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喷射成形7055铝合金FSW焊工艺与性能

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摘 要：采用搅拌摩擦焊接方法对厚度为4 mm的喷射成形7055铝合金板进行焊接试验. 分析了焊接速度和旋转频率对接头力学性能的影响，对焊缝的显微组织和断口进行了微观分析. 结果表明，当焊接工艺参数选择合适时，可得到外形美观，无缺陷的焊缝. 另外焊接接头力学性能与焊接工艺参数存在一定的关系，在旋转频率为1 000 r/min，且焊接速度为100 mm/min时，可以获得较好的焊接性能，抗拉强度可以达到455 MP，断裂形式为韧性和脆性的混合型断裂；焊缝中存在3个组织变化区，其中焊核区内是细小均匀的等轴晶；焊缝显微硬度的最低值出现在前进侧，说明前进侧是焊缝的薄弱环节.

关键词：喷射成形铝合金7055；搅拌摩擦焊；工艺；显微组织
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0 序 言

喷射成形工艺与传统的铸造工艺相比，其具有冷却速度快，材料元素固溶度大、晶粒细小、组织均匀、偏析程度小等特点. 喷射成形7055系铝合金具有超高强度和塑性，其综合性能在国际上处于领先地位，其强度在现有成熟牌号铝合金中最高[1]. 国外对喷射成形7xxx系铝合金的研究主要应用于无需焊接的大型飞机轮毂等产品，对喷射成形7xxx系铝合金焊接性的研究尚无国内外相关报道.

由于喷射成形铝合金的强化机理和熔焊截然不同，采用普通的熔焊工艺方法焊接存在明显的接头软化问题，很难达到喷射成形的强度[2]. 搅拌摩擦焊接(FSW)具有连接温度最低，对母材性能影响最小的特点. 对于同一种铝合金用搅拌摩擦焊与传统的氩弧焊相比，其焊接接头的抗拉强度提高15%～20%，断后伸长率提高1倍，断裂韧度提高30%，接头区为细晶组织，焊缝中无气孔、裂纹等缺陷，焊后残余变形很小，焊缝中残余应力低[2]. 因此文中选择不加填充材料的搅拌摩擦焊作为喷射成形铝合金的重点连接方法开展研究. 基于搅拌摩擦焊焊接的特点，可以认为是喷射成形7055铝合金最有前途的焊接技术.

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1 试验方法

1.1 试验材料

试验材料选择厚度为4 mm的喷射成形7055铝合金板材. 母材经挤压、轧制加工制备，其尺寸为250 mm×100 mm×4 mm. 表1为该材料的化学成分.

表1 母材化学成分(质量分数，%)
Table 1 Chemical compositions of base metal

Mg	Cu	Zn	Si	Fe	Mn	Cr	Ti	Al
1.8～2.3	2.0～2.6	7.6～8.4	0.1	0.15	0.05	0.04	0.06	余量

1.2 焊接工艺

FSW试验是在数控四坐标四联动搅拌摩擦焊焊机和自制的夹具上进行的. 试验采用轴肩16 mm、探针长度3.85 mm的圆锥型的搅拌头进行焊接，在轴肩压入量为0.15 mm，搅拌头倾角为2.5°，旋转频率400～1 500 r/min，焊接速度在40～180 mm/min的范围变化时，研究其接头的成形与性能.

2 试验结果及分析

2.1 焊接速度对接头力学性能的影响

焊接速度是搅拌摩擦焊接中一个重要的工艺参数，在旋转频率(1 000 r/min)不变的情况下，分别

在 40 ~ 180 mm/min 内取值进行焊接. 当焊接速度为 180 mm/min 时,焊接接头无法成形,焊缝无法焊合,并有大量粉末状金属经搅拌甩出,形成沟槽缺陷,当焊接速度降到 150 mm/min 时情况有所好转,表面成形良好,但切开焊接接头横截面观察,内部出现隧道形缺陷,且隧道形缺陷出现在焊缝前进侧,如图 1 所示.

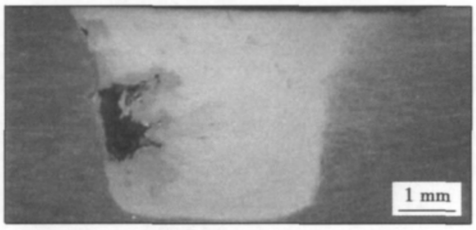
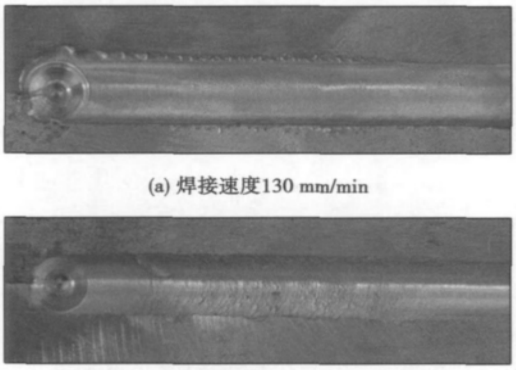


图 1 喷射成形 7055 铝合金焊缝隧道缺陷

Fig. 1 Spray formed 7055 aluminum alloy tunnel flaw

当焊接速度降至 130 mm/min 时焊缝能够焊合且表面成形性良好,如图 2a. 当焊接速度降至 60 mm/min时,焊缝表面很不平整,成形不好,表面粗糙,如图 2b.



(a) 焊接速度130 mm/min

(b) 焊接速度60 mm/min

图 2 焊缝宏观形貌

Fig. 2 Macrograph of weld joint

选取旋转频率为 1 000 r/min,焊接速度在 60 ~ 150 mm/min 的条件下,研究焊接速度对喷射成形 7055 铝合金板材焊缝力学性能的影响,试验结果如图 3 所示. 在此范围内焊缝的力学性能随着焊接速度的增加先增加后减小,且在当搅拌头旋转频率为 1 000 r/min,焊接速度为 100 mm/min 时达到最高值 455 MPa.

从图 3 可见焊接速度对喷射成形 7055 铝合金焊缝成形和接头力学性能有着重要的影响,当焊接速度过大,热输入较小时,搅拌头摩擦产热不足,焊

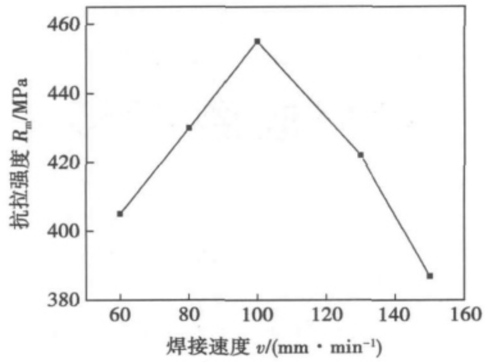


图 3 不同焊接速度时焊缝的抗拉强度

Fig. 3 Tensile strength for different welding speeds

缝成形很差,容易出现沟槽、隧道等缺陷,从而导致力学性能的降低. 当焊接速度过小时,由于摩擦生热过多,有时甚至使焊合区表面温度接近熔点,焊缝表面凸凹不平,热力影响区晶粒严重粗化,同样会影响接头的力学性能. 可见只有适中的焊接速度焊缝成形最佳. 因此对 4 mm 喷射成形 7055 铝合金试板进行搅拌摩擦焊,在旋转频率为 1 000 r/min 时,焊接速度的范围应该是 80 ~ 130 mm/min.

2.2 旋转频率对接头力学性能的影响

旋转频率不仅对焊缝表面宏观形貌有影响,而且直接影响焊缝的成形和焊接接头的力学性能. 焊接速度(80 mm/min)不变的情况下,在 400 ~ 1 500 r/min 的范围内调整搅拌头的旋转频率. 当旋转频率为 400 r/min 时,搅拌针在焊接过程中根部断裂,不能实现焊接过程. 继续提高旋转频率到 600 r/min,焊缝正面成形较好,但背面较为粗糙. 随着旋转频率提高至 800 ~ 1 200 r/min 时,焊缝正面及背面成形逐渐好转. 但当旋转频率升高至 1 300 r/min 时,热力影响区过大,当旋转频率继续升高至 1 500 r/min 时,由于产热过高,甚至出现表面熔化粘连搅拌头的现象. 对于喷射成形 7055 铝合金试板进行搅拌摩擦焊时,旋转频率为 800 ~ 1 200 r/min 较为合适.

焊接接头力学性能试验结果如图 4 所示,焊接速度为 80 mm/min,旋转频率为 800 ~ 1 200 r/min 时力学性能较好且较稳定,当旋转频率降低到 600 r/min 时力学性能有所降低,主要是因为旋转频率过低,接头处得到的能量不足以使金属完全塑化,当旋转频率达到 1 500 r/min 时,由于旋转频率过高,接头内部也会出现过热的粗大组织,以至于接头强度下降[4].

2.3 喷射成形 7055 铝合金 FSW 焊缝的显微组织

对旋转频率 1 000 r/min、焊接速度 100 mm/min

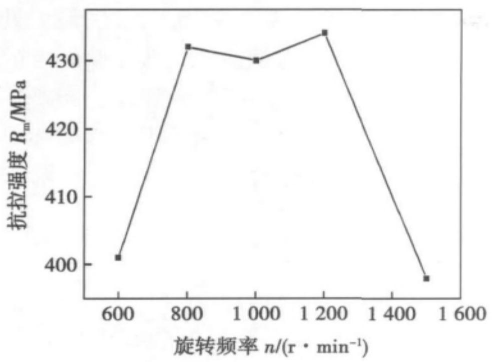


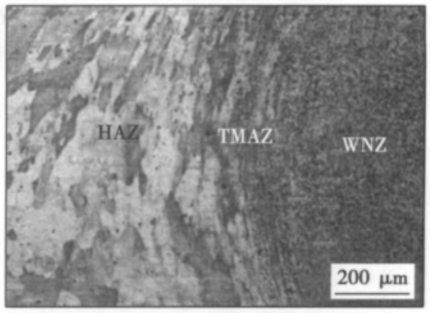
图 4　不同旋转频率时焊缝的抗拉性能
Fig. 4　Tensile strength for different rotation frequencies

下喷射成形 7055 铝合金 FSW 焊接接头显微组织进行取样观察，焊接横截面金像组织如图 5 所示. 由图 5a 可见，焊缝中原始板条状形貌发生显著改变，焊缝的组织、方向、形貌均发生较大的变化，可将焊缝分为 3 个区域：焊核区（WNZ）、热力影响区（TMAZ）和热影响区（HAZ），见图 5b ~ 图 5d.

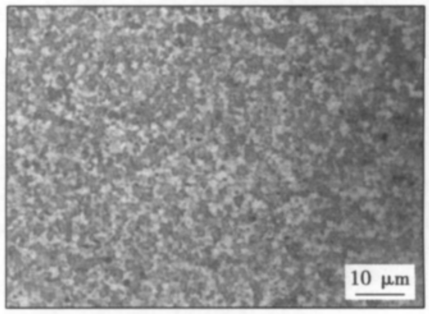
图 5b 显示的焊核区位于焊接接头的中心，是最接近搅拌头轴肩的区域，由于受到搅拌头强烈的搅拌作用以及由剧烈摩擦产生的局部高温作用，组织发生完全动态再结晶，由母材原始的板条状转变成细小的等轴晶.

图 5c 显示的热力影响区为发生了塑性变形与动态再结晶的焊缝组织所对应的区域. 在搅拌头的搅拌作用下，母材内原始板条组织发生了较大的弯曲变形和破碎现象，并在焊接热循环下发生了回复和再结晶长大，其晶粒大小和形貌变化很大.

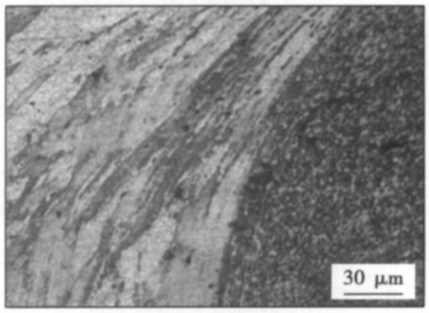
图 5d 显示的热影响区为受到了焊接热循环作用但没有受到机械作用的区域. 发现其晶粒与母材相似，但出现了晶粒粗化现象，而且各个区域的晶粒粗化程度也不同. 原因在于该区域的材料受热循环的影响，微观组织和力学性能均发生了变化，但没有发生塑性变形. HAZ 各部位所经历的焊接热循环，实际上是各自进行着一个特殊的热处理过程. 虽然保持着母材板条状的基本形貌，但这种焊接热循环造成的特殊热处理，引起了不均匀的组织变化，带给焊缝不良的影响[5].



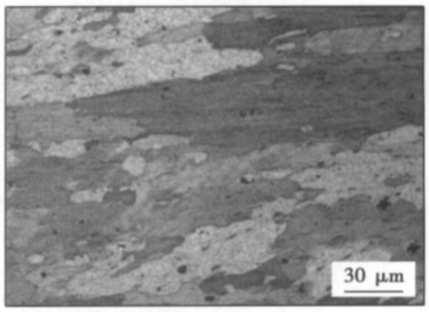
(a) 焊缝全貌



(b) 焊核区



(c) 热力影响区



(d) 热影响区

图 5　喷射成形 7055 焊缝的显微组织
Fig. 5　Microstructure of spray formed 7055 aluminum alloy

2.4　喷射成形 7055 铝合金 FSW 焊缝断口分析

从喷射成形 7055 铝合金板焊缝在旋转频率为 1 000 r/min，焊接速度为 80 mm/min 时的拉伸试样断口来看，试样断裂在焊缝前进侧热力影响区处，试样稍有颈缩但不明显. 图 6 为焊缝断口的微观形貌. 由图 6 可见，焊缝拉伸断口断面上分布的韧窝尺寸较小，断口微观形貌中有少量断口平坦区域，带有轻微的脆性断裂特征，因此拉伸断口为混合型断口，焊缝断裂为混合型断裂. 韧窝中还出现了韧性断裂常见的颗粒，有完整的颗粒，也有断裂的颗粒，断裂的颗粒一般较大，切断裂面垂直于拉伸轴，这些颗粒是焊后析出的第二相. 在拉伸断裂过程中，大尺寸的颗粒断裂几率较大，主要是因为大颗粒周围

的残余应力及颗粒中所含裂纹的几率较大，此外在受拉时容易在大颗粒周围产生应力集中，因此在拉应力作用下容易沿拉应力垂直方向发生断裂[2].

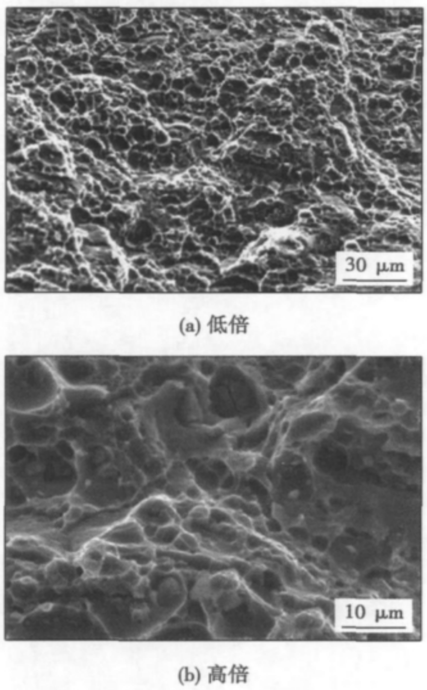


图6　喷射成形7055铝合金接头断口扫描电镜形貌

Fig. 6　SEM images of tensile fracture of spray formed 7055 aluminum alloy welds

2.5　喷射成形7055铝合金焊缝显微硬度分析

图7为旋转频率1 000 r/min、焊接速度100 mm/min的厚度4 mm喷射成形7055铝合金搅拌摩擦焊焊缝横截面中部的显微硬度分布曲线.

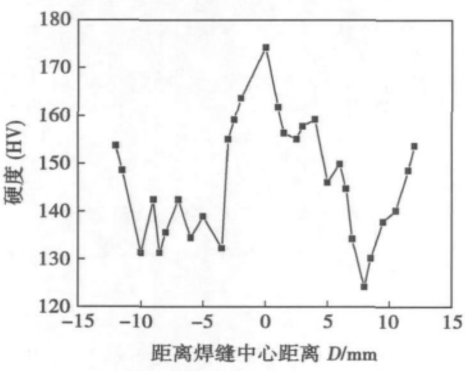


图7　喷射成形7055铝合金焊缝显微硬度分布

Fig. 7　Micro-hardness of spray formed 7055 aluminum weld

从图7中可见沿焊缝横截面硬度的分布呈W形，即焊缝两侧母材硬度最高，到热力影响区硬度逐渐降低，至焊核区硬度又逐渐升高，硬度最低处位于前进侧的TMAZ-HAZ过渡区域. 从显微硬度的分布来看和常规的搅拌摩擦焊接头的硬度分布规律基本相同，最薄弱的是前进侧，说明采用搅拌摩擦焊焊接喷射成形铝合金是可行的.

3　结　　论

（1）成功的实现了厚度4 mm喷射成形7055铝合金板的搅拌摩擦焊，在旋转频率为1 000 r/min，且焊接速度为100 mm/min时，可以获得较好的焊接性能，抗拉强度可以达到455 MPa.

（2）喷射成形7055铝合金焊缝的断裂形式为韧性和脆性混合型断裂.

（3）焊缝显微硬度的最低值出现在前进侧TMAZ-HAZ过渡区域，说明前进侧是薄弱环节.

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Abstract: Based on explicit analysis, a 3D FE model coupled with thermo-mechanical of radial friction lap welding joint was established with 45 steel by applying ABAQUS software. Assuming that the deformation rate is known, it is discussed the field of temperature on the welding interface and the loading force on the radial ring in the paper. Using the Johnson-cook constitutive model, thermal properties, friction coefficient changing with temperature and plastic deformation heat were also considered, The temperature field distribution and the deviation of loading pressure were predicted and analyzed. The results show that without considering the heat transfer of the radial ring and the fixture, the radial ring is formed to fixture as the center to form an elliptical temperature gradient distribution and to fixture void as the center to form an strip temperature gradient distribution. The maximum temperature reached 1 260 ℃ and 1 050 ℃. In order to simplify the welding process, the loading force curve fit for three compression process. The explicit analysis, the standards and the constitutive model were feasible.

Key words: radial friction welding; temperature field; friction heat; numerical simulation

Microstructure and properties of titanium alloys welds using ultrasonic frequency pulse GTAW YANG Mingxuan, QI Bojin, CONG Baoqiang, WANG Lexiao (School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China). pp 39 – 42

Abstract: Based on butt welding during Ti-6Al-4V (TC4) titanium alloys plate with the thickness of 1.5mm, microstructure of weld face and properties of welded joint were investigated by ultrasonic frequency pulse gas tungsten arc welding (GTAW). Compared with conventional direct current GTAW process, the experimental results show that ultrasonic frequency pulse current causes the energy concentration with an obvious pinch effect of arc plasma and the increasing escape speed of gas pore. Grain refining and the elimination of gas pore are due to the enhancement of fluid flow by ultrasonic frequency pulse GTAW process for Ti-6Al-4V titanium alloys. The main structure of subcrystal is the basketweave microstructure composed of rod-shaped martensite or the interlaced microstructure composed of both rod-shaped and plate phase. Similarly, ultrasonic frequency pulse GTAW process could also improve the elongation and reduction of area.

Key words: ultrasonic frequency pulse GTAW process; microstructure; mechanical properties; grain refining

Effect of holding time on interface structure and bonding strength of diffusion bonding joint of TiAl and Ni-based alloy LI Haixin, LIN Tiesong, HE Peng, WEI Hongmei, FENG Jicai (State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China). pp 43 – 46

Abstract: Diffusion bonding of TiAl to Ni-based alloy (GH99) with Ti interlayer was carried out. The reaction products and the interface structures of the joints were investigated by scanning electron microscopy, electron probe X-ray microanalysis and X-ray diffraction. The results show that four kinds of reaction layers are formed at the interface between the GH99 alloy and Ti interlayer, such as $(Ni, Cr)_{ss}$, rich Ti-$(Ni, Cr)_{ss}$, TiNi and Ti_2Ni. When the holding time is short, $Ti(Al)_{ss}$ layer is formed at the interface between Ti interlayer and TiAl alloy. With the holding time increasing, the $Ti(Al)_{ss}$ reaction layer transformed into Ti3Al and Al_3NiTi_2. With the holding time increasing, the thickness of TiNi reaction layer increases, while the thickness of Ti_2Ni layer increases firstly and then decreases. The shear test results show that the shear strength of the joint increases at first, then decreases, and then increases with the holding time increasing. The fractographs of the joints show that the fracture mainly occurs in the Ti_2Ni reaction layer.

Key words: titanium aluminium alloy; Ni-based alloy; diffusion bonding; interface structure; shear strength

Relationship between metal transfer and arc shape in twin-wire indirect arc welding CAO Meiqing[1], ZOU Zengda[2], QU Shiyao[2] (1. College of Material Science and Engineering, SUST, Qingdao, Shandong 266510, China; 2. College of Material Science and Engineering, Shandong University, Jinan 250061, China). pp 47 – 50

Abstract: Relationship between metal transfer, arc shape and arc voltage was investigated with high speed camcorder system and digital oscillograph. Results show that metal transfer has a close relationship with arc voltage and the regular variation of arc shape. It shows that the regular changes of metal transfer make polarity spots spacing and arc beam resistance change and cause the arc voltage fluctuations, so that the arc shape changes regularly. Droplet transfer pattern changes and droplet size dereases with the increasing of welding current, different metal transfer mode has different arc voltage fluctuation, spraying transfer has lower variation of voltage but short transfer's arc voltage variation is bigger.

Key words: metal transfer; arc shape; arc voltage

Study on process and property of FSW of spray formed 7055 aluminum alloy YAN Keng, LIU Jun, SHI Chao (Provincial Key Lab of Advanced Welding Technology, Jiangsu University of Science and Technology, Zhenjiang 212003, China). pp 51 – 54

Abstract: Friction-stir welding was employed in the welding experiment of spray formed 7055 aluminium alloy plate with thickness of 4 mm. The influence of the rotating rate and the welding speed on the mechanical properties of the joint, microstructure of the weld, and the fracture mode were analyzed. The results showed that good-looking, defectless welds could be obtained with proper welding parameters. The mechanical properties of the joints were related to the welding parameters. When the rotating rate was 1 000 r/min and the welding speed was 100 mm/min, the joints achieved good mechanical properties. The tension strengths of the joints reached 455 MP, and the fracture mode was ductile and brittle mixed. The welds consisted of three zones, among which the weld-nugget zone consisted of fine equiaxed grains. The minimum micro-hardness occurred on the advancing side, which indicated the advancing side is the weakness of the weld.

Key words: spray formed 7055 aluminium alloy; FSW; welding process; microstructure