AZ31 镁合金搅拌摩擦点焊

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摘　要: 研究了搅拌头旋转频率以及停留时间对 AZ31 镁合金搅拌摩擦点焊接头力学性能的影响. 随着旋转频率的增大，不同搅拌针条件下，AZ31 搅拌摩擦点焊接头的力学性能均呈现先增大后减小的趋势. 随着停留时间的延长，AZ31 搅拌摩擦点焊接头的力学性能先增大随后在一定范围内波动. 结果表明，结合宽度是影响搅拌摩擦点焊接头力学性能的重要因素，结合宽度越大，点焊接头的力学性能越好; 此外，上下板之间界面特征对搅拌摩擦点焊接头的力学性能也具有重要的影响.

关键词: 搅拌摩擦点焊; 力学性能; 旋转频率; 停留时间; 结合宽度

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0　序　言

搅拌摩擦点焊技术是在搅拌摩擦缝焊的基础上发展起来的一种新型焊接技术[1]. 在焊接过程中，搅拌头在固定位置形成点焊接头从而实现上下板之间的连接. 该过程主要包括三个阶段，即搅拌头压入过程、连接过程和搅拌头回撤过程. 搅拌头退出后，在焊点中心留下一个退出凹孔.

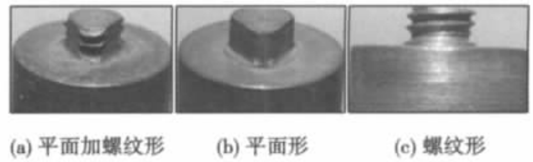
目前关于搅拌摩擦点焊的研究主要集中在铝合金方面，包括焊接工艺参数(搅拌头旋转频率、停留时间和压入深度等)[2-8]以及搅拌头形状(包括搅拌针、轴肩几何尺寸及形状等)[9-12]对接头微观结构及力学性能的影响. 研究表明，搅拌头旋转频率以及停留时间对搅拌摩擦点焊接头的力学性能具有直接的影响; 此外，改变搅拌头的形状通常会引起焊点结构特征的变化，包括搅拌区、结合区大小以及上下板界面处的连接形态等，从而影响搅拌摩擦点焊接头的力学性能.

由于目前搅拌摩擦点焊的研究主要是在铝合金的基础上开展的，关于镁合金搅拌摩擦点焊的研究还少有报道. 针对这一情况，主要对搅拌摩擦点焊工艺参数即搅拌头旋转频率、停留时间对 AZ31 镁合金搅拌摩擦点焊接头结合区域大小以及力学性能的影响进行了研究，提出了优化 AZ31 镁合金搅拌摩擦点焊接头的理论依据，并为镁合金搅拌摩擦点焊的深入研究提供了一定的基础.

1　试验方法

试验材料为厚度 1.5 mm 的 AZ31 板材(Mg-Al3.02-Zn0.80-Mn0.30-Si0.01，质量分数，%). 所有接头都采用搭接形式，试板尺寸为 100 mm × 25 mm，搭接长度为 25 mm，每组焊接参数重复试验 4 次，一个用于金相分析，其余三个用于拉伸试验.

试验过程中，所使用的搅拌头形状如图 1 所示，其中前两种用于改变搅拌头旋转频率的研究，第三种用于改变搅拌头停留时间的研究. 搅拌头材料均为 H13 钢，经热处理后其硬度达到 46 ~ 48 HRC，轴肩直径为 10 mm，搅拌针直径为 4 mm，搅拌针长度为 1.8 mm. 焊接过程中均采用恒定压入速度 2.5 mm/s，当改变搅拌头旋转频率时，保持停留时间 1 s 不变; 当改变停留时间时，保持搅拌头旋转频率为 2 250 r/min固定不变. 在金相试样的制备过程中，



(a) 平面加螺纹形　(b) 平面形　(c) 螺纹形

图 1　不同形状搅拌头

Fig. 1　Different tool designs of friction stir spot welding

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采用乙酸—苦味酸溶液腐蚀(10 mL 乙酸,4.2 g 苦味酸,10 mL 水和 70 mL 95% 的酒精).

2 试验结果及讨论

2.1 旋转频率对接头力学性能的影响

采用图 1a,b 两种不同形状搅拌头,保持下压速度 2.5 mm/s,停留时间 1 s 恒定的条件下,改变搅拌头旋转频率(1 000,1 500,2 250 和 3 000 r/min),研究旋转频率对 AZ31 搅拌摩擦点焊接头力学性能的影响.

图 2 所示为 AZ31 镁合金点焊接头在不同搅拌头旋转频率下的断裂载荷. 从图 2 中可以看出,随着搅拌头旋转频率的增大(1 000,1 500 和 2 250 r/min),接头的力学性能不断提高;旋转频率进一步增大到 3 000 r/min,接头的力学性能却有所下降. 当旋转频率为 1 000 r/min 时,力学性能最差,介于 1.0~1.5 kN 之间;当旋转频率为 2 250 r/min 时,接头的力学性能最好,为 2.5 kN 左右.

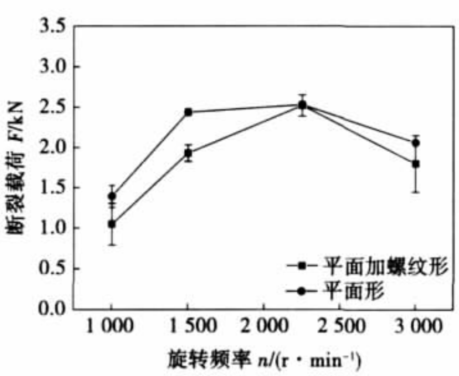

图 2 搅拌头旋转频率与断裂载荷之间的关系

Fig. 2 Relationship between tool rotational speed and failure load

当搅拌头旋转频率为 1 000 r/min 时,搅拌摩擦点焊过程中能量输入较低,上下板之间不能形成充分的冶金结合,导致结合区域宽度过窄,如图 3 所示.

在拉伸试验过程中,裂纹从未结合区域末端开始沿上下板之间的界面扩展,随后直接穿过狭窄的搅拌区而破坏,如图 4a 所示. 随着搅拌头旋转频率的增加,与 1 000 r/min 相比,焊接过程中的能量输入明显增大,上下板之间形成良好的冶金结合,结合区域较大,表现为点焊接头的结合宽度逐渐增大,如图 3 所示. 在拉伸试验过程中,裂纹并非直接穿过搅拌区,而是沿搅拌区边缘向上扩展,最后破坏在接头的上表面,如图 4b 所示.

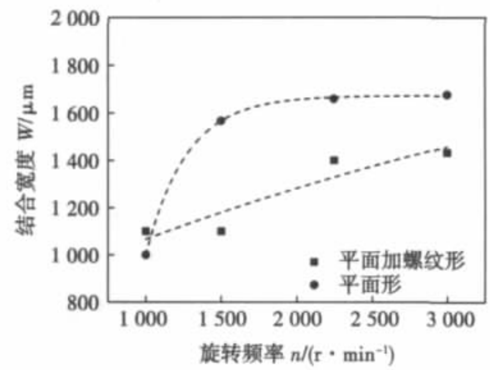

图 3 搅拌头旋转频率与结合宽度之间的关系

Fig. 3 Relationship between tool rotational speed and bonded width

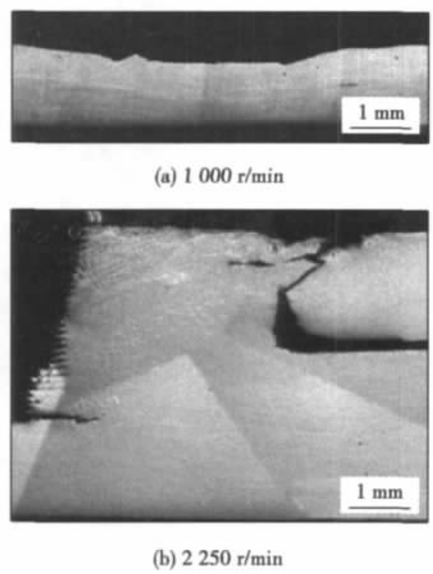

图 4 AZ31 搅拌摩擦点焊接头破坏形式

Fig. 4 Fracture modes of AZ31 spot welds

与平面加螺纹形搅拌针相比,由平面形搅拌针所产生的点焊接头具有较大的结合宽度,如图 3 所示,因此,在使用平面形搅拌针的情况下,AZ31 镁合金搅拌摩擦点焊接头的断裂载荷普遍高于由平面加螺纹形搅拌针所产生的点焊接头,如图 2 所示.

由图 2,图 3 还可以看出,当搅拌头旋转频率为 3 000 r/min 时,点焊接头结合区域达到最大值,但是与 2 250 r/min 相比,接头的力学性能却明显下降. 在 AZ31 搅拌摩擦点焊过程中,上下两板之间的界面不再是一平面,而是随焊接过程的进行发生了明显的变化,呈一向上弯曲的曲面,如图 5 所示. 两板之间的界线由破碎的氧化物粒子组成,即图 5 中的黑色分界线,称之为"Hook",这一区域表现为部分冶金结合,构成了点焊接头的不完全结合区域. 在拉伸试验过程中,裂纹首先沿着这一边界即

"Hook"扩展，随后向接头上表面运动，因此"Hook"末端距接头上表面距离的大小对接头的力学性能具有较大的影响. 为了便于测量，定义"Hook"的高度为 h，那么 h 越大，"Hook"末端距接头上表面的距离越小，接头的性能越差，相反则越好. 随着搅拌头旋转频率从 2 250 增加大 3 000 r/min，当采用平面形搅拌针时，"Hook"的高度 h 从 110 μm 增加到 180 μm，当采用平面加螺纹形搅拌针时，"Hook"高度 h 则从 80 μm 增加到了 490 μm. 正是由于"Hook"高度 h 的增加直接导致了"Hook"末端到接头上表面距离的减小，使得裂纹扩展路径变短，引起了 AZ31 搅拌摩擦点焊接头的力学性能的下降.

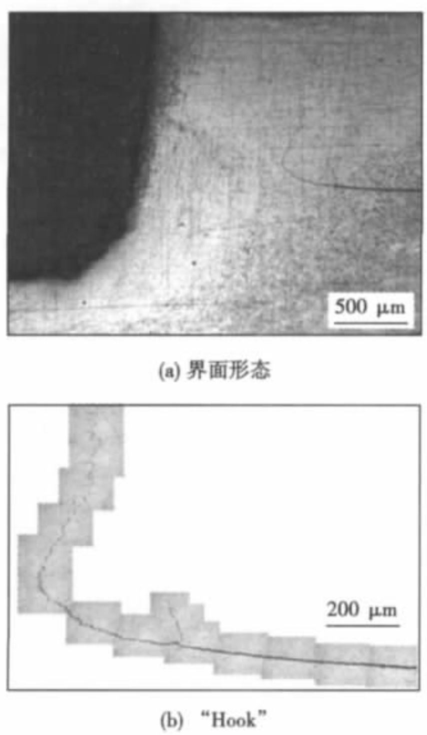

图 5　AZ31 搅拌摩擦点焊接头典型界面形态及"Hook"

Fig. 5　Typical interface of AZ31 friction stir spot weld and "Hook"

总的说来，AZ31 搅拌摩擦点焊接头的力学性能随搅拌头旋转频率的增加呈现先增大后减小的趋势. 在相同的搅拌头旋转频率条件下，与平面加螺纹形搅拌针相比，采用平面形搅拌针的接头具有相对较大的结合宽度，因此接头的力学性能较好.

2.2　停留时间对接头力学性能的影响

采用图 1c 所示螺纹形搅拌头，保持旋转频率 2 250 r/min，下压速度 2.5 mm/s 恒定的条件下，改变停留时间（0，1，2，3 和 4 s），研究停留时间对 AZ31 搅拌摩擦点焊接头力学性能的影响.

图 6 为不同停留时间 AZ31 搅拌摩擦点焊接头的断裂载荷. 首先随着停留时间的延长，接头的力学性能不断提高，当停留时间为 0 s 时，接头的力学性能最差，为 0.7 kN 左右；当停留时间超过 2 s 之后，接头的力学性能则无较大变化（将标准偏差考虑在内），停留时间为 2，3 和 4 s 时接头的断裂载荷分别为 2.12 kN ± 0.25 kN，2.32 kN ± 0.21 kN，2.25 kN ± 0.22 kN.

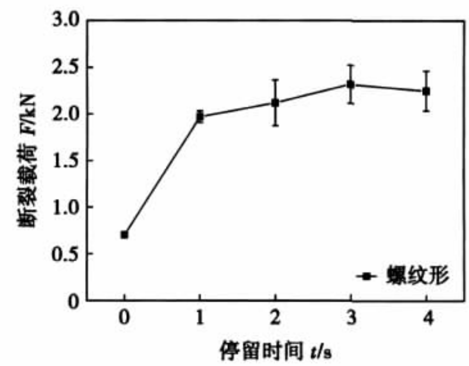

图 6　停留时间与断裂载荷之间的关系

Fig. 6　Relationship between dwell time and failure load

当停留时间为 0 s 时，由于轴肩与被焊材料接触时间较短，焊接过程中由轴肩与工件之间以及搅拌针与工件之间搅拌摩擦所产生的热量较少，能量输入过低，此外上下两板之间结合所必需的由轴肩提供的轴向压力严重不足，导致接头的结合区域过小（约为 800 μm），如图 7 所示. 在拉伸试验过程中，裂纹直接穿过狭窄结合区域破坏，其形式与图 4a 相类似，点焊接头的力学性能较差. 随着停留时间的延长，一方面轴肩与接头上表面充分接触，搅拌针与母材作用时间延长，能量输入明显增大，另一方面轴肩与接头上表面的充分接触，为上下两板之间的结合提供了足够的轴向压力，从而形成了具有较大的结合区域的搅拌摩擦点焊接头. 在拉伸试验过程中，点焊接头呈现出与图 4b 所示相同的破坏形式. 另外，由图 7 还可以看出，当停留时间分别为 2，3，4 s 时，AZ31 搅拌摩擦点焊接头的结合宽度无明显变化，这一趋势与图 6 所示接头的力学性能随停留时间的变化趋势相吻合；此外，当停留时间分别为 2，3，4 s 时，"Hook"高度 h 也无明显变化，在 250 μm 左右变化. 据此分析可知，随着停留时间的延长，AZ31 搅拌摩擦点焊接头的力学性能首先表现为增加的趋势（0 ~ 2 s），随着停留时间的进一步延长，点焊接头的力学性能则无明显变化（2 ~ 4 s），在一定数值范围内波动.

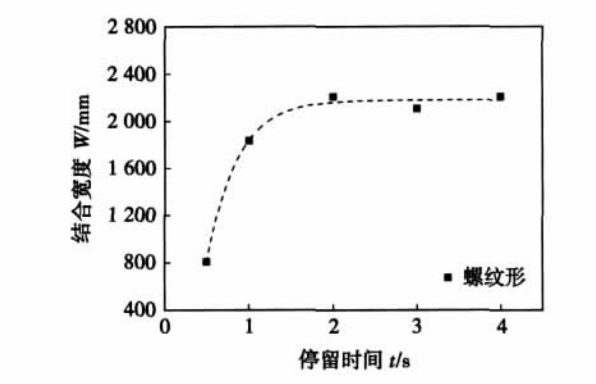

图 7 停留时间与结合宽度之间的关系
Fig. 7 Relationship between dwell time and bonded width

3 结 论

(1) 随着搅拌头旋转频率的增加,AZ31 搅拌摩擦点焊接头的力学性能首先呈线性增大趋势,1 000 r/min时接头力学性能最差,2 250 r/min 时接头力学性能最好; 随着旋转频率进一步增大到 3 000 r/min,接头的力学性能有所下降. 在相同的搅拌头旋转频率下,平面形搅拌针所产生的点焊接头与平面加螺纹形搅拌针相比,具有较好的力学性能.

(2) AZ31 搅拌摩擦点焊接头的力学性能随停留时间的延长首先表现为增加的趋势,0 s 时接头力学性能最差; 当停留时间超过 2 s 后,点焊接头的力学性能无明显变化,在一定范围内波动.

(3) 结合宽度是影响 AZ31 搅拌摩擦点焊接头力学性能的重要因素,结合宽度越大,点焊接头的力学性能越好; 此外,上下两板连接过程中界面处所形成的“Hook”的高度对搅拌摩擦点焊接头的力学性能也具有重要的影响.

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moved reversely 178 mV, the breakdown potential(0.1 V) of the substrate was higher than that of coating(−0.1 V), which demonstrated the corrosion resistance of the substrate was better than coating.

Key words: plasma cladding; Ni-based alloys; microstructure; corrosion resistance

Microstructure and performance of in-situ synthesis TiN particle reinforced Ni-matrix composite coating WANG Zhenting, ZHENG Wei, ZHOU Xiaohui (College of Materials Science and Engineering, Heilongjiang Institute of Science and Technology, Harbin 150027, China). p 93 − 96

Abstract: Ni-based composite coating reinforced by TiN particles were prepared on the surface of Q345D steel by means of argon arc cladding technique using Ti, BN and Ni powders as raw materials. The microstructure of the clad layer was observed by scanning electron microscope (SEM) and X-ray diffraction analysis (XRD). The TiN exhibited sphericity, irregular ellipse and dendrite shapes. The performance of coating were investigated by microhardness test and friction & wear machine. The average hardness of coating was about 840 HV. The argon arc clad composite coating had high hardness and excellent wear resistance under dry sliding wear test conditions.

Key words: argon arc cladding; in-situ synthesis; TiN; composite coating; wear resistance

Complex curved welding seam off-line teaching and tracking based on B3-spline WU Shide, HU Hao, YU Liang (School of Mechanical and Electronic Engineering, China University of Petroleum (Beijing), Changping, Beijing 102249, China). p 97 − 100

Abstract: The method of fitting and interpolation for the complex space curved welding seam tracking, depending on offline samples teaching style by B3-spline curves, was introduced in this paper. In order to improve both accuracy and efficiency of interpolation in seam tracking, the improved dichotomy was proposed for changeable step-size control by the look-up table method. From the Matlab simulation results of pipe welding intersecting lines samples teaching, the methods above could be proved effectively in the process of weld seam tracking control, it provided experimental foundation for developing actual welding control system. Finally, the validity of the method has been verified by welding test.

Key words: B3-spline; interpolation; improved dichotomy; seam tacking; teaching

Friction stir spot welding of AZ31 Mg-alloy YIN Yuhuan[1,2], HU Shengsun[1,2], North T. H.[3], ZHANG Xiaobo[4], SUN Na[5] (1. School of Material Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin University, Tianjin 300072, China; 3. University of Toronto Department of Materials Science and Engineering, Toronto M5S 3E4, Canada; 4. Shanghai Baosteel Casting Corporation, Shanghai 201900, China; 5. Key Laboratory of Automobile Materials of Ministry of Education, Jilin University, Changchun 130025, China). p 101 − 104

Abstract: The influences of tool rotational speed and dwell time on the mechanical properties of AZ31 friction stir spot welds were investigated. Along with the increase in tool rotational speed, the mechanical properties of AZ31 friction stir spot welds which were made by different tool designs increased first and then decreased. Along with the increase of dwell time, the mechanical properties of AZ31 friction stir spot welds increased first and then kept relatively constant. Bonded width affected the properties of friction stir spot welds significantly. The bigger the bonded widths, the better the properties of the friction stir spot welds were. In addition, the feature of the interface between the upper and the lower sheet also had an important influence on the properties of AZ31 friction stir spot welds.

Key words: friction stir spot welding; mechanical property; tool rotational speed; dwell time; bonded width

Characteristics of welding-brazed joint between Nb-1Zr alloy and 304 stainless steel LI Xin, ZHENG Jianping, ZHAO Jun (China Institute of Atomic Energy, P. O. Box 275-51, Beijing 102413, China). p 105 − 108

Abstract: Electron beam brazing of Nb-1Zr alloy to 304 stainless steel were investigated. It was found that two intermetallic compound layers were formed at brazing interface between stainless steel weld and Nb-1Zr alloy. The reaction layer Ⅰ on Nb-1Zr alloy side was loose organization formed of the Fe_2Nb, while reaction layer Ⅱ on stainless steel weld was formed pillar crystal which was composed of laminated Fe_2Nb and Fe-Cr. The reaction layer Ⅰ brought on frailty of joint and crack in welding. Thickness of reaction layer Ⅰ related to electron beam focus offset, and caused changes in joint strength over 100 MPa. It was not obvious in this experiment that the electron beam current and welding speed caused changes of joint characteristics.

Key words: Nb-1Zr alloy; EBW-brazing; intermetallic compound

Study on microstructure and propertys of TiC-VC particles reinforced surfacing layer prepared by novel twin electrodes welding SHI Hanchao, ZOU Zengda, ZOU Yong, WANG Yufu (Key Lab of Liquid Structure and Heredity of Materials, Ministry of Education, Shandong University, Jinan 250061, China). p 109 − 112

Abstract: The TiC-VC particles reinforced surfacing layer synthesized from ferrotitanium, ferrovanadium and graphite through metallurgy interaction by novel twin electrodes welding arc had been investigated in this paper. The microstructure and abrasion resistance of surfacing layer were analyzed by XRD、SEM and wear test machine. The results showed that Ti element mainly acted as deoxidize due to the unique twin electrodes welding arc structure, only a small quantity of TiC was formed in the surfacing layer. The main reinforcing phases in surfacing layer were in situ VC, as well as a litter (Ti,V)C phase dispersed in matrix. The surfacing layer had higher surface rigidity of exceeded 55 HRC and better abrasion resistance property. Wear weight loss of surfacing layer was only 1/16 of that of Q235 substrate.

Key words: twin electrodes; TiC-VC; surfacing layer; microstructure; abrasion resistance