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旋转频率对镁/铝异种金属填充式摩擦点焊接头组织及力学性能的影响

郭立杰[1]，　封小松[1]，　苗玉刚[2]，　韩端锋[2]
(1. 上海航天设备制造总厂，上海　200245; 2. 哈尔滨工程大学 船舶工程学院，哈尔滨　150001)

摘　要: 以 AZ31 镁合金和 5A06 铝合金为研究对象，采用填充式摩擦点焊技术实现了镁/铝异种金属的有效连接，测试了不同旋转频率下摩擦点焊接头的剪切力，并观察和分析了旋转频率对焊点形貌、界面组织以及元素分布的影响规律. 结果表明，随着焊接工具旋转频率的增加，焊点的剪切力先增加后减小，且在 2 400 r/min 附近有最高的剪切力，约为 1.9 kN. 当旋转频率较低时，镁/铝之间界面反应不充分，无明显的界面层组织，甚至存在“未焊合”区. 当旋转频率较高时，镁/铝间形成的界面层较厚(约 5 μm)，界面组织明显，界面结合良好.
关键词: 填充式摩擦点焊; 异种金属; 旋转频率; 界面层; 力学性能
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郭立杰

0　序　　言

由于具有熔点低、密度小、比强度高等特点，铝合金、镁合金被广泛应用在汽车、航空航天等工业制造中[1,2]. 随着铝合金、镁合金的广泛使用，在实际应用中经常会涉及到镁合金与铝合金的连接问题. 但是由于 Mg 元素和 Al 元素均属较活泼元素，且熔点较低，采用传统熔焊方法焊接时，焊缝中极易形成脆性的 Mg-Al 金属间化合物，常出现裂纹、气孔、元素烧损等问题[3-5]，故采用熔焊方法难以获得良好的 Mg/Al 焊接接头.

摩擦点焊技术是在搅拌摩擦焊技术的基础上发展而来的，与搅拌摩擦焊一样，都属于固相连接. 其中填充式摩擦点焊技术由德国 GKSS 研究中心发明[6]，由于解决了焊点表面的搅拌针退出孔问题而受到广泛关注. 目前铝合金、镁合金、异种金属及金属/非金属复合结构的摩擦点焊技术研究已有一些研究结果[7,8]，但针对镁/铝异种金属填充式摩擦点焊工艺机理方面尚未见到系统研究报道.

文中以中国航天领域广泛使用的 5A06 铝合金和 AZ31 镁合金为研究对象，系统分析了搅拌工具旋转频率对镁/铝异种金属焊点的接头形貌、力学性能、界面组织以及元素分布的影响规律.

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1　试验方法

试验采用厚度均为 1.5 mm 的 5A06 铝合金和 AZ31 镁合金板材进行搭接点焊，二者的化学成分如表 1 所示. 焊接前使用化学清洗和丙酮擦拭方法除去材料表面的油污和氧化膜.

表 1　5A06 和 AZ31 的化学成分(质量分数,%)
Table 1　Chemical compositions of 5A06 and AZ31

	Al	Zn	Mn	Si	Mg
5A06	余量	0.2	0.5~0.8	0.4	5.8~6.8
AZ31	2.5~3.5	0.5~1.5	0.2~0.5	≤0.1	余量

图 1 为镁/铝异种金属填充式摩擦点焊技术示意图. 可以看出该方法由分离的内套环、中心轴和压紧套组成. 焊接时压紧套始终在工件表面压紧和拘束材料，而中心轴和内套环在保持高速旋转的同时可进行轴向运动，通过内套环下压摩擦连接界面，然后中心轴下压将材料回填至内套环回抽留下的空腔，最终形成表面平整的焊点. 文中采用德国 Riftec 公司的标准填充型摩擦点焊设备(设备型号 RPS100)，采用的焊接工具内套环直径为 9 mm、中心轴直径为 5.2 mm.

焊后制作金相试样和剪切试件，采用金相显微镜、Quanta200 扫描电镜(SEM)观察点焊接头形貌和微观组织特征，并利用能谱分析仪(EDS)分析界

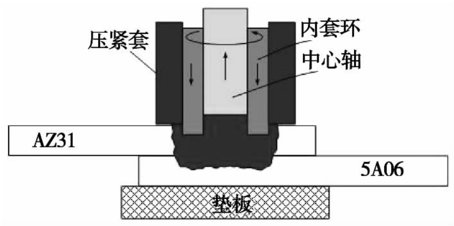


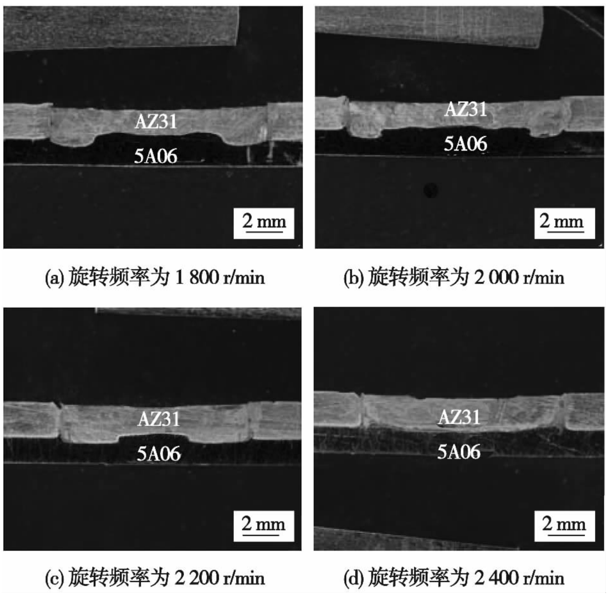
图1 镁/铝异种金属填充式摩擦点焊技术示意图
Fig. 1 Sketch for refill friction spot welded Mg/Al

面元素分布,在 CSS-44300 电子万能拉伸试验机上进行接头剪切试验.

2 试验结果及分析

2.1 旋转频率对接头形貌的影响

为了定量考核焊接工艺对镁/铝异种金属摩擦点焊过程的影响,在保持其它工艺参数不变的条件下,研究了工具旋转频率对镁/铝点焊接头组织及力学性能的影响规律,其余工艺参数为焊接时间 1.5 s,内套环下压量 1.5 mm,搅拌头整体压入量 0.05 mm. 图2 为不同工具旋转频率时,镁/铝异种金属填充式摩擦点焊的接头形貌.



(a) 旋转频率为 1 800 r/min (b) 旋转频率为 2 000 r/min (c) 旋转频率为 2 200 r/min (d) 旋转频率为 2 400 r/min

图2 不同工具旋转频率时接头形貌
Fig. 2 Cross-section of different tool rotation frequencies

由图2 可以看出随着搅拌工具旋转频率逐渐增大,内套环对底面边界的影响也逐渐扩大,焊核与铝合金母材的水平分界线由原来的阶梯状界面逐渐转变为平直形、甚至下凹形界面. 同时焊核与镁合金母材之间的垂直分界线也逐渐变得弯曲且平滑. 分析认为,填充式搅拌摩擦点焊的过程中一个非常重要的特征是中心轴和内套环在焊缝垂直方向上的相对运动,使塑性材料沿焊缝垂直方向相互搅拌、混合,焊缝区塑性材料承受巨大的顶锻压力,当中心轴和内套环停止运动与旋转后,仍然会在焊缝区施加一个顶锻压力. 在填充式摩擦点焊过程中,随着旋转频率的增加,单位时间内作用在材料上的热量(热输入)逐渐增加,使母材发生塑性流动的区域逐渐增加,在内套环与中心轴的顶锻压力作用下,焊核与铝母材之间的阶梯状水平分界线逐渐变得平直甚至下凹. 此外由于内套环侧面与被搭接板材摩擦产热,使其附近材料达到塑性状态,且呈塑性状态的材料在中心轴与内套环旋转作用下在水平方向上具有一定的旋转频率,导致焊核与镁合金母材之间的垂直分界线逐渐弯曲.

2.2 旋转频率对接头力学性能的影响

在保持其它工艺参数不变的条件下,研究了工具旋转频率对点焊接头力学性能的影响规律,进而探索接头形貌与接头力学性能之间的关系. 图3 为焊接旋转频率与焊点力学性能之间的关系.

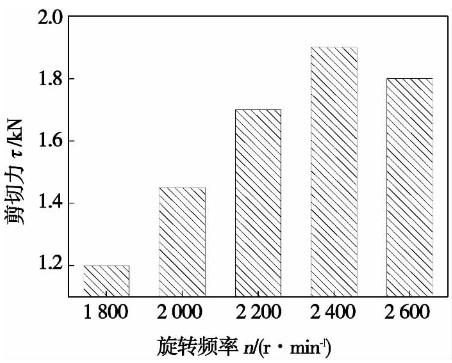


图3 焊接工具旋转频率对焊点力学性能的影响
Fig. 3 Mechanical properties of different tool rotation frequencies

从图3 可以看出,随着焊接工具旋转频率的增加,焊点的抗剪力先增加后减小,且在 2 400 r/min 附近有最高的剪切力,约为 1.9 kN. 此后随着焊接工具旋转的增加,剪切力出现下降. 分析认为,工具旋转频率的增加,在一定程度上会增加焊接热输入,使得焊接区域的材料塑性流动性变好,此时焊点搭接界面容易获得良好的摩擦搅拌作用与再结晶温度,可获得细小、均匀的微观组织以及良好的下凸形界面结合,接头的力学性能较好; 但当工具旋转频率增加到一定程度时,在界面处形成的 Mg-Al 金属间化合物层的厚度必然增加,不利于接头力学性能的提高. 因此合适的旋转频率是保证焊点抗剪切能力

的关键.

2.3　旋转频率对接头界面组织的影响

图 4 为旋转频率较低时点焊接头界面的结合形貌. 可见当旋转频率较低时，焊核与镁合金母材间竖直界面的结合情况较差，存在少量的孔洞、微裂纹等缺陷，见图 4a. 在焊核与铝母材之间的水平界面处（图 4b），形成的界面层很薄，未见明显的界面层组织，且界面处易出现“未焊合”、夹杂等缺陷. 这可能是因为在旋转频率较低（热输入低）时，材料的塑性流动较差，当材料回填至内套环回抽留下的空腔时，回填的材料在界面上与母材无物质交换、无重复的流动搅拌作用加上温度较低，氧化膜、杂质得不到有效破除和弥散化，在界面处易出现孔洞、“未焊合”、夹杂等焊接缺陷.

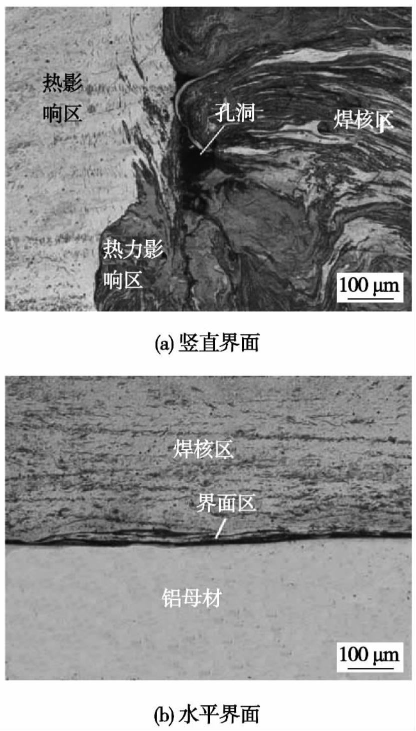


图 4　旋转频率为 2 000 r/min 时界面结合形貌

Fig. 4　Interface bonding with 2 000 r/min rotation frequencies

图 5 为旋转频率较高时点焊接头界面的结合形貌. 从图 5a 可知，当焊接工具旋转频率较高时，焊核与镁母材之间的竖直界面结合良好，未发现孔洞、微裂纹等现象. 这是因为随着工具旋转频率（热输入）的增加，使母材发生塑性流动的区域逐渐增大，有利于界面的良好结合和夹杂物的排出. 此外由于填充式搅拌摩擦点焊焊接时间短、焊接热输入小，可以有效降低焊接热输入过大对接头性能产生的影响，且填充式搅拌摩擦点焊焊缝组织细密，与母材基本可以实现平滑过渡，有效地保证了接头的连接性能.

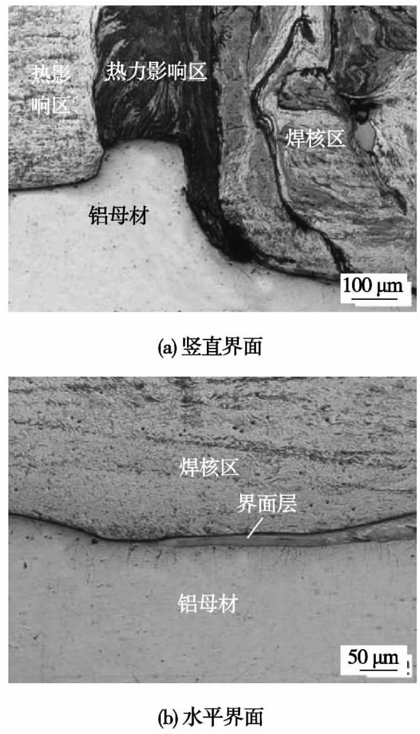


图 5　旋转频率为 2 600 r/min 时界面结合形貌

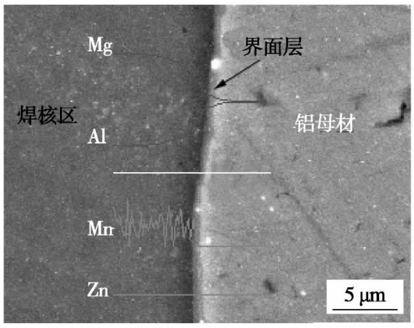
Fig. 5　Interface bonding with 2 600 r/min rotation frequencies

从图 5b 可见，在焊核区与铝母材之间的水平界面处存在明显的界面层组织，且界面结合良好，未见明显的焊接缺陷，但界面层厚度不均匀. 分析认为，该界面层组织的形成可能与此处焊接工具对材料的剧烈摩擦和顶锻作用有关. 由于搅拌工具旋转频率很高（热输入大），可能引起过渡区域的温度达到了镁/铝共晶反应温度，易生成镁/铝金属间化合物，相关研究另有文献专述.

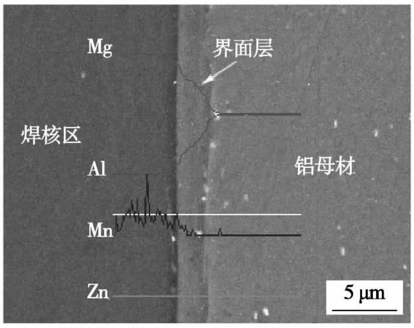
2.4　旋转频率对界面元素分布的影响

图 6 为不同旋转频率时镁/铝界面处的元素线分布测量结果. 可见 Al，Mg 元素在界面处有一个明显的渐变过程，这是搅拌摩擦点焊时 Al，Fe 两种元素向对方基体扩散的结果；Mn 元素富集在镁侧焊核区，这可能是 Mn 原子在镁合金中的扩散系数较小造成的.

从图 6a 还可以看出，当旋转频率为 1 800 r/min 时，Mg/Al 间形成的界面层很薄，这主要是低旋转频率（低热输入）时 Mg/Al 界面处温度较低所致，此位置易引起界面反应不充分，从而导致界面结合薄弱，甚至存在“未焊合”区，成为接头断裂的起源. 在旋转频率为 2 400 r/min 时，镁/铝之间形成的界面层



(a) 1 800 r/min



(b) 2 400 r/min

图6 不同旋转频率时界面元素线分布

Fig. 6 Element distributions of different rotation frequencies

较厚(约5 μm),见图6b. 这是因为在高旋转频率(大热输入)时,界面处温度较高,界面反应充分,形成的金属间化合物层较厚. 因此对于Mg/Al异种金属连接,界面金属间化合物的厚度需要控制在一定的范围,过厚的化合物层容易自身断裂,而化合物层过薄会造成结合不良.

3 结 论

(1) 随着搅拌工具旋转频率逐渐增大,焊接区域的塑性流动变好,在内套环与中心轴的顶锻压力作用下,焊核与铝母材之间的阶梯状水平分界线逐渐变得平直甚至下凹. 同时由于内套环附近材料塑性流动性的增大,导致焊核与镁合金母材之间的垂直分界线逐渐变得弯曲且平滑.

(2) 随工具旋转频率增加,焊接热输入增大,母材发生塑性流动的区域逐渐增大,有利于界面的良好结合和夹杂物的排出,使得焊点的剪切力增大,但当工具旋转频率过大时,镁/铝界面处的金属间化合层过厚,不利于接头承载能力的提高. 因此合适的旋转频率是保证焊点抗剪能力的关键.

(3) 当旋转频率较低(如1 800 r/min)时,焊接区域的温度较低,Mg/Al之间的界面反应不充分,未见明显的界面层组织,且存在"未焊合"区. 当旋转频率较高(如2 400 r/min)时,Mg/Al界面处的温度较高,形成的界面层组织较厚,界面处结合良好.

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作者简介: 郭立杰,男,1961年出生,硕士,研究员. 主要从事航天飞行器铝合金结构制造工艺及技术管理工作. 发表论文10余篇. Email: guolijie149@yahoo.com.cn

通讯作者: 苗玉刚,男,博士,副教授. Email: miaoyg@hrbeu.edu.cn

MAIN TOPICS, ABSTRACTS & KEY WORDS

Welding deformation of top beam structure in hydraulic support by CO_2 double-wire gas shield welding based on inherent strain method FANG Chenfu, WU Wenlie, LIU Chuan, ZHONG Xulang (Provincial Key Laboratory of Advanced Welding Technology, Jiangsu University of Science and Technology, Zhenjiang 212003, China). pp 1 – 4

Abstract: The welding experiment on 30 mm thick Q690 steel plate in full-scale top beam structure of hydraulic support was carried out. The welding deformation of a relatively small structure selected from the top beam structure was firstly simulated with the thermal-elastic-plastic finite element method based on the efficient heat source model, and then the inherent strain was obtained from the small model, finally the acquired inherent strain was input into the full-scale shell element model of the hydraulic beam support structure to calculate the welding distortion deformation. The results show that, the proposed method can predict the welding deformations of large structures efficiently and accurately, the computational welding deformations of the top beam structure agree well with the experimental results; the angular distortion deformation is the main deformation of the top beam structure, which is not uniform on both sides.

Key words: hydraulic support; finite element method; inherent strain; numerical simulation; welding deformation

Analysis of 3D reconstruction algorithm of laser welding molten pool image GAO Xiangdong, YANG Yongchen, ZHANG Yanxi (School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China). pp 5 – 8

Abstract: The molten pool in high-power disk laser welding is related to the welding quality. The welding molten pool images were captured by a laser welding monitoring system. In order to reconstruct 3D shapes of the welding molten pools and further analyze the relationship between the shape features such as weld bead height, weld bead width and the welding quality, the shape from shading (SFS) technology based on single welding molten pool image was researched. 3D molten pool shapes could be recovered by the gray variations of welding molten pool image. The experimental apparatus included an auxiliary diode illuminant and a high-speed camera with near infrared filter to capture the welding molten pools in real time. The slant and tilt of illuminant source were estimated by the statistical algorithm. The 3D shape of welding molten pool surface was reconstructed by using the localization method of SFS. Also, the methods of median filter and cubic spline interpolation were applied to remove the noise and smooth the shape of molten pool. Experimental results showed that the proposed method can reconstruct the welding molten pool surface effectively. The 3D molten pool shape can be estimated by the molten pool image during high-power disk laser welding.

Key words: high-power disk laser welding; welding molten pool; 3D reconstruction

Effect of rotation frequency on microstructure and mechanical properties of refill friction spot welded Mg/Al dissimilar metals GUO Lijie[1], FENG Xiaosong[1], MIAO Yugang[2], HAN Duanfeng[2] (1. Shanghai Aerospace Equipments Manufacturer, Shanghai 200245, China; 2. College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China). pp 9 – 12

Abstract: AZ31 Mg alloy and 5A06 Al alloy were welded successfully with refill friction spot welding process. The shear stress of the spot joint with different tool rotation frequencies was tested. The effect of rotation frequency on the cross-section, interface layer and element distribution was analyzed. With the increase of the tool rotation speed, the shear stress of the joints increases firstly and then decreases. In particular, when the rotation speed is 2 400 r/min, the average shear stress can reach a maximum of 1.9 kN. When the rotation frequency is lower, the interface layer of Mg/Al is thiner. Due to the insufficient interface reaction, the phenomenon of incomplete fusion appears. If the rotation frequency is higher, the interface layer of Mg/Al is thicker (about 5 μm). The interface bonding is very good.

Key words: refill friction spot welding; dissimilar metals; rotation frequency; interface layer; mechanical properties

Formability and microstructure of magnesium alloy welded by A-TIG under magnetic field SU Yunhai[1,2], LIN Jinliang[1], JIANG Huanwen[1], LIU Zhengjun[1] (1. Liaoning Provincal Key Laboratory of Advaced Welding Technology and Automation, Shenyang Unviersity of Technology, Shenyang 110870, China; 2. Chinese National Engineering Research Center, Liaoning Julong Financial Equipment Corp., Anshan 114041, China). pp 13 – 16

Abstract: The AZ31B magnesium alloy plates of 5 mm in thickness were welded by A-TIG welding under longitudinal magnetic field. The mixed oxides were used as activating fluxes. The form factor, microstructure and mechanical properties of welded joint at different magnetic field parameters were tested. The effects of magnetic field parameters on A-TIG welding process of magnesium alloy were also investigated. The results show that the formability and microstructure of magnesium alloy welded joint can be improved due to the magnetic field. When the magnetic frequency is 10Hz and the magnetic current is 2 A, the form factor and properties of welded joint are tested, the form factor is 2.304 and the hardness is 980.98 MPa. The flow of molten pool will be changed by the activating fluxes and electromagnetic (which forming by magnetic field). The liquid metal in molten pool will move from all around to center, which makes the weld be deeper, refines the microstructure and improves the properties