

# 预镀层钛合金与铝合金电弧熔钎焊接头界面组织及力学性能分析

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**摘 要:** 钛合金板坡口位置预先热浸镀纯铝镀层, 采用 TIG 电弧熔钎焊的方法连接镀层钛合金与铝合金, 对比分析了有镀层和无镀层条件下形成的接头界面组织及焊缝强度。结果表明, 两种条件下界面处生成相同成分的金属间化合物  $\text{TiAl}_3$ , 其中无镀层条件下  $\text{Ti}/\text{Al}$  界面反应层呈锯齿状, 厚度  $4 \sim 6 \mu\text{m}$ , 焊缝平均拉伸强度  $118 \text{ MPa}$ , 以脆性断裂为主; 镀层条件下界面生成均匀稳定金属间化合物, 厚度  $2 \mu\text{m}$  以下, 焊缝平均拉伸强度  $205 \text{ MPa}$ , 以韧性断裂为主。镀层的引入减薄了金属间化合物反应层厚度, 从根本上改变了接头的断裂的方式。

**关键词:** 热浸镀;  $\text{Ti}/\text{Al}$  异种金属; 电弧熔钎焊; 断裂机制

**中图分类号:** TG 444.74 **文献标识码:** A **文章编号:** 0253-360X(2016)10-0125-04

## 0 序 言

钛合金与铝合金以其各自优异的性能在航空航天、海洋工程、汽车化工等领域得到了广泛的应用。钛合金高强, 但难于加工, 铝合金轻质, 但是强度太低。若将钛合金与铝合金焊接形成复合构件, 能克服单一材料性能上的缺陷, 而且能最大限度上发挥组合构件高强、轻质的优势<sup>[1]</sup>。国内外对于钛/铝异种合金的焊接涉及的焊接方法包括激光焊<sup>[2]</sup>、钎焊<sup>[3]</sup>、摩擦焊<sup>[4]</sup>等, 其涉及的主要问题还是在于  $\text{Ti}/\text{Al}$  界面反应层的控制。

由于钛合金和铝合金物理性能的差异, 化学上不相容, 熔焊过程中过高的热输入导致大量金属间化合物在界面处生成, 脆性的金属间化合物易造成焊接接头低应力破坏。激光熔钎焊  $\text{Ti}/\text{Al}$ , 裂纹的萌生与扩展依赖于界面组织特征<sup>[5]</sup>, 即界面反应层的结构直接影响焊接接头的强度。

电弧熔钎焊的方法连接钛合金与铝合金, 经济简便, 在低熔点铝合金一侧形成熔焊接头, 在高熔点钛合金一侧形成钎焊接头, 由于钛合金不发生熔化, 有效的控制了金属间化合物在界面的生长。一些电弧熔钎焊钛/铝异种合金的研究已取得了一些成果<sup>[6]</sup>, 但电弧的大热输入量, 导致  $\text{Ti}/\text{Al}$  界面反应层的大量生长, 严重的限制了熔钎焊接头的力学性能。试验中, 在焊接之前引入热浸镀环节, 在钛板表面浸

镀纯铝镀层, 随后再进行钛/铝电弧熔钎焊, 试图通过钛板表面的铝镀层缓解焊接过程中  $\text{Ti}/\text{Al}$  的不相容性, 对界面反应层特征进一步的改观。试验过程着重对比有、无镀层两种条件下焊接接头微观组织、断口形貌以及宏观强度特征, 结合分析两种条件下焊缝断裂路径, 建立  $\text{Ti}/\text{Al}$  接头微观界面结构与宏观性能间的关联。

## 1 试验方法

试验母材为  $2 \text{ mm}$  厚的 TC4 钛合金和 LF6 铝合金板材, 试件开 Y 形坡口以促进钎料润湿铺展。试验分为两组, 其中一组钛合金板, 坡口位置预先浸镀纯铝镀层, 另一组的钛板不进行任何处理。焊接过程中, 填充纯铝焊丝, 将铝合金板与无镀层的钛合金板以及预镀层的钛合金板分别连接。

热浸镀过程是将钛合金板插入熔融液态铝中, 保温  $3 \text{ min}$  后匀速提出铝液, 钛板坡口表面形成一层均匀的纯铝镀层。焊接装置示意图如图 1 所示。装配成对接接头, 接头反面设置成形槽, 采用交流 TIG 焊机进行熔钎焊。

焊前将钨极置于钛合金坡口上方  $2 \sim 3 \text{ mm}$ 。焊接工艺参数: 焊接电流  $110 \text{ A}$ , 焊接速度  $1.25 \text{ mm/s}$ 。填充纯铝焊丝与浸镀用纯铝相同, 母材、焊丝以及浸镀用纯铝镀液的化学成分如表 1 所示。浸镀及焊前用钢丝刷清除坡口附近的氧化膜, 丙酮擦拭去除油污。

收稿日期: 2014-11-02

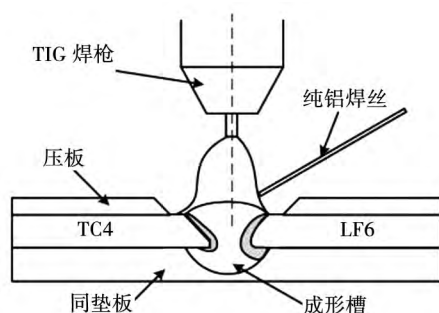


图 1 电弧熔钎焊 Ti/Al 异种合金示意图

Fig. 1 Section and microstructure of precoating titanium

焊后通过扫描电镜观察接头钎焊界面和断口的形貌,并用能谱仪分析接头的化学成分和界面物相组成.强度测试前将接头余高磨平以测试焊缝强度,依据国家标准 GB/T228—2010《金属材料室温拉伸试验方法》,在 INSTRON-5569 试验机上进行,拉伸试样尺寸如图 2 所示,加载速率为 1 mm/min.

表 1 试验材料的化学成分(质量分数,%)

Table 1 Chemical compositions of bonding couple

	Mg	Cu	V	Al	Ti
TC4	—	—	3.5~4.5	5.5~6.8	余量
LF6	5.8~6.8	0.1	—	余量	0.02
纯铝	—	<0.1	—	余量	—

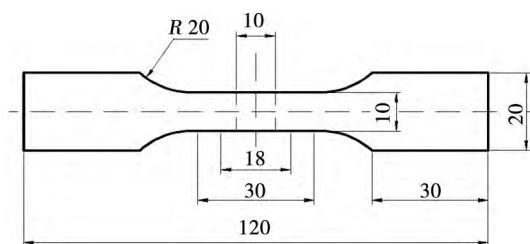


图 2 拉伸试样尺寸(mm)

Fig. 2 Diamission of tensile sample

## 2 试验结果与分析

### 2.1 热浸镀 Ti/Al 界面特征

经过浸镀后的钛板,坡口周围形成一层纯铝镀层,经过机械打磨后,镀层的厚度 20  $\mu\text{m}$  左右,如图 3a 所示.对镀层与基板间界面进行显微分析,扫描电镜下界面结构如图 3b 所示,深色的铝和浅色的钛之间形成了一层反应层,能谱分析显示反应层原子比 Ti 21.87%,Al 78.13%,判断其结构为  $\text{TiAl}_3$ ,厚度在 1  $\mu\text{m}$  以下.

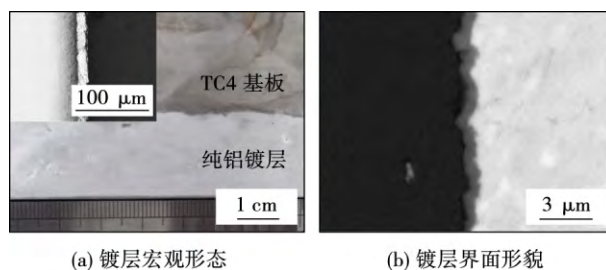
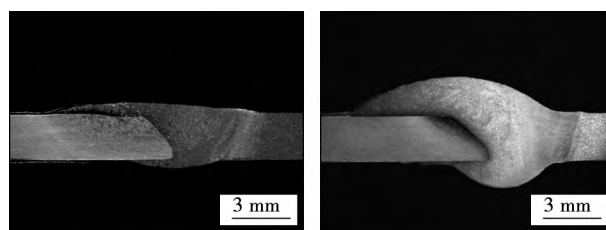


图 3 镀层形貌

Fig. 3 Section and microstructure of precoating titanium

### 2.2 接头界面组织特征

图 4a、b 分别为无镀层条件下 Ti/Al 熔钎焊接头和有镀层条件下的接头宏观形貌,相同的焊接参数下,无论有无镀层,均形成了稳定无缺陷的熔钎焊接头.其中铝合金一侧坡口完全熔化形成熔钎接头,钛合金一侧保持了原来坡口形状,形成钎焊接头.不同之处在于,镀层条件下接头,纯铝焊丝更多流向钛合金板,焊缝凝固后在钛合金板侧形成了较大的余高,这主要是由于铝镀层促进了液态焊丝对钛板的润湿所致.



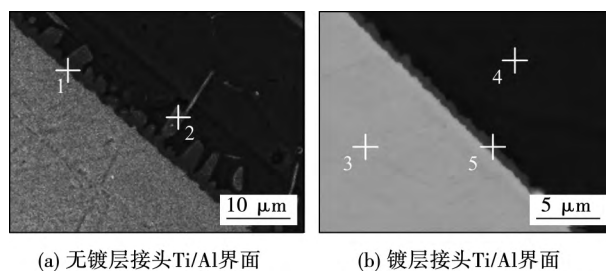
(a) 无镀层焊接接头宏观

(b) 镀层焊接接头宏观

图 4 熔钎焊接头宏观形貌

Fig. 4 Macrostructure of welding-brazing joint

取坡口斜面处界面微小区域进行 SEM 分析,如图 5a 所示为无镀层条件下 Ti/Al 界面反应层的微观形貌,可知纯铝焊丝填充时界面形成了锯齿状的化合物层,厚度为 4~6  $\mu\text{m}$ .图 5b 为镀铝层钛板与铝合金熔钎焊接头界面反应层特征,如图所示 Ti/Al 界面生成一层均匀连续化合物,厚度 2  $\mu\text{m}$  以下.



(a) 无镀层接头 Ti/Al 界面

(b) 镀层接头 Ti/Al 界面

图 5 熔钎焊接头 Ti/Al 界面结构特征

Fig. 5 Microstructure of interface of Ti/Al

对图 5 中特征位置进行能谱分析,结果如表 2 所示,图 5a 中位置 2 处反应层处 Ti,Al 原子比接近 1:3,参考文献[7]中对于 Ti/Al 界面反应研究结果,判定反应层主体结构为  $\text{TiAl}_3$ ,而位置 1 处反应物原子比判断,为  $\text{Ti}_3\text{Al}$ ,但是这层反应层很薄,只是在靠近钛板一层生长.图 5b 中的特征点能谱分析结果显示,反应层主要组成仍为  $\text{TiAl}_3$ ,在钛一侧也可能会有  $\text{Ti}_3\text{Al}$  生成,只是由于反应层过薄而不可见.

对比上述两种条件下接头微观结构发现,界面反应层的主体结构是相同,均为  $\text{TiAl}_3$ ,不同在于反应层的形貌和厚度.在镀层条件下 Ti/Al 界面反应层明显变薄,形态上也更加均匀稳定.

表 2 特征点能谱测试结果(质量分数,%)

Table 2 Energy spectrum test result of characteristic points

位置	Al	Ti	V	Mg	物质组成
1	29.15	70.85	—	—	$\text{Ti}_3\text{Al}$
2	70.85	29.15	—	—	$\text{TiAl}_3$
3	15.13	81.8	3.07	—	TC4
4	98.66	—	—	1.34	纯 Al
5	85.45	14.55	—	—	$\text{TiAl}_3$

如前面所述,在钛板热浸镀过程中,钛、铝间已经发生了反应,在镀层界面生成的浸镀反应层,反应层厚度在  $1\text{ }\mu\text{m}$  左右.随后的焊接过程中,由于热的作用,界面反应层会继续生长,最终形成了镀层条件下焊接接头界面微观结构,如图 5b 所示.但需要强调的是,正是由于浸镀反应层的存在,阻碍了焊接过程中原子的扩散,从而抑制了界面反应层的生长.因此,Ti/Al 异种金属电弧熔钎焊,由于镀层的引入,减薄了界面反应层的厚度.

### 2.3 焊接接头的断裂路径

测试有镀层和无镀层两种条件下焊缝的抗拉强度,如图 6 所示,无镀层条件下焊缝平均抗拉强度  $118\text{ MPa}$ ,镀层条件下焊缝平均强度为  $205\text{ MPa}$ .同

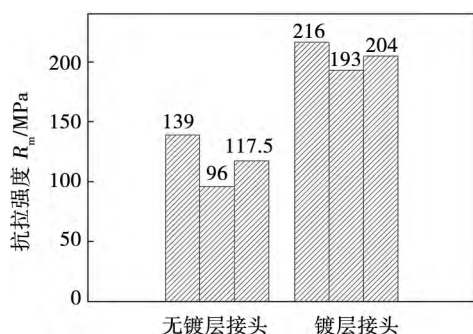


图 6 焊缝抗拉强度

Fig. 6 Tensile test results of welding seam

样使用纯铝焊丝,镀层条件下的焊缝强度明显的提高.从多组拉伸试验得出的结果中看出,镀层条件下,焊缝强度的波动性明显好于无镀层焊缝,这也是预镀层焊缝整体强度好于无镀层焊缝的关键,相信这主要源于预镀层焊缝界面反应层更加均匀稳定.

更深入的探究这种强度的变化原因,如图 7a 所示为无镀层条件下焊缝拉伸断裂路径.从图 7 中可以看到断裂完全沿着钛合金坡口,坡口斜面放大如图 7b 所示,裂纹完全贯穿界面反应层,接头铝合金焊缝中出现了微弱的“缩颈”现象.断口特征如图 7c,宏观上在斜面区域的断口较为平整,呈现出河流状花样,为典型的脆性断裂,这也印证了裂纹贯穿脆性金属间化合物的现象.只是在坡口上沿出现撕裂棱区域,这是裂纹在铝合金内扩展的现象,如图 7d 所示.所以整个断口主要以脆性断裂为主,局部微小区域出现撕裂现象.

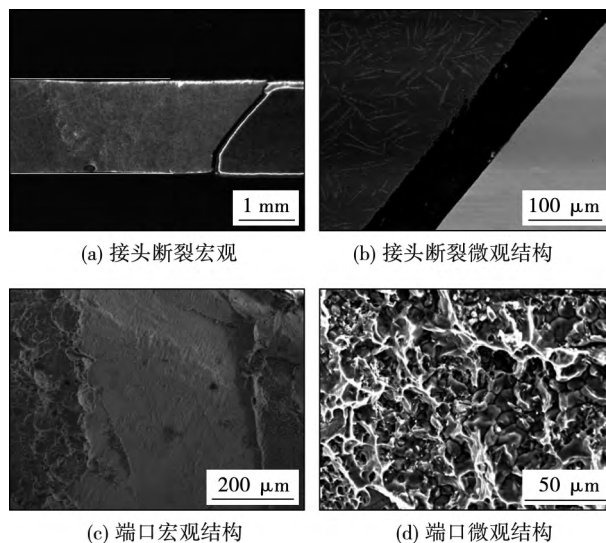


图 7 无镀层接头断裂特征

Fig. 7 Fracture character of non-precoating weld

镀层条件下熔钎焊接头断裂路径如图 8a 所示,整个焊缝在断裂过程中发生了明显的颈缩现象,断裂位置几乎全部在焊缝之内,与纵向呈  $45^\circ$  切断的痕迹.从切断的方向和焊缝变形情况可以判断裂纹萌生于焊缝内部,如图 8b 所示钝边拐角处局部放大照片,钝边上暴露反应层,反应层是熔钎焊接头的薄弱环节,裂纹极有可能从此处萌生并扩展.钛板一侧断口形貌如图 8c 所示,对平坦区域能谱分析结果显示,Ti、Al 原子含量(原子分数,%) : Ti73 左右,Al27 左右,说明平坦区域为金属间化合物  $\text{Ti}_3\text{Al}$  层,其周围的粗糙区域为纯铝,断口为典型韧窝特征,如图 8d.

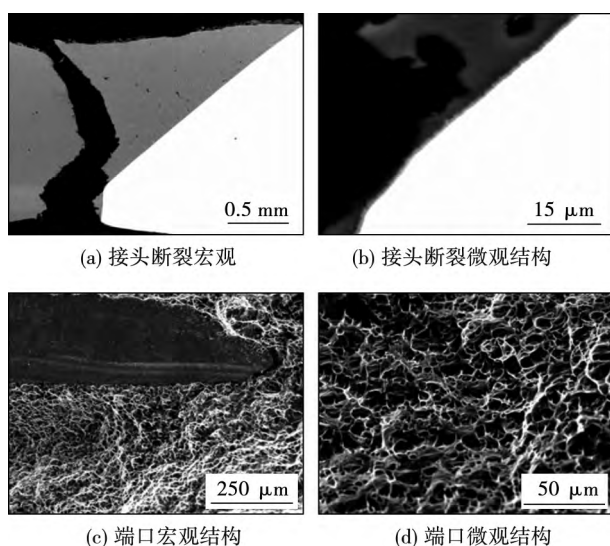


图 8 镀层接头断裂特征

Fig. 8 Fracture character of precoating weld

在无镀层焊接接头中,裂纹源萌生并向周围扩展,即主裂纹扩展。因为反应层较厚,层中存在大量的微细裂纹,这些微裂纹端部的应力强度因子超过临界应力强度因子<sup>[6]</sup>,也会在界面反应层内部扩展,这些微细的裂纹会与主裂纹汇合,加速裂纹扩展过程,反应层中的微细裂纹在引导主裂纹在界面反应层中扩展,最终形成沿界面的脆性断裂,如图 9a 所示。镀层条件下的焊接接头中,由于反应层的厚度得到有效控制,反应层中的微裂纹也大幅度的减少<sup>[8]</sup>,裂纹虽然在钝边处萌生,但因为反应层薄,主裂纹在曲折向前扩展过程中,极容易滑出反应层,进入焊缝中。此时在薄的反应层中,微细裂纹密度大大减低,加之坡口斜面受力状态的改变,正应力减小,所以反应层中的裂纹无法诱使主裂纹重新进入反应层中扩展,主裂纹就会在扩展阻力相对较小的焊缝中继续扩展,最终形成沿焊缝的断裂,如图 9b 所示。

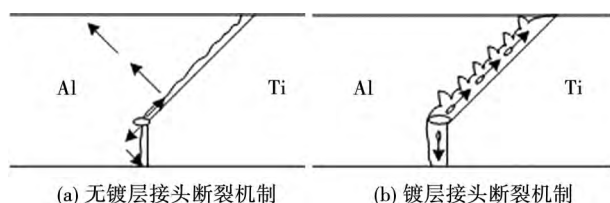


图 9 熔钎焊接头的断裂机制

Fig. 9 Fracture mechanisms of welding-brazing weld

在熔钎焊连接钛/铝异种合金过程中,由于热浸镀过程的引入,使得界面反应层结构变得均匀,厚度得到减薄,因此提高了焊接接头的强度。焊接接头强度的变化源于焊缝拉伸过程中裂纹扩展路径的变

化,而裂纹扩展路径的变化又源于 Ti/Al 界面反应层结构的变化。

### 3 结 论

(1) 电弧熔钎焊方法实现了预镀层钛合金与铝合金的连接,相比于无镀层条件下的焊接接头,金属间化合物的厚度得到有效的减薄。

(2) 预镀层钛合金与铝合金熔钎焊接头焊缝抗拉强度 218 MPa,相比于无镀层条件焊接接头,强度提高 73%,焊缝以韧性断裂为主。

(3) 建立了 Ti/Al 熔钎焊接头中微观组织与宏观性能间的关联,即通过减薄 Ti/Al 界面反应层厚度,使焊接接头的拉伸性能得到提高。

### 参考文献:

- [1] Taban E, Gould J E and Lippold J C. Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: properties and microstructural characterization [J]. *Materials and Design*, 2010, 31(5): 2305–2311.
- [2] 兰 天,董 鹏,肖荣诗. 铝/钛异种合金激光深熔钎焊试验分析[J]. *焊接学报*, 2010, 31(8): 109–113.  
Lan Tian, Dong Peng, Xiao Rongshi. Analysis of laser deep penetration brazing of aluminium and titanium [J]. *Transactions of the China Welding Institution*, 2010, 31(8): 109–113.
- [3] Takemoto T, Nakamura H, Okamoto I. Vacuum brazing of Al/Ti Joints with aluminum filler metals [J]. *Journal of Japan Institute of Light Metals*, 1986, 36(10): 627–632.
- [4] 白建红,傅 莉,杜随更. 钛合金/纯铝异种金属摩擦焊接工艺[J]. *焊接学报*, 2006, 27(11): 50–53.  
Bai Jianhong, Fu Li, Du Suigeng. Friction welding technology between titanium alloy and pure aluminum [J]. *Transactions of the China Welding Institution*, 2006, 27(11): 50–53.
- [5] Chen Y B, Chen S H, Li L Q. Influence of interfacial reaction layer morphologies on crack initiation and propagation in Ti/Al joint by laser welding-brazing [J]. *Materials and Design*, 2010, 31(1): 227–233.
- [6] 吕世雄,崔庆龙,黄永宪,等. Ti/Al 异种合金电弧熔钎焊接头界面断裂行为分析[J]. *焊接学报*, 2013, 34(6): 33–36.  
Lu Shixiong, Cui Qinglong, Huang Yongxian, et al. Analysis of interface fracture behavior of arc fusion-brazed joint between titanium and aluminum dissimilar alloys [J]. *Transactions of the China Welding Institution* 2013, 34(6): 33–36.
- [7] Sujata M, Bhargava S, Sangal S. On the formation of  $TiAl_3$  during reaction between solid Ti and liquid Al [J]. *Journal of Materials Science Letters*, 1997, 16(13): 1175–1178.
- [8] Yoshikuni N, Kazutoshi N, Kazuyoshi S, et al. Improvement in bonding strength of  $Si_3N_4$  to metals joints by controlling reaction layer thickness [J]. *Quarterly Journal of the Japan Welding Society*, 1993, 11(2): 294–300.

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**Key words:** activating flux; pulsed laser beam welding; plasma; acoustic emission

**Research on residual distortion of welded tubular structure based on FEA**

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**Abstract:** In order to figure out the residual distortion of welded tubular structure, a thermal-elastic-plastic model using commercial FEA software MSC. Marc was established by considering material nonlinearity and geometry nonlinearity. The active and death element method was employed to simulate the welding process of shell plate and two tubes at different locations, respectively. The results show that the welded tube exists swelling distortion with its axial line offset, and buckling deformation occurs in the shell plate near weld. Before simulation, the rationality of the input parameters were discussed by comparing the experimental and simulated results of butt joint in three aspects of thermal cycles, longitudinal and transverse residual stresses of certain locations and angular distortion.

**Key words:** tubular structure; welding residual distortion; thermal-elastic-plastic FEM

**Vacuum diffusion brazing of SiCp/Al composites**

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**Abstract:** Vacuum diffusion brazing of SiC particle reinforced aluminum matrix was performed with Al/Cu/Al composite foils. The microstructure of the joint was investigated by SEM, EDS and XRD. The formation mechanism of the joints was analyzed according to Al-Cu binary phase diagram. The effects of brazing temperature on the interfacial microstructure and shear strength were studied. The results shows that as the brazing temperature rise from 590 °C to 640 °C, the interfacial products change from  $Al_2Cu + \alpha Al$  eutectic structure to discontinuous  $Al_2Cu$  intermetallic compound. The diffusion distance of liquid into base materials increase and the shear strength of joints increases and then decreases with brazing parameters. When the brazing temperature is 620 °C, the holding time is 10 min and the bonding pressure is 1 MPa, the shear strength of the joints is up to the maximum value of 69 MPa.

**Key words:** SiC particle reinforced aluminum matrix; diffusion brazing; interface structure; shear strength

**Porosity defects of 2219 aluminum alloy intersection weld by FSW and VPPAW**

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**Abstract:** FSW-VPPA intersection weld on 2219 aluminum of 6 mm in thickness was perpendicularly conducted by friction stir welding (FSW) and variable polarity plasma arc (VPPA) welding and it is found that there are porosity defects in cross-connectors. Therefore, porosity defects of 2219 aluminum alloy intersection weld by FSW and VPPA were analyzed to determine the type of porosities. The effects of welding parameters such as FSW heat input and VPPA welding speed on the porosity defects were compared and analyzed. The results show that the degree of porosity defects of cross-weld joint decreases with the FSW heat input being increased, which is due to the transient cavity formed in the FSW process. However, the degree of porosity defects of cross-joint increases with VPPA welding speed being increased. In order to reduce the degree of porosity defects of cross-joint, some measures had been taken, such as insert gas shielding, increase of the FSW heat input and reduction of VPPA welding speed appropriately.

**Key words:** FSW; VPPA; cross-weld joint; porosity defect

**Microstructure and mechanical properties of TIG welded-brazed joint of pre-coating titanium and aluminum alloy**

CUI Qinglong (Engineering Research Center of Extreme Precision Optics, Fine Mechanics and Physics, Changchun Institute of Optics, Chinese Academy of Sciences, Changchun 130033, China). pp 125-128

**Abstract:** The titanium alloy plate was hot-dipped pure aluminum coating by the position of groove, then the pre-coating titanium alloy was joined to aluminum alloy by TIG welding-brazing. Comparison was made between the uncoated and coated joint to analyze interfacial structure and the strength of weld seam. The test results showed that, the same component  $TiAl_3$  formed under two kinds of interface conditions. There is a interface reaction layer with the thickness of 4 ~ 6  $\mu m$  in the non-coating joint, and the average tensile strength of the joint is 118 MPa, brittle fracture is the main fracture mode in tensile test. And the pre-coating joint has the interface reaction layer with the thickness of 2  $\mu m$ , the average tensile strength of the joint is 205 MPa, and the fracture mode is ductile fracture. The introduction of coating can make the intermetallic compound layer thinner and the fracture mode be changed.

**Key words:** hot-dipping; dissimilar alloys; TIG welding-brazing; fracture mechanism