Incoloy 825 镍基高温合金电子束焊工艺及接头组织与力学性能分析

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摘要: 采用电子束焊, 对空冷器管箱 Incoloy 825 镍基高温合金进行对接焊试验. 通过对焊接接头的组织观察, 并结合拉伸力学性能以及接头的冲击韧性等试验, 分析镍基高温合金电子束焊接头的组织和力学性能. 结果表明, 采用电子束焊焊接镍基高温合金可以得到良好的焊接接头, 焊缝区组织由大片等轴晶和少量柱状晶组成; 焊缝区没有出现明显的元素烧损现象; 焊缝、热影响区硬度达到母材硬度值; 焊缝接头抗拉强度达到 600 MPa, 接近母材抗拉强度, 接头断裂形式为韧性断裂; 焊缝和热影响区的冲击吸收能量高于母材区, 其中焊缝区的冲击吸收能量达到了 262 J, 冲击断口形貌为韧窝状.

关键词: 电子束焊; 镍基高温合金; 微观组织; 力学性能
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0 序言

Incoloy 825 以 Ni-Fe-Cr 为基体, 由于其较高的力学性能, 较好的高温耐腐蚀性能以及在高温服役条件下的性能稳定性[1-3], 被广泛应用于石油化工、涡轮发动机、核能以及航空航天等领域[4]. 因其通常服役于高温高压的疲劳条件下, 因此对其材料焊接提出了更高的要求, 特别是对腐蚀条件下的高温、高压镍基合金大厚板的焊接提出了挑战性高的工程需求, 近几年来学者们一直致力于该材料的稳定及可靠的焊接工艺的探索.

电子束焊接是以高能量密度的电子束轰击焊接接头处的金属使其快速熔化, 以达到焊接目的[5]. 相比传统焊接方法 (SMAW, SAW, GTAW 等), 电子束焊在提高产品焊接质量及效率, 降低焊接污染及排放等方面有显著优势, 并且电子束具有熔深大、熔宽小、热效率高等特点[6], 因而工件的变形极小, 焊缝热影响区很窄[7-8]. 电子束焊不仅能焊接各种高难熔金属及合金材料, 减小焊接过程误差, 而且可以精确地确定焊缝的位置, 特别是对厚板的焊接, 与其它焊接方式比较, 大大提升了精确率[9]. 众多学者对电子束焊厚板焊接进行了研究. 王喆等人[10] 对 40 mm 厚 316L 不锈钢进行电子束焊接试验, 得到单面焊双面成形的平行焊缝, 焊缝力学性能优良. Vivek 等人[11] 对 lnconel 718 电子束焊进行研究, 分析了不同热输入对焊缝的影响. 近年来, 空冷器作为炼油、化工、电力等行业不可或缺的设备, 需求量呈上升趋势[12]. 在制造空冷器过程中, 工作量大部分集中在空冷管箱的焊接, 在国外空冷器制造行业真空电子束焊已有成熟的经验和大量的应用, 而国内的空冷器制造行业采用真空电子束焊接目前处于空白.

采用电子束焊对空冷器管箱 Incoloy 825 镍基高温合金进行对接焊, 利用 SEM、夏比冲击试验、拉伸等手段, 探究镍基高温合金电子束焊的显微组织和力学性能, 为镍基高温合金空冷器的电子束焊应用提供试验基础.

1 试验方法

试验采用 THDW-30 电子束焊机进行电子束焊. 该系统是由真空系统和直热式电子枪组成. 为了达到试验所需的真空环境, 电子束系统被安置在

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真空室中，真空室由聚焦线圈、偏转线圈、电源及焊接小车等部件组成. 其中，焊接加速电压为 85 kV，电子束流为 165 mA，电子枪室压力为 5×10^{-2} Pa，焊接速度为 400 mm/min，聚焦电流为表面聚焦. 试验中采用两块尺寸为 120 mm × 150 mm × 32 mm 的 Incoloy 825 镍基高温合金作为试验材料进行对接焊，并在两块基材下面加垫板，以保证全焊透. 焊接前采用钨极氩弧焊对焊件、垫板进行点焊固定，确保试样边界之间的间隙小于 0.15 mm. 固定后对试样进行机械打磨和丙酮清洗，防止焊缝产生缺陷和降低力学性能. Incoloy 825 镍基高温合金的化学成分见表 1.

表 1　Incoloy 825 镍基高温合金化学成分表 (质量分数，%)

Table 1　Chemical composition of commercial Incoloy 825

Ni	Cr	Fe	Mo	Cu	Ti	Mn	Si	S	C
38 ~ 46	19.5 ~ 22.5	≥ 22	2.5 ~ 3.5	1.5 ~ 3	0.6 ~ 1.2	≤ 1	≤ .5	≤ 0.03	≤ 0.05

2　结果与分析

2.1　焊缝微观组织分析

为研究电子束焊对焊接接头组织及性能的影响，对试样进行金相组织分析. 经过打磨抛光和腐蚀完成金相试样的制备. 所选用的腐蚀液为浓盐酸和浓硝酸按体积比为 3∶1 配成的王水，接头横截面宏观形貌如图 1 所示，焊缝形貌整体呈现“钉字形”，并且从图中可以看出，焊接接头截面无可见杂质、气孔、裂纹等缺陷存在，实现了很好的冶金接合. 图中 A, B, C 位置的熔深熔宽比分别为 33∶4, 33∶3, 33∶2, 没有明显的变形.

图 1　接头横截面宏观形貌

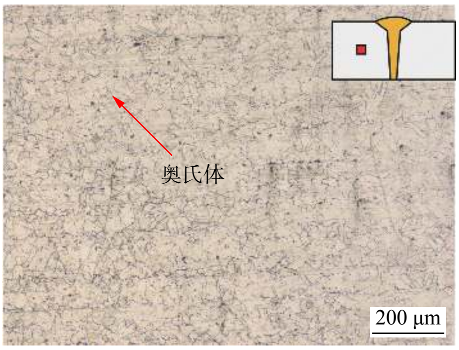
Fig. 1　Section morphology of welded joint cross section

采用光学金相显微镜对接头截面的母材区、焊缝区和热影响区的显微组织特征进行分析. 图 2 为不同位置的显微组织，从图 2a中可以看出基材由奥氏体组成. 图 2b 为焊缝与母材交界区域，母材由于受到热影响，奥氏体晶粒变大. 在焊缝一侧靠近母材区域主要由柱状晶组成，这是由于结晶过程刚刚开始时温度梯度较大，导致成分过冷区较小，难以在液相中发生均匀形核，因此在母材的晶体表面发生非均匀形核而形成联生结晶现象，枝晶沿着温度梯度最大的焊缝方向生长，从而生成柱状晶. 而由于电子束焊焊缝宽度小，冷却速度快，成分过冷迅速增大，溶质原子很快在焊缝中心处的液相中形成新的晶核，并沿着各个方向均匀生长，同时也阻碍了柱状晶的生长形成大片等轴晶区域. 图 2c 中由于焊缝下层较窄，出现等轴晶柱状晶共存的区域，而图 2d 焊缝较宽，焊缝中心成分过冷区域大量形核出现了大片的晶粒细小的等轴晶区. 细小的等轴晶组织能改善焊缝的力学性能，从而达到母材的性能要求.

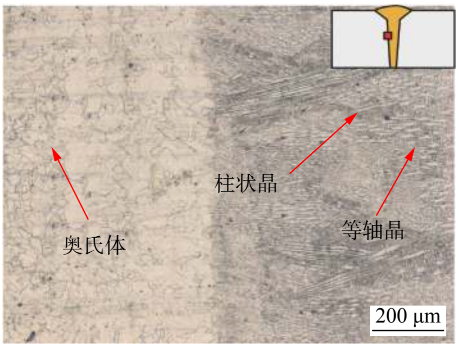
对焊缝的不同位置进行元素线扫描，图 3 为不同区域线扫描，左侧为焊缝区，右侧为热影响区，由图可知，试验所测得熔合线两侧的元素含量没有发生明显的变化，都呈现出比较平均的状态，说明电子束焊所得到的焊缝元素分布均匀，从而保证了焊缝区域较好的力学性能.

2.2　焊接接头的力学性能

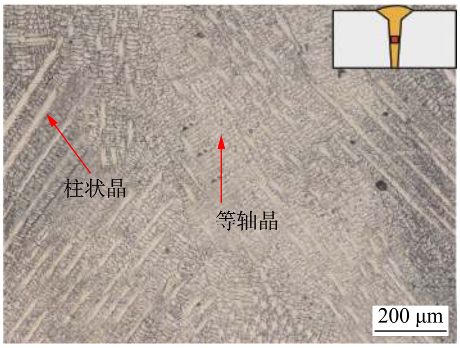
图 4 所示为不同区域显微硬度分布，通过对沿焊缝和垂直于焊缝的上、中、下层硬度对比可以看出，硬度在试样上呈均匀分布，焊缝中心的细小等轴晶区域内，硬度跟母材保持接近，热影响区由于范围窄，没有明显的划分区域，因此硬度也与母材相差不大，所测量的 3 个位置硬度值都在 180 ~ 230 HV 之间. 沿焊缝高度可以看出，随着距焊缝上表面越远，硬度下降的趋势越明显，这是由于靠近



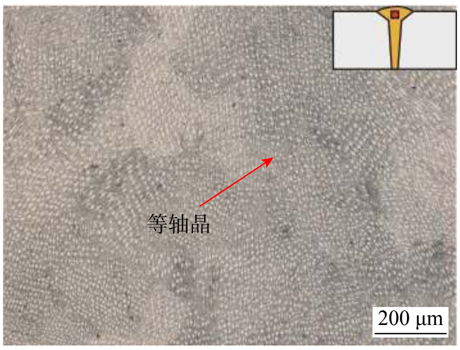
(a) 母材



(b) 熔合线



(c) 焊缝中部

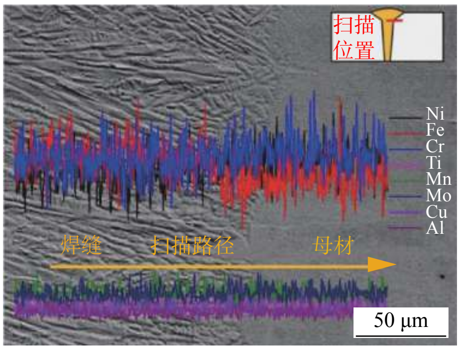


(d) 焊缝上部

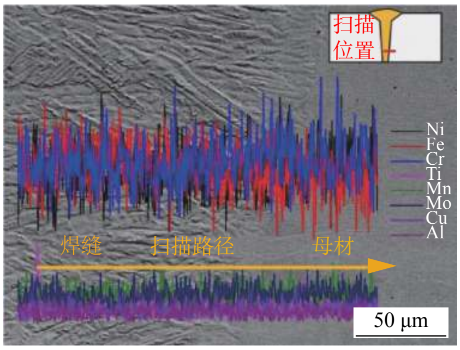
图 2　接头截面微观组织

Fig. 2　Microstructure of joint. (a) base metal; (b) fusion line; (c) middle part of the joint; (d) upper part of the joint

上表面的位置有大量等轴晶聚集，而焊缝越深，熔宽越小，金相组织中出现较多的柱状晶，但总体硬度仍然保持在 190 HV 以上，因此电子束焊接



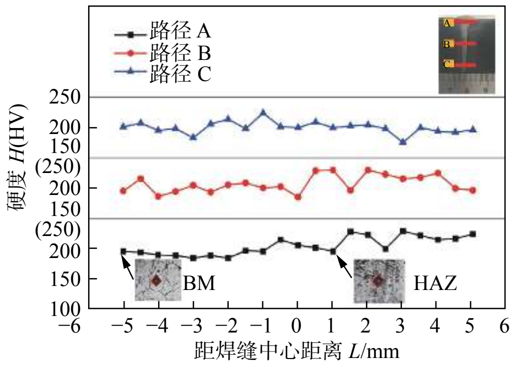
(a) 焊缝上部



(b) 焊缝下部

图 3　不同焊缝区域线扫描图

Fig. 3　Line scanning of microstructure in different welding areas. (a) upper part of the joint; (b) bottom part of the joint



(a) 垂直于焊缝方向

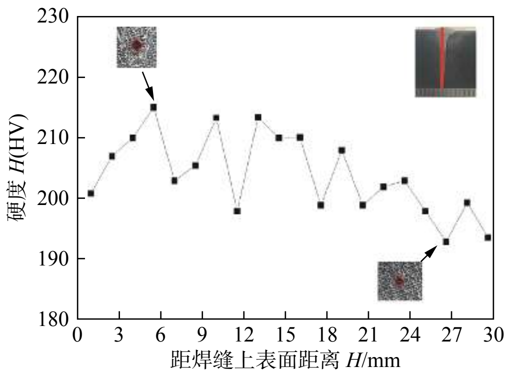


图 4　接头的硬度分布

Fig. 4　Micro-hardness distribution in joints. (a) along transvers direction of joint; (b) along the joint

Incoloy 825 镍基合金后得到的焊缝显微硬度达到母材硬度性能要求.

对 Incoloy 825 镍基高温合金母材试样和焊接试样进行了拉伸性能分析, 图 5 为焊件试样拉伸曲线, 从曲线中可以看出试样抗拉强度达到 600 MPa, 而母材的抗拉强度在 613 MPa 左右, 因此所得到的焊缝抗拉强度基本达到母材强度. 从曲线中可以看出断裂方式为韧性断裂, 应变达到 17%, 说明焊缝具有较好的塑性. 图 6 为拉伸试件宏观断裂形貌, 断口呈现明显的颈缩. 图 7 为焊缝拉伸断口形貌, 焊件试样断裂在焊缝区, 从图 7 中可以看到明显的韧窝, 断裂方式为典型的韧性断裂. 韧窝的形状和大小不同, 形状多表现为圆形和椭圆形, 大小交错分布, 主要呈现为一个大韧窝周围分布多个小韧窝的形貌, 同时在韧窝中出现较多的第二相颗粒. 这些小颗粒与基体结合良好, 在拉伸过程中延缓了微裂纹的产生, 增加焊缝的抗拉强度和断后伸长率; 并且材料在拉伸过程中, 会产生较大的变形, 在该过程中, 伴随着位错的产生与运动, 这些第二相小颗粒的存在, 对位错的运动起到了一定的阻碍作用, 对焊缝强度的提高起到了促进作用.

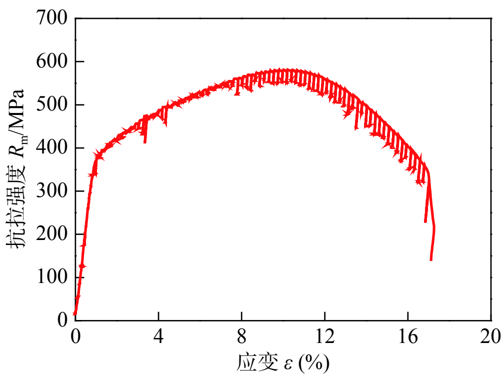


图 5　拉伸曲线

Fig. 5　Stress-strain curve of joint

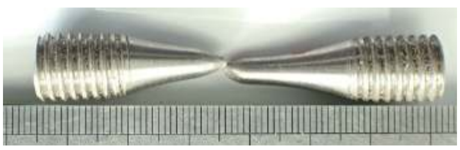


图 6　拉伸件宏观断裂形貌

Fig. 6　Macroscopic fracture morphology of tensile parts

为了进一步研究焊接接头的力学性能, 采用微机控制摆锤冲击试验机, 在低温−196 ℃ 条件下对母材、焊缝区和热影响区试样进行冲击性能试验, 分析电子束焊对镍基高温合金的焊缝、热影响区和母材的影响, 试样尺寸遵循夏比冲击试验试样标准. 图 8 中可以看出, 焊缝区冲击吸收能量在 262 J 左右, 热影响区与焊缝接近, 在 255 J 左右, 焊缝区和热影响区的冲击吸收功都达到母材的强度, 这是由于焊缝处晶粒多为等轴晶, 并且在元素线扫描中, 不论是焊缝区还是热影响区, 没有出现明显的元素烧损, 因此强度和塑性都比较好, 表现出的冲击性能与母材接近, 达到了与母材等强度的要求.

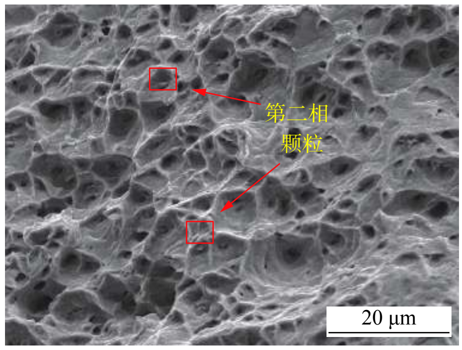


图 7　接头拉伸断口形貌

Fig. 7　Tensile fracture morphology of joint

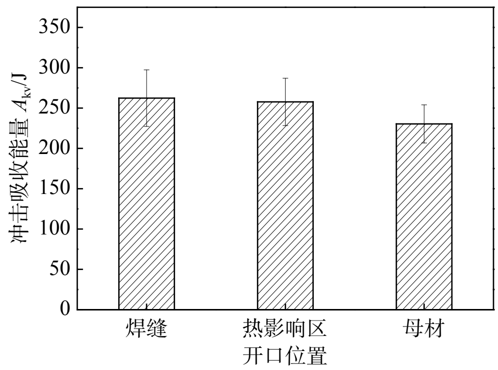
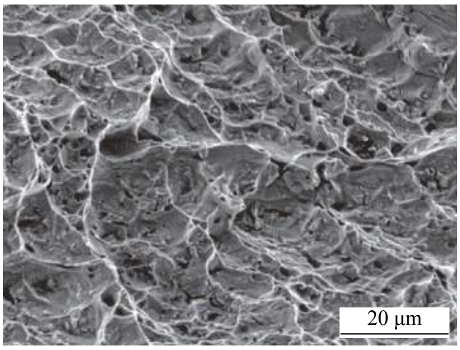


图 8　不同位置冲击吸收能量

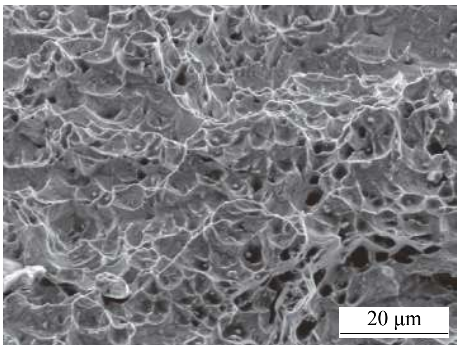
Fig. 8　Impact work of different areas

图 9 为不同开口位置的冲击断口形貌, 不同开口区域所呈现的断口形貌都为韧窝状, 焊缝和热影响区的韧窝较小, 数量大, 而母材的韧窝较大, 大韧窝里包含着许多小韧窝, 同时可以发现断口中也存在大量的析出相, 这些析出相保证了焊缝的力学性能及稳定性.

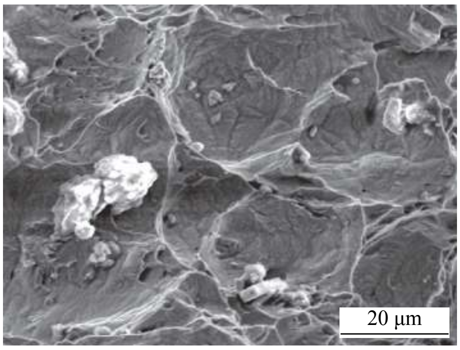
为测试焊缝处承受弯曲应力的能力, 对试样进行了弯曲试验, 并观察焊缝处是否失效, 图 10 为焊缝处的内外弯曲试验, 内弯试样和外弯试样均没有出现开裂, 基体均完好, 电子束焊焊缝强度基本符合要求.



(a) 焊缝冲击断口



(b) 热影响区冲击断口



(c) 母材冲击断口

图 9 冲击断口形貌

Fig. 9 Impact fracture morphology. (a) impact fracture of weld; (b) impact fracture of heat affected zone; (c) impact fracture of base metal

图 10 弯曲试样

Fig. 10 The simples for bending test

3 结论

(1) 采用电子束焊方法成功实现了 Incoloy 825 镍基高温合金的焊接，接头形貌优良，镍基高温合金由奥氏体组成. 靠近母材的焊缝区由大量的柱状晶和少量的等轴晶组成，等轴晶在焊缝中呈均匀分布，柱状晶出现在熔合线附近.

(2) 焊缝、热影响区和母材元素含量一致，没有出现明显的元素烧损或偏析的现象；焊缝、热影响区和母材 3 个区域显微硬度达到 200 HV 左右，基本达到母材硬度值.

(3) 通过对焊接接头进行力学性能试验，拉伸强度达到 600 MPa，基本达到母材抗拉强度；焊缝处冲击强度可达到 262 J，断口形貌为韧窝状；在弯曲试验结果没有发现开裂等有害因素，焊缝力学性能符合要求.

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Microstructures and mechanical properties of the welded joint were investigated. Energy disperse spectroscopy (EDS) was used to measure the burning loss of alloy elements in different regions of the weld. The tensile strength and microhardness of the weld were also measured. The results showed microstructures in the upper area were smaller than that in the lower area, the content of Mg and Zn in the upper part of weld was lower than that in the lower edge. Microhardness in the upper center was higher than that in the lower center, while microhardness at the upper edge was smaller than that at the lower edge. A ductile fracture was observed as the key characteristic for the welded joint, and the tensile strength was 325 MPa, of 65.9% of base metal. The decrease of the tensile strength was caused by the burning loss of Mg, Zn, welding stresses and porosity defects.

Key words: 7A52 alloy; laser beam welding; microstructure; mechanical properties

Microstructure and properties analysis of Incoloy 825 nickel base alloy electron beam welding ZHANG Jianxiao[1,2], GUAN Zhichen[1], HUANG Jiangkang[1], YANG Zhihai[3], FAN Ding[1] (1. State Key Laboratory of Advanced Processing and Recycling of Non-ferrous Metals, Lanzhou University of Technology, Lanzhou, 730050, China; 2. Lanzhou LS Heavy Equipment Co., LTD., Lanzhou, 730314, China; 3. Lanzhou Changzheng Machinery Co., LTD., Lanzhou, 730299, China). pp 32-37

Abstract: The butt test of Incoloy 825 nickel base superalloy in air cooler tube box was studied by electron beam welding. The microstructure of electron beam welded joints was analyzed by observing the structure of welded joints, and the mechanical properties of electron beam welded joints were analyzed with tensile properties and impact toughness tests. The results show that good weld joint of lncoloy 825 alloy can be obtained by electron beam welding. The weld zone is composed of large equiaxed grains and a few columnar crystals. There is no obvious element loss in the we4ld area. The hardness of weld and heat affected zone reaches the hardness value of base metal. The tensile strength of the weld joint reaches 600 MPa, which is close to the tensile strength of the base metal, and the fracture form of the joint is ductile fracture. The impact value in the weld and heat affected zone is higher than that of the base metal, in which the impact energy in the weld joint reaches 262 J, and the impact fracture morphology is ductile fracture.

Key words: electron beam welding; Incoloy 825; microstructure; mechanical property

Effect of ultrasonic impact treatment on corrosion behavior of FSW joints of 2A12 aluminum alloy ZHANG Timing[1], DENG Yunfa[1], CHEN Yuhua[1], FANG Yu[2], HU Xuebing[3] (1. Nanchang Hangkong University, Nanchang, 330063, China; 2. Shanghai Aerospace Equipments Manufacturer, Shanghai, 200245, China; 3. Sino-Pipeline International Co., Ltd., Beijing, 100007, China). pp 38-41,78

Abstract: In this work, the corrosion behavior of friction stir welding (FSW) joints of 2A12 aluminum alloy with and without ultrasonic impact treatment (UIT) was investigated by immersion corrosion test and polarization curve test in 3.5% NaCl aqueous solution. The results showed that the average corrosion rate of the joints with UIT was about half of that without UIT. The corrosion potential of the heat affected zone (HAZ) without UIT was −0.629 V (Ag/AgCl), indicating the worst corrosion resistance. And the average corrosion depth of HAZ induced by pitting corrosion and intergranular corrosion was about 125 μm. After UIT, the corrosion potentials of each sub-area of the FSW joints increased, and the corresponding corrosion current density decreased. The maximum depth of corrosion pit did not exceed 40 μm. The whole surface of the joint exhibited a form of uniform corrosion. Ultrasonic impact makes the surface grains of the material finer and denser, and the bond between the strengthening phase and the base metal is tighter, which is the main reason for the improvement of the corrosion resistance of the material. The main reason for the improvement of the corrosion resistance of the joints was that the grains of the material were refined and densified after UIT.

Key words: 2A12 aluminum alloy; friction stir welding; ultrasonic impact treatment; corrosion behavior

Characteristics of TIG overlaying welded joints of aluminum alloy before and after implementing ultrasonic frequency pulse electric signal CHEN Qihao[1,2], CUI Shancheng[1], LIN Sanbao[2], GAO Xiang[1], ZHANG Ao[1] (1. Jiangsu University of Science and Technology, Zhenjiang, 212100, China; 2. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, 150001, China). pp 42-46

Abstract: As a low-cost and high-efficiency welding method, arc overlaying welding has a broad application