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搅拌摩擦焊接缺陷的补焊方法

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摘　要：搅拌摩擦焊接方法在某些条件下也会造成焊接缺陷的产生，其中对接头性能有显著影响的缺陷包括沟槽、孔洞和未焊合。针对这三种类型的缺陷，用搅拌摩擦焊接方法进行补焊，以此研究补焊接头的焊缝成形和力学性能。结果表明，采用搅拌摩擦补焊方法能够消除沟槽、孔洞和未焊合等搅拌摩擦焊接缺陷；在优化的补焊工艺参数下，能够获得焊缝成形良好的补焊接头，其性能与优质原始接头的性能相当；补焊接头在拉伸测试中均在焊缝的后退侧发生断裂，拉伸断口具有明显的韧窝特征.

关键词：搅拌摩擦焊接；焊接缺陷；补焊；焊缝成形；力学性能
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0　序　言

搅拌摩擦焊接(friction stir welding，简称 FSW)是近年来开发出的一种新型固态连接技术，它不仅具有高质量、低成本、低变形、易于自动化等特点，而且不需要填充材料和保护气、能耗低、对环境无污染，是一种理想的绿色连接技术[1,2]．它的出现解决了难于熔焊材料的焊接问题，并且扩大了结构设计过程中材料的选择范围[3,4]．然而，人们在搅拌摩擦焊接方法得到迅速发展及应用过程中已经发现，尽管这种方法本身可以获得高质量的焊接接头，但由于搅拌头设计、工艺参数选取以及工件装卡不当等因素的存在，也会导致焊接缺陷的产生．因此，搅拌摩擦焊接缺陷及其补焊技术应该引起足够重视，以满足焊接生产对接头质量的要求．根据以往的研究结果可以认为，对接头性能有显著影响的搅拌摩擦焊接缺陷主要有三种类型，即沟槽、孔洞和未焊合[5,6]．

文中针对这三种类型的缺陷，再用搅拌摩擦焊接方法进行补焊，从而消除缺陷对接头性能的影响．这对于保证焊接构件的质量和可靠性是具有重要的意义．

1　试验方法

1.1　试验材料及设备

试验采用的被焊材料为 7.5 mm 厚的 2219 铝合金板，其化学成分和力学性能如表 1 所示．每个焊接试板的尺寸为 300 mm×100 mm×7.5 mm，沿试板长度方向进行对接．焊接及补焊所用的焊接设备为 FSW－3LM－003 型龙门式数控搅拌摩擦焊机，其上装有锥状螺纹型搅拌头．

表 1　2219 铝合金的化学成分（质量分数，%）及力学性能
Table 1　Chemical compositions and mechanical properties of 2219 aluminum alloy

Cu	Mn	Fe	Ti	V	Zn	Si	Zr	Al	抗拉强度 R_m/MPa	屈服强度 R_{eL}/MPa	断后伸长率 A(%)
6.48	0.32	0.23	0.06	0.08	0.04	0.49	0.2	余量	432	315	11

1.2　焊接及补焊方法

为方便起见，将对原始母材直接焊接所形成的接头（或焊缝）称为原始接头（或原始焊缝），而将对原始接头（或原始焊缝）再进行补焊所形成的接头（或焊缝）称为补焊接头（或补焊焊缝）．焊前对板材表面进行机械清理以去除表面氧化膜，并用丙酮擦拭去除表面油污．根据前期的研究工作，按照表 2

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给出的工艺参数,可以焊出分别含有沟槽、孔洞及未焊合等三种典型缺陷的搅拌摩擦焊接原始接头,以便用于补焊试验研究.

表 2　含有缺陷的原始接头的焊接工艺参数

Table 2　Technological parameters of initial welded joints with defects

缺陷类型	转速 ω/(r·min)	焊速 v/(mm·min⁻¹)	压力 p/kN	倾角 θ/(°)
沟槽	1 000	200	4.6	2.5
孔洞	400	300	5.5	2.5
未焊合	600	200	4.6	2.5

对含有缺陷的原始接头进行补焊时,补焊的对中位置一般处于原始焊缝的中心线上.但对于沟槽缺陷,由于其尺寸较大,应对中在缺陷所处的部位,以确保补焊接头不再产生新的缺陷.为减小接头组织及性能在焊缝两侧的不对称性,将补焊方向定为原焊接方向的反方向.已有研究结果表明[5],当转速为 600 r/min,焊速为 200 mm/min,压力为 4.6 kN 时可以得到抗拉强度为 343 MPa 的优质原始接头,因此,补焊参数即依据优质原始接头的焊接参数进行选择,同时兼顾缺陷种类进行微调,最终优化的补焊工艺参数如表 3 所示.

表 3　优化的补焊工艺参数

Table 3　Optimal parameters for repair welding

转速 ω/(r·min)	焊速 v/(mm·min⁻¹)	压力 p/kN	倾角 θ/(°)
600	200	4.6～8	2.5

1.3　测试分析方法

沿垂直于焊接方向截取接头横截面,经粗磨、精磨和抛光处理后,用混合酸溶液(3 mL 硝酸+6 mL 盐酸+6 mL 氢氟酸+150 mL 水)对试样进行腐蚀,并用 Olympus —MPG3 光学显微镜分析接头的焊接缺陷及微观特征.

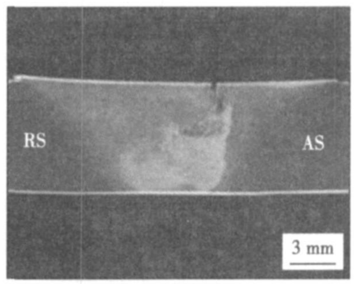
按照国家标准 GB2625 —89《焊接接头拉伸测试方法》,采用电火花数控切割机将接头切成标准试样,在 Instron —1186 力学性能试验机上进行常温拉伸测试,并以三个试样的平均值作为评定结果.拉伸测试后,采用 Hitachi —S4700 扫描电镜对接头拉伸断口进行分析.

2　试验结果及分析

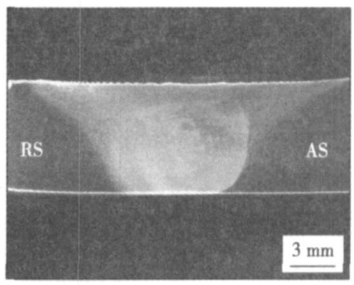
2.1　焊缝成形

对焊缝截面进行分析,考察焊缝成形情况,可以获得焊接缺陷是否存在的直接信息.因此,通过观察接头在补焊前后的焊缝成形即可判定补焊是否成功.

当焊接热输入不当时,软化的材料不能在搅拌针后表面附近回填到焊缝前进侧,从而在焊缝前进侧搅拌针表面附近形成了连续、贯通焊缝表面的沟槽缺陷,如图 1a 所示.当以沟槽所在位置为中心进行补焊后,沟槽缺陷已经被完全消除,如图 1b 所示.由于补焊焊缝相对原始焊缝有一定的偏移,新焊核与原焊核相互交叠,因而使补焊接头的整体焊核尺寸有所增大.



(a) 原始焊缝

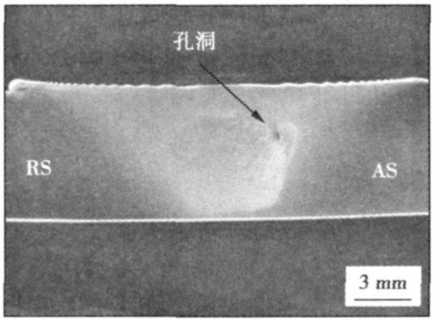


(b) 补焊焊缝

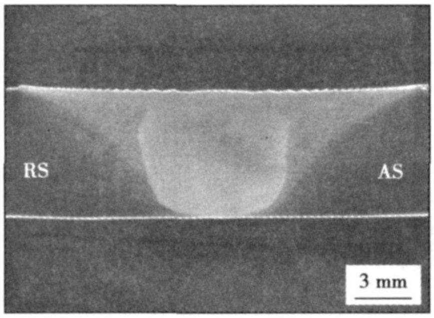
图 1　含有沟槽缺陷的原始焊缝及其补焊焊缝

Fig 1　Cross-sections of initial weld with groove defect and its repaired weld

当焊速较高、转速较低或压力不足时,软化材料不能充分填充搅拌针过后所形成的暂时空腔,从而在焊缝内部形成断续或连续的永久性孔洞(图 2a).采用优化的工艺参数对含有孔洞缺陷的接头进行补焊后,孔洞缺陷已被消除,焊核致密、饱满(图 2b).当压力较小或搅拌针长度较短以及焊速较大时,易导致焊缝根部没有受到充分的搅拌作用,从而保留母材原始的对接状态,形成所谓的未焊合缺陷(图 3a).进一步观察此图可以看出,不但未焊合缺陷尺寸较大,而且缺陷处仍保留原始母材的组织.采用优化的工艺参数进行补焊后,由于焊缝根部得到了充分的搅拌作用,未焊合缺陷被消除的同时,粗大的母材组织也得到了充分的细化(图 3b).



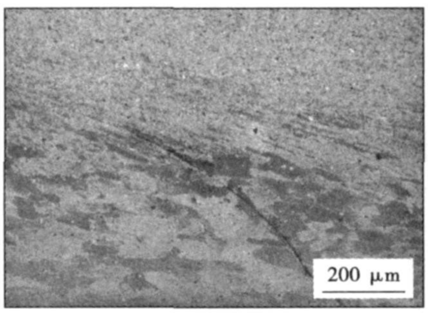
(a) 原始焊缝



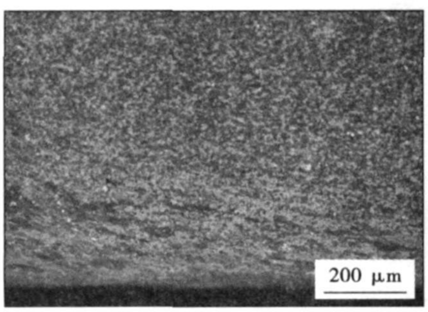
(b) 补焊焊缝

图 2　含有孔洞缺陷的原始焊缝及其补焊焊缝

Fig. 2　Cross-sections of initial weld with void defect and its repaired weld



(a) 原始焊缝根部



(b) 补焊焊缝根部

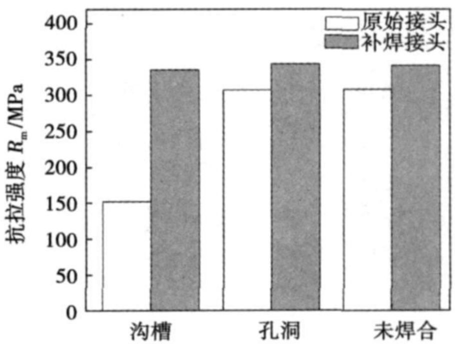
图 3　含有未焊合缺陷的原始焊缝根部及其补焊焊缝根部

Fig. 3　Cross-sections of initial weld root with kissing bond defect and its repaired weld root

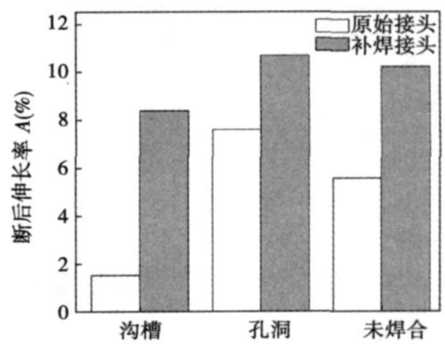
2.2　接头力学性能

补焊的主要目的是在消除焊接缺陷的同时，获得高强度的补焊接头. 图 4 给出了含有沟槽、孔洞和未焊合三种缺陷的原始接头及其补焊接头的性能对比. 由图可以看出，三种原始接头的抗拉强度均较低，尤其是含有沟槽缺陷的接头. 这说明焊接缺陷对接头性能具有显著的影响，因而不能允许它们在焊接结构中存在，一旦出现，必须加以消除.

采用优化的工艺参数进行补焊后，原来含有沟槽缺陷的接头强度从 152 MPa 提高到了 335 MPa，而原来含有孔洞和未焊合缺陷的接头强度分别从 307 和 308 MPa 提高到了 343，341 MPa，都接近于优质原始接头的强度，达到母材强度的 78％以上. 与此同时，原来含有沟槽缺陷的原始接头经补焊后其断后伸长率达到 8.4％，而原来含有孔洞缺陷和未焊合缺陷的原始接头经补焊后其断后伸长率均已达到 10％，是母材的 91％. 这些结果表明，采用搅拌摩擦补焊技术可以消除原始接头中所存在的焊接缺陷，而且接头性能能够达到优质原始接头的性能，满足工程对接头质量和力学性能的要求.



(a) 抗拉强度



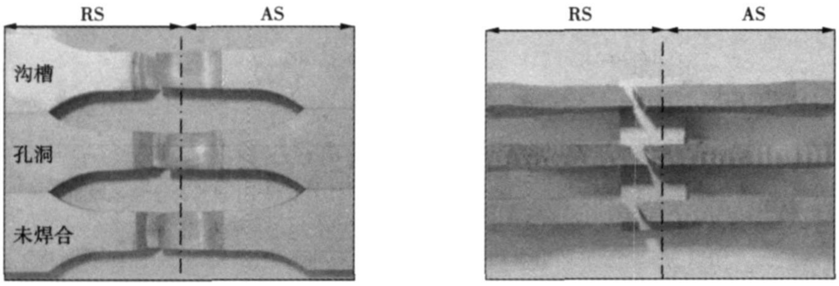
(b) 断后伸长率

图 4　含有不同缺陷的原始接头及其补焊接头的力学性能

Fig. 4　Mechanical properties of initial joints with different defects and its corresponding repaired joints

图 5 给出了与沟槽、孔洞和未焊合缺陷相对应的补焊接头的拉伸断裂位置. 补焊前，所有含有缺陷的原始接头在拉伸测试中均在缺陷所处部位发生断裂；经补焊后，所有补焊接头拉伸时均断在焊缝的

后退侧(即 RS),具体位置介于焊缝与热影响区的界面附近,断裂方向与焊缝表面成一定的角度. 至于拉伸时补焊接头均断在焊缝后退侧的原因,则有待于进一步的研究.

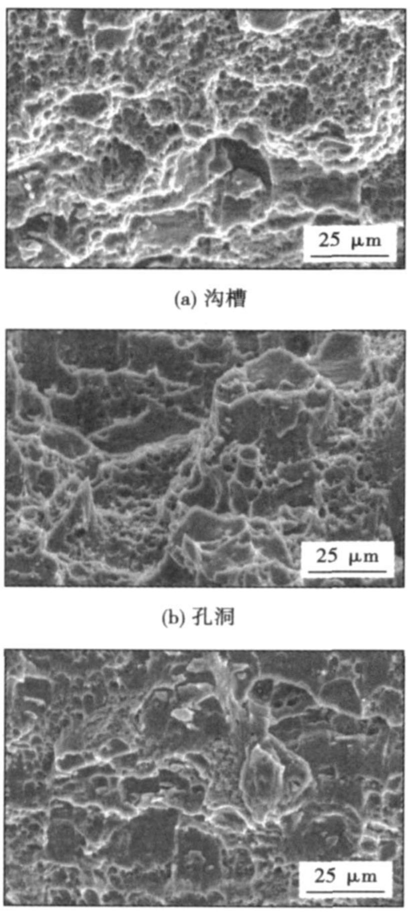


(a) 正面 (b) 侧面

图 5 与不同缺陷对应的补焊接头的拉伸断裂位置

Fig. 5 Fracture locations of repaired joints corresponding to different defects

由图 6 给出的断口扫描电镜形貌可以进一步看出,所有补焊接头的断口都具有典型的韧窝特征,断口上布满了大小不等的圆形或椭圆形的杯状凹坑群,而且在凹坑的底部有沉淀强化相存在. 在拉伸过程中,伴随着塑性变形的加剧,在颈缩中心部位,裂纹开始形核,成为多个显微孔洞,并在空间三个方向上均匀长大,最终形成圆形或椭圆形韧窝.



(a) 沟槽

(b) 孔洞

(c) 未焊合

图 6 与不同缺陷对应的补焊接头的断口

Fig. 6 Fracture surfaces of repaired joints corresponding to different defects

3 结 论

(1) 采用搅拌摩擦补焊技术能够消除对接头性能有显著影响的沟槽、孔洞和未焊合等搅拌摩擦焊接缺陷.

(2) 在优化的补焊工艺参数下,能够获得焊缝成形良好的补焊接头,其性能与优质的原始接头性能相当,抗拉强度达到母材的 78%以上.

(3) 无论哪种缺陷,其对应的补焊接头在拉伸测试中均在焊缝的后退侧发生断裂,拉伸断口具有明显的韧窝特征.

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Study of repair welding technology of friction stir welding defects

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Abstract: Welding defects can be also formed during friction stir welding under improper welding technology conditions, and the friction stir welding defects such as groove, void and kissing bond significantly influence the mechanical properties of joints. Friction stir welding process is utilized to repair these defects, and the focus is placed on the weld morphology and mechanical properties of the repaired joints. The experimental results indicated that the friction stir welding process can remove the above-mentioned welding defects, and the repaired joints have good weld morphology and excellent mechanical properties when optimum repair parameters are used. The fracture analysis showed that the repaired joints are ruptured on the retreating side of the weld in the tensile test, and the fracture surfaces are characterized by the clear plastic deformation dimples.

Key words: friction stir welding; welding defect; repair welding; weld morphology; mechanical property

Effects of different fluxes on the characteristics of Sn-Zn solders

WANG Hui, XUE Songbai, CHEN Wenxue, WANG Jianxin (College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211100, China). p5—8

Abstract: The wetting characteristics of Sn-Zn solders with three different types of flux were researched by wetting balance method. Results indicated that Sn-Zn solders exhibited excellent wettability using $ZnCl_2$-NH_4Cl flux. Additionally, the spreading of Sn-9Zn solder on Cu substrate with different types of flux was investigated, and the characteristics of the intermetallic compounds (IMC) between the solder and substrate were also analyzed and compared, results showed that a flat IMC layer was present adjacent to the Cu substrate while a scallop IMC layer was close to the solder. Moreover, the characteristics of IMC and the appearances of soldered joints varied by using different fluxes. Plenty of ZnO exists on the surface of Sn-Zn solders, thus removing the ZnO is critical for the flux of Sn-Zn solders.

Key words: lead-free solder; Sn-Zn; flux; wettability

Properties of Sn-3.0Ag-0.5Cu-xNi lead-free solders and soldering joints

WANG Lifeng[1,2], SUN Fenglian[2], LÜ Ye[2], SHEN Xuwei[2] (1. State Key Laboratory of Advanced Welding Production Technology, Harbin Instiute of Technology, Harbin 150001, China; 2. Harbin University of Science and Technology, Harbin 150040, China). p9—12

Abstract: The influences of the addition Nickel to Sn-3.0Ag-0.5Cu lead-free solder on the melting point, wettability, tensile properties and the properties of soldering joints were studied. The results show that the solder alloy exhibited improved wettability with the addition of small amount of Nickel. The wetting time decreases gradually and the wetting force increases gradually as Nickel content is within 0.03%~0.1%. When Nickel content is 0.05% the wetting time is the shortest. When Nickel content is 0.1% the wetting force is the biggest. The solder alloy exhibited very little change on the melting point. The solder alloy of the addition of Nickel exhibited improved elongation percentage and shear strength. When Nickel content is 0.1%, the elongation percentage and shear strength are the highest. Scanning fracture exhibits obvious ductility characteristic. The suitable of addition to the solder Nickel is within 0.05%~0.1%.

Key words: lead-free solder; wettability; shear strength

Arc sensor seam offset identification system based on LabVIEW and support vector regression machine

ZENG Songsheng, WANG Guorong, SHI Yonghua, HUANG Guoxing (South China University of Technology, School of Mechanics and Automotive Engineering, Guangzhou 510640, China). p13—16

Abstract: The new welding seam offset identification system of arc sensor was developed with the virtual instrument LabVIEW in this paper. The data detection, wavelet filtering, data normalizing, vertical mean filtering and horizontal dimensionality reduction were depicted based on LabVIEW. The basic principle of the support vector regression machine and data-dependent kernel function was introduced. The algorithm realization of the support vector regression machine with Matlab was proposed. The design method and the control flowchart of the seam offset identification software were proposed using LabVIEW and Matlab. The experiment results confirmed that the way was feasible, the identification precision could meet the actual application in the seam tracking system.

Key words: LabVIEW; support vector regression machine; Matlab; offset identification

Microstructure and wear resistance of metal-based ceramics composite coating deposited by plasma arc surfacing

LIU Zhengjun[1], ZONG Lin[1,2], SUN Jinggang[1], CI Honggang[1], SONG