第 31卷 第 4期
2010年 4月
焊 接 学 报
TRANSACTIONS OF THE CHINA WELDING INSTITUTION
Vol 31 No. 4
April 2010

控制焊接残余应力方法的超声波监控

张世平[1], 路 浩[2], 刘夕林[1], 方洪渊[3]
(1. 哈尔滨工业大学 电气工程及自动化学院, 哈尔滨 150001;
2. 南车青岛四方机车车辆股份有限公司 焊接实验室, 山东 青岛 266111;
3. 哈尔滨工业大学 现代焊接生产技术国家重点实验室, 哈尔滨 150001)

张世平

摘 要: 为了减少焊接件的残余应力测量时间,基于声弹性效应,采用对应力最为敏感的临界折射纵波,建立了焊接残余应力超声波测量系统,可以准确的检测出焊接结构的内部应力. 用该测量系统对随焊旋转挤压法、随焊冲击碾压法、电磁冲击法、预置应力法等一系列降低焊接残余应力的控制方法进行了监控,试验结果给出了各控制方法的残余应力降低程度,确认了工艺参数的合理性. 该试验过程无损快速克服了传统切割释放测量方法的耗时费力,加快了控制方法的研制进程.

关键词: 超声波法; 应力控制方法; 焊接残余应力
中图分类号: TG404 **文献标识码**: A **文章编号**: 0253 - 360X(2010)04 - 0077 - 04

0 序 言

为了降低焊接残余应力,需要研发新的残余应力和变形控制方法,但这些方法在研究过程中摸索合理的工艺参数工作量非常巨大,占用了新方法研制过程的一半时间以上. 新方法工艺参数是否合理的重要评价标准之一是残余应力水平降低程度的大小,根据残余应力的降低结果来选取最优的工艺参数. 这些新方法主要是对壁厚在 3 mm左右的薄壁铝合金焊接件进行残余应力和变形控制. 而传统残余应力测量方法中小孔法无法对壁厚 5 mm以下的薄壁结构进行测量,一般只能使用切割释放法对焊接件进行残余应力测量,其测量过程耗时费力,大大延迟了新方法工艺参数的探寻,延缓了新方法的研究进度.

基于声弹性效应并采用对应力最为敏感的临界折射纵波,开发了焊接残余应力超声波法测量系统[1]. 文中使用该系统对随焊旋转挤压法、随焊冲击碾压法、电磁冲击法、预置应力法等一系列降低残余应力新方法的效果进行了评定,不仅看出残余应力得到显著的降低说明新方法的有效性,另外也说明了焊接残余应力超声波法测量的可靠性,试验过程无损、实时快速,为焊接新方法的研制提供了便捷的验证手段,从而加快了研制的进程.

收稿日期: 2008 - 10 - 20
基金项目: 中俄政府间科技合作资助项目 (2007DFR70070)

1 超声波法应力测量系统

建立的焊接残余应力超声波测量装置结构如图 1所示.

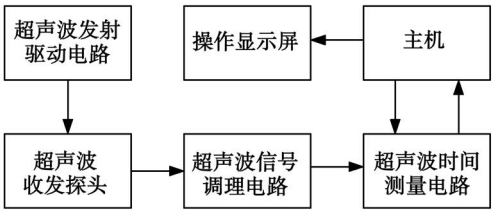

图 1 测量装置组成

Fig. 1 Schematic diagram of measurement device

测量装置本体大小类似于一个普通台式计算机的主机,如图 2所示. 超声波探头是特殊加工的用来产生临界折射纵波,在测量铝合金应力时的入射角度为 27.6°;超声波的收、发探头加工为一体,发、收探头的引出线分别接到测量装置留出的激励和测量的接口,数字键盘用于测量时的功能输入.

测量时首先对零应力板进行校准,可以克服温度等外界条件的改变对测量结果的影响. 每一个应力点连续测量 10次后取平均,同时可以输入测量点距焊缝中心的距离,系统将自动绘制出残余应力的分布曲线;最后将测试数据存储在优盘供计算机读取分析用.

图 2 测量装置照片

Fig. 2 Photo of measurement device

使用此测量系统对铝合金和钢材两种结构的焊接残余应力进行了测量[2,3],并与有限元模拟、应变片法和激光全息小孔法进行了对比测量,验证了该测量系统的准确可靠[4],而且还在高速列车车体上进行了测量应用和验证[5]. 此外该系统克服了薄壁结构件测量中特殊波形的影响,实现了 2 mm 薄壁焊接结构件的应力测量[6].

2 控制方法降低残余应力的评定

2.1 随焊旋转挤压法

随焊旋转挤压是一种高效的随焊控制焊接变形的新方法,其原理是通过置于焊枪后方一定距离的柱状挤压杆对焊后尚处高温的焊缝金属进行旋转挤压作用来延展焊缝,从而达到减小焊接残余应力,控制焊后变形的目的[7].

试验材料为 LY12 铝合金,试样规格为 300 mm ×140 mm ×2 mm,焊接方法为交流钨极氩弧焊,采用不填丝的表面熔敷方式,旋转挤压杆直径 10 mm. 试件 A为常规焊,试件 B的旋转挤压位置在焊缝中心,试件 C的旋转挤压位置在焊缝两侧,试件外观见图 3.

由于铝合金平板厚度为 2 mm,不适合用小孔法验证,因此用超声波测量铝合金薄板焊接残余应力

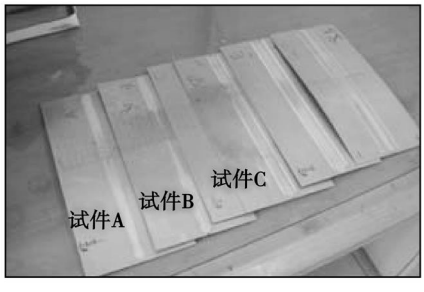

图 3 随焊旋转挤压试件

Fig. 3 Samples welded by trailing rotating extrusion method

的同时,选取试件 A和试件 B通过切割释放用应变片测量来进行验证. 测量结果如图 4a和图 4b所示,试件 C和试件 A的残余应力对比如图 4c所示.

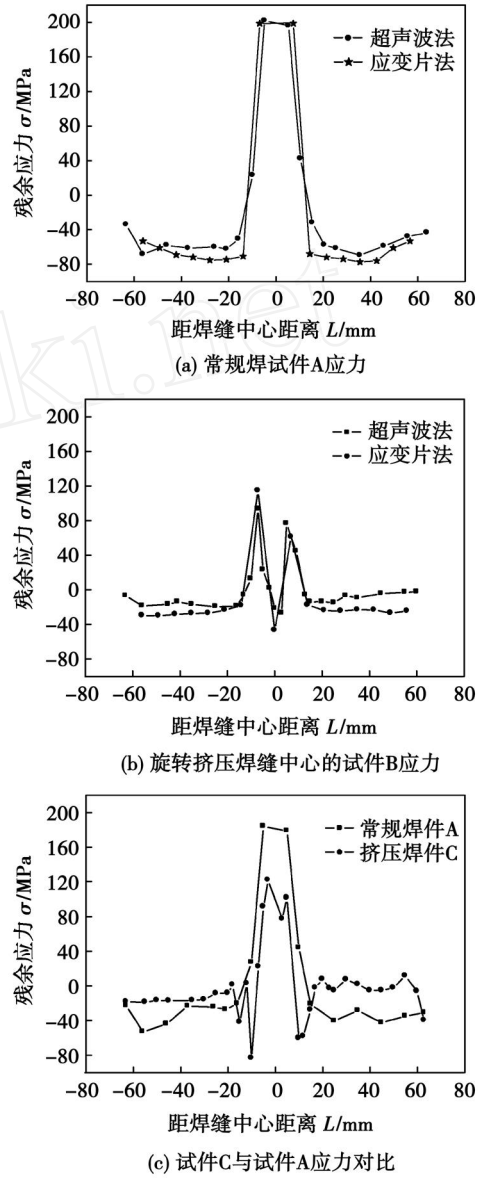

图 4 随焊旋转挤压旋法的评定

Fig. 4 Assessment of trailing rotating extrusion method

从图 4a和图 4b中可以看出,超声波法和应变片法测得的残余应力分布吻合良好. 试件 B焊缝中心残余应力相对试件 A从 190 MPa降到 - 40 MPa,说明旋转挤压法能够降低焊接残余应力,而且旋转碾压部位都出现了压应力. 此外对比图 4b和图 4c可知,旋转挤压法旋转挤压焊缝中心降低残余应力的效果最为明显.

2.2 随焊冲击碾压法

随焊冲击碾压控制焊接应力变形防止热裂纹新方法是以空气锤作为冲击动力源,通过前后冲击碾

压轮对焊接接头的不同部位实施一定频率的同步冲击碾压作用,控制、调整焊缝区的应变场和塑性流变场的分布,将接头的残余变形控制在较低的水平.强化接头,改善了残余应力的分布状态,实现了高强铝合金薄壁结构低应力小变形无热裂焊接,实现了平面封闭焊缝残余应力变形的随焊控制[8].

试验材料采用 LY12铝合金,两个试样由两个圆环镶嵌焊接而成(图 5). 大环外径 340 mm,内径 162 mm,小环外径 162 mm,内径 75 mm,厚度为 2 mm. 图中左侧的工件为常规焊试件,右侧的工件采用了随焊碾压处理,随焊冲击力 35 N.

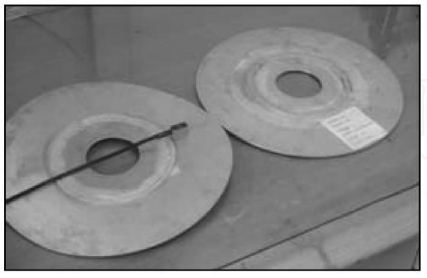

图 5　随焊冲击碾压试件

Fig. 5　Samples welded by trailing impactive rolling method

用超声波法测量了两个试件直径方向上的径向和切向残余应力,结果如图 6所示. 常规焊圆环件的应力分布与理论值相符,随焊碾压法有效地降低了残余应力. 常规焊焊址部位应力达 200 MPa,经随焊碾压处理后其应力值降低了一半,同时径向和切向残余应力梯度明显变缓,切向残余应力梯度几乎呈水平线分布,拉应力区宽度减小了三分之一,压应力绝对值明显减小.

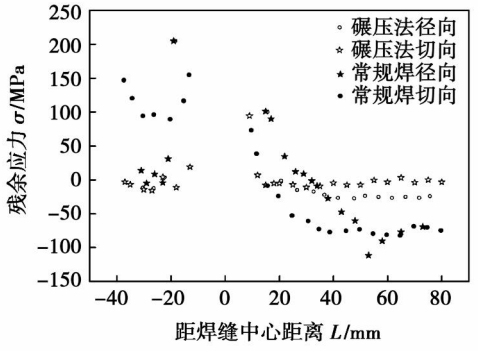

图 6　随焊冲击碾压法的评定

Fig. 6　Assessment of trailing impactive rolling method

2.3　电磁冲击法

电磁冲击控制焊接应力变形法是根据电磁感应原理,利用电磁力冲击焊缝附近区域,对焊缝施加额外的拉伸应变,使焊缝得到延展,从而控制焊接应力与变形. 该方法可实现非接触控制焊接应力和变形,对焊缝不产生损伤,冲击能量易于控制,操作方便灵活. 该方法不改变焊缝成分,能量易于控制,可实现无机械接触控制热裂纹,焊件表面无损伤,不影响接头疲劳性能[9].

试验材料采用 1060H24工业纯铝,工件如图 7所示. 此种方法目前是焊后处理,图中可以看到处理后的工件变形明显减小.

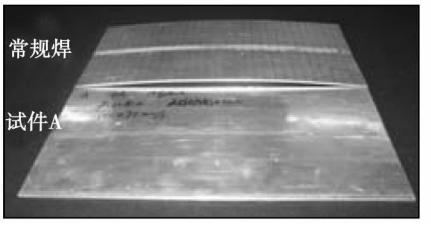

图 7　电磁冲击试件

Fig. 7　Samples by electromagnetic impact method

试验测量了电磁冲击前后同一测量线的残余应力值,图 8为常规焊和电磁冲击试件纵向残余应力分布的对比图,经过电磁冲击后纵向残余应力峰值明显降低,拉应力峰值比常规焊降低了 66%,拉应力的范围变大,应力分布更加平缓. 分析认为这是由于在电磁冲击的过程中焊缝金属的纵向压缩塑性变形受到了充分的延展,使得焊缝金属有所伸长. 压缩塑性变形得到延展,残余应力水平降低.

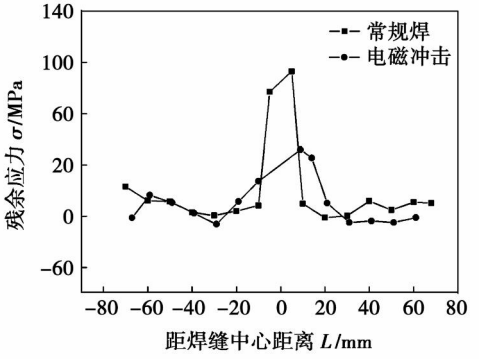

图 8　电磁冲击法的评定

Fig. 8　Assessment of electromagnetic impact method

2.4　预置应力法

双向预置应力控制焊接变形和残余应力新工艺,解决了焊接变形和热裂纹问题. 预置纵向拉应力控制焊接变形和降低焊接残余应力,与此同时预置横向压应力抵消焊缝金属固有的凝固收缩时受到的拉应变以及预置纵向拉应力对焊缝金属造成的额

外拉应变,从而起到防止热裂纹的作用[10].

试验材料为 LY12铝合金,尺寸为 200 mm ×310 mm ×2 mm,外观形貌见图 9所示.

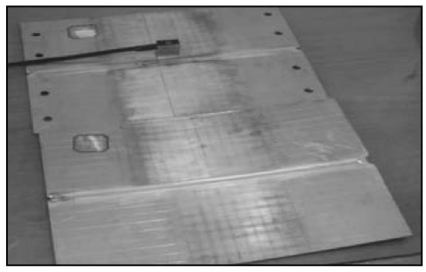

图 9 铝合金预置应力试件

Fig. 9 Samples by pre-stress method

预置应力法试验结果见图 10所示. 预置应力为 0.3倍屈服强度. 从结果看,预置应力明显降低了残余应力值.

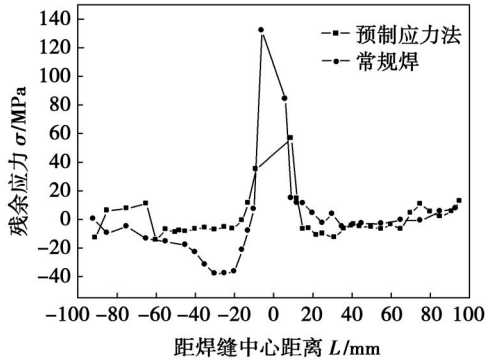

图 10 应力法的评定

Fig. 10 Assessment of pre-stress method

3 结 论

(1) 使用超声波法对一系列降低残余应力控制方法的效果进行了评定,并进行了对比验证,表明该方法的测量结果可靠. 试验过程无损、实时快速,说明该测量系统为焊接控制方法的研制提供了便捷的验证手段.

(2) 随焊旋转挤压法、随焊冲击碾压法、电磁冲击法、预置应力法等一系列控制方法有效地降低了焊接残余应力,具有实用价值.

参考文献:

[1] Lu H, Liu X S, Yang J G, *et al* Ultrasonic stress evaluation on welded plates with LCR wave [J]. Science & Technology of Welding and Joining, 2008, 13(1): 70 - 75.

[2] 路 浩, 张世平, 刘雪松, 等. 双丝焊铝合金平板残余应力梯度超声波法建立 [J]. 焊接学报, 2008, 29(2): 61 - 64.
Lu Hao, Zhang Shiping, Liu Xuesong, *et al* Establishment of longitudinal twin wire welding residual stress gradient of 2219 aluminum alloy plate by ultrasonic method [J]. Transactions of the China Welding Institution, 2008, 29(2): 61 - 64.

[3] 路 浩, 刘雪松, 杨建国, 等. 低碳钢双丝焊平板横向残余应力超声波法测量 [J]. 焊接学报, 2008, 29(5): 30 - 32.
Lu Hao, Liu Xuesong, Yang Jianguo, *et al* Evaluation of transverse residual stress in twin wire welded plates by ultrasonic method [J]. Transactions of the China Welding Institution, 2008, 29(5): 30 - 32.

[4] 路 浩, 刘雪松, 杨建国, 等. 激光全息小孔法验证超声波法残余应力无损测量 [J]. 焊接学报, 2008, 29(8): 77 - 79.
Lu Hao, Liu Xuesong, Yang Jianguo, *et al* Verification of ultrasonic residual stress evaluation method by laser hologram method [J]. Transactions of the China Welding Institution, 2008, 29(8): 77 - 79.

[5] 路 浩, 刘雪松, 杨建国, 等. 高速列车车体服役状态残余应力超声波法无损测量及验证 [J]. 焊接学报, 2009, 30(4): 81 - 83.
Lu Hao, Liu Xuesong, Yang Jianguo, *et al* Residual stress evaluation of high-speed train body structure by ultrasonic method and verification [J]. Transactions of the China Welding Institution, 2009, 30(4): 81 - 83.

[6] 张世平, 路 浩, 朱 政, 等. 薄壁 LY12铝合金焊接残余应力超声波法无损测量及验证 [J]. 焊接学报, 2009, 30(9): 25 - 28.
Zhang Shiping, Lu Hao, Zhu Zheng, *et al* Residual stress evaluation of thin-plate LY12 by ultrasonic method and verification [J]. Transactions of the China Welding Institution, 2009, 30(9): 25 - 28.

[7] 李 军, 杨建国, 翁路露, 等. 随焊旋转挤压对铝合金焊接接头组织和性能的影响 [J]. 焊接学报, 2008, 29(6): 101 - 104.
Li Jun, Yang Jianguo, Weng Lulu, *et al* Effect of welding with trailing rotating extrusion on microstructure and mechanical properties of aluminum alloy welded joints [J]. Transactions of the China Welding Institution, 2008, 29(6): 101 - 104.

[8] 范成磊, 方洪渊, 杨建国, 等. 随焊冲击碾压控制焊接应力变形新方法 [J]. 机械工程学报, 2004, 8(40): 87 - 90.
Fan Chenglei, Fang Honhyuan, Yang Jianguo, *et al* New technology to control welding stress and distortion with trailing impactive rolling [J]. Chinese Journal of Mechanical Engineering, 2004, 8(40): 87 - 90.

[9] 徐 达, 许 威, 徐文立, 等. 电磁力随焊控制焊接应力装置的研制及应用 [J]. 焊接学报, 2008, 29(1): 9 - 13.
Xu Da, Xu Wei, Xu Wenli, *et al* Investigation and application of pulse electromagnetic force generator for trailing control of welding stress [J]. Transactions of the China Welding Institution, 2008, 29(1): 9 - 13.

[10] 周广涛, 刘雪松, 方洪渊. 纵向预置应力法控制薄板焊接残余应力与变形 [J]. 机械工程材料, 2008, 32(3): 78 - 81.
Zhou Guangtao, Liu Xuesong, Fang Hongyuan. Controlling of welding residual stress and deflection distortion for flat plate by longitudinal pre-stress Method [J]. Materials for Mechanical Engineering, 2008, 32(3): 78 - 81.

作者简介: 张世平,男,1974年出生,博士,副教授. 主要研究方向为焊接残余应力的无损测量. 已发表论文 10余篇.

Email: tempspzhang@163.com

periment results demonstrate that the appearance of the joint is good and the inner in the joint is detect-free under optimum joining conditions. When the rotating speed is 960 r/min and the welding speed is 70 mm/min, the tensile strength of the joint reaches 186.6 MPa, and the conductivity of the joint is approximately equal to that of the base metal.

Key words: friction stir welding; T2 copper; thick plate; mechanical properties

Ultrasonic monitoring of residual stress reduction methods ZHANG Shiping[1], LU Hao[2], LIU Xilin[1], FANG Hongyuan[3] (1. School of Electrical Engineering and Automatic, Harbin Institute of Technology, Harbin 15001, China; 2. CSR Sifang Locomotive and Rolling Stock Company Limited, Qingdao 266000, China; 3. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 15001, China). p 77 - 80

Abstract: The ultrasonic system of accurately measuring internal stress of welding structure is established based on acoustoelasticity effect and critically refracted longitudinal wave that is most sensitive to stress in order to shorten the time of the welding residual stress measurement. A new series decreasing residual stress methods, such as trailing rotating extrusion, trailing impactive rolling, electromagnetic impact and pre-stress, are verified by this measurement system. The experiment results show that the decreasing degree of residual stress can validate the effectiveness of technical parameters by those methods. The measurement speed of the nondestructive system is quicker than that of traditional section release methods, which accelerates the research process.

Key words: ultrasonic measurement; control residual stress methods; welding residual stress

Effects of service conditions on properties of in-situ particle-reinforced composite solder joint TAI Feng, GUO Fu, MA Limin, HAN Mengting (College of Materials Science and Engineering, Beijing University of Technology, Beijing 100124, China). p 81 - 84

Abstract: In-situ particle-reinforced composite solder was considered as an effective method to enhance the properties of lead-free solders. In-situ Cu_6Sn_5 particles were added into the eutectic Sn-3.5Ag solder to form in-situ metal particles enhanced SnAg-based composite solder. The microstructure and mechanical properties of the composite solder joint during reflow and isothermal aging were investigated, and the fracture mode of composite solder joint and the role of in-situ Cu_6Sn_5 particles were analyzed. Experimental results show that the microstructure and dimensions of in-situ Cu_6Sn_5 particles in composite solder matrix have changed during reflow and isothermal aging. So the shear strengths of composite solder joints have influenced by the sizes of in-situ Cu_6Sn_5 particles. Besides, the deformation of composite solder joint is dominated by shear bonding mode, and the in-situ Cu_6Sn_5 reinforced particles can retard the fracture path of shear bonds.

Key words: in-situ Cu_6Sn_5 particle; composite solder; reflow; aging; shear strength

Microstructure and mechanical properties of ultrafast-convert VPTIG arc welding of 2219 high strength aluminum alloy CONG Baoqiang, QI Bojin, ZHOU Xingguo, LUO Jun (School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Beijing 100191, China). p 85 - 88

Abstract: A novel ultrafast-convert intermediate and high-frequency variable polarity arc welding technology for aluminum alloys was developed. The effect of variable polarity current frequency on the microstructure and mechanical properties of 2219-T87 weld joints was researched based on the variable polarity TIG welding process. The experimental results show that the structure in the weld zone is predominantly columnar in the case of lower variable polarity current frequency. The grain structures in the weld zone become finer and more equiaxed with the increase of current frequency. Tensile strength and percentage elongation of the weld joints also improve predominantly. The type of weld fracture is changed from brittle to the mixture of dimple and brittle. Under the current frequency of 1 kHz, the rates of weld tensile strength and percentage elongation of the joints are 69% and 58% than those of the base metal respectively.

Key words: high strength aluminum alloy; ultrafast convert; variable polarity; grain refinement

Nonlinear multiple regression model of resistance spot welding for galvanized steel sheet LUO Yi[1], PI Fengxian[2], XIONG Chengzhi[1], LIU Lin[1] (1. School of Material Science and Engineering, Chongqing University of Technology, Chongqing 400050, China; 2. Chongqing South Jinkang Auto Parts Ltd., Chongqing 401120, China). p 89 - 92

Abstract: A method of nonlinear multiple orthogonal regression assembling design was applied in the investigation of the resistance spot welding process on galvanized steel sheet. The indexes studied in experiments were nugget geometry and tensile-shear strength of spot welds. Furthermore, four process parameters, namely welding current, electrode force, welding current duration and preheat current, and interactions among them were considered as the factors impacting indexes. The experimental results showed that there was a more accurate prediction on nugget size and mechanical properties of spot welds by the models optimized. Based on these prediction results, the optimization of welding process also was realized by the analysis to the effect of parameters and interactions on the welding quality.

Key words: galvanized steel sheet; spot welding; regression model; nugget diameter; tensile-shear strength

Condenser discharge percussion welding of iron wire to copper sheet KANG Jing[1], ZHAO Maiqun[1], LÜ Juan[1], ZHAO Xueqin[1], Suzuki JIPPEI[2] (1. College of Material Science and Engineering, Xi'an University of Technology, Xi'an 710048, China; 2. Faculty of Mechanical Engineering, Mie University, Tsu 514-8507, Japan). p 93 - 96

Abstract: In order to study new jointing technique about