中国激光

TC4 钛合金激光填丝焊工艺参数对焊缝宏观成形的影响

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摘要 以 TC4 钛合金焊丝为填充材料，对 1.2 mm 厚的 TC4 钛合金板材进行激光填丝焊接试验研究，以分析工艺参数对焊缝宏观成形的影响。通过开展单一变量试验，探索激光功率、焊接速度以及送丝速度对焊缝宏观成形的影响规律。同时，还对相同工艺参数、不同试板装夹间隙宽度情况下的焊缝成形情况进行研究，探讨所获得的较优工艺参数的适用情况。最终得到 1.2 mm 厚的 TC4 钛合金激光填丝焊接的较优工艺参数：激光功率为 1.5 kW，焊接速度为 1.2 m/min，送丝速度为 2.5 m/min。此工艺参数组合下得到的焊接接头焊缝宏观成形良好，无明显外观缺陷。

关键词 激光光学；激光填丝焊接；TC4 钛合金；工艺参数；宏观成形

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1 引　　言

TC4 钛合金(Ti-6Al-4V)是一种 α+β 型双相钛合金，由于其在比强度、耐蚀性、热强性等方面有着优异的性能表现，综合性能优良，因此被广泛应用于航空航天、石油化工、造船汽车等领域，是一种重要的新型结构材料[1-3]。

传统的钛合金焊接技术多为氩弧焊接技术，电弧焊在焊接操作与观察方面有着极大的便利性，且可焊接材料范围广，但存在焊接热影响区大、焊接应力和焊后变形大等难以避免的缺点。与氩弧焊接技术相比，激光焊接技术具有能量密度高、热影响区窄、焊后变形小等优点，能够得到满足使用要求的优质焊接接头[4-5]。

目前，激光自熔焊是较为常用的激光焊接方式，但不填丝的自熔焊极易形成焊缝表面凹陷，出现焊漏等问题，在对焊缝成形有着较高要求的航空航天领域的应用十分受限。此外，对于中厚板乃至大厚板的连接，仅仅依靠自熔焊工艺是完全不够的。而在激光焊接时采取填入焊丝的策略能够有效改善焊漏问题，并能对焊接过程中母材合金元素的蒸发和烧损进行补充，最终得到成形良好的优质焊接接头[6-7]。国内外学者对激光填丝焊接方法进行了一些研究：程好等[8]对 1 mm 厚的 TC4 钛合金板进行了激光填丝拼焊试验，就激光工艺参数对接头截面尺寸和组织的影响进行了研究；朱晓欧[9]研究了 0.5 mm 厚的 TC4 钛合金双激光束填丝焊成形工艺，分析了焊丝填充量、激光功率、焊接速度、离焦量等对焊缝成形和内部质量的影响，阐明了双激光束填丝焊与单光束填丝焊相比存在的优势；韩德成等[10]使用单激光焊接、激光填丝焊接、激光-MIG 复合焊接 3 种焊接方法对 1.5 mm 厚 TC4 钛合金板进行了焊接试验，并对比分析了 3 种焊接方法下的焊缝成形质量、接头显微组织、接头显微硬度、接头拉伸性能等；郭宁等[11]采用双层气体保护罩，对 1 mm 厚 TC4 钛合金的水下激光填丝焊接工艺进行了研究，并在合适的焊接参数下获得了高质量的水下焊缝。

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本文针对 1.2 mm 厚 TC4 钛合金蒙皮间隙较大时采用激光不填丝焊接易产生焊漏，进而造成焊缝成形质量差的问题，开展了激光填丝焊接工艺的最优参数探讨。根据试验结果，分析不同工艺参数对激光填丝焊接 TC4 钛合金焊缝宏观成形的影响，并对焊接工艺参数进行了优化，以得到成形良好的焊接接头，为焊接构件的实际生产提供一定参考。

2 试验材料和方法

激光填丝焊接试验所用的母材为 TC4 钛合金，厚度为 1.2 mm，使用的焊丝是与母材同一组分的 TC4 钛合金焊丝。使用的激光器为 TruDisk 12003 碟片式激光器，最大功率可达 12000 W，其产出的光束质量极高，性能稳定；设备运行可靠，利用率高，综合使用成本较低；同时，一台激光器最多可以分时或分功率供应 6 个工作站，可充分发挥激光器的效用并提高系统的可用性。

本试验中使用的 KR60HA 机器人是德国 KUKA 公司专门为激光焊接研发的高精度机器人，包括机器人本体、机器人控制柜（KRC4）、示教盒（KCP）及供电电缆和外部轴电机。相比于其他类型或型号的机器人，此机器人具有更高的重复定位精度、定位精度和更大的有效负载。图 1 为 TruDisk 12003 碟片式激光器和 KUKA 机器人 KR60HA 实物图。焊接参数见表 1。

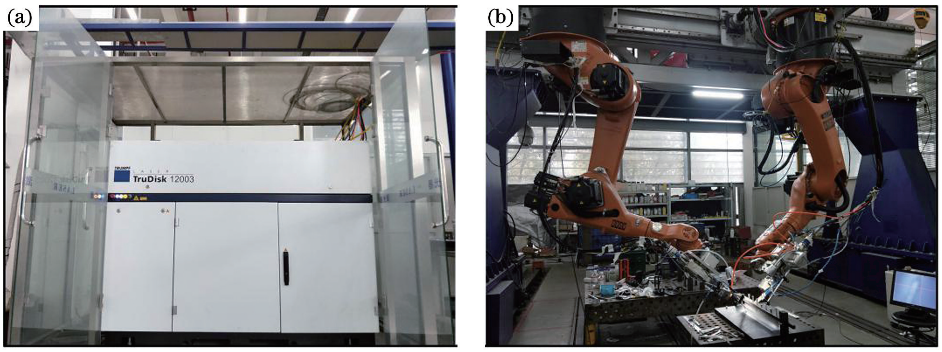

图 1 焊接设备。(a) TruDisk 12003 碟片式激光器；(b) KUKA 机器人 KR60HA

Fig. 1 Welding equipments. (a) TruDisk 12003 disc laser generator; (b) KUKA robot KR60HA

表 1 激光填丝焊接参数

Table 1 Process parameters of laser wire filling welding

Case	Laser power P/kW	Welding speed V_w/ (m·min^{-1})	Filling speed V_s/ (m·min^{-1})
1	1.3	1.5	1.5
2	1.5	1.5	1.5
3	1.5	1.2	1.5
4	1.5	1.2	1.3
5	1.5	1.2	2.0
6	1.5	1.2	2.2
7	1.5	1.2	2.5

3 不同工艺参数下焊缝宏观成形分析

3.1 激光功率对焊缝宏观成形的影响

为得出合适的工艺参数范围，前期已初步进行激光填丝焊接工艺试验。激光功率、焊接速度及送丝速度是对焊接质量影响较大的几个参数，将其选定为变量。在前期试验的基础上，对部分参数进行敲定，确定送丝角度为 42°，离焦量为 5。

当焊接速度为 1.5 m/min，离焦量为 5，送丝速度为 1.5 m/min，试板装夹留有 0.4 mm 间隙时，只改变激光功率，得到了图 2 所示的焊缝宏观形貌。由图 2(a)、(b)可知，激光功率为 1.3 kW 时，焊缝正面与背面的连续性均较差，原因为此时设定的焊接速度过快，输入的激光能量不能够熔覆充足的焊丝形成连续焊缝。而当激光功率提高至 1.5 kW 时，焊缝出现焊漏情况，这与焊接速度和送丝速度不匹配有关。此时的焊接速度对于所设定的送丝速度来说过快，送进的焊丝没有充足的时间熔覆形成焊缝，故而出现焊漏情况。可见，选择合理的工艺参数对于得到连续、美观的焊缝有着很重要的作用。

3.2 焊接速度对焊缝宏观成形的影响

焊接速度过快，与送丝速度不匹配，会导致焊丝没有充足的时间熔覆形成焊缝，故而导致焊缝成形差、不均匀，出现焊漏、焊缝连续性差等问题。保持图 2(c)所示试板的其他参数不变，只将焊接速度由 1.5 m/min 降低至 1.2 m/min，得到的试板焊缝宏观形貌如图 3(c)、(d)所示。两种焊接速度下的焊缝宏观形貌对比如图3所示。由图3可

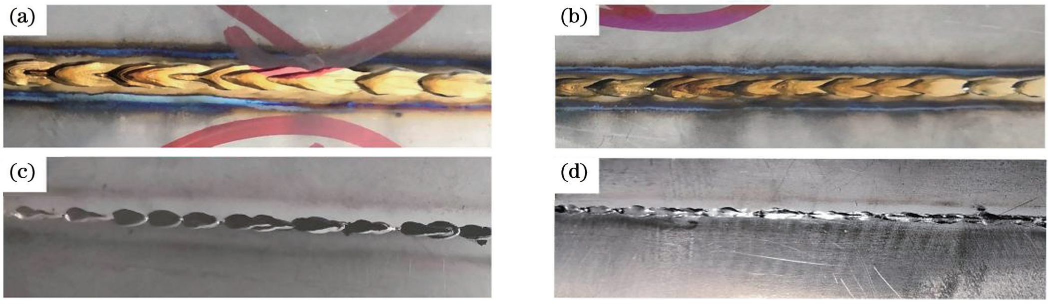

图 2　不同激光功率下焊缝宏观形貌。(a)1.3 kW，焊缝正面；(b)1.3 kW，焊缝背面；(c)1.5 kW，焊缝正面；(d)1.5 kW，焊缝背面

Fig. 2　Macromorphology of weld seam under different laser power. (a) 1.3 kW, front of weld seam; (b) 1.3 kW, back of weld seam; (c) 1.5 kW, front of weld seam; (d) 1.5 kW, back of weld seam

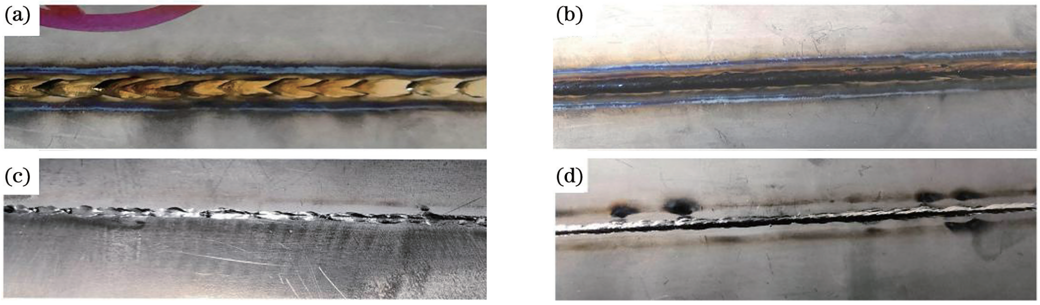

图 3　不同焊接速度下焊缝宏观形貌。(a)1.5 m/min，焊缝正面；(b)1.5 m/min，焊缝背面；(c)1.2 m/min，焊缝正面；(d)1.2 m/min，焊缝背面

Fig. 3　Macromorphology of weld seam under different welding speeds. (a) 1.5 m/min, front of weld seam; (b) 1.5 m/min, back of weld seam; (c) 1.2 m/min, front of weld seam; (d) 1.2 m/min, back of weld seam

知，焊接速度为 1.2 m/min 时，未出现焊漏情况，整体成形较好，但焊缝连续性依旧较差，且焊缝表面氧化较为严重。其原因为送丝速度较慢，熔化的焊丝量不足以填充间隙，因此焊接过程中无法形成连续美观的焊缝。

3.3　送丝速度对焊缝宏观成形的影响

焊缝不连续和焊漏均对接头成形质量有很大影响，不仅会大幅降低其强度，更是导致接头断裂的隐患之一。

保持图 3(c)所示试板的激光功率为 1.5 kW、焊接速度为 1.2 m/min 以及离焦量为 5，只改变送丝速度，继续探索焊缝成形良好的最优工艺参数组合。不同送丝速度下的焊缝宏观形貌如图 4 所示。由图 4(a)可知，当送丝速度降低至 1.3 m/min

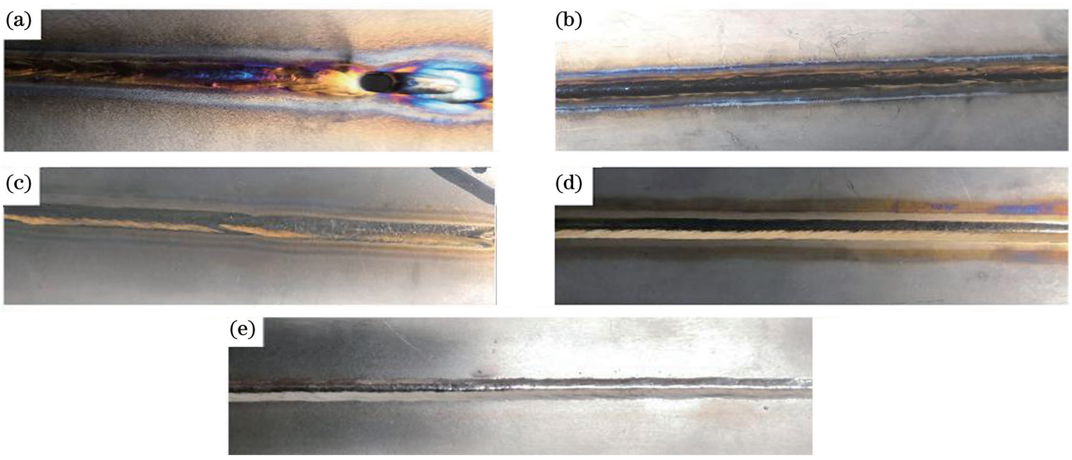

图 4　不同送丝速度下焊缝宏观形貌。(a)1.3 m/min；(b)1.5 m/min；(c)2.0 m/min；(d)2.2 m/min；(e)2.5 m/min

Fig. 4　Macromorphology of weld seam under different wire feeding speeds. (a) 1.3 m/min; (b) 1.5 m/min; (c) 2.0 m/min; (d) 2.2 m/min; (e) 2.5 m/min

时，焊缝成形差，存在大量焊漏位置。随着送丝速度的提高，焊缝成形质量得到明显的改善，焊缝整体成形较好。当送丝速度分别提高至 2.2 m/min 和 2.5 m/min 时，能够得到成形良好的焊缝。对比图 4(d)和图 4(e)可知，当送丝速度为 2.5 m/min 时，焊缝更为饱和美观，连续性更好。

试验过程发现在实际装配后，蒙皮间隙在一定范围内变化较大，因此，进一步探索蒙皮间隙对焊缝成形的影响规律十分有必要。图 5 所示为试板装夹间隙宽度分别为 0.4 mm 和 0.3 mm 时试板焊缝成形情况。可以看到，间隙宽度为 0.3 mm 时得到的焊缝连续性较差。可知，本试验摸索得到的最优参数适用于蒙皮间隙较大的情况，当蒙皮实际装配后间隙较小时，可根据具体情况对焊接参数进行适当调整。

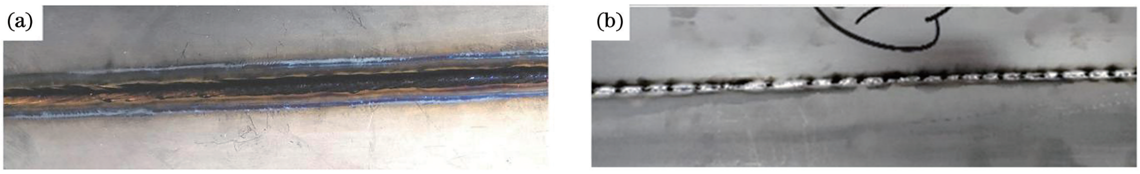

图 5 不同间隙宽度时焊缝宏观形貌。(a) 0.4 mm；(b) 0.3 mm

Fig. 5 Macromorphology of weld seam under different interstice widths. (a) 0.4 mm; (b) 0.3 mm

随着焊接工艺参数的变化，钛合金激光焊焊缝的形貌发生变化，主要用上余高(H_1)、下余高(H_2)、上熔宽(W_1)和下熔宽(W_2)4 个参数来表征焊缝成形特征，部分焊接工艺参数下得到的激光填丝焊接焊缝横截面形貌如图 6～8 所示。可以看到，在激光填丝焊接中由于焊丝的引入，在填充量充足的情况下，均在不同程度上存在余高。图 6 所示为 1.5 m/min 送丝速度时得到的焊接接头截面形貌，可以看到，接头成形较好，不存在咬边、焊瘤等焊接缺陷。图 7 所示为增大送丝速度至 2.0 m/min 时获得的接头截面形貌，可以看到，接头的上、下余高均有所增加。继续增大送丝速度至 2.5 m/min，得到的接头截面形貌如图 8 所示。可以看到，接头上余高明显增大，下余高较小，其原因为输入的激光热量多用于熔化焊丝，熔池底部对流激烈程度减弱，故下余高较小。

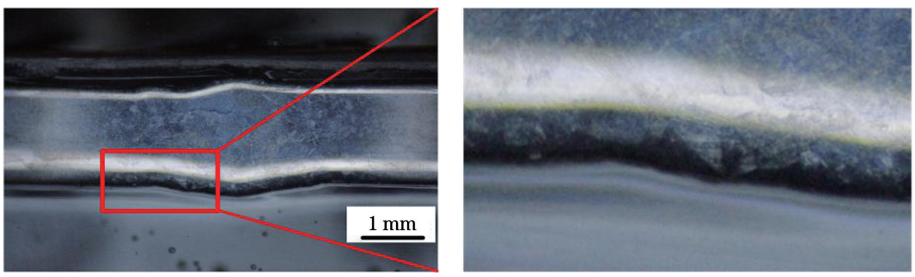

图 6 $P=1.5$ kW、$V_w=1.2$ m/min、$V_s=1.5$ m/min 时激光填丝焊接接头截面形貌

Fig. 6 Cross section morphology of laser filled wire welded joint at $P=1.5$ kW, $V_w=1.2$ m/min, and $V_s=1.5$ m/min

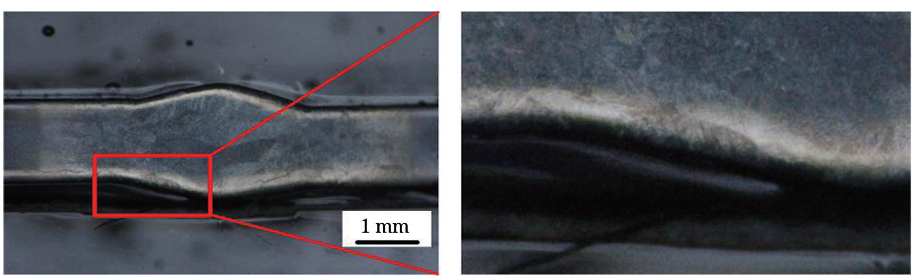

图 7 $P=1.5$ kW、$V_w=1.2$ m/min、$V_s=2.0$ m/min 时激光填丝焊接接头截面形貌

Fig. 7 Cross section morphology of laser filled wire welded joint at $P=1.5$ kW, $V_w=1.2$ m/min, and $V_s=2.0$ m/min

所测得的焊接接头各区域具体尺寸见表 2。当激光功率和焊接速度相同时，上余高(H_1)、上熔宽(W_1)和下熔宽(W_2)及焊缝横截面积均随着送丝速度的增加而增大，其原因为单位时间内送进熔覆装置的焊丝质量增加，故焊缝填充量也随之增加。当送丝速度为 2.5 m/min 时，下余高(H_2)减小，其原因为此时单位时间内焊丝的送进量较大，激光束产生的热量多用于熔化送进的焊丝，形成焊缝，导致抵

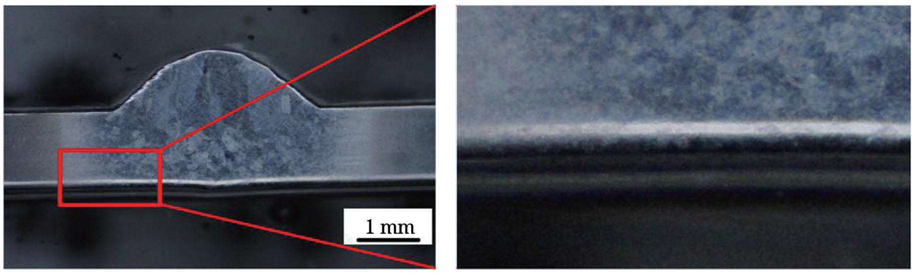

图 8　$P=1.5$ kW、$V_w=1.2$ m/min、$V_s=2.5$ m/min 时激光填丝焊接接头截面形貌

Fig. 8　Cross section morphology of laser filled wire welded joint at $P=1.5$ kW, $V_w=1.2$ m/min, and $V_s=2.5$ m/min

达试板底部的热量减少，故下余高(H_2)减小。

表 2　不同焊接工艺参数下激光填丝焊接接头截面尺寸

Table 2　Section size of laser filled wire welded joint under different welding process parameters

Sample	#1	#2	#3
Laser power P /kW	1.5	1.5	1.5
Welding speed V_w/(m·min^{-1})	1.2	1.2	1.2
Wire feeding speed V_s/(m·min^{-1})	1.5	2.0	2.5
Upper excess weld metal H_1/mm	0.12	0.25	0.53
Lower excess weld metal H_2/mm	0.12	0.18	0.05
Upper welding width W_1/mm	1.22	1.68	1.88
Lower welding width W_2/mm	1.00	1.50	1.73

4　结　　论

对 1.2 mm 厚的 TC4 钛合金进行激光填丝焊接时，焊接工艺参数的选择对接头的成形质量有着重要影响。若焊接速度与送丝速度不匹配，焊丝没有充足的时间熔覆形成连续、美观的焊缝，容易出现漏焊问题。这是因为送丝速度一般根据板材厚度、焊接位置和焊丝直径等确定；焊接速度要根据实际焊接的焊缝成形要求来确定，焊接速度过低时，金属堆积导致焊缝尺寸较大，过高时，容易出现咬边未熔合等情况。只有二者匹配时，才能获得优质的焊接接头。

送丝速度也应与激光功率匹配。激光功率过小时，输入的热量少；送丝速度过慢时，送进的焊丝量少。这均会导致实际熔覆的焊丝量不足，易使焊缝连续性差。此外，装配间隙宽度也会对焊漏、焊缝不连续等外观缺陷的形成产生影响，本研究得到的优化后的工艺参数适用于装配间隙宽度较大的情况，装配间隙宽度改变时，应根据具体情况适当调整工艺参数。

研究发现，1.2 mm 厚的 TC4 钛合金激光填丝焊接选取激光功率为 1.5 kW，焊接速度为 1.2 m/min，送丝速度为 2.5 m/min 时，焊缝宏观成形良好，焊缝外观连续均匀，无咬边、焊瘤、漏焊等明显外观缺陷。

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Influence of the Technological Parameters of TC4 Titanium Alloy Laser Wire Filling Welding on Weld Seam Macroformation

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Abstract

Objective TC4 titanium alloy (Ti-6Al-4V) is widely used in aerospace, petrochemical, shipbuilding, and automobile fields because of its excellent performance in specific strength, corrosion resistance, and thermal strength. It is an important new structural material. The traditional welding technology of titanium alloy is argon-arc welding technology. Arc welding has great convenience in welding operation and observation. It can be employed to weld several materials. However, it has some unavoidable disadvantages, such as large welding heat-affected zone, large welding stress, and deformation after welding. Moreover, laser welding technology has the advantages of high energy density, narrow heat-affected zone, and small deformation after welding. It can obtain high-quality welded joints to meet the requirements. At present, laser self-melt welding is a common laser welding technique; however, it can easily cause depression on the surface of the weld seam, welding leakage, and other problems due to the lack of filler wire. Therefore, its application in aerospace field with high requirements for weld forming has limitations. In this study, the laser wire filling welding experiment of thin Ti-6Al-4V with a thickness of 1.2 mm was performed, and the influence of the process parameters on weld seam forming was studied. Finally, an optimized process parameter combination with a small clamping gap was obtained. This study is an effective supplement and new exploration of traditional thin plate laser welding without filler wire. It is highly consistent with the long life and airworthiness requirements of aircraft. In addition, it has distinct innovation and application value.

Methods The base metal adopted in this laser wire filling welding experiment is Ti-6Al-4V with a thickness of 1.2 mm; the filler wire used is Ti-6Al-4V filler wire with the same composition as the base metal. The laser generator used is TruDisk 12003 disc laser generator with a maximum power of up to 12000 W, and the KR60HA robot is a high-precision robot specially developed for laser welding by KUKA company of Germany.

Results and Discussions When the welding speed is 1.5 m/min, the wire-feeding speed is 1.5 m/min, and only the laser power changed in the experiment. The continuity of the front and back of the weld seam is poor when the laser power is 1.3 kW. The reason is that the welding speed is too fast, and the laser energy input cannot melt enough filler wire to form a continuous weld seam. However, when the laser power increased to 1.5 kW, weld leakage occurs, which is related to the mismatch of welding speed and wire-feeding speed (Fig. 2). Then, the welding speed is reduced from 1.5 m/min to 1.2 m/min, and the laser power is maintained. At this time, there is no welding leakage, the whole forming is better, but the continuity is still poor. It is due to the wire-feeding speed is slow, and the amount of molten filler wire is not enough to fill the gap, so the continuous and beautiful weld seam cannot be formed in the welding process (Fig. 3). Keep laser power 1.5 kW and welding speed 1.2 m/min unchanged, only change wire-feeding speed. When the wire-feeding speed is reduced to 1.3 m/min, the weld seam formation is poor, and there are a large number of welding leakage positions. With the increase of wire-feeding speed, the weld forming obviously improved. When the wire-feeding speed is 2.5 m/min, the weld seam is saturated and beautiful, and the continuity is good (Fig. 4).

Conclusions The results show that suitable choice and matches of process parameters play a significant role in obtaining high-quality joints during laser wire filling welding of Ti-6Al-4V with a thickness of 1.2 mm. If the welding speed does not match with the wire-feeding speed, the welding wire has insufficient time to melt and form a continuous and beautiful weld seam, which can easily cause a welding leakage problem. In addition, the wire-feeding speed should also match the laser power. When the laser power is too small, the heat input is less; and when the wire-feeding speed is too slow, the amount of filler wire fed is less, which will cause an insufficient amount of molten filler wire and can easily cause poor continuity of weld seam. Moreover, the selection of assembly clearance size will affect the formation of appearance defects such as welding leakage and discontinuous weld seam. The optimized process parameters obtained in this paper is suitable for the situation when the assembly clearance size is large. When the assembly clearance changes, the process parameters should be adjusted appropriately according to the specific situation. In this paper, when the laser power is 1.5 kW, the welding speed and wire-feeding speed are 1.2 m/min and 2.5 m/min, respectively, the weld seam has satisfactory macroformation, the appearance of the weld seam is continuous and uniform, and there are no obvious appearance defects such as undercut, weld bead, and weld leakage.

Key words laser optics; laser wire filling welding; TC4 titanium alloy; process parameters; macroscopic forming

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