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电子束焊—钎焊复合焊 T 形接头组织性能分析

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摘 要：实现了 TA15 钛合金 T 形接头的电子束焊—钎焊复合焊接。采用扫描电镜、能谱分析仪和 X 射线衍射分析仪等测试手段，对接头的微观组织形貌、元素成分分布和界面反应产物等进行分析研究。并分别对复合焊接头和电子束焊接头的弯曲性能进行了比较分析。结果表明，在适当的工艺条件下，可以实现 TA15 钛合金 T 形接头的电子束—钎焊复合焊接。在电子束焊缝和钎焊缝的界面处存在 Cu，Ni 元素的扩散和界面反应。复合焊接头的塑性要优于电子束焊，其所承受的最大压强略低于电子束焊。

关键词：电子束焊—钎焊复合焊；T 形接头；微观组织；弯曲性能

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0 序 言

在飞机制造加工中，有部分钛合金构件存在 T 形接头的结构形式，对于这种结构形式国内外多采用焊接技术进行拼焊，同整体数控加工相比，具有加工成本低、周期短、生产效率较高、材料利用率高等优点[1]。随着焊接技术的不断发展，俄罗斯、乌克兰及美国等国相继开展了电子束焊接钛合金 T 形接头技术的研究。但目前最新的研究方向是利用真空电子束焊与钎焊复合焊接技术焊接钛合金 T 形接头[2]。其基本原理是电子束焊接前在平板与筋板之间，焊前安装适量钎料，利用电子束焊接时产生的热量对钎料进行加热，使其熔化、润湿、填充接头间隙并形成加强圆角。这是一种新型、先进的焊接技术，目前欧美发达国家已成功地应用到飞机壁板的制造中[3,4]。

国内对于钛合金 T 形接头真空电子束焊与钎焊复合焊接技术的研究尚属于关注阶段。作者针对 TA15 钛合金 T 形接头真空电子束焊与钎焊复合焊接技术进行了试验研究。采用扫描电镜、能谱分析和 X 射线衍射等测试手段对复合焊接头的微观组织形貌及界面反应产物进行了观察及分析，并对复合焊接头与电子束焊接头的弯曲性能进行了比较分析，为该技术的工程化应用提供了一定的试验数据及理论研究基础。

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1 试验方法及条件

1.1 试验材料

所用钎料为粉状钛基钎料，其主要成分见表 1。试验所用的钛合金为 TA15，其主要合金元素组成见表 2，平板尺寸为 350 mm×50 mm×2.5 mm，筋板尺寸为 300 mm×25 mm×1.5 mm。

表 1 钛基钎料的主要组成(质量分数，%)
Table 1 Chemical composition of Ti—based brazing filler metal

元素	Ti	Cu	Ni	Zr	Al
含量	45～46	34～35	10～11	6～7	1～1.5

1.2 焊接

将 TA15 钛合金平板与筋板待焊表面，用机械打磨的方法去除表面氧化层，将待钎焊表面用 400 号砂纸沿一定方向打磨，打磨后的试板用酒精清洗后吹干。

焊接在 ZD150—15B 高压型电子束焊机上进行。电子束焊—钎焊复合焊试板及钎料采用专用工装装夹。

1.3 测试

复合焊接头试样经机械研磨和抛光后，用近 α

表 2 TA15 钛合金的主要组成(质量分数, %)

Table 2 Chemical composition of TA15 titanium alloy

合金元素					杂质(不大于)						
Al	Zr	Mo	V	Ti	Fe	Si	C	N	H	O	余量
5.5~7.0	1.5~2.5	0.5~2.0	0.8~2.5	余量	0.25	0.15	0.10	0.05	0.015	0.15	0.30

型钛合金腐蚀液腐蚀。用日立 S—3500N 型扫描电镜和牛津 INCA 能谱分析仪对试样进行了微观组织观察,对元素的成分分布进行了能谱分析,用 BRUKER D—8 型 X 射线衍射仪对界面反应产物进行了测试分析。弯曲性能测试在 RSA250(德国)250 kN 电子万能试验机上进行。弯曲试样尺寸及受力示意图如图 1 所示。

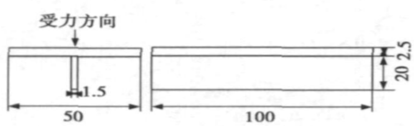


图 1 弯曲试样尺寸及受力方向示意图(mm)

Fig. 1 Sketch map of dimension and direction of force of sample

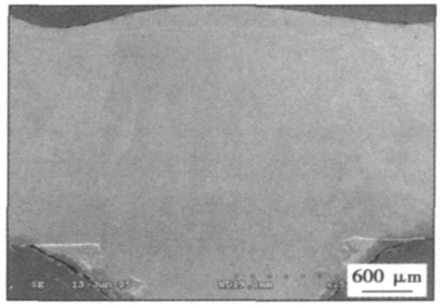
2 试验结果及分析

2.1 复合焊接头的 SEM 分析

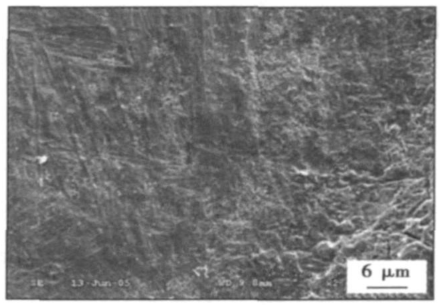
图2 是 TA15 钛合金复合焊接接头的 SEM 图像。图2a 为复合焊接头全貌照片,由图可看出,电子束焊熔穿平板,钉扎在筋板上,在直角处的电子束焊缝表面不平整,有许多凹陷及褶皱。而在钎焊过程中,由于钎料的毛细作用及其对被钎焊表面的润湿和铺展,填充了这些表面缺陷,使得平板与筋板间形成了光滑的圆角过渡,从而改善了 T 形接头的电子束焊缝成形。图 2b 为电子束焊缝与钎焊缝过渡区组织形貌,图中从左到右,电子束焊缝的针状组织逐步过渡到钎焊的不规则组织。

2.2 复合焊接头的能谱分析

图3 是复合焊接头的电子束焊缝和钎焊缝过渡区面扫描图像,图中深色区域代表元素分布处。图3a显示了面扫描区域,在图 3b, c 中,由于电子束焊缝中不含 Cu, Ni 元素,所以可很明确判断出钎缝中的 Cu, Ni 元素向电子束焊缝中扩散。此外,由于电子束焊缝及钎焊缝中均含有 Ti, Zr 元素,而且在电子束焊缝中 Ti 元素含量比钎焊缝多, Zr 元素含量



(a) 复合焊接头全貌



(b) 钎焊与电子束焊过渡区组织形貌

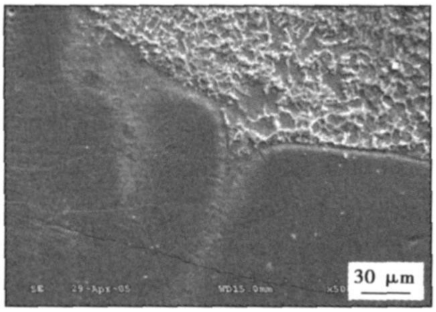
图 2 复合焊接头的 SEM 图像

Fig. 2 SEM micrograph of joint by hybrid electron beam welding with brazing

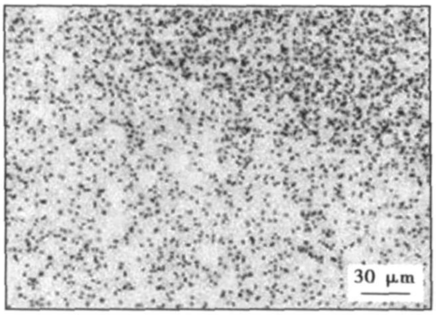
比钎焊缝少,这与图 3d, e 中各元素分布相符合,且分布均匀,所以无法判断出是否存在 Ti, Zr 元素在电子束焊缝与钎焊缝之间的扩散。

2.3 复合焊接头的 X 射线衍射分析

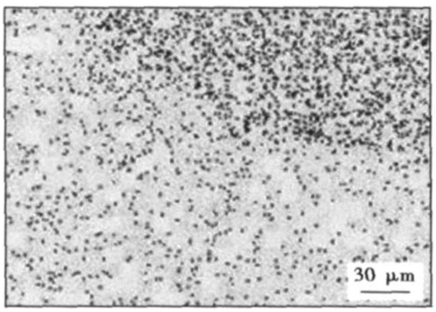
图 4 为电子束焊缝区、钎焊缝区及复合焊缝横断面的X 射线衍射分析图谱,图中 d 为晶面间距。根据图 4a 的衍射图谱可判断,电子束焊缝区组织为 α 相和 β 相的两相组织。由图4b 的衍射图谱可分析认为,钎缝区组织为 α 相和 β 相,以及少量的具有体心四方结构的 Al_2Ti, Ti_3Cu。从图 4d 的衍射图谱中排除图 4a, b 中已知衍射峰之外,还可见明显的未知衍射峰。说明在复合焊缝的界面发生了界面反应,界面有新相生成,是由 Al, V, Ti 形成的具有体心四方结构的复杂化合物 $Al_3V_{0.333}Ti_{0.666}$以及由 Ti, Ni, Cu 形成的具有单斜点阵结构的复杂化合物 $TiNi_{0.8}Cu_{0.2}$。



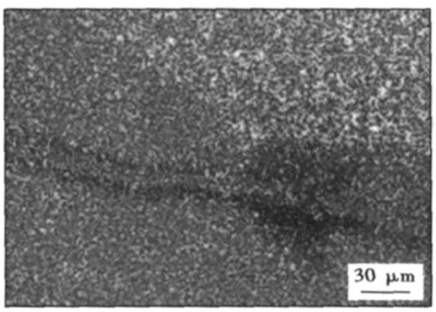
(a) 复合焊接头组织形貌



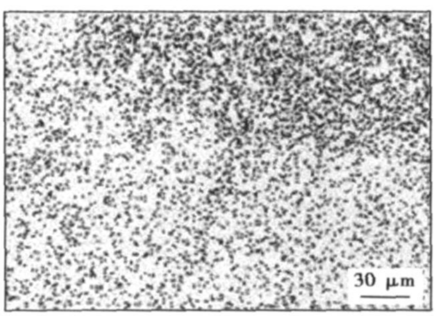
(b) 铜元素



(c) 镍元素



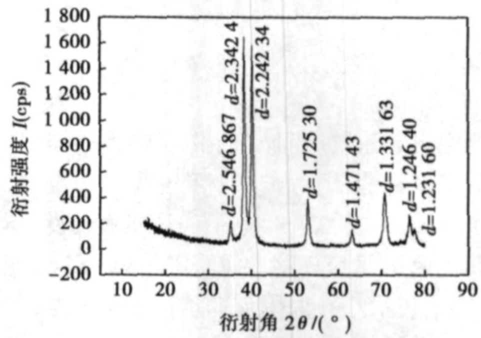
(d) 钛元素



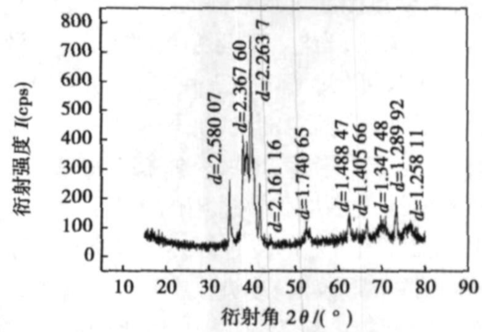
(e) 锆元素

图 3　复合焊接头的面扫描图像

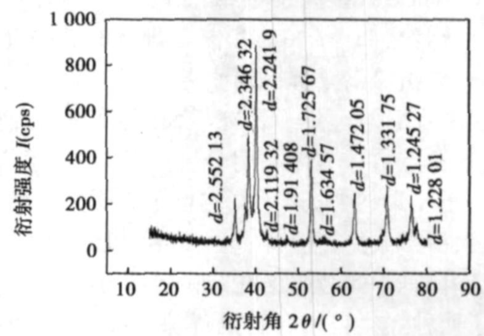
Fig. 3　Scaning micrograph of joint by hybrid electron beam welding with brazing



(a) 电子束焊缝区



(b) 钎焊缝区



(c) 复合焊缝横断面

图 4　不同区域的 X 射线衍射分析图谱

Fig. 4　XRD spectrum of diffrent sections

2.4　复合焊与电子束焊弯曲性能比较分析

复合焊与电子束焊弯曲性能试验结果如表 3 所示。从表中可明显看出，复合焊接头的弯曲角比电子束焊接头小，说明复合焊接头的塑性要优于电子束焊。从试件所受最大压强来看，复合焊所承受的压强略低于电子束焊，为后者的 92%左右。

表 3　弯曲试验结果

Table 3　Result of bending test

焊接方法	支点跨距 d/mm	最大压强 p/MPa	断裂时的位移 H/mm	断裂时的弯角 θ/(°)	卸载后的弯角 θ'/(°)
电子束焊	50	29.7	5.49	155.26	157.0
复合焊	50	27.2	6.43	150.57	152.97

3 讨 论

真空电子束焊—钎焊的复合焊接过程，是集电子束焊接和钎焊于一体的焊接过程。一方面，当高速电子束撞到工件表面，电子的动能就转变为热能，使金属迅速熔化和蒸发。随着电子束与工件相对运动，液态金属沿小孔周围流向熔池后部逐渐冷却，凝固形成了电子束焊缝。另一方面，在电子束焊接过程中，有部分热能通过热传导的作用，使电子束焊缝周边的金属加热，当温度高于钎料的熔点时，液态钎料发生润湿及铺展，填充接头间隙，并与周边的金属相互扩散而实现连接。当单独采用电子束焊接T形接头时，容易产生未熔合的缝隙，接头强度差，且具有缺口和腐蚀敏感性。在适当的工艺条件下，采用真空电子束焊—钎焊的复合焊接可以避免上述的缺陷，获得焊缝成形较好、接头强度较高的T形接头。

在复合焊接的钎焊过程中，熔化的钎料在填隙过程中与周边的金属发生相互作用。一方面，钎料中的部分元素如Cu，Ni向电子束焊缝的晶粒边界扩散，这一点由能谱分析得到证实。另一方面，在钎缝与电子束焊缝的边界上存在界面反应，并有化合物生成，这一点由X射线衍射分析获得。

对于T形接头，采用真空电子束焊—钎焊的复合焊接，所形成的复合焊缝强度主要是靠电子束焊缝保证，而钎焊焊缝起到补充和增强的作用，充分的发挥了两种焊接技术各自的优势。并且，由于在复合焊接时不必采用散焦方式，故电子束焊缝窄、焊接变形小、工艺难度降低、焊接效率提高。复合焊接接头可以在焊缝成形、减小变形等诸多方面改善单独电子束焊接T形接头的性能。

4 结 论

（1）在适当的工艺条件下，可以实现TA15钛合金T形接头的电子束焊—钎焊复合焊接。

（2）在电子束焊缝和钎焊缝的界面处存在Cu，Ni元素的扩散和界面反应。

（3）根据三点弯曲性能试验可知，复合焊接头的塑性要优于电子束焊，其所承受的最大压强略低于电子束焊。

（4）TA15钛合金T形接头复合焊接头的微观组织及弯曲性能试验分析为电子束焊—钎焊复合焊的实际应用提供了一定的试验依据。但是，在电子束焊—钎焊复合焊的工程化应用方面仍需进一步的研究和工作。

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taken to reconstruct the three dimension shape of welding pool. Welding reflection map was established and was solved by using linear approximation, from which the depth iteration equation was obtained. It then presented the improved measure for this algorithm based on Kalman filter. Finally, the experiment validate that this algorithm is fast and effective.

Key words: shape from shading; pulsed gas tungsten arc welding; three dimension model of pool

Constricting arc characteristic with flux strips ZHENG Shaoxian, ZHU Liang, ZHANG Xulei, CHEN Jianhong (State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China). p57—61

Abstract: Because constricted arc has many merits, such as high energy density and high velocity of plasma, it is applied in many welding fields. The characteristics of constricting arc with flux strips was studied by sending two pieces of flux strips into arc along both sides of the arc. The results show that flux strips are melted by heating of arc column under a stable welding condition, and certain action length of flux strips that act on the arc are formed on both sides of the arc, and the length will increase with the decrease of voltage and the increase of velocity of feeding flux strips. Action length can directly influence on the morphology of constricting arc with flux strips, and with action length increase, arc width will shorten and arc length will elongate, as a result the welds become deep and narrow; when the distance from the center of the arc to the flux strip is reduced, arc width will distinctly become narrow, and weld depth will become deep and weld width will become narrow; ultra-narrow gap welding can be achieved by use of the characteristics of constricting arc with flux strips.

Key words: constricting arc with flux strips; arc characteristic; ultra-narrow gap welding

Safety assessment of surface pit in penstock XU Zunping[1], CHENG Nanpu[1], LEI Binlong[2], CHEN Zhiqian[1] (1. Schoole of Materials Science and Engineering, Southwest University, Chongqing 400715, China; 2. Institute of Applied Engineering, Southwest Jiaotong University, Chengdu 610031, China). p62—64

Abstract: Based on the calculated results of finite element analysis and given the pit size, the criterion of safety assessment for in-service pressure vessels containing defects suggested by China was applied to assess the surface pit in penstock. The assessment wes carried out according to the CTOD (crack tip opeaning displacement) test result. Different assessment methods were used according to the pit distribution. The assessment results indicated that the assessment points are located within the safe region defined on the failure assessment diagrams. So the surface pit can be accepted.

Key words: penstock; pit; failure assessment diagram; safe assessment

Corrosion behavior of Q235 steel joint welded by different methots in the ammonium sulfite LEI Ali, FENG Lajun, ZHANG Min, ZHANG Shengchao (School of Materials Science and Engineering, Xi' an University of Technology, Xi' an 710048, China). p65—68

Abstract: In order to solve the serious corrosion of carbon steel welded joint in the ammonium sulfite during papermaking process, the corrosion behavior of the carbon steel welded joints, adopting shielded metal arc welding with J422 electrode, TIG welding and CO_2 gas shielded arc welding, has been studied by three electrode electrochemical test and metallurgical structure analyses. The results show that the polarization curve of the Q235 steel joint welded by CO_2 gas shielded welding process in the 5%—11% ammonium sulfite at 20—80 ℃ is quite similar to the one of the base alloy, i. e. the two curves is close to each other, which means this kind of joint has the best corrosion resistance. The microstructure of Q235 steel joint welded by CO_2 gas shielded welding shows that the welded joint structure is consisted of massive amounts of pearlite and acicular ferrite, in which the fine perlites are dispersed in the ferrite.

Key words: galvano-chemistry; ammonium sulfite; welded joint; weld corrosion

Microstructure and properties of T joint by EBW-brazing hybrid welding LIU Xin, TAN Zhenyun, MAO Zhiyong (Key Laboratory of High Energy Density Beam Processing Technology, Bejjing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). p69—72

Abstract: TA15 titanium alloy T joint obtained by EBW (electron beam welding)-brazing hybrid welding was investigated. The microstructure, element distribution and interfacial reaction were studied by means of scanning electron microscope, energy dispersive spectvoscope and X-ray diffraction. The bending properties of the joints both by hybrid electron beam welding with brazing and by electron beam welding were tested. The results showed that TA15 titanium alloy T joint was acquired by EBW-brazing hybrid welding with proper parameter. Element diffusion and interfacial reaction exist in the interface of electron beam welding and brazing. The plastic properties of the joint acquired by hybrid electron beam welding with brazing preceded the one only by electron beam welding. But the maximum intensity of pressure endured by the former is slightly lower than the later.

Key words: electron beam welding-brazing hybrid welding; T joint; microstructure; bending properties

Modeling and analysis of droplet forming in gas metal arc welding short circuiting transfer WANG Guangwei, CAI Yan, HUA Xueming, WU Yixiong (Laser Processing Laboratory, Shanghai Jiaotong University, Shanghai 200240, China). p73—76

Abstract: The conception and modeling of droplet forming in gas metal arc welding short circuiting transfer was proposed. By virtue of Micro Focus High Speed Photography technique and digital image processing technique, the gravitation, electromagnetic force and the maintaining force rooted in the surface tension of the little guttate metal in droplet forming process were analyzed and calculated