Ti_3Al 基合金 TLP 扩散连接界面的组织演变

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摘 要: 以Ti-37.5Zr-15Cu-10Ni(质量分数,%)非晶箔带为中间层,研究了TLP扩散连接Ti-23Al-17Nb(质量分数,%)合金的界面组织演变过程. 结果表明,Ti元素和Nb元素向中间层扩散而Ni,Cu和Zr元素向母材扩散驱动了界面组织演变;在扩散初始阶段即930 ℃,保温5 min时,界面已形成冶金结合;随保温时间延长至15 min,界面析出条形 $TiNi_3$(Cu,Zr)化合物,其随保温时间延长更加细小呈弥散分布;直至保温时间延长至120~200 min,界面组织转变为均一、粗大的针状魏氏组织. 保温时间是影响 $TiNi_3$(Cu,Zr)化合物析出形态和分布的主要因素,控制保温时间可有效改变界面化合物状态,该方法是优化此类界面组织以提高接头强度的有效途径.

关键词: Ti_3Al 基合金; TLP扩散焊; 界面
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0 序 言

Ti-Al合金具有较高比强度和比弹性模量、优良的抗蠕变和抗氧化性能,适用于650~750 ℃的环境,是近年来重点开发和应用的航空航天用轻质高温结构材料[1-4]. 目前在 Ti_3Al 和 Ti_2AlNb 合金的钎焊及瞬态液相扩散焊(transient liquid phase bonding,TLP)等技术方面已开展较多研究,采用中间层合金或中间层包括镍基、钛基、银基及铜基合金,采用钛基中间层合金或中间层时连接强度较高[5-9].

有报道以Ti-15Cu-15Ni(质量分数,%)为中间层,采用990 ℃,90 min工艺TLP扩散连接Ti-22Al-25Nb(质量分数,%)的接头强度可达到母材强度的95%[10]. 但Ti-15Cu-15Ni中间层的熔点较高,使连接温度较高、母材在焊接过程中易产生组织粗化,不利于焊后材料的综合力学性能. 添加Zr元素可有效降低中间层合金的熔点,但导致界面形成化合物相—Ti_2Ni,$Ti(Cu,Al)_2$ 成为接头脆性的主要因素. 有报道指出[11],采用含Zr元素中间层和合理TLP扩散焊工艺,可获得与采用无Zr元素中间层(即Ti-Zr-Ni)等强度的焊接接头. 因此适当添加Zr元素含量的中间层和合理的连接工艺应是控制接头脆性相和提高接头强度的有效途径,且有利于兼顾焊后材料的综合力学性能.

以 Ti_3Al 基合金——Ti-23Al-17Nb(质量分数,%)为试验材料,以830~840 ℃熔点的Ti-37.5Zr-15Cu-10Ni(质量分数,%)非晶箔带为中间层,观察TLP扩散连接界面微观组织,分析中间层合金元素的扩散情况,研究得出界面组织的演变规律,为TLP扩散焊工艺的制定提供依据.

1 试验方法

试验中母材名义成分为Ti-23Al-17Nb(质量分数,%),室温组织由 α_2 相、B_2 相和O相组成,α_2 相弥散分布于 B_2 相基体上,微量O相分布于 α_2 相和 B_2 相界面处. 合金的退火工艺为1 020 ℃,3 h,空冷,室温抗拉强度为966 MPa. 以熔点在830~840 ℃的非晶箔带Ti-37.5Zr-15Cu-10Ni(质量分数,%)为试验用中间层合金. 在低于母材退火温度而高于中间层熔点的温度范围,使用真空钎焊炉进行TLP扩散焊,工艺为800 ℃,30 min+930 ℃,(5,15,30,60,120,200 min),真空度不低于 10^{-3} Pa.

界面组织观察用焊接试样规格为 ϕ10 mm×5 mm,接头强度测试用焊接试样规格为 ϕ10 mm×35 mm,中间层规格为 ϕ10×(0.04~0.05) mm,采用对接方式进行. 用线切割方法将焊后试样沿轴向中心线切开,使用水砂纸研磨线切割面至粗糙度达到0.08 μm,然后腐蚀该研磨面. 采用扫描电子显

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微镜观察连接界面的微观组织形貌,采用电子探针分析界面元素的分布,参考试验结果评价界面组织均匀性,得出界面组织的演变规律,并通过透射电子显微镜对焊后界面的生成物进行鉴定,讨论生成相对界面强度的影响.

2 试验结果与分析

2.1 界面微观组织和元素扩散

图1所示为930 ℃时TLP扩散连接界面的微观组织形貌. 图1a为保温时间5 min时中间层合金与母材形成的冶金结合界面,中间层合金由Ti,Zr,Cu和Ni4种元素组成,由于在背散射电子下原子量较大元素富集区的衬度较大,因而该温度下中间层凝固后元素偏析严重,界面中心部位富集Zr,Cu和Ni元素,但母材未发生组织明显变化; 图1b为保温时间15 min时连接界面宽度约40 μm,可见部分熔融态的中间层合金组织,即残留液相层; 图1c为保温时间延长至30 min时,液相层已经完全消失,界面宽度增至约50 μm,即中间层的扩散程度显著增加. 由图1b,c可见,在保温时间15 min和30 min下,中间层凝固后均由两种衬度的组织组成,即以富集Zr,Cu和Ni元素的为基体,富集Ti元素的深黑色组织弥散分布于其内; 长时间保温下,灰白色组织向母材以树枝状形态扩展,其界面合金元素的扩散尚不充分,界面组织也不均匀.

图2所示当保温时间分别延长至60,120,200 min时,界面为钛基中间层合金经TLP扩散焊后形成的(α+β相)魏氏组织,而Zr元素的富集区演变为界面中心的狭长区域,宽度为10 μm,此时界面组织均一,TLP扩散焊过程基本完成.

采用电子探针对930 ℃,60 min下连接界面元

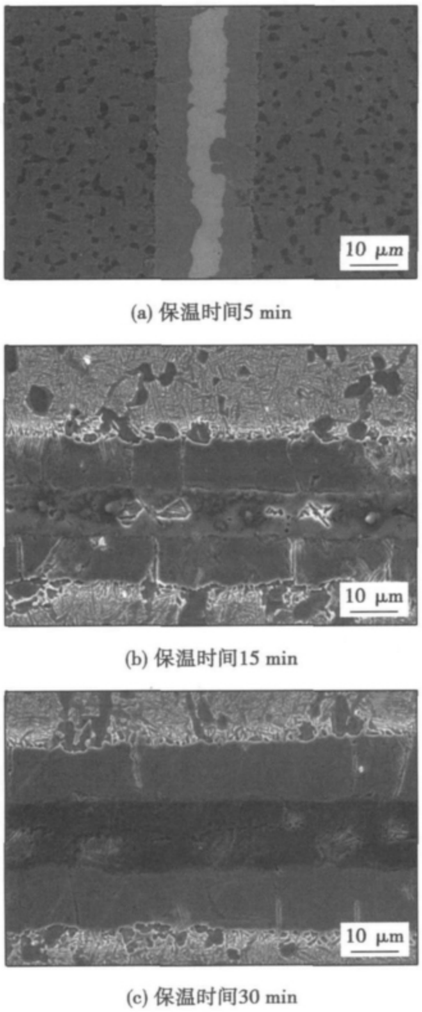


图1 930 ℃下TLP扩散连接界面的微观组织形貌

Fig. 1 TLP diffusing interface microstructure at 930 ℃

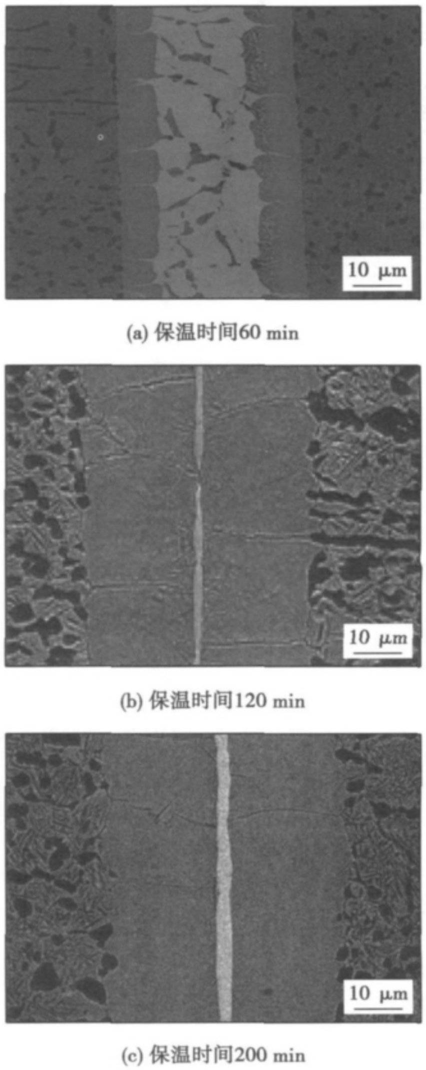


图2 930 ℃下TLP扩散连接接头微观组织演变过程

Fig. 2 Evolution processing of TLP diffusing interface microstructure at 930 ℃

素含量进行分析，如图 3 所示．结果发现，Ti 和 Nb 元素由基体向界面扩散，Zr，Cu 和 Ni 元素由中间层向基体扩散，对比各元素由母材至界面中心的含量变化得出，Zr 元素扩散对界面演变起到主要作用，如图 4 和表 1 所示．

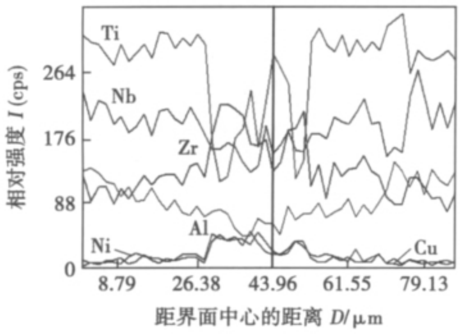


图 3　界面元素分布（黑线为界面中心）

Fig. 3　Element distributing at welded interface

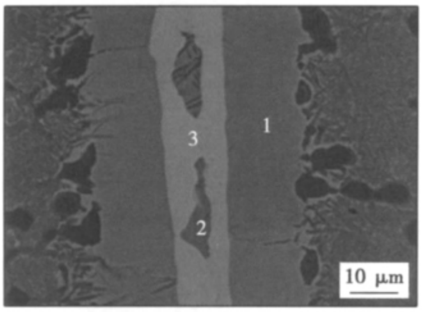


图 4　中间层合金组织

Fig. 4　Solder microstructure

表 1　界面化学成分（质量分数，%）（相应图 4）

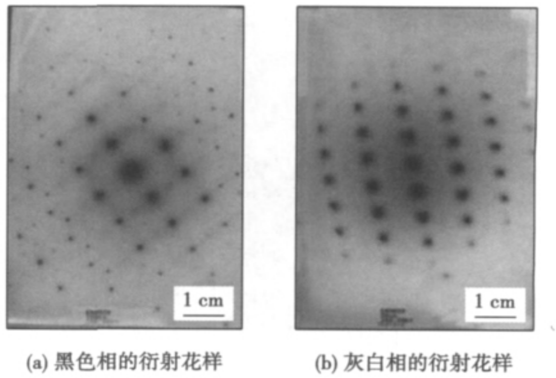
Table 1　Element content at welded interface

位置	Al	Ti	Ni	Cu	Zr	Nb
1	5.91	56.39	2.47	2.88	8.05	24.29
2	4.26	58.18	1.61	7.53	9.96	18.45
3	5.59	27.65	15.36	15.88	32.30	3.23

2.2　中间层焊后组织分析

在以上组织演变过程中存在两种典型组织，分别是 930 ℃，60 min 和 930 ℃，200 min 下界面组织．其中，930 ℃，60 min 的连接界面内可见细小、弥散分布的析出物．析出物尤其是化合物对界面可能产生不利作用，这与化合物的种类和晶体结构有关．

采用 X 射线获得界面组织的电子衍射花样，如图 5 所示．分析得出，中间层经 930 ℃，60 min 焊后形成了六方晶体结构相和 bcc 晶体结构相，分别为 $TiNi_3$（Cu，Zr）化合物和钛基固溶体．呈六方晶体结构的 $TiNi_3$ 化合物中富集 Zr，Cu 和 Ni 元素，为灰白色相；而钛基固溶体为黑色相．据此可推测，随着保温时间由 60 ~ 200 min 延长，钛基固溶体与扩散区内元素的进一步充分扩散形成了图 2b，c 中的粗大针状组织的扩散区，即（$\alpha+\beta$ 相）魏氏组织．



(a) 黑色相的衍射花样　(b) 灰白相的衍射花样

图 5　界面上中间层的 X 射线衍射花样

Fig. 5　Diffraction pattern of solder at interface by X-ray

$TiNi_3$（Cu，Zr）化合物会不利于接头的韧性，而具有 bcc 结构的钛基固溶体具有较好的塑性．这两种相的尺寸和分布情况将是该 TLP 工艺下接头强度和塑性的主要影响因素．当化合物尺寸较大、或分布不均匀时，加剧接头脆化，而当化合物相尺寸细小、且弥散分布时，可降低脆性化合物对接头性能的不利影响．

3　结　论

（1）界面组织演变过程包括以下 4 个阶段，冶金结合界面形成、中间层残留液相消失、界面化合物析出和界面组织均匀化完成．

（2）Ti 元素和 Nb 元素向中间层扩散而 Ni，Cu 和 Zr 元素向母材扩散驱动了界面组织演变．

（3）保温时间是影响界面 $TiNi_3$（Cu，Zr）析出物形态和分布的主要因素，通过控制保温时间可有效改变界面化合物状态．该方法可成为优化界面组织以提高接头强度的有效途径．

参考文献：

[1] 李世琼．航天运载火箭发动机用 Ti_3Al 基合金研究［J］．材料导报，2001，15(2)：10－13.
Li Shiqiong. The research on Ti_3Al alloys for engine in space launch vehicle［J］. Materials Review，2001，15(2)：10－13.

[2] Bird R K，Hoffman E K. Evaluation of the transient liquid phase

(TLP) bonding process for Ti_3Al-based honeycomb core sandwich structure NASA/TP [R]. Hampton: National Aeronautics and Space Administration, 1998.

[3] 李卓然，曹 健，冯吉才，等. TiAl 基合金与 Ti 合金的真空钎焊 [J]. 焊接，2006(3): 51－55.
Li Zhuoran, Cao Jian, Feng Jicai, *et al*. The vacuum brazing for the TiAl based alloys and the Ti-based alloys [J]. Welding & Joining, 2006(3): 51－55.

[4] 秦 川. 高温用 TiAl 合金的钎焊 [J]. 稀有金属与硬质合金，2003，31(2): 51－55.
Qin Chuan. The brazing for the high temperature TiAl alloys [J]. Rare Metals and Cemented Carbides, 2003, 31(2): 51－55.

[5] Li Zhuoran, Feng Jicai, Cao Jian. Vacuum diffusion bonding of TiB_2 cermet to TiAl-based alloys [J]. Materials Science and Technology, 2004, 20(12): 1666－1668.

[6] Lee S J, Wu S K, Lin R Y. Infrared joining of TiAl intermetallics using Ti-15Cr-15Ni foil [J]. Acta Materialia, 1998, 46(4): 1283－1295.

[7] Cam G, Clemens H, Gerling R, *et al*. Diffusion bonding of γ-TiAl sheets [J]. Intermetallics, 1999(7): 1021－1031.

[8] Li Zhuoran. Vacuum brazing of TiB_2 cermet to $TiAl_2$ based alloys using Ag-Cu-Zn fillermetal [J]. Transaction of Nonferrous Metals Society of China, 2003, 13(s1): 39－41.

[9] Tetsui T. Effects of brazing filler on properties of brazed joints between TiAl and metallic materials [J]. Intermetallics, 2001 (9): 253－260.

[10] 邹贵生，白海林，谢二虎，等. Ti_2AlNb 相合金 Ti-22Al-25Nb 的 TLP 扩散连接 [J]. 稀有金属材料与工程，2008，37(12): 2181－2185.
Zou Guisheng, Bai Hailin, Xie Erhu, *et al*. The TLP-transition liquid welding for the Ti_2AlNb alloys [J]. Rare Metal Materials and Engineering, 2008, 37(12): 2181－2185.

[11] 宁立芹，梁德彬，李海刚，等. Zr 对 Ti_3Al 基金属间化合物 TLP 扩散焊接头组织性能的影响 [J]. 宇航材料工艺，2008 (2): 71－75.
Ning Liqin, Liang Debin, Li Haigang, *et al*. The affection from the content of Zr element for the microstructure and the mechanical properties in the TLP-transition liquid welding interface on Ti_3Al based alloys [J]. Aerospace Materials and Technology, 2008(2): 71－75.

[12] 胡美娟，刘金合，康文军，等. 电子束局部热处理对 TC4 钛合金焊接接头组织和性能的影响 [J]. 焊接学报，2008，29 (2): 104－107.
Hu Meijuan, Liu Jinhe, Kang Wenjun, *et al*. Effects of local heat treatment by electron beam on microstructure and properties of TC4 titanium alloy welded join [J]. Transactions of the China Welding Institution, 2008, 29(2): 104－107.

[13] 张田仓，李 晶，季亚娟，等. TC4 钛合金线性摩擦焊接头组织和力学性能 [J]. 焊接学报，2010，31(2): 53－56.
Zhang Tiancang, Li Jing, Ji Yajuan, *et al*. Structure and mechanical properties of linear friction welding joint [J]. Transactions of the China Welding Institution, 2010, 31(2): 53－56.

[14] 马铁军，杨思乾，张 勇，等. TC4 线性摩擦焊接头的力学性能及组织变化特点 [J]. 焊接学报，2007，28(10): 17－20.
Ma Tiejun, Yang Siqian, Zhang Yong, *et al*. Mechanical properties and microstructure features of linear friction welded TC4 titanium alloy joint [J]. Transactions of the China Welding Institution, 2007, 28(10): 17－20.

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SiO_2, TiO_2, CaF_2, Cr_2O_3 and $BaCl_2$. The mechanism to increase weld penetration was analyzed by considering the change of arc shape in A-TIG welding process. The experimental results indicate that all the above activating fluxes improve weld penetration. The most remarkable effect is obtained when the flux is SiO_2, but the effect of CaF_2 on penetration is not obvious. The weld appearance is poor when the base metal is coated with SiO_2, while good weld appearance can be obtained when the flux of TiO_2 is used. The phenomenon of arc contraction is not remarkable when the arc moves into the flux zone. The significant improvement of weld penetration may be the result of increase in heat input caused by the change of resistance in conducting channel.

Key words: aluminum alloy; A-TIG; activating flux; weld morphologies

Analysis of bending property of dissimilar steels welded joints WANG Rui[1], WANG Fenghui[2], TIAN Huaming[3], ZHI Derui[1], SUN Jie[3], DU Jianfeng[3], WANG Xibao[2] (1. School of Science, Tianjin University of Commerce, Tianjin 300134, China; 2. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 3. The Tianjin University Beiyang Chemical Equipment Co., Ltd, Tianjin 300072, China). pp 58 – 62

Abstract: The dissimilar steel welded joints were made between Q235-B carbon steel and 316L stainless steel by submerge arc welding using Y and I patterns of welding groove. Based on the observation and analysis of the microstructure, elements distribution and micro hardness in the weld fusion zone near the Q235-B base metal, the hard and brittle transition layer would form in the fusion area near the carbon structural steel, when the dissimilar steels were welded. The decrease of width of brittle transition layer is the most important to improve the bending property of the dissimilar steels welded joint. Furthermore, the influences of different welding procedures on the bending property of the welded joint were investigated. The process of Y pattern groove and Ni-riched welding wire can minimize the width of brittle transition layer and raise the bending property of the welded joint. Besides, this welding procedure also avoids the welding fault of burning through when the butt joint of the dissimilar thin steel was welded by submerged arc welding on the double sides.

Key words: welded point; dissimilar steel; brittle transition layer; bending property

Synchronous acquisition and analysis of metal transfer images and electrical parameters in CO_2 arc welding JIANG Yuanning, CHEN Maoai, WU Chuansong (Institute for Materials Joining, Shandong University, Jinan 250061, China). pp 63 – 66

Abstract: By using high speed camera and multi-channel sensing and data acquisition system, a LabVIEW-based system was developed to acquire metal transfer images and electrical parameters in short circuiting CO_2 arc welding. The difference in startup delay time between data acquisition system and high speed camera was calibrated by experiment, and the offset by software method to realize synchronous acquisition. The system was used to analyze the electrical parameters and metal transfer images. Metal transfer under different welding conditions was investigated and the correlation between electrical parameters, metal transfer image and the stability of short-circuiting transfer process was analyzed with the developed system.

Key words: CO_2 arc welding; virtual instrument; synchronous acquisition

Growth mechanism of in situ Ti(C_yN_{1-y}) particles in laser deposited coating QI Yongtian[1], ZOU Zengda[2] (1. Inner Mongolia Baotou Vocational and Technical College, Baotou 014030, China; 2. School of Materials Science and Engineering, Shandong University, Jinan 250061, China). pp 67 – 70

Abstract: A new in-situ synthesis method was used to prepare the composite coating reinforced by Ti(C_yN_{1-y}) particles through CO_2 laser cladding technology. Scanning electron microscope (SEM) and electron probe microscopy analyzer (EPMA) were used to analyze the phases in the composite coating. The results show that Ti(C_yN_{1-y}) particles are formed by an in-situ metallurgical reaction of TiN particle and graphite powder during laser cladding process. The nucleation and growth mechanism of the formation of Ti(C, N) particles have close relationship with the original titanium nitride (TiN). When the size of the original titanium nitride particles is small (<5 μm), a great deal of energy absorbed by the cladding material may cause the dissolution of the original titanium nitride (TiN) particles to form the titanium carbonitride Ti(C_yN_{1-y}) particles, whose shapes are rhombus. If the size of original titanium nitride particles is big (>5 μm), energy absorbed by the cladding material is limited, so it only causes the outer marginal dissolution of the original titanium nitride (TiN) particles. Finally, the annular structure ceramic particles named titanium carbonitride Ti(C_yN_{1-y}) are synthesized by a solid-solution metallurgical reaction in the laser cladding process.

Key words: Ti(C_yN_{1-y}); in-situ formation; laser cladding; microstructure

Microstructure evolution of TLP bonding interface for Ti_3Al based alloy JING Yongjuan, LI Xiaohong, HOU Jinbao, YUE Xishan (Beijing Aviation Manufacturing Engineering Research Institute, Beijing 100024, China). pp 71 – 74

Abstract: With Ti-37.5Zr-15Cu-10Ni (%) amorphous foil as the brazing filler metal, the microstructure evolution of the TLP (Transient liquid phase) diffusion bonding interface for Ti_3Al-based alloys was studied. The Ti and Nb elements diffuse into the brazing filler and the Ni, Cu, Zr elements diffuse into the matrix to drive the interface evolution. At 930 ℃ the metallurgical bonding is achieved after holding time of 5 min. The $Ti-Ni_3(Cu, Zr)$ compound in the shape of strip is precipitated after holding time of 15 min. This compound will get refined and dispersed with the holding time being longer. When the holding time lasts until to 120-200 min, the interface microstructure evolved to the coarse and homogeneous Widmanstaten structure. Since the compound character is affected by the holding time, it can be an effective method to control the microstructure and strengthen the interface by controlling the holding time.

Key words: Ti_3Al-based alloy; transient liquid phase diffusion bonding; interface

Measurement of creep stress exponent of Zn-Al filler metal at room temperature by using nanoindentation

JI Feng[1], XUE Songbai[1], LIU Shuang[1], LOU Jiyuan[2], LOU Yinbin[2] (1. College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; 2. Zhejiang Xinrui Welding Material Co., Ltd, Shaoxing 312400, China). pp 75 – 78

Abstract: The creep behavior of Zn-22Al and Zn-22Al-0.03Ti filler metals at room temperature were studied by nanoindentation in this paper, and constant loading rate method was used to calculate the creep stress exponent. The results indicate that, both the Zn-22Al and Zn-22Al-0.03Ti produced obvious creep deformation under holding load. Both the depth and creep displacement of Zn-22Al-0.03Ti were less than that of Zn-22Al, and the maximum difference were 15.68% and 26.87%, respectively. Under the constant time, the filler metals produced different creep displacement with different loadings. The creep stress exponents of two filler metals at room temperature were obtained by fitting method. Zn-22Al-0.03Ti had a higher creep stress exponent than Zn-22Al filler metal, which implied that Ti-bearing filler metals had better creep resistance than Zn-22Al alloy. The grain of Zn-22Al filler metal could be refined remarkably with the Ti addition, which might result in the increase of grain boundary and finally enhanced the creep resistance of alloy.

Key words: nanoindentation; Zn-Al filler metal; creep; creep stress exponent

Structure and mechanical properties on DH40 ship building steel joints by multi-layer and multi-pass welding technology

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Abstract: The weldability experiments of DH40 ship building steel were carried out by using the flux-cored wire CO_2 gas shielded multi-pass welding technology. The microstructure and mechanical properties of the joint were studied systematically and the impact toughness was discussed, especially the reason why the impact toughness at HAZ of 5 mm from fusion line of weld root decreased greatly. The results showed that the tensile strength of joints is higher than that of the base metal of 575 MPa. All the samples used in the bending test are qualified and meet the plasticity requirement. The brittleness band is easily formed at HAZ, 5 mm from the fusion line at the weld root. The effect of microstructure heredity results in the coarse crystal grain, which is the secondary reason for the impact ductility decreasing, and the basic reason is the formation of a large amount of granular bainite.

Key words: DH40 steel; multi-pass welding technology; mechanical properties; microstructure

Effect of process parameters on mechanical properties of friction stir welded Al-Li alloy lap joints

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Abstract: Through analyzing the microstructure and testing mechanical properties of friction stir welded Al-Li alloy lap joints, the effect of FSW welding parameters on the tensile properties of the lap joints was investigated. The results showed that the length of stir pin has significant influence on the tensile properties of lap joints. When the length of pin is changed from 2.8 mm to 2.5 mm, the ultimate strength and elongation of lap joints are obviously improved. Furthermore, the rotation speed / welding speed (η) also affected the performance of joints. When there was a small increasing in η, the tensile properties of lap joints increased accordingly. For the Al-Li alloy lap structure, the optimum tool rotational speed is 800 r/min, welding speed is 200 mm/min and the length of pin is 2.5 mm, the ultimate strength of lap joint reaches 467 MPa, which is equivalent to 94% that of the base metal and the elongation is 3.18%. In addition, the analysis of tensile fracture appearance indicated that the tensile cracks initiate from the location of "Hooking" defect in the advancing side and grow along the HAZ until to the base metal.

Key words: friction stir welding; aluminum-lithium alloy (Al-Li); tensile properties; fracture

Test and analysis of dynamic process for spot welding of multilayer low carbon steel sheets

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Abstract: In the spot welding process, the spot-welded joints of multilayer sheets were always available. The variation of the sheet thickness is obvious in the spot welding process, which makes the impedance fluctuation drastic in secondary circuit of welding power transformer. Thus, the spot welding heat also fluctuates evidently. In this case, the nugget quality cannot be guaranteed if welding heat is not regulated effectively in real time. By means of dynamic test and analysis of welding thermal process, the applicability of different monitoring methods was discussed for spot welding of multilayer low carbon steel sheets. The scientific basis therefore can be provided for manufacturing enterprises to select the exact monitoring method and to achieve the effective quality control.

Key words: low carbon steel; multilayer sheets; spot welding; dynamic process; monitoring method selection

Numerical simulation of metal plastic flow in friction stir welding affected by pin shape

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