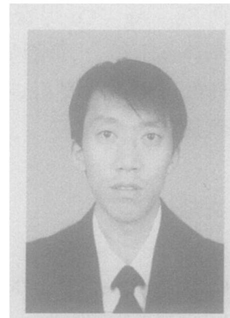
钛合金/纯铝异种金属摩擦焊接工艺

白建红， 傅 莉， 杜随更
（西北工业大学 材料学院， 西安 710072）



白建红

摘 要：进行了TC4钛合金与L5纯铝异种金属的摩擦焊接工艺及其焊后回火热处理工艺研究，利用光学金相分析、扫描电镜EDX线扫描、拉伸性能及硬度的测试，探讨了TC4钛合金与L5纯铝异种焊接接头焊合区的微观组织及其力学性能。研究表明，TC4钛合金与L5纯铝间具有良好的摩擦焊接性，焊合区无金属间化合物相生成，焊接接头强度等于或高于铝基材。经焊后回火热处理，摩擦焊接头两侧主要合金元素的扩散区宽度增大，焊合区钛合金侧的硬度值因时效作用而有所提高。

关键词：摩擦焊接； 焊后热处理； TC4钛合金； L5纯铝； 微观组织
中图分类号：TG H23 文献标识码：A 文章编号：0253—360X(2006)10—050—03

0 序 言

铝合金和钛合金由于其比强度高，耐腐蚀和耐高温等优良性能而成为航空、航天领域的主要结构材料。由于某些特殊性能的要求，使铝合金和钛合金连接而形成复合结构变得越来越重要。徐国庆[1]等采用钛热浸铝工艺试验了Ti/Al的扩散焊，研究表明铝棒与钛棒扩散焊接的最佳工艺为490 ℃下采用10 MPa的焊接压力扩散焊接20 min，同时在焊前采用钛热浸铝工艺。赵鹏飞[2]等对Ti/Al真空钎焊的研究认为，同时含有Sn、Ga的钎料对Al/Ti异种合金钎焊时的铺展性和抗剪强度有较大的好处。Kim等[3]从力学和冶金学的角度对Ti/Al摩擦焊接头进行了研究，认为焊接接头性能好坏的判据不完全是力学性能的高低，还取决于所形成的金属间化合物层宽度，其临界值约为5 μm。

由于Ti合金与纯铝的熔点、导热系数、线膨胀系数等物理性能相差悬殊，在两种材料的熔化焊接过程中，会导致焊缝化学成分不均匀，降低接头强度；同时Ti金属与Al金属在高温下极易氧化，严重影响焊接接头质量[4]。此外，采用一般的熔化焊接方法，还会在Ti/Al结合面上形成大量层状的质硬而脆的金属间化合物Ti_3Al等，引起应力集中，降低焊接接头塑性与韧性。因此，选择合适的焊接方法和焊后热处理工艺是获得满意的Ti/Al异种金属焊接质量的关键。探讨了TC4钛合金与L5纯铝摩擦焊接及焊后回火热处理工艺，以实现钛合金与纯铝异种金属的连接。

1 试验材料及方法

研究所采用的焊件材料尺寸分别是：TC4钛合金为Φ20 mm×160 mm(旋转端)和L5纯铝Φ20 mm×160 mm(移动端)，焊前均为热轧态。

焊接试验在自行研制的C200型连续驱动摩擦焊机上进行，其主轴电机功率75 kW，最大焊接力200 kN，主轴电机采用变频调速，转速可在100～3000 r/min间变化。该焊机配备了工业计算机闭环控制系统，能实现焊接过程参数(焊接压力、转速、摩擦扭矩与轴向缩短量)的实时检测与控制。采用的焊接工艺参数为：摩擦转速400 r/min；摩擦压力100 MPa；摩擦位移2 mm；顶锻压力200 MPa；顶锻时间6 s；顶锻提前时间0.3 s。焊前试件端面采用纤维砂轮抛光去除氧化物，再用丙酮清洗。

焊后采用SX—4—10型箱式电子炉对TC4/L5摩擦焊接头进行去应力回火热处理。该设备额定功率为4 kW，并采用SHIMDEM的SR73A数显表和自制的炉温自动控制仪进行热处理温度的显示与控制。热处理温度为300 ℃，保温时间为1.5 h，然后将试样空冷到室温。

焊后将试样沿轴向剖切[5]，并进行抛光，经腐蚀后，采用OLYMPUS PMG3型光学显微镜测试摩擦焊接头焊合区的微观组织形态；采用AMRAY—100B型扫描电镜测试焊态和热处理状态下主要合金元素沿焊合区的分布；采用HX—1000型显微硬度计，测

收稿日期：2005—11—07
基金项目：航空科学基金资助项目(03H53035)

量沿摩擦焊接头轴向的硬度分布,加载载荷为 100 g,加载时间为 15 s;焊接接头的拉伸性能测试在 WE—30型万能材料试验机上进行,并取 5 件试样测量结果的平均值作为该规范下焊合区的平均抗拉强度。

2 试验结果与分析

2.1 TC4 钛合金与 L5 纯铝摩擦焊接头组织

研究采用的 TC4 钛合金组织为α+β 型双相钛合金,α—Ti 与β—Ti 间的转变温度在850 ℃左右[6]。TC4 钛合金/L5 纯铝摩擦焊接头一般由焊缝区 WZ(weld zone)、热力影响区 HFZ(heat and force—affected zone)和基材区 BM(base metal)组成。在摩擦焊接过程中,焊合区温度最高、变形程度最大,是主要的产热源。在焊接热与力的作用下,焊合区金属发生了强烈的塑性变形与流动、相互搅拌与混合、相互扩散与渗透、加热与冷却相变、动态回复与再结晶等物理冶金与力学冶金过程,两侧材料的相互机械混合与啮合现象非常明显,焊合面凸凹不平,如图 1 所示。由于 TC4 钛合金/L5 纯铝焊接时转速低(400 r/min),所以焊接界面温度较低,焊合区及焊接热力影响区钛合金侧仍保留了基材的α+β 双相组织(图 2),不产生金属间化合物相。

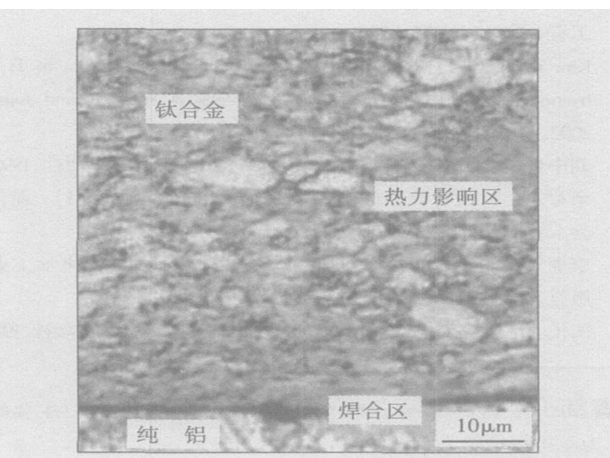


图 1 TC4 与 L5 摩擦焊合区微观形貌
Fig. 1 Microstructure of friction welded joint of TC4 alloy and L5 Aluminum

2.2 焊后热处理对 TC4/L5 摩擦焊接头合金元素扩散行为的影响

TC4 钛合金与 L5 纯铝摩擦焊接头分别在焊态及焊后热处理态下,主要合金元素沿接头轴向的扩散宽度如表 1 所示。由表可知,TC4/L5 摩擦焊接头经焊后热处理后,主要合金元素 Ti, Al, V 在焊合区的扩散宽度增大。异种材料摩擦焊接过程中,扩散对焊接接头力学性能有着重要的影响。在有色金属中固态扩散是在晶体点阵中的原子跃迁过程。一般情况下,原子扩散是与电位梯度、浓度梯度、温度梯度、应变梯度共同作用下所造成的化学势梯度有关。其中,温度决定了扩散的可能性,化学势梯度决定了扩散的方向,时间决定了扩散的强度。在 TC4/L5 摩擦焊接过程中,由于摩擦时间和顶锻时间较短,使得原子扩散不能充分进行;此外,L5 纯铝的传热较快,使焊后焊合区温度迅速降低,致使扩散不能充分进行。通过焊后热处理可以降低摩擦焊接过程中因 TC4 钛合金与纯铝热物理性能参数差异而引起的残余应力,增强焊合区主要合金元素的扩散,从而提高 TC4 钛合金与 L5 纯铝异种摩擦焊接头性能。

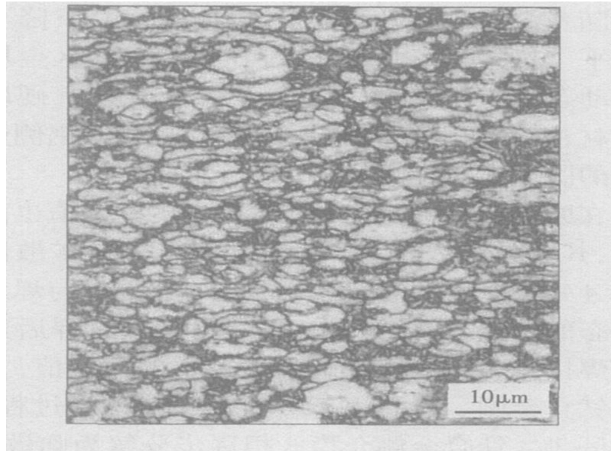


图 2 TC4 钛合金母材微观组织
Fig. 2 Microstructure of base metal of TC4 alloy

表 1 主要元素沿焊接接头轴向的扩散宽度
Table 1 Diffusion width of main alloying elements along axial direction in friction welded joint between TC4 alloy and L5 Aluminum

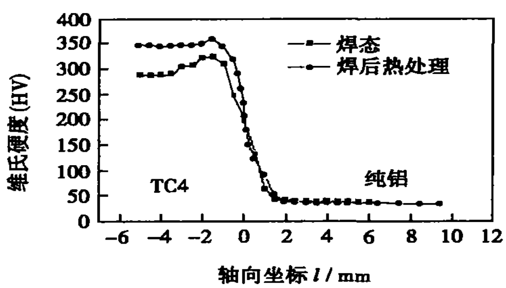
试样状态	扩散宽度		
	W_{Ti}/μm	W_{Al}/μm	W_V/μm
焊态	5	5	5
焊后热处理态	10	15	15

2.3 焊后热处理对 TC4/L5 摩擦焊接头力学性能的影响

图 3 为 TC4 钛合金与 L5 纯铝摩擦焊接头焊态及热处理态的显微硬度沿轴向的分布曲线。从图中可以看出,焊合区(0 点位置)铝侧的硬度高于基材,

并且随着距焊缝位置的增加，硬度值逐渐下降至基材水平。其原因一方面是 Al/Ti 摩擦焊合区金属发生了动态再结晶，由此引起的细晶强化使其硬度高于母材；另一方面是由于钛的扩散，使接头铝侧产生一定的固溶强化作用。

在摩擦焊接头钛合金侧近缝区的硬度值也高出母材，其原因是摩擦焊接过程中 Al 元素的扩散促进了 TC4 钛合金侧的时效强化[7]。对比焊态与焊后热处理态的焊合区硬度分布可以看出，经过焊后热处理的焊接接头硬度值均高于焊态下的硬度值，尤其是在钛合金侧。这是由于焊后回火热处理过程中，焊合区 TC4 钛合金侧介稳β相逐步分解为弥散的α+β相[7]，从而进一步加强了摩擦焊合区钛合金侧的时效强化效果，致使焊合区 TC4 钛合金侧的硬度值大幅度提高。



注：0 点左侧为 TC4 钛合金，0 点右侧为 L5 纯铝

图 3 TC4/L5 摩擦焊接头显微硬度沿轴向的分布曲线

Fig. 3 Microhardness distribution along axial direction in friction welded joint between TC4 alloy and L5 Aluminum

焊接接头拉伸试验结果表明，在文中研究所设定的摩擦焊接工艺参数下，TC4 钛合金/L5 纯铝摩擦焊接头的拉伸试验均断于铝侧母材，其平均抗拉强度为82.17 MPa，超过铝母材的抗拉强度（80～100 MPa），焊接系数大于 1。典型 TC4/L5 摩擦焊接头拉伸试样宏观形貌如图 4 所示。

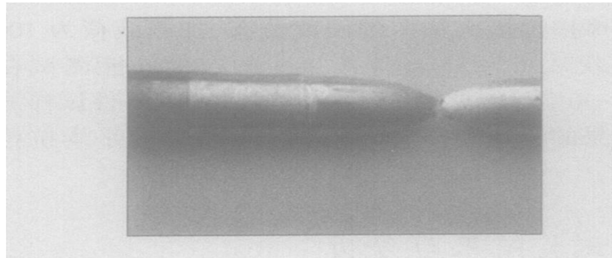


图 4 钛合金/纯铝摩擦焊头拉伸试样宏观形貌

Fig. 4 Macrostructure of friction welding joint of TC4 alloy and L5 Aluminum after tensile test

4 结 论

（1）采用文中的摩擦焊接工艺参数可以实现 TC4 钛合金与 L5 纯铝异种金属的连接；在其界面上不产生金属间化合物相。

（2）采用文中的焊接工艺参数，焊态下焊接接头抗拉强度可以达到或超过铝侧基材水平。

（3）TC4 钛合金与 L5 纯铝摩擦焊接头经焊后回火热处理后，主要合金元素沿焊合区的扩散区宽度增大；焊合区钛合金侧硬度值显著提高。

参考文献：

[1] 徐国庆，曾 岚，牛济泰，等. Al/Ti 的扩散焊工艺[J]. 焊接，2000(3)：21－24.

[2] 赵鹏飞，康 慧. Al－Ti 异种合金真空钎焊的研究[J]. 材料工程，2001(4)：25－28.

[3] Kim Y C, Fuji A. Factors dominating joint characteristics in Ti－Al friction welds[J]. Science and Technology of Welding and Joining, 2002, 7(3)：149－154.

[4] 刘中青，邸 斌. 异种材料的焊接[M]. 北京：科学出版社，1990.

[5] 余存烨. 钛及钛合金的金相制样使用技术与经验[J]. 理化检验－物理分册，2001，37(2)：61－63.

[6] 李亚江. 异种难焊材料的焊接及应用[M]. 北京：化学工业出版社，2004.

[7] 田长生. 金属材料及热处理[M]. 西安：西北工业大学出版社，1985.

作者简介：白建红，男，1980 年 7 月出生，硕士研究生。主要研究方向为摩擦焊接工艺及设备。

Email：Johnny.bai@liteon.com

portions with same length to approximate the complicated space curve under the conditions of keeping constant welding speed and satisfying the given approximation error. It takes the general connection form of cylinder pipe for example to illustrate the algorithm, and then OpenGL is used to simulate the composite motion track. Simulation results show that the real-time interpolation algorithm is feasible.

Key words: line of intersection; welding; interpolation algorithm; simulation

Characterization of mechanical properties for aluminium alloy welded joint QIAO Ji-sen, ZHOU Qing-lin, ZHU Liang, CHEN Jian-hong (State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China). p41—44, 49

Abstract: The characterization of local material properties has been evaluated using the punch shearing test. An inversed technique was illustrated to assess the tension behavior of materials from this punch shearing test. In addition, an typical aluminium alloy 6063 and welded joints for auto industry have been tested by the punch shearing procedure to identify the relation between yield strength, ultimate strength and strain-hardening coefficient of local material of welded joint. Results show that the material mechanical properties can be identified accurately by the punch shearing procedure, which will supply the information of joint deformation and failure for aluminium automobile crash assessment.

Key words: punch-shearing test; local mechanical properties; welded joint

Effects of heating time on wettability and spreadability of paste solders on Cu substrate with diode laser soldering system HUANG Xiang, XUE Song-bai, ZHANG Ling, WANG Jian-xin, HAN Zong-jie (College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China). p45—49

Abstract: Diode laser soldering system was used to study and explore the ways to improve the wettability and spreadability of Sn63Pb37 paste solder and Sn96Ag3.5Cu0.5 lead-free paste solder on Cu substrate. The effects of heating time of the laser on the wettability of paste solders were investigated and it was also analyzed that the microstructures of the joints and interfacial region of Sn63Pb37 and Sn96Ag3.5Cu0.5 under different time conditions by means of SEM. The Results indicate that the wettability and spreadability of the two kinds of solders on Cu substrate are improved with the increase of heating time under the condition of selected laser output power. When the heating time is longer than 1.5 s, the spreading area and wetting angle of Sn63Pb37 solder are tending towards stability and when the heating time is longer than 2.5 s, the spreading area and wetting angle of Sn-Ag-Cu solder are tending towards stability as well.

Key words: diode laser soldering; wettability; Sn-Pb solder; Sn-Ag-Cu solder

Friction welding technology between titanium alloy and pure aluminum BAI Jian-hong, FU Li, DU Sui-geng (College of Materials Science, Northwestern Polytechnical University, Xi' an 710072, China). p50—52

Abstract: Titanium alloy and aluminum alloy are good for the structure materials in the fields of aerospace and aviation because of their excellent properties. It is necessary to join these two materials for wider applications. TC4 titanium alloy and L5 pure aluminum are joined by friction welded and then post-welding tempering treatment have been conducted. By means of the optical microscope detecting, EDX analysis, micro-sclerometer and tensile test, we explore experimentally the microstructure characteristics and diffusion behavior of the friction welded joint of TC4 titanium alloy and L5 pure aluminum. As expected, there are good friction weldability between TC4 titanium alloy and L5 pure aluminum and no intermetallic phases created in friction welding zone under the welding parameters used in this trial. Furthermore, the tensile strength of the welded joint exceeds that of the base metal aluminum. After post-welding heat treatment, the diffusion zone of main alloying elements Ti, Al and V widens and the microhardness of the friction welded joints near titanium increases greatly because of the aging effect.

Key words: friction welding; post-welding heat treatment; TC4 titanium alloy; L5 pure aluminum; microstructure

MAG welding molten pool image character and useful information analysis WANG Ke-hong, SHEN Ying-ji, QIAN Feng, YOU Qiu-rong (Dept of materials, Nanjing University Science & Technology, Nanjing 210094, China). p53—56

Abstract: A passive vision sensing system for taking the image of MAG welding molten pool has been set up. Near-infrared CCD and compound filters system composed of 1 064 nm narrow-band filer and 0.1% neutral dimmer film are used to eliminate the arc light disturbance and a lot of clear images are obtained. Image-processing software is used to extract the characteristic information which reflects the welding quality. For the single image, the gray character is analyzed and three equivalent contour lines are obtained. For continuous multi-frame images, the image aberration shade detection and mean gray distribution are put forward to study the process of MAG welding.

Key words: metal active-gas welding; molten pool image; characteristic information; gray analysis

Numerical simulation of hydrogen diffusion under welding residual stress JIANG Wen-chun, GONG Jian-ming, TANG Jian-qun, CHEN Hu, TU Shan-dong (College of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 210009, China). p57—60, 64

Abstract: Using finite element analysis code ABAQUS, a sequential coupling calculating program on hydrogen diffusion has been developed. Using this program, the effect of as-welded residual stress on the hydrogen diffusion was numerically simulated for the