

钢/铝异种金属激光胶接焊

戴 婷, 刘金水, 周怙武, 彭 艳

(湖南大学 汽车车身先进设计制造国家重点实验室, 长沙 410082)

摘 要: 采用光纤激光器对 1.4 mm 厚的 DC56D + ZF 镀锌钢和 1.2 mm 厚的 6016 铝合金平板试件进行了加入胶层的激光搭接焊试验, 分析了焊接接头的微观组织、断口形貌和力学性能, 研究了不同工艺参数对钢/铝胶接正面与横截面焊缝形貌的影响。结果表明, 在激光功率为 1 650 W, 焊接速度 35 mm/s, 离焦量 +3.0 mm, 氩气为保护气体且流量为 20 L/min 的最佳工艺条件下, 加入胶层, 焊接试样正面焊缝均匀连续, 无气孔、裂纹缺陷, 钢/铝连接良好; 焊接接头抗剪强度与平均剪切力分别为 41.45 MPa 和 1.04 kN, 力学性能并没有因为胶层的加入而减弱, 焊缝区断裂形貌为韧性断裂与准解理断裂的混合形貌。

关键词: 钢/铝异种金属; 激光焊; 胶层; 焊缝形貌

中图分类号: TG495 **文献标识码:** A **文章编号:** 0253-360X(2013)04-0011-04



戴 婷

0 序 言

随着现代交通运输工具轻量化战略的实施, 钢/铝复合结构件发挥两种材料性能优势、减轻重量, 在汽车、高速列车、船舶等行业有良好应用前景, 然而异种金属的优质高效连接是制约钢/铝复合结构件在工程中推广应用的重大技术瓶颈^[1-2]。实现钢/铝连接的方法主要有粘接、机械连接和焊接。粘接得到连接接头的力学性能有限, 只能在一些性能要求较低的场合应用。机械连接虽然得到较高性能的连接接头, 但接头的气密性无法保证且接头质量大。激光焊用激光束作焊接热源, 具有能量密度高、热输入量小、热量集中、热源易控制、焊缝深宽比大、热影响区窄、焊接变形小以及高效高自动化等诸多优点, 是实现钢/铝连接的理想方法, 但产生的脆性 Fe-Al 金属间化合物影响接头性能^[3-5]。在激光焊接中加入胶层, 增加金属板材对激光的吸收率, 改变熔池的流动性, 避免熔池区明显的母材熔入, 获得良好连接性能^[6-7]。为探索钢铝异种金属连接接头缺陷少、气密性好、力学性能优良的一种新的连接方法, 以 1.4 mm 厚的 DC56D + ZF 镀锌 1.2 mm 厚的 6016 铝合金平板试件作为研究对象, 采用光纤激光器, 进行了

加入胶层的激光搭接焊试验, 利用卧式金相显微镜、扫描电镜、微机控制电子万能试验机等手段分析了焊接接头的微观组织、断口形貌和力学性能, 研究了不同激光功率、焊接速度、离焦量等工艺参数对钢/铝胶接正面与横截面焊缝形貌的影响。文中研究结果期望为钢铝异种金属结构件激光焊接的推广应用提供重要理论和试验基础。

1 试验方法

试验采用光束质量高的光纤激光器作为焊接热源, 激光器主要技术参数见表 1。执行机构为 ABB 机器人, 试验材料为 DC56D + ZF 镀锌钢和 6016 铝合金, 其化学成分见表 2, 板料尺寸分别为 100 mm × 30 mm × 1.4 mm 和 100 mm × 30 mm × 1.2 mm。焊前用丙酮清洗板材表面的油脂及氧化膜, 然后在搭接长度为 30 mm 的区域内涂上自制厚度约为 0.1 mm 的胶层, 对板材试样施以一定的压力, 在室温下自然固化 24 h。焊接时, 采用镀锌钢板置于铝合金上侧的搭接形式, 采用氩气为保护气体。焊接工艺参数的选择见表 3。激光胶接焊的示意图如图 1 所示。焊后利用线切割将试样切割成检测标准剪切试样, 体视显微镜观察钢/铝正面焊缝的表面形貌, 如图 2 所示。将线切割后所得的焊缝横截面进行打磨抛光制成 6 mm × 8 mm 的金相试样, 使用 4% 的硝酸酒精溶液腐蚀试样, 利用卧式金相显微镜观察

收稿日期: 2012-03-23

基金项目: 国家高技术研究发展计划(863)重点资助项目(2007-AA042006); 湖南大学汽车车身国家重点实验室自主课题(71075003)资助项目

钢/铝横截面焊缝的微观组织;利用微机控制电子万能试验机测试焊接试件的抗剪强度与平均剪切力;采用 FEI Quanta200 电子扫描电镜观察断口形貌。

表 1 激光器主要技术参数
Table 1 Main technical parameters of laser device

激光器 功率 P/kW	激光输 出模式	发散角 α/rad	聚焦镜 焦距 f/mm	聚焦光 斑直径 d/mm	波长 λ/nm
性能指标 ≤ 4.0 (连续)	TEM00	<0.15	200	0.4	1 070

表 2 DC56D + ZF 镀锌钢和 6016 铝合金成分(质量分数, %)

Table 2 Chemical compositions of DC56D + ZF Zn-coated steel and 6016 Al alloy

牌号	C	Si	Cu	Mn	Mg
DC56D + ZF	0.014	0.008	—	0.118	—
6016	—	1 ~ 1.3	0.2	0.2	0.3 ~ 0.5

牌号	S	P	Fe	Al
DC56D + ZF	0.030	0.014	余量	—
6016	—	—	0.5	余量

表 3 焊接工艺参数

Table 3 Parameters of laser weld

编号	激光功率 P/W	进给速度 $v/(\text{mm}\cdot\text{s}^{-1})$	离焦量 $\Delta f/\text{mm}$
1	1 600	32	+1
2	1 650	35	+2
3	1 700	38	+3

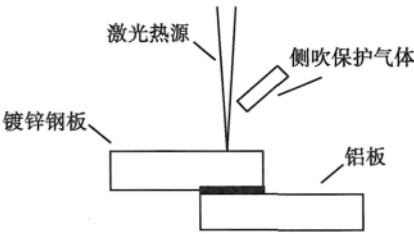


图 1 钢-铝激光胶接焊示意图
Fig. 1 Laser bonding weld of steel-Al

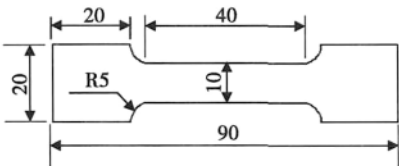


图 2 剪切试样尺寸(mm)
Fig. 2 Tensile shear test sample

2 试验结果与分析

2.1 激光功率对钢/铝激光胶接焊焊缝的影响

图 3 是焊接速度 35 mm/s,离焦量 +3 mm,保护气体流量 20 L/min 的条件下,随着激光功率变化的焊缝正面形貌,可看出激光功率由 1 600 W 增加至 1 700 W,焊缝正面的熔池宽度均在 2 ~ 2.5 mm,变化不大,而焊缝的表面质量却差别很大。当功率为 1 600 W 时,焊缝前半段不连续,熔融金属飞溅较严重,在焊缝区形成凹坑。后半段焊缝较连续,但出现凸起和塌边的现象。当功率为 1 650 W 时,焊缝表面鱼鳞状波纹均匀且连续,没有出现气孔、裂纹等现象。当功率继续增大到 1 700 W 时,焊缝出现明显的飞溅、凹坑、气孔等缺陷。表明激光功率的较低或较高,都会对焊缝的表面质量产生影响,激光功率取 1 650 W 较适合。

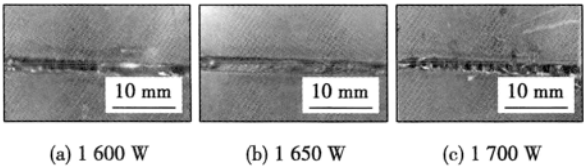


图 3 激光功率变化时的焊缝形貌
Fig. 3 Feature of welding line at different laser power

2.2 焊接速度对钢/铝激光胶接焊焊缝的影响

图 4 是激光功率 1 650 W,离焦量 +3 mm,保护气体流量 20 L/min 的条件下,随着焊接速度变化的焊缝正面形貌,可看出当焊接速度为 32 mm/s 时,焊缝虽有间断的鱼鳞状波纹,但出现了气孔和焊瘤。焊接速度为 35 mm/s 时,焊缝光滑平整,没有明显缺陷。焊接速度增大到 38 mm/s,焊缝出现严重的飞溅、凹坑和塌边现象。说明焊接速度较慢时,由于胶层在焊接过程中受热很容易气化,焊接速度较慢可让气体有充足的时间逃逸。可当焊接速度降至 32 mm/s 时,由于速度慢,熔化的焊缝区附件的胶层会阻碍熔池的流动,出现一些由流动阻滞而出现的

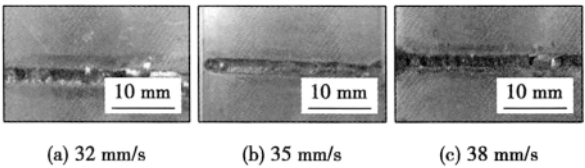


图 4 焊接速度变化时的焊缝形貌
Fig. 4 Feature of welding line at different welding speed

漩涡凹坑或者熔融金属堆积而成的焊瘤。当焊接速度在 38 mm/s 时,由于焊接时金属汽化产生的等离子体和胶层汽化产生的气体的共同作用,导致飞溅严重,焊缝表面出现许多凹坑。因此,焊接速度取 35 mm/s 适宜。

2.3 离焦量对钢/铝激光胶接焊焊缝的影响

焦点位置影响工件表面激光光斑的大小,使工件表面辐射照度发生变化,从而影响焊缝成形。图 5 是随着离焦量变化的焊缝正面形貌图可看出,当离焦量由 +1 ~ +3 mm 变化时,焊缝表面的气孔、凹坑和飞溅等缺陷随着离焦量的增加而减少。当离焦量为 +3 mm 时,焊缝表面成形良好。这是由于随着离焦量的增加,工件表面所吸收的热量减少。热量较大时,下板铝合金充分的熔融并与胶层以及上板熔融的钢充分混合,在等离子体效应以及胶层汽化的协同作用下,容易出现飞溅而形成凹坑或者气孔等缺陷。而当离焦量为 +3 mm 时,由于钢的传导热而熔融的铝合金较少,熔池混合均匀,焊缝成形性好,故离焦量选取 +3 mm 较好。

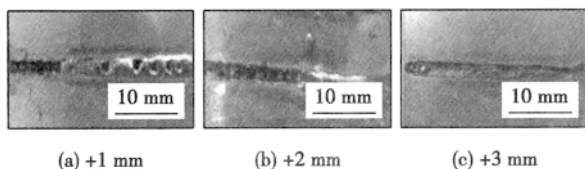


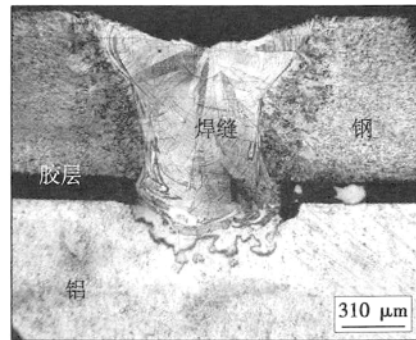
图 5 离焦量变化时的焊缝形貌

Fig. 5 Feature of welding line at different defocusing distance

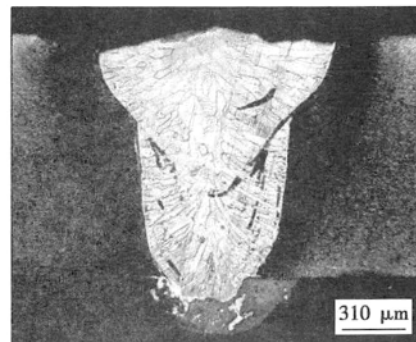
2.4 钢/铝激光胶接焊的微观组织分析

图 6a 是功率为 1 650 W,焊接速度为 35 mm/s,离焦量为 +3 mm,保护气体流量为 20 L/min 的工艺参数下,激光胶接焊焊缝区横截面的整体形貌,发现焊缝熔深约为 0.5 mm,整个焊缝区没有裂纹、气孔、夹杂等缺陷。熔合线光滑平整,表明焊接成形性好。熔池由柱状晶组成,这是因为焊接过程中温度梯度大,冷却速度快,柱状晶得到充分发展。图 6b 是与图 6a 相同的工艺参数下,未加胶激光焊接焊缝区整体形貌,熔深约为 0.4 mm。熔池区有明显的母材熔入的情况,其热影响区比激光胶接焊的热影响区宽。这是由于在焊接过程中,加热速度和冷却速度越大,焊后热影响区的显微组织和性能变化越大,由于焊接不均匀加热和冷却而引起热影响区显微组织性能变化对接头性能影响很大。从图 6a 可看出,胶层的加入,使上下板紧密连接,减弱了由于板间间隙而导致热量传递受阻的现象,使加热和冷却过程均匀进

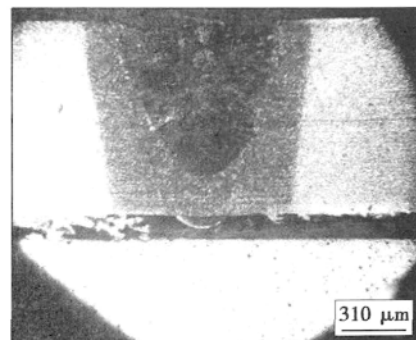
行,同时一定程度上提高了未融化铝合金板的表面温度,由于材料对激光的吸收率随着温度升高而增加,故激光胶接焊在一定程度上增加了焊接接头



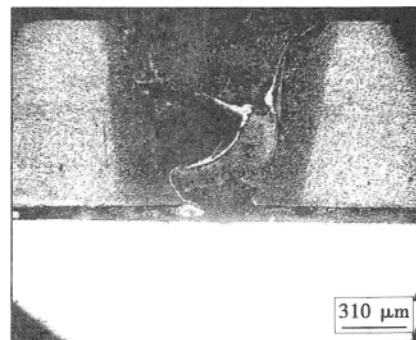
(a) $P=1\ 650\ W$, $v=35\ mm/s$, $f=+3\ mm$, $q=20\ L/min$ 加胶



(b) $P=1\ 650\ W$, $v=35\ mm/s$, $f=+3\ mm$, $q=20\ L/min$ 未加胶



(c) $P=1\ 600\ W$, $v=35\ mm/s$, $f=+3\ mm$, $q=20\ L/min$ 加胶



(d) $P=1\ 650\ W$, $v=38\ mm/s$, $f=+3\ mm$, $q=20\ L/min$ 加胶

图 6 钢-铝激光胶接焊/激光焊焊缝横截面微观组织
Fig. 6 Microstructure of laser weld bonding steel-Al joint/laser welding joint

的熔深. 图 6c 是功率为 1 600 W, 焊接速度为 35 mm/s, 离焦量为 +3 mm, 保护气体流量为 20 L/min 的工艺参数下, 激光胶接焊焊缝区的整体形貌, 由于激光功率偏小, 出现了焊接接头未焊上的缺陷. 图 6d 是功率为 1 650 W, 焊接速度为 38 mm/s, 离焦量为 +3 mm, 保护气体流量为 20 L/min 的工艺参数下, 激光胶接焊焊缝区的整体形貌, 在焊缝区出现了严重的裂纹、气孔等缺陷, 这是由于胶层汽化后没有足够的时间逃逸造成的, 表明在其它工艺参数不变的情况下, 焊接速度越大, 焊缝熔深越浅, 使得板材出现未焊上的情况.

2.5 力学性能与断口形貌分析

使用微机控制电子万能试验机对激光胶接焊板材进行剪切试验, 测得的平均剪切力为 1.04 kN, 抗剪强度为 41.45 MPa, 激光焊接板材平均剪切力为 1.05 kN, 抗剪强度为 42.15 MPa, 比较发现激光焊接中加入胶层, 力学性能并没有因为胶层的加入而减弱. 图 7a 是钢-铝激光胶接焊接头断裂后的剪

切试样, 图 7b~d 为断口处的微观形貌. 可看出断口表面具有一些浅和小的韧窝, 断面上有较短、不连续、汇合特征不明显的河流状花样, 焊缝区断裂形貌表现为韧性断裂与准解理断裂的混合形貌.

3 结 论

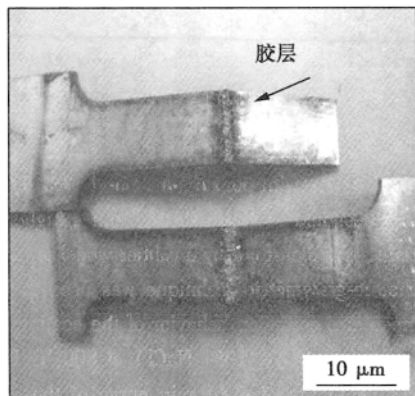
(1) 激光功率为 1 650 W, 焊接速度 35 m/s, 离焦量 +3.0 mm, 氩气为保护气体且流量为 20 L/min 的工艺条件下, 加入胶层, 焊接试样正面焊缝均匀连续, 无气孔、裂纹缺陷.

(2) 胶层的加入改善了搭接焊中因间隙而产生的热传递受阻现象, 与未加胶层相比, 横截面金属平板试件间隙减少, 熔深值增大, 钢/铝连接良好.

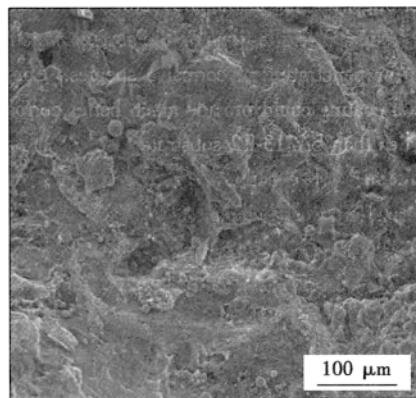
(3) 在激光焊接中加入胶层, 焊接接头抗剪强度与平均剪切力分别为 41.45 MPa 和 1.04 kN, 力学性能并没有因为胶层的加入而减弱, 焊缝区断裂形貌为韧性断裂与准解理断裂的混合形貌.

参考文献:

- [1] 吴 军, 李 亮. 激光焊接工艺对铝-钢焊接质量影响研究[J]. 焊接技术, 2000, 5(29): 19-21.
Wu Jun, Li Liang. Investigation on laser welding quality of Steel-Al[J]. Welding Technology, 2000, 5(29): 19-21.
- [2] 雷 振, 王旭友, 王伟波, 等. 铝/镀锌钢复合热源熔-钎接头中的 Al-Fe 金属间化合物层分析[J]. 焊接学报, 2007, 28(11): 65-71.
Lei Zhen, Wang Xuyou, Wang Weibo, et al. Analysis of Al-Fe intermetallic compounds layer of fusion-brazed joints between aluminium and zinc-coated steel by hybrid welding[J]. Transactions of China Welding Institution, 2007, 28(11): 65-71.
- [3] Weichiat C, Pual A, Pal M. CO₂ laser welding of galvanized steel sheets using went holes[J]. Materials and Design, 2009, (30): 245-251.
- [4] Bretz T, Lazarz A, Hill J, et al. Adhesive bonding and corrosion protection of a die cast magnesium automotive door[J]. Magnesium Technology, 2004, 15(8): 113-119.
- [5] Qi X, Song G. Interfacial structure of the joints between magnesium alloy and mild steel with nickel as interlayer by hybrid laser-TIG welding[J]. Mater Des, 2010, 31(20): 605-609.
- [6] Liu X J, Huang R S, Wang H Y. Improvement of TIG lap weld ability of dissimilar metals of Al and Mg[J]. Science & Technology of Welding & Joining, 2007, 12: 258.
- [7] 王红阳, 张兆栋, 刘黎明. 胶层对镁铝异种金属激光胶接过程中热量传递的影响[C]// 轻金属与高强材料焊接国际论坛. 北京: 机械工业出版社, 2008: 94-99.



(a) 钢铝激光胶接焊剪切试样断口形貌



(b) 400倍钢铝熔合界面的显微形貌

图 7 钢-铝激光胶接焊接头的剪切断裂试样和断口微观形貌

Fig. 7 SEM microstructure of laser weld bonding steel-Al joint fracture and failure adhesive bonded joint in tensile shear test

作者简介: 戴 婷, 女, 1989 年出生, 硕士研究生. 主要从事汽车车身激光焊接方面的科研工作. Email: daiting0216@126.com

通讯作者: 周佑武, 男, 教授. Email: ZDWe_mail@yahoo.com.cn

MAIN TOPICS ,ABSTRACTS & KEY WORDS

Principle of weld formation in variable polarity keyhole plasma arc transverse welding of aluminum alloy CHEN Shujun¹ , JIANG Fan¹ , ZHANG Junlin¹ , HUANG Ning¹ , ZHANG Yuming² (1. Beijing University of Technology , College of Mechanical Engineering and Applied Electronics Technology , Beijing 100124 , China; 2. University of Kentucky , Center for Manufacturing , Lexington KY 40506 , USA) . pp 1 – 6

Abstract: Taking the keyhole molten pool in plasma arc welding as the study object , the weld formation in variable polarity keyhole plasma arc transverse welding of aluminum alloy was investigated by using both experiments and numerical simulation according to the characteristic of heat source. The study indicates the deviated phenomena between the highest temperature point and the widest fusion width section in keyhole molten pool root surface under the heat source due to the welding speed fluctuation and effect of thickness of plate. By making division of the keyhole molten pool root surface , the concept named temperature width deviation was defined as the deviation between the highest temperature point and the widest fusion width point in molten pool root surface , to describe the state of keyhole molten pool root surface and the welding formation. Temperature width deviation was changed by adjusting the welding torch position , so as to reduce the effect of gravity in welding process , with other parameters being unaltered , to get a good weld formation of variable polarity keyhole plasma arc welding at transverse position.

Key words: temperature width deviation; variable polarity plasma arc welding; keyhole welding pool; transverse welding; weld formation

Microstructure and impact property of 690 MPa level HSLA steel weld WANG Aihua^{1,2} , PENG Yun² , XIAO Hongjun² , TIAN Zhiling² , WANG Jing¹ (1. Chengde Petroleum College , Chengde 067000 , China; 2. State Key Laboratory of Advanced Steel Processes and Products , Central Iron & Steel Research Institute , Beijing 100081 , China) . pp 7 – 10 , 42

Abstract: The weld metal of 690 MPa level high strength low alloy (HSLA) steel was investigated in this paper. The M-A constituents were etched with Lepera reagent , and the microstructure , residual austenite and grain boundary in the welded metal were observed with optical microscope (OM) , transmission electron microscope (TEM) and electron back-scattering diffraction (EBSD) , and the impact property was tested. The results reveal that the average Charpy impact values of welded metals made with shielded metal arc welding process and metal inert gas (MIG) welding process were 31 J and 98 J at – 50 °C respectively. The volume fractions of M-A constituents in welded metals made with shielded metal arc welding and MIG welding processes were 4.4% and 2.52% , respectively. The increase of volume fraction of M-A constituents resulted in the deterioration

of impact property of welded metal with shielded metal arc welding , and the decrease of residual austenite and large grain boundary in the welded metal also led to the degradation of impact property.

Key words: impact property; chemical composition; martensite-austenite constituent; residual austenite; large grain boundary

Laser-adhesive hybrid bonding of dissimilar metals between steel and aluminum alloy DAI Ting , LIU Jinshui , ZHOU Dianwu , PENG Yan (State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body , Hunan University , Changsha 410082 , China) . pp 11 – 14

Abstract: Fiber laser was adopted with adhesive layer to join 1.4 mm thick DC56D + ZF galvanized steel and 1.2 mm thick 6016 aluminum alloy sheets. The microstructure , fracture appearance and mechanical properties of the joint were investigated. The influences of welding parameters on the weld appearance were analyzed. The results show that with the addition of adhesive layer , no pores or cracking were observed on the welds. The average shearing strength and shearing load of the steel/aluminum joint were 41 MPa and 1.04 kN. The failure mode of welded joint presented a mixture of ductile and quasi-cleavage fractures.

Key words: laser-adhesive hybrid welding; steel; aluminum; weld appearance; tensile strength

Effect of heat input on microstructure and mechanical properties of ultra-thin 443 ferritic stainless steel ZHANG Hongxia¹ , LI Hongzhi¹ , WANG Zhibin² , WANG Wenxian¹ , ZHANG Xinbao² , YAN Zhifeng¹ (1. College of Materials Science and Engineering , Taiyuan University of Technology , Taiyuan 030024 , China; 2. TISCO Technology Center , Taiyuan 030003 , China) . pp 15 – 18 , 34

Abstract: Tungsten inert gas (TIG) welding , pulsed tungsten inert gas (P-TIG) welding and pulsed laser beam welding (P-LBW) of ultra-thin 443 ferritic stainless steel sheets were conducted to investigate the problems of coarsened grain and brittleness in the weld. The effects of different welding processes on the microstructure and mechanical properties of resultant joints were analyzed with optical microscope (OM) and scanning electron microscope (SEM) . The effects of welding heat input on microstructure , tensile property and cupping property of joints were evaluated. The experimental results reveal that the welding heat input was the key factor to determine the microstructure and mechanical properties of 443 ferritic stainless steel welded joints. And grain refinement by pulsed welding process can improve the comprehensive mechanical properties of the resultant joint.

Key words: 443 ferritic stainless steel; tungsten inert gas