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光斑形式对 Ti/Al 异种合金激光熔钎焊特性的影响

陈树海， 李俐群， 陈彦宾
（哈尔滨工业大学 现代焊接生产技术国家重点实验室，哈尔滨 150001）

陈树海

摘 要：采用椭圆形和矩形两种光斑形式对 Ti/Al 异种合金进行了激光填丝熔钎焊的试验研究，分析了不同工艺参数对焊缝成形的影响规律，获得不同热源作用方式下的界面形态规律及其对界面强度的影响。结果表明，采用椭圆形光斑和矩形光斑进行激光填丝熔钎焊均可获得较满意的焊缝成形。其中矩形光斑具有更好的焊接适应性，更容易控制焊缝成形。抗拉强度测试结果表明，椭圆形和矩形光斑接头的最高抗拉强度分别达到铝母材的75%和80%。

关键词：矩形光斑；椭圆形光斑；激光熔钎焊；Ti/Al 异种合金
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0 序 言

在航空、航天和汽车等工业中为实现结构件的轻量化，大量采用铝合金和钛合金作为结构材料。但是由于它们之间的热物理化学性能相差很大，用传统的焊接方法焊接时会产生大量的脆性的金属间化合物，从而影响接头性能。目前 Ti/Al 异种合金的传统的焊接方法主要有电弧熔钎焊[1]、扩散焊[2]、钎焊[3]、摩擦焊[4]以及爆炸焊[5]等等。

熔钎焊是利用两种合金熔点相差很大的特点，在焊接过程中使低熔点材料熔化，而使高熔点材料始终保持在固态，可有效地避免 Ti/Al 两种合金充分混合而生成大量的脆性的金属间化合物的一种焊接方法。采用激光作为热源，具有柔性好、能量密度高、光斑形式可调、热输入精确可控以及冷却速度快等一系列优点，成为熔钎焊热源的首选。早在2001年德国的 Kreimeyer 等人[6,7]针对 Ti/Al 异种合金的物理化学特性，提出激光直接照射钛合金并保持固态，通过热传导使铝合金熔化的激光熔钎焊实现了二者的连接，获得了较好的接头力学性能，但该方法对装配及焊接路径的精度要求非常严格，需要配备高精度的焊缝跟踪系统和附加的机械加压装置，在生产应用中受到了限制。

作者从提高激光熔钎焊的适应性，简化焊接装配的角度出发，提出采用 CO_2 激光作为热源，用 Al-Si12 作为填充焊丝，通过椭圆形和矩形两种光斑形式，用激光熔钎焊的方法焊接对接形式的 Ti/Al 异种合金板材。对焊接过程的影响因素、焊接接头的成形特性、界面的微观组织及力学性能进行了较为深入的研究。

1 试验方法

试验母材为1.5 mm厚的 Ti－6Al－4V 钛合金和 LF6 铝合金。母材用丙酮去除油污等杂质，然后钛合金用酸洗，铝合金用碱洗，烘干后进行焊接。选用 AlSi12 共晶合金焊丝，焊丝熔点范围为575～590 ℃。焊接过程的示意图如图1所示。

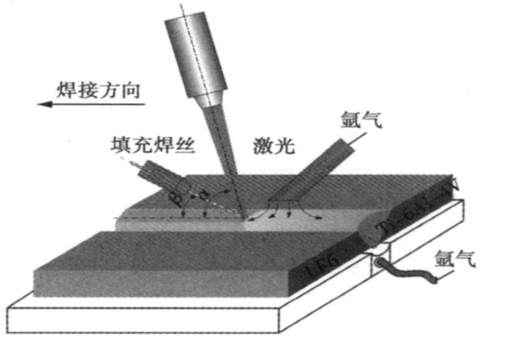

图1 焊接过程示意图

Fig 1 Schematic map of laser welding-brazing

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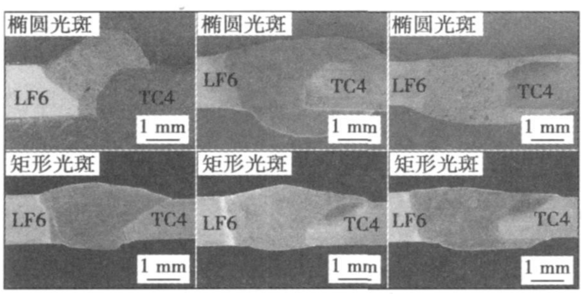
分别采用椭圆形和矩形两种光斑进行焊接试验。激光采用倾斜入射方式,与工件之间的夹角 α 为60°,获得椭圆光斑,离焦量为 50 mm;采用积分镜对激光束进行调制,获得能量密度均匀分布的矩形光斑,采用聚焦(2 mm× 4 mm)形式垂直照射工件表面。考虑到光斑为矩形,相对于焊接方向分为光斑横向排布和光斑纵向排布。焊丝的送丝角度 β 为30°,在激光束前方自动送入,采用氩气双面保护。为提高焊接过程中的润湿铺展效果,工件需开出 Y 形坡口。

采用扩散冷却射频激励 CO_2 激光器进行焊接试验;采用金相显微镜和 SEM 对接头的微观组织进行观察和分析;采用 INSTRON—5569 电子万能材料试验机进行室温拉伸试验,拉伸速度为 1.0 mm/min。

2 试验结果与分析

2.1 光斑形式对焊缝成形特性的影响

由于激光熔钎焊过程中钎料在液态条件下停留时间很短,钎料的毛细作用不明显,因而母材之间需要一定的对接间隙,依靠重力和保护气体的吹力使钎料向下流动,润湿铺展母材。为保证焊缝成形,对接间隙需要一定的范围,椭圆光斑激光熔钎焊的对接间隙应保证在 0.4~0.6 mm 之间,而对于矩形光斑的两种运动模式,对接间隙均应在 0.3~0.7 mm 之间,二者之间的对比如图 2 所示。

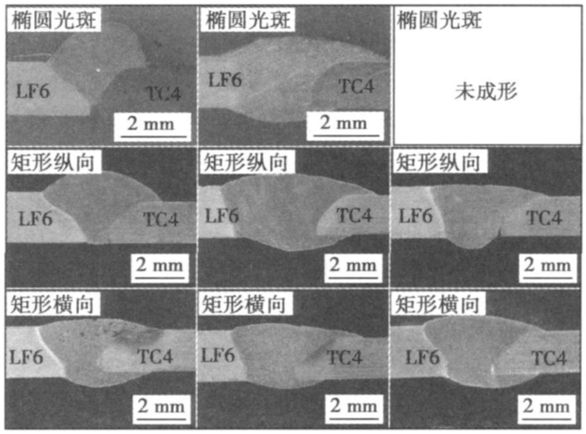


(a) 间隙 0.3 mm (b) 间隙 0.5 mm (c) 间隙 0.7 mm

图 2 对接间隙对焊缝成形的影响

Fig 2 Cross sections of joint with different gap

铝的导热系数和反射率很高,焊接过程中热量损失严重,需要调整光束的偏移量来调整两种母材的热量分配。试验发现,椭圆光斑偏向铝一侧 1 mm 左右时,可补偿这种差异,并能获得良好的焊缝成形。但是其对该偏移量较为敏感,焊接过程不容易控制,而能量密度均匀分布的矩形光斑可以有效地解决该问题,对于纵向及横向模式需分别向铝侧偏移 0.5~1 mm 及 1~2 mm,如图 3 所示。此外,对于横向的光斑模式在光束居中时激光会直接加热钛合金母材,使其熔化并与液态钎料反应生成大量的金属间化合物,同时出现了大量的气孔,因此这也是光斑需要向铝侧偏移的重要原因。



(a) 偏移量为零 (b) 偏移量 1 mm (c) 偏移量 2 mm

图 3 光束的偏移位置对焊缝成形的影响

Fig. 3 Effect of offset position of laser spot on welding

为获得良好的焊缝成形,避免界面的剧烈反应,需要对热输入进行严格控制,试验条件下,椭圆光斑热输入只能控制在 150~280 kJ/m 范围内,而矩形光斑横向排布方式大约需要 180~600 kJ/m,纵向排布方式大约需要 150~500 kJ/m。

焊缝的填充量取决于送丝速度与焊接速度的比值 K ($K = v_{送}/v_{焊}$),针对试件尺寸与间隙大小,若保证足够的热输入,对于椭圆光斑 K 值为 3.5~5.3 较为合适。因矩形光斑的最高功率密度较低,焊缝的填充量不宜过大,否则会导致钎料熔化不充分,润湿铺展性变差,影响焊缝成形。通过试验表明 K 值大约为 2.0~4.5 可以获得良好的焊缝成形。

综上所述,同椭圆光斑相比,矩形光斑对焊接 Ti/Al 异种合金的激光熔钎焊具有明显的优势,较为均匀的能量分布,可以允许较大的对接间隙保证焊丝及铝母材的熔化,降低了对偏移量的敏感性,具有更佳的焊接稳定性。此外在焊接过程中由于某些原因使焊丝发生抖动,能量呈高斯分布的椭圆光斑,能量密度梯度较大,若抖动幅度过大,焊丝很可能位于较低能量密度的位置,使焊丝熔化不良而影响焊缝成形,但是能量较为均匀分布的矩形光斑可以在一定程度上克服该问题,具有良好的适应性及稳定性。工艺参数及焊接效果对比如表 1 所示。

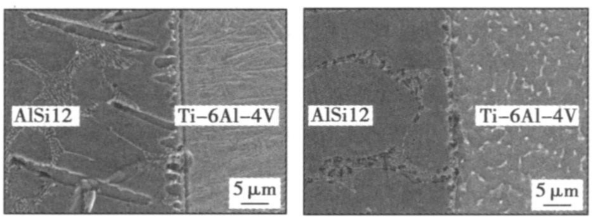
表 1　椭圆光斑和矩形光斑的工艺参数及焊接效果

Table 1　Welding parameters with ellipse and rectangular spot and their welding results

光斑形式	间隙 b/mm	偏移量 c/mm	热输入 E/(kJ·m^{-1})	速度比值 K	焊缝成形	适应性
椭圆	0.4～0.6	1	150～280	3.5～5.3	一般	一般
矩形纵向	0.3～0.7	0.5～1	150～500	2.0～4.5	好	良
矩形横向	0.3～0.7	1～2	180～600	2.0～4.5	好	好

2.2　光斑形式对界面微观组织的影响

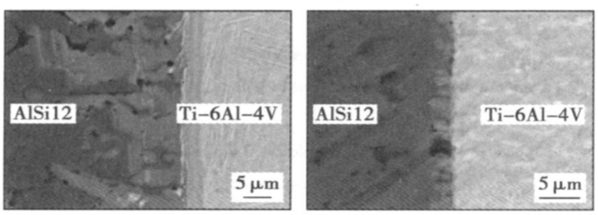
图4 及图 5 分别为椭圆光斑和矩形光斑横向的接头界面形态。在图中可以发现，界面的金属间化合物的界面大致厚度从接头的上部到下部逐渐减小，而椭圆光斑在下部没有观察到金属间化合物的生成。这是由于在焊接过程中接头的上部距离激光辐照位置较近，液态钎料的温度较高，界面反应充分，而在界面的下部距离激光辐照位置较远，界面反应不充分，甚至没有发生有效的反应。此外，界面的金属间化合物呈锯齿状或棒状形貌。在图 5a 中可以看出矩形光斑可以在一定程度上加强接头下部的界面反应，这对界面强度会产生较为有利的影响。



(a) 接头上部　　(b) 接头下部

图 4　椭圆光斑界面形态

Fig. 4　Microstructures of interface with ellipse spot

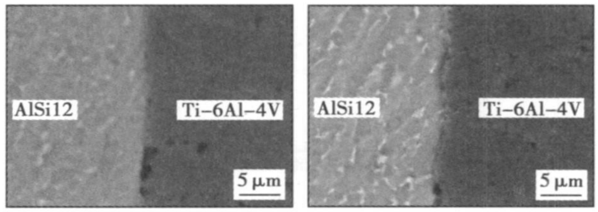


(a) 接头上部　　(b) 接头下部

图 5　矩形光斑横向界面形态

Fig. 5　Microstructures of interface with rectangular spot

图6 为在较低的热输入条件下矩形光斑纵向的上下界面形态，可以看出在较低的热输入条件下，并没有观察到明显的界面金属间化合物。对于矩形光斑纵向的界面空间分布规律与矩形光斑横向类似。



(a) 接头上部　　(b) 接头下部

图 6　矩形光斑纵向界面形态

Fig 6　Microstructures of interface with ellipse spot

2.3　光斑形式对接头界面力学性能的影响

由于焊接接头存在余高，接头抗拉强度不能足以反映界面的连接强度，因此试验用砂纸将上下余高磨平，抗拉强度测试结果如图 7 所示。椭圆光斑和矩形光斑的焊缝抗拉强度分别可达铝合金母材的 75%和 80%（铝合金母材的最大抗拉强度为 350 MPa）。在图 7a 中可以发现，椭圆光斑的激光熔钎焊接头的抗拉强度对焊接热输入不敏感，而矩形光斑的激光熔钎焊接头的抗拉强度随着热输入的增加呈现先增大而后减小的趋势。分析试验结果表明，椭圆光斑焊接接头的断裂位置基本位于界面附近的焊缝，界面的下部是较为薄弱的环节，一般在接头的下部断裂发生在界面，而在接头的上部断裂发生在焊缝；而对于矩形光斑的焊接接头在热输入较低时，几乎完全断裂在钎料与钛合金母材的界面，相应的强度也较低；在较高的热输入时，接头断裂在焊缝位置，相应的抗拉强度也较高，若进一步提高热输入，将生成大量的金属间化合物，使断裂发生在界面，此时强度较低。

结合接头微观组织，椭圆光斑的界面上部进行了较为充分的界面反应，连接较为牢固，而下部界面反应不充分，导致在拉伸的过程中下部界面首先开裂，当裂纹扩展至界面结合较为牢固的上部时，断裂将发生在焊缝。此外，热输入对椭圆光斑的焊接接头的界面形态规律影响较小，均为上部界面反应充分，而下部界面反应较为欠缺，因而接头的强度对热输入不敏感。对于矩形光斑的焊接，光斑有部分辐照于母材，母材温度升高，有利于钎料的润湿铺展，但在热输入较低时，虽然焊缝成形良好但整个界面没有发生充分反应，抗拉强度较低；随着热输入的增大，界面反应将充分进行，强度提高，特别是在钛合金母材的下部界面，反应也可以进行，所以矩形光斑接头的最大抗拉强度（282 MPa）要高于椭圆光斑

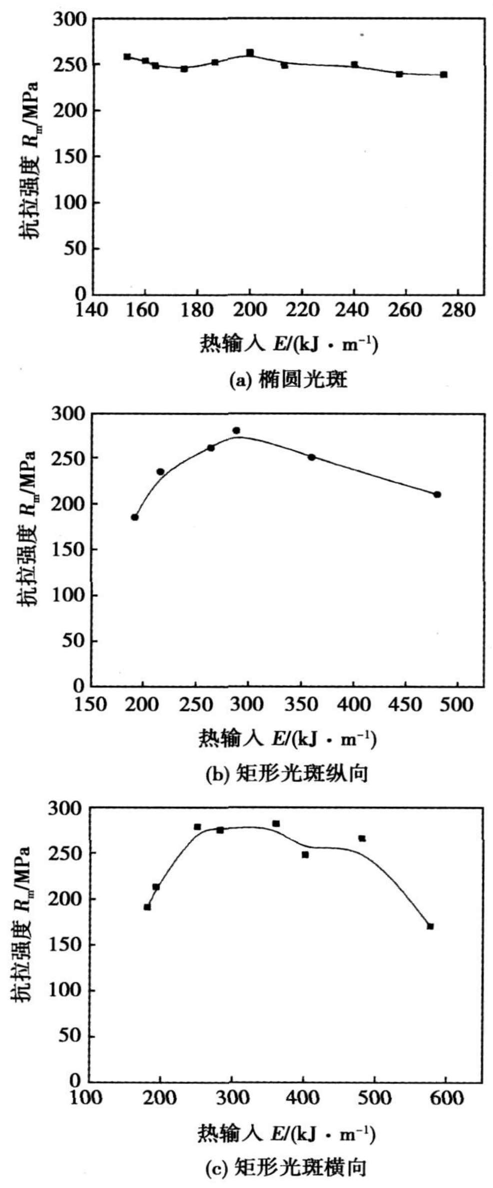


图 7 接头界面的抗拉强度

Fig 7 Tensile strength of joint interface

(262.7 MPa); 当热输入增大到一定程度时界面将发生剧烈的反应, 生成大量的金属间化合物, 使接头脆性增加, 强度降低。

此外, 由于矩形光斑可以获得良好的焊缝成形, 椭圆光斑能够在一定程度上使界面发生合适的界面反应, 钎料与母材之间的能量分配起着重要的作用, 二者需要合适的能量配比。所以可以认为, 对于激光熔钎焊而言, 界面反应决定于钎料的温度, 而钎料的润湿铺展能力取决于母材的温度, 激光熔钎焊要协调这两大因素, 既能获得良好的焊缝成形的同时又能使界面发生合适的反应。

4 结 论

(1) 采用椭圆光斑的 Ti/Al 异种合金激光熔钎焊, 可以获得满意的焊缝成形及焊接接头, 但是其工艺参数范围较窄, 稳定性一般; 采用矩形光斑可以获得更宽的工艺参数范围, 焊接稳定性好, 其中矩形光斑横向最佳。

(2) 界面金属间化合物呈锯齿状或棒状, 其厚度从接头的上部到下部逐渐变薄, 甚至消失。同椭圆光斑相比, 矩形光斑有利于促进在接头的下部的界面反应。

(3) 椭圆光斑的最大抗拉强度可达铝母材的 75%, 矩形光斑的最大抗拉强度达铝母材的 80%。椭圆光斑对热输入不敏感, 而矩形光斑的接头界面强度随着热输入的增加呈现先增大而后减小的趋势。

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作者简介: 陈树海, 男, 1979 年出生, 博士研究生。主要从事激光钎焊界面行为方面的研究工作。发表论文 1 篇。

Email: shchenhit@gmail.com

tured weld image, a on-line detection method of molten pool width is proposed. The laser-structured vision sensor is fixed behind the welding torch and put into water with waterproof guard. According to the feature of underwater weld image, the molten pool width is extracted through window processing, laplace sharpening, thresholding, mathematic morphology filtering and thinning procedure. The experimental results show that the processing speed is fast and the detection precision is high. If the distance between the molten pool centre and the strip light detecting point is less than 35 mm, the comparative error of molten pool width can be controlled within 3%.

Key words: underwater welding; molten pool width; strip-structured light; image processing

Simulation on temperature field for Invar alloy during TIG welding XU Peiquan[1], ZHAO Xiaohui[2], HE Jianping[1], XU Guoxiang[1], YU Zhishui[1] (1. College of Materials Engineering, Shanghai University of Engineering Science, Shanghai 201620, China; 2. Institute of Welding Technology, DHI·DCW Group Co., Ltd., Dalian 116031, Liaoning, China). p37—40

Abstract: According to TIG welding character of Invar alloy and 45 carbon steel, geometric model was founded and double ellipsoid heat source model was selected as welding heat source. Temperature fields of base materials with different thickness were simulated using ANSYS, and coupled field of temperature and stress was realized to simulate the residual stress distribution. Experiments under different thickness and welding parameters were carried out and distortion of base materials with different position was detected. Thus comparison between simulation results and experimental results can be carried out. The results show, welded joint with well metallurgy and penetration of invar alloys can be obtained using welding parameters of 132 A, 17.1 V, 4 mm/s and 1.88 mm thickness; and the results of temperature fields simulated by finite element method accords well with experiment results.

Key words: Invar alloy; TIG welding; temperature field

Comparison of two modeling method of 3D curve welding seam CHEN Haiyong[1], XU De[1], WANG Hong[2] (1. Institute of Automation, CAS, Beijing 100080, China; 2. Control Systems Centre, School of Electrical and Electronics Engineering, the University of Manchester, Manchester M601QD, UK). p41—44

Abstract: Three Dimension (3D) curve welding seam modeling is one of key technologies for seam tracking. The model can reduce the noise interference, improve the stability and robustness of welding system. Moreover, the system can obtain the fault tolerant ability from the model. The 3D curve welding seam was represented by using cubic parametric curve function, then the cubic parametric curve seam position model was obtained by using least square(LQ). Furthermore, the position model was also established by using cubic B spline approximation. The pose model was gotten by employing the position model and other welding seam coordinates. The performance of the two model was compared and analyzed. Simulation result verifies that B spline seam model excel the cubic parametric curve seam model and provid better approximation to the original welding seam.

Key words: 3D welding seam model; B spline function; cubic parametric curve function

Quality of resistance spot welding based on variable electrode force SUN Haitao, ZHANG Yansong, LAI Xinmin, CHEN Guanlong (School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, China). p45—48

Abstract: Hot dipped galvanized (HDG) low carbon steels have been widely used in internal and outside plates of auto body. Constant electrode force was utilized under conventional pneumatic guns, which led to unstable welding quality. However, the quality of resistance spot welding (RSW) on galvanized steels was sensitive to variable electrode force. Considering controlling electrode force exactly with servo guns, a design of experiment (DOE) method was applied to analyze the influence of three stages of electrode force during the welding process, including preliminary force, welding force and forging force, on welding quality and to obtain optimum parameters of variable electrode force. The results showed that forging force was noted as the most important factor, welding force as secondary one, squeeze force as least important one, and that optimum parameters could increase tensile-shear force and nugget diameter of welds significantly. This method would be the foundation of real-time quality evaluation and control based on electrode force.

Key words: electrode force; DOE method; hot dipped galvanized low carbon steels; resistance spot welding

Welding characteristics of Al/Ti dissimilar alloys by laser welding-brazing with different spot CHEN Shuhai, LI Liqun, CHEN Yanbin (State Key Laboratory of Advance Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p49—52

Abstract: Ellipse spot and rectangular laser spot were used as the heat source respectively to experimentally research laser welding-brazing with filler wire for Al/Ti dissimilar alloys. And the influence of gap and heat input on weld appearance were analyzed, furthermore, the welding interface characteristics with different heat source were obtained. Experimental results show that both ellipse spot and rectangular beam can gain the good weld appearance. Increasing heat input is of advantage to enhance the interface strength, but it is of disadvantage to control the weld appearance. Welding stability and processing control with rectangular spot are better than those with ellipse spot. The maximum tensile strength of joint gained by ellipse spot and rectangular spot is respectively high up to 75% and 80% of aluminum base material.

Key words: rectangular spot; ellipse spot; laser welding-brazing; Al/Ti dissimilar alloys

Kinetic analysis of spray transfer welding arc in a longitudinal magnetic field HUA Aibing, CHEN Shujun, ZHANG Xiaoliang, YIN Shuyan (College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, China). p53—56

Abstract: A miniaturized generator device for longitudinal