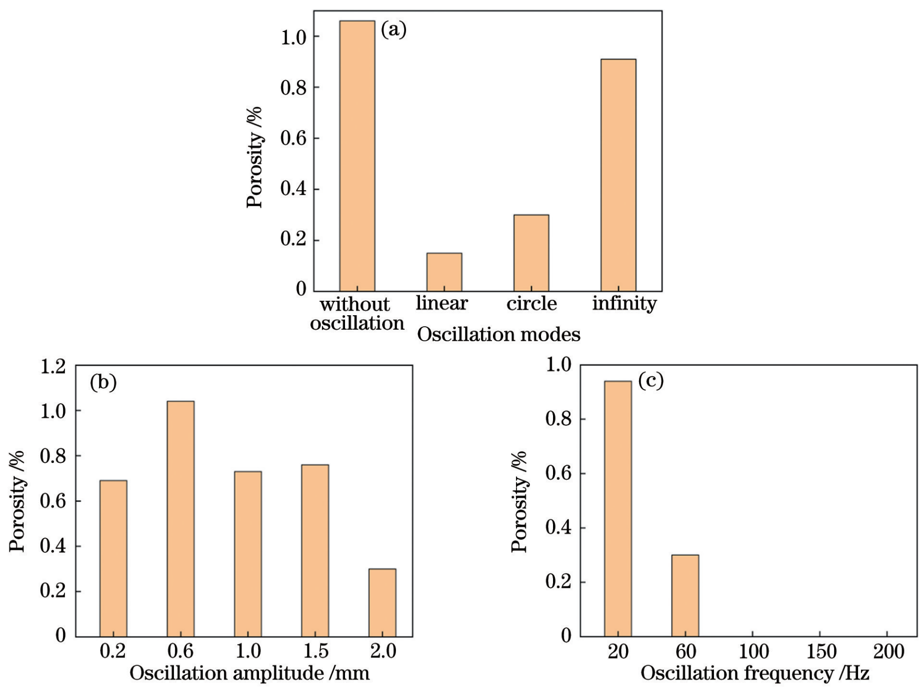



图 5 摆动工艺对气孔率的影响。(a)摆动方式;(b)摆动幅度;(c)摆动频率

Fig. 5 Effect of oscillation parameters on porosity. (a) Oscillation modes; (b) oscillation amplitude; (c) oscillation frequency

由图 5(a)可以看出,垂直和圆形摆动的气孔率较低,无穷形摆动相比于无摆动情况,气孔未得到明显抑制。图 5(b)反映了摆动幅度对气孔率的影响,摆动幅度较小时,激光匙孔的形状没有发生根本性变化,熔池流动扩张不明显,能量集中于焊缝中部;摆幅为 2 mm 时,气孔率较低,此时能量向两侧扩散,气孔容易浮出,摆幅过大会烧损上方未焊侧壁及表面坡口,从而影响焊接接头性能,应根据坡口间隙情况适当选择较大的摆幅。图 5(c)为不同摆动频率下的气孔率,可以看出,当频率大于 100 Hz 时,未发现气孔,如图 6 所示,在摆动频率为 60 Hz 的情况下焊缝中心存在的气孔尺寸较小,分析认为,无摆动焊接条件下,熔池的运动状态相对比较单一,气体较难快速逸出;当摆动频率大于 100 Hz 时,焊缝气孔的数量减少直至消失,如图 6(c)~(e)所示。

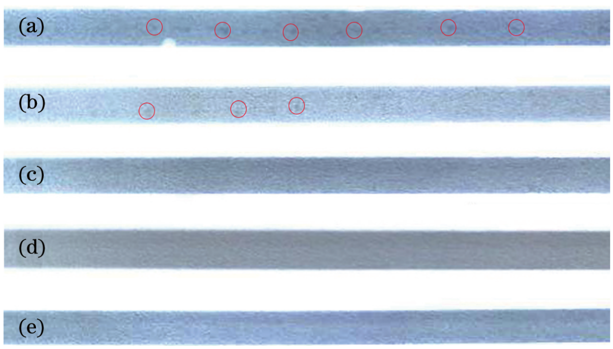



图 6 不同摆动频率下的 X 射线底片。(a)20 Hz;(b)60 Hz;(c)100 Hz;(d)150 Hz;(e)200 Hz

Fig. 6 X-ray films with different oscillation frequencies. (a) 20 Hz; (b) 60 Hz ; (c) 100 Hz; (d) 150 Hz; (e) 200 Hz

### 3.3 20 mm 厚钛合金窄间隙激光填丝焊接

在综合考虑焊缝表面成形以及气孔率等因素后,对摆动工艺参数进行优化:选择圆形摆动模式、频率为 100 Hz、摆幅为 2 mm 的工艺参数进行 20 mm 厚钛合金平板窄间隙激光摆动填丝焊接。

考虑到焊接过程中引起的变形及间隙收缩问题,设计 2°的 U 型坡口,坡口间隙为 3.5 mm,钝边为 4 mm 厚,坡口形式如图 7 所示。焊接过程由激光自熔打底焊和激光填丝焊接组成,自熔焊采用激光功率为 2.8 kW、焊接速度为 0.6 m/min,填充焊的焊接参数为激光功率为 3 kW、焊接速度为 0.6 m/min、送丝速度为 3 m/min。在单道多层焊接过程中,每焊完 1 道后进行层间清理,防止坡口中残余的飞溅、杂质影响后续焊接质量,并控制层间温度至 40 °C 以下再进行后续焊接。共完成 1 道激光自熔焊和 9 道激光填充焊,如图 8(c)所示。

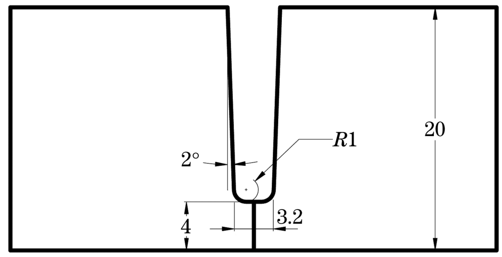



图 7 20 mm 厚 TC4 钛合金窄间隙焊接坡口尺寸

Fig. 7 Groove dimension of narrow gap welding for 20 mm TC4 titanium alloy

焊后得到的接头整体形貌如图 8 所示。焊接接头表面成形良好,呈银白色,说明保护效果较好。整个接头经 X 射线检测,如图 9 所示,未发现明显的未熔合、裂纹、气孔等焊接缺陷。表 5 为 20 mm 厚钛合金焊接接头的抗拉强度,取样位置及断口形貌如图 10 所示,可见断口中存在大量韧窝,试样呈韧性断裂。抗拉强度最大值为 930 MPa,达到母材的 100%,断后伸长率较好,断裂位置均在母材。

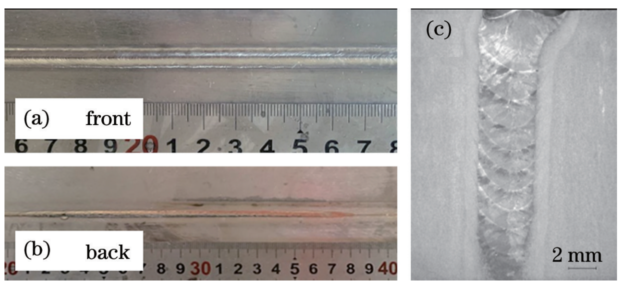



图 8 20 mm 厚 TC4 钛合金窄间隙焊接接头形貌、宏观结构。(a)正面;(b)背面;(c)横截面

Fig. 8 Morphology and macrostructure of 20 mm TC4 titanium alloy narrow gap joint. (a) Front; (b) back; (c) cross section

图 9 20 mm 厚 TC4 钛合金接头 X 射线底片

Fig. 9 X-ray film of 20 mm TC4 titanium alloy joint

表 5 20 mm 厚 TC4 钛合金焊接接头拉伸强度

Table 5 Tensile strength of 20 mm TC4 titanium alloy joint

| Sample code | Tensile strength /MPa | Elongation /% | Fracture location |
|---|---|---|---|
| 1 | 925 | 9.5 | Base |
| 2 | 930 | 9.4 | Base |

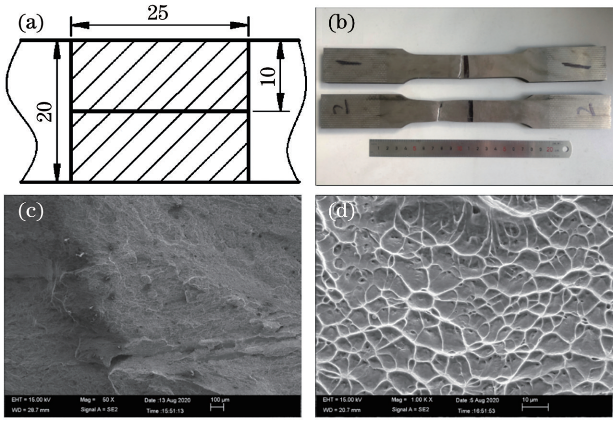



图 10 拉伸试样取样位置、断裂位置及断口形貌。(a)取样位置;(b)断裂位置;(c)断口形貌 50 倍;(d)断口形貌 1000 倍

Fig. 10 Tensile sampling position, fracture location, and fracture morphology. (a) Sampling position; (b) fracture location; (c) fracture morphology 50 ×; (d) fracture morphology 1000×

## 4 结 论

在 TC4 钛合金窄间隙激光填丝焊接中,与非摆动激光焊相比,光束摆动后能改善表面成形,得到连续平滑的焊缝,且在圆形摆动下,摆幅为 1.5~2 mm、频率为 20~100 Hz 时,能得到成形良好的焊缝。摆动方式为垂直和圆形时,气孔较少;摆动方式为不摆动和无穷形摆动时气孔率较大。摆幅为 2 mm 时,气孔率较小;当摆动频率在 100~200 Hz 之间时未发现明显气孔。

综合考虑焊缝成形和气孔率的情况下,采用圆形摆动、2 mm 摆幅、100 Hz 频率的摆动工艺参数,完成了 20 mm 厚钛合金窄间隙激光摆动填丝焊接,接头表面成形良好, X 射线检测无明显缺陷,接头抗拉强度最大为 930 MPa,为韧性断裂,拉伸试样断裂在母材,接头强度与母材等强。

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# Effects of Oscillation Parameters on Weld Formation and Porosity of Titanium Alloy Narrow-Gap Laser Wire Filling Welding


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## Abstract


**Objective** Titanium and its alloys are indispensable and satisfactory owing to its superior physical and chemical properties: high specific strength and modulus，excellent thermal strength，and corrosion resistance．Against the background of the industrial rapid development，the aerospace manufacturing industry has put forward requirements for light-weight and large-scale aircraft，which intensely increased the use of titanium alloys．There are considerable studies based on laser welding of titanium alloy sheets，and significant effort has been made．However，a few studies have been conducted on the joining of thick titanium alloy plates，leaving many technical problems unsolved．For the welding of a thick titanium alloy plate，the arc welding process is a low-cost method，with poor weld beam formation，high residual stress，and wide heat-affected zone．Electron beam welding (EBW) is one of the high energy density welding processes．The challenges of EBW is obvious，and its application is severely limited by the vacuum condition．Several studies stated that narrow-gap laser filling welding is an optimal choice for the joining of thick plates，compared with other welding processes．In this paper，we investigate and analyze the effects of laser beam swing parameters on the formation and porosity of TC4(Ti-6Al-4V) titanium alloy narrow-gap laser filling welding．We obtain that it could eliminate the lack of fusion and reduce porosity with matched laser beam oscillation mode，amplifier，and frequency．It could provide basic data and theoretical supports for thick titanium alloy welding．

**Methods** Titanium alloy plate (TC4(Ti-6Al-4V)) and wire (TC3(Ti-5Al-4V)) are used in this study．First，2 mm-wide-gap TC4(Ti-6Al-4V) is filled with TC3 wire by laser swing welding，which takes different oscillation modes: amplitude and frequency．A well-formed surface and cross-section with low porosity are selected as suitable oscillation parameters．Next，20 mm-thick TC4(Ti-6Al-4V) is welded by selected parameters．Apart from surface formation and cross-section，the weld joint has been analyzed by X-ray pore detection and tested tensile strength．

Then, the tensile fracture is analyzed by a scanning electron microscope.

**Results and Discussions** The weld surface formation cloud improves a lot despite the laser beam oscillation mode considered. The fusion depth gets smaller, and the fusion width gets bigger in the cross-section (Table 2), which could reduce the lack of fusion. When the oscillation amplitude is between 1.5 mm and 2 mm, and the frequency is between 100 Hz and 200 Hz with circular oscillation, the surface of the weld becomes continuously smooth, and the cross-section turns wider and shallower (Table 3 and Table 4). A bigger form factor of weld applies to narrow-gap welding to reduce lack of fusion matched oscillation parameters could be selected with form factor and porosity (Fig. 4). When the oscillation frequency is between 100 Hz and 200 Hz with 2 mm amplitude and circular swing, no pore was detected on the X-ray films (Fig. 5). 20-mm-thick TC4(Ti-6Al-4V) has been welded by narrow-gap laser beam swing with circular 2 mm and 100 Hz oscillation. The results showed that the weld joint gets a well-formed surface and has no pore in the X-ray film. In the tensile strength tests, the weld joint maximal tensile strength reaches 930 MPa, which is the same as base metal and the tensile samples are ductile fracture (Fig. 10).

**Conclusions** In this study, narrow-gap TC4(Ti-6Al-4V) plates are welded by swing laser wire filling welding. Compared with non-oscillating laser welding, the surface forming can be improved after the beam swings, and the continuous smooth weld can be obtained. Under the circular oscillation, when the oscillation amplitude is between 1.5 mm and 2 mm, and the frequency is between 20 Hz and 100 Hz, the well-formed weld can be obtained. When the oscillation mode is linear and circular, the porosity is relatively small, while when the oscillation mode is non-oscillating and infinite oscillation, the porosity is relatively large. When the oscillation amplitude is 2 mm, the porosity is small, and no obvious pore is found from the X-ray films when the oscillation frequency is between 100 Hz and 200 Hz. Owing to comprehensive consideration of weld formation and porosity, with the circular oscillation 2 mm amplitude and 100 Hz frequency of the oscillation parameters, we have completed the 20 mm-thick TC4(Ti-6Al-4V) narrow-gap laser wire filling welding with well forming joint surface, and no obvious pore was detected from X-ray detection. The maximum tensile strength of the 20 mm-thick weld joint reaches 930 MPa, which is the same as base metal, and the fracture mode is a ductile fracture with a dimple fracture surface under the scanning electron microscope. We obtain matched oscillation parameters. The data has been validated with well formation and property from the test of the 20 mm-thick weld joint, which plays a significant role in thick titanium alloy welding.

**Key words** laser technique; laser beam oscillation; titanium alloy; weld formation; porosity

**OCIS codes** 140.3390; 350.3850; 350.3390