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超声时间和预留间隙对超声波辅助钎焊镁合金钎料填缝性能的影响

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摘　要：采用高速摄影对超声波辅助钎焊镁合金过程熔态钎料的填缝行为进行了实时观察，并研究了不等间隙中钎料的填缝行为及接头性能. 结果表明，超声波在钎焊固/液界面传播对钎料填缝行为有显著的影响. 钎料在平行于超声波能量传播方向上填缝，填缝长度和超声时间的动力学曲线呈直线型. 超声时间相同时，预留间隙越大，钎料的填缝速度越低. 在大间隙端加钎料，随超声时间增加，填缝长度减小，钎缝致密性较好；小间隙端加钎料，随超声时间增加，填缝长度先增大后减小，整个钎缝均存在缺陷. 认为钎料在不等间隙的流动行为受超声诱导填缝和毛细填缝共同作用的影响.

关键词：超声钎焊；　高速摄影；　间隙；　填缝；　动力学
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0　序　　言

钎焊实际上是破膜—溶解—渗透—润湿—铺展—凝固的复杂交错的过程[1]，界面润湿及钎料铺展和流动行为非常复杂. 钎料的填缝过程受温度、预留间隙、熔态钎料和固态母材反应性、外加物理场（如电场，超声场）等因素影响，决定了钎焊接头的均匀性、致密性和接头强度.

声波作为一种机械运动是携带能量的载体. 钎焊时超声波在固/液界面传播，在极短时间（10^{-4} ~ 10^{-6} s）内即可以产生极高的压强（10^{-7} ~ 10^{4} MPa）和较高的能量（10^{-1} ~ 1 eV）[2]，钎料填缝行为更为复杂，钎料流动速度、钎焊接头性能与超声时间、填缝间隙（包括间隙大小，等/不等间隙）密切相关. 文献[3]认为钎料填缝与超声时间、次数及传播距离有直接关系，超声时间太短，易出现钎料未填满现象；超声时间过长，填缝到一定程度即停止，甚至连续施加超声都不能促进钎料继续填缝. 文献[4]研究发现，在超声作用下间隙越小钎料填缝速度越快，而无超声作用下时，在一定范围内，随间隙增大，填缝速度增大. 文献[5]中对超声作用下钎料在不等间隙中的流动趋势进行了模拟，结果发现在不等间隙中钎料有向小间隙端流动的趋势.

文中针对超声波辅助钎焊镁合金，采用玻璃作为连接组件中的一个部件，用高速摄影进行拍摄，动态观察钎料在缝隙中的流动状态，揭示钎料在平行于超声波能量传播方向填缝的动力学行为；并进行不等间隙填缝试验，研究超声时间和间隙对钎料填缝行为及接头致密性的影响.

1　试验方法

试验母材为 AZ31B 镁合金和普通玻璃，尺寸为 50 mm × 10 mm × 3 mm. 钎料为 54.6Mg－3.8Al－41.6Zn（质量分数，%），固相线为 338 ℃，液相线为 347 ℃，尺寸为 10 mm × 3 mm × 3 mm. 试验装置使用自制的超声波辅助钎焊设备，超声波频率为 20 kHz，振幅为 55 μm. 试验加热温度为 360 ~ 370 ℃. 镁合金板及钎料表面经 400 号砂纸打磨和丙酮清洗后，镁合金板作为下板，玻璃作为上板，以搭接形式装配，放置在夹具上进行加热，搭接长度为 30 mm. 钎缝预留间隙分别为 0.15，0.20，0.25，0.30 mm，待钎料熔化时向下板施加超声振动至液态钎料填满间隙. 钎料填缝的动态过程采用高速摄影采集图像（50 帧/s），使用 AutoCAD 图像处理软件测量出不

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同时间段的填缝长度，每组试样为 3 件，填缝长度取平均值.

超声作用下钎料在 AZ31B 镁合金板的填缝试验工艺参数如表 1 所示. A_1，A_2，A_3 分别表示钎料在等间隙端、大间隙端、小间隙端填缝. 超声振动 1 ~ 3 s，钎料填缝后随夹具自然冷却形成钎焊接头. 采用 AutoCAD 图像处理软件测量不同工艺参数下的填缝长度，每组试样为 3 件，填缝长度取平均值. 沿钎料流动方向取截面，用 OLYMPUS DPR6 金相显微镜进行微观组织观察.

表 1 填缝工艺参数

Table 1 Gap-filling experiment parameters

序号	搭接长度 l/mm	钎料填入端宽度 d_1/mm	末端宽度 d_2/mm	超声时间 t_u/s
A_1	30	0.20	0.20	1,2,3
A_2	30	0.35	0.05	1,2,3
A_3	30	0.05	0.35	1,2,3

2 试验结果与分析

2.1 钎料在平行于超声波能量传播方向填缝的动力学行为

图 1 为高速摄影拍摄的预留间隙 0.3 mm、超声时间 0.1 s 时钎料填缝前沿的路线，从图 1 能清楚地观察到流动时间 t_f = 0，0.1，0.2，0.3，0.4 s 时钎料填缝前沿的形貌. 根据高速摄影拍摄的不同预留间隙 0.15 ~ 0.3 mm 的钎料流动状态，计算获得如图 2 所示的填缝长度与超声时间的动力学关系曲线.

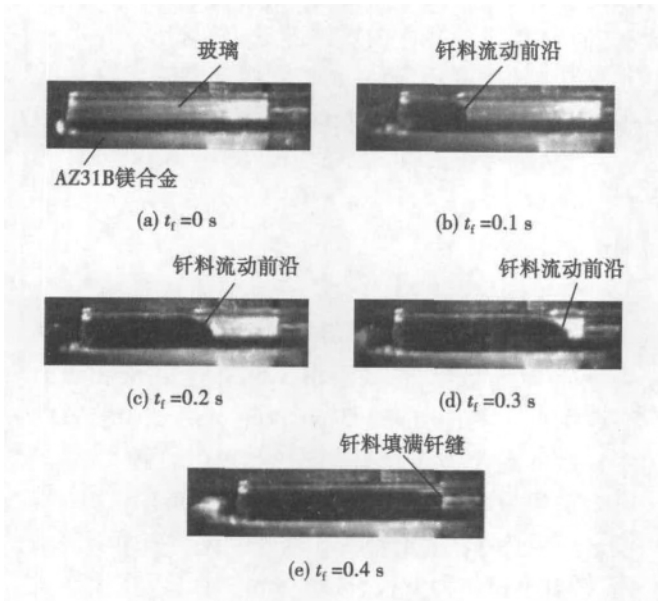

图 1 预留间隙 0.3 mm，超声时间 0.1 s 时钎料填缝动态过程的高速摄影截图

Fig. 1 High velocity photography screen shots for dynamic flowing of filler metal through 0.3 mm gap when ultrasonic time is 0.1 s

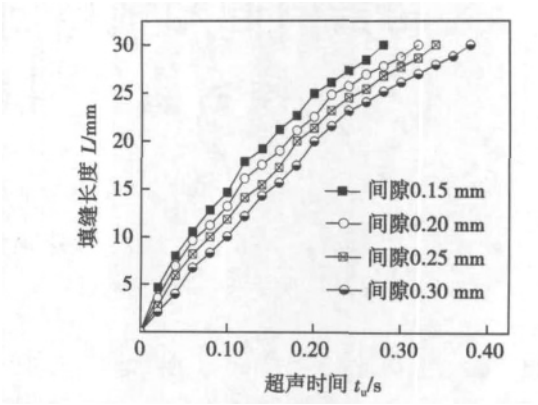

图 2 不同间隙下钎料填缝长度与超声时间的动力学曲线

Fig. 2 Dynamic curve of filling-gap distance and ultrasonic time under different thickness gaps

由图 2 可见，对于不同厚度的预留间隙，钎料填缝长度与超声时间的动力学曲线基本呈直线型规律，钎料填缝长度随超声时间增加而增大. 刚开始时钎料流动速度较快（前 0.2 s 平均速度为 99.9 mm/s），随后速度降低（0.2 ~ 0.4 s 平均速度为 50.1 mm/s），但整体的流动速度还是较快. 预留间隙 λ = 0.30 mm 时，填满整个接头所需时间为 0.4 s，平均速度为 78.9 mm/s. 在预留间隙 λ = 0.15 ~ 0.30 mm 范围内，在相同的超声作用时间下，预留间隙越大，钎料填缝距离越小，即填缝速度越小. 例如超声时间为 0.1 s 时，随着预留间隙从 0.15 mm 增大至 0.30 mm，填充距离分别为 14.65，13.21，11.82，10.05 mm.

2.2 不等间隙对钎焊填缝行为的影响

图 3 为等间隙和不等间隙下的钎料填缝长度与超声时间的关系曲线. 大间隙端加钎料，随超声时间增加，钎料填缝长度先增加后减小（20.3 ~ 14.6 mm）；小间隙端加钎料，钎料填缝长度先增大后略有减小，总体变化不大（13.9 ~ 19.2 mm）；钎料在等间隙填缝，随超声时间增加，填缝长度显著增大，最大值为 27.9 mm.

图 4 为超声作用下大间隙端加钎料，沿钎料流动方向的钎缝横截面形貌. 图 4a，b，c 为超声 1 s 时初始端、中间、末端形貌. 图 4d，e，f 为超声 2 s 时初始端、中间、末端形貌. 图 4g，h，i 为超声 3 s 时初始端、中间、末端形貌. 超声 1，2，3 s 时钎缝除了初始端间隙过大导致未焊合部分，其余部分结合致密.

从图 4 可见，在同一超声时间下，钎缝初始端、中间和末端的微观形貌存在较大差别. 沿钎料流动方向，钎缝宽度逐渐减小. 在填缝初始端，钎料与母

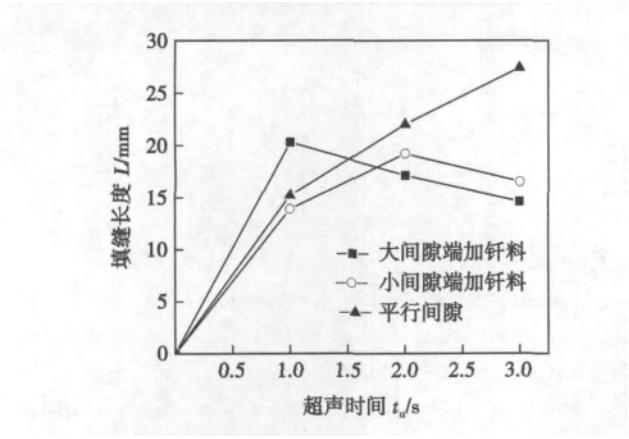

图 3　等间隙和不等间隙情况下钎料填缝长度与超声时间的关系曲线

Fig. 3　Relationship between filling-gap distance and ultrasonic time under parallel and unparallel gaps

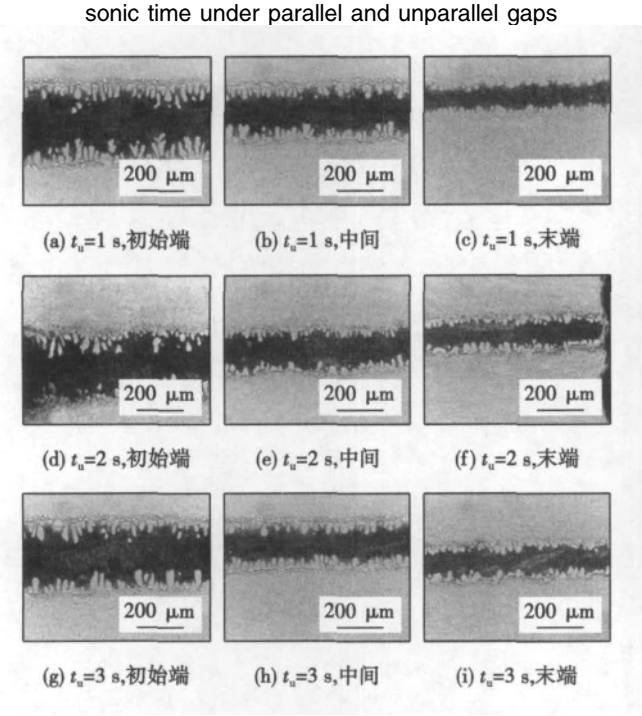

图 4　不同超声时间下大间隙端加钎料,沿钎料流动方向钎缝初始端、中间、末端微观形貌

Fig. 4　Micromorphology of front, middle and end of joint along flowing direction when putting filler metal in maximum gap under different ultrasonic time

材反应较充分,焊缝中含有部分球形富镁相,钎缝较宽; 而在中间和末端,母材中只有少量的 Mg 元素溶入钎缝,钎缝逐渐变窄,且中间较填缝末端界面层略宽. 虽然初始端钎料的填缝速度很快,但沿钎料流动方向的组织存在较大的差异. 可以推断钎焊过程超声波并不是将基体表面的氧化膜同时去除,而是随着钎料流动逐步去除. 超声波在固/液界面传播,空化作用首先去除钎缝前端的氧化膜,使得钎料在继续流动和冷却凝固过程中一直与基体间发生溶解和扩散作用,作用时间长且反应充分; 而钎缝末端的氧化膜只有在钎料填充完成时才被去除,空化作用时间短,钎料与基体作用时间短且反应不充分. 因此沿填缝方向界面反应和传质作用逐渐减弱,界面反应层厚度减小,钎缝宽度也略有减小.

图 5 为超声作用下小间隙端加钎料,沿钎料流动方向的钎缝截面形貌. 超声 1 s 时,在整个钎缝中存在大量未焊合等致密性缺陷; 超声 2 s 时,钎缝的初始端存在大量缺陷,中间较为致密,当间隙大于 0.15 mm 后又出现较多缺陷; 超声 3 s 时,钎缝的初始端及中间较为致密,在末端间隙大于 0.2 mm 后出现较多未焊合等缺陷.

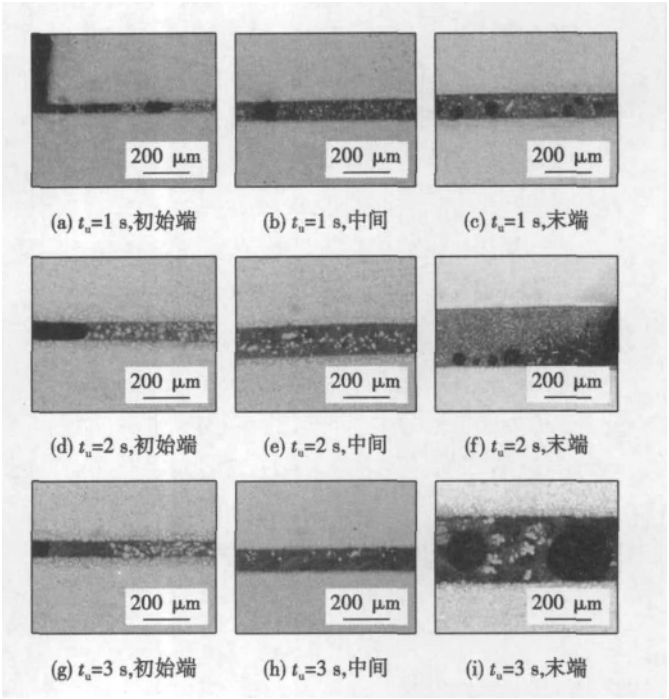

图 5　不同超声时间下小间隙端加钎料,沿钎料流动方向接头初始端、中间、末端微观形貌

Fig. 5　Micromorphology of front, middle and end of joint along flowing direction when putting filler metal in minimum gap under different ultrasonic time

等间隙和不等间隙条件下钎料填缝长度和接头微观形貌的显著差别是由于超声诱导填缝和毛细填缝共同作用的结果. 在常规钎焊中,钎料主要是靠毛细作用作为填缝的驱动力,毛细作用与间隙大小成反比,液态钎料有优先填充小间隙的趋势[6]. 试验中在大间隙端加钎料,超声诱导填缝方向也恰好是朝向小间隙方向,钎料很快填缝,除前端因间隙过大以致未焊合部位外,接头其余部分比较致密. 接头中气泡大端的曲率小,附加压力也小. 而小端的曲率大,附加压力也大. 因此作用在气泡上的附加压力的合力将指向大间隙端,为夹气等缺陷从大间

隙端自动排除创造了条件; 而超声作用下在小间隙端加钎料,超声诱导填缝方向朝向大间隙方向,与常规钎焊相比填缝时间极短(1 ~ 3 s) ,而且钎料流入端间隙很小(0.05 mm) ,使得钎料流入不够顺畅,气泡很难从大间隙端排除,接头缺陷较多. 因此对于超声辅助钎焊,在设计预留间隙时,始端和末端宽度不能相差过于悬殊,在 0.1 ~ 0.2 mm 的范围内较为合适,且为提高钎缝致密性,可优先考虑大间隙端加钎料.

3 结 论

(1) 钎料在平行于超声波能量传播方向填缝,对于不同厚度的预留间隙,钎料填缝长度与超声时间的动力学曲线基本呈直线型规律,钎料填缝长度随超声时间增加而增大. 预留间隙为 0.15 ~ 0.3 mm 时,相同的超声波作用时间,间隙越大,液态钎料填缝距离越小,即填缝速度越低.

(2) 超声波作用下钎料在不等间隙填缝,在同一超声时间下,钎料填缝初始端、中间部位和末端的微观形貌存在较大差别. 在大间隙端加钎料,随超声时间增加,钎料填缝长度减小,除初始端未焊合部位外,其余部分致密性均较好; 在小间隙端加钎料,随超声时间增加,钎料填缝长度先增大后减小,整个钎缝均存在缺陷. 分析认为不等间隙条件下钎料填缝长度和接头微观形貌的显著差别是由于超声诱导填缝和毛细填缝共同作用的结果.

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ence and Technology, Changchun 130022, China). pp 17 – 20

Abstract: The distributions of the elements in CO_2 laser-metal active gas (MAG) hybrid welding were investigated with scanning electron microscope. The relation between the forming process of weld and the distribution of the element in CO_2 laser-MAG hybrid welding process was analysed with high-speed camera and scanning electron microscope. Both the melting metal flow and position of adding elements decide the element distributions. Metal flow varies due to changes of DLA (distance between laser and arc). The fluctuation of the keyhole can promote the uniform distribution of the element, but the impactness of the metal vapour enriches element in local zone of welding pool. The scanning and stiring of laser beam further make the uniform element distribution. The highest content and uniform distribution of elements can be obtained in the molten pool when the distance between laser and arc is 3 mm and elements are added from the location 1.0 mm away from the surface.

Key words: CO_2 laser-arc hybrid welding; melting metal flow; element distribution

Analysis of arc pressure and its weld quality in hybrid ultra-high frequency pulse VP-GTAW process CONG Baoqiang[1], QI Bojin[1], YANG Mingxuan[1], LI Wei[1,2], WANG Lexiao[1*] (1. School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China; 2. Department of Electrical Engineering, Beijing Institute of Petro-chemical Technology, Beijing 102617, China). pp 21 – 24

Abstract: The variations of arc pressure and weld characteristics in the welding of 2219, 2A14 and 5A06 aluminum alloys were investigated based on the hybrid ultrahigh frequency pulse current variable polarity gas tungsten arc welding (HPVP-GTAW) process. The experimental results show that compared with the conventional VP-GTAW (variable polarity gas tungsten arc welding) process, arc pressure and weld penetration expressed by the ratio of weld depth to width are enhanced predominantly with the effect of high frequency pulse current. Mechanical properties of welded joints are improved obviously. At the given pulse current amplitude and pulse duty cycle, the welding process is influenced significantly by the pulse current frequency in the range of 10 kHz to 80 kHz. At the given pulse frequency of 40 kHz, arc pressure and weld penetration of welded joints increased by about 90% and 70%, respectively, compared with that of welded joints with no effect of pulse current.

Key words: ultrahigh frequency pulse current; variable polarity gas tungsten arc welding; arc pressure; weld quality

Nanoindentation properties of intermetallic compounds in lead-free solder joints QIN Fei, AN Tong, ZHONG Weixu, LIU Chengyan (College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China). pp 25 – 28, 32

Abstract: The growth of intermetallic compounds (IMC) at the Sn3.0Ag0.5Cu/Cu interface was investigated under isothermal aging temperature of 150 ℃ and aging time of 100, 300, 500 and 1 000 h, respectively. The relationship between the thickness of the IMCs layer and aging time was fitted out, and the growth law of the IMCs layer at Sn3.0Ag0.5Cu/Cu interface under isothermal aging condition was obtained. Mechanical properties of the Cu_6Sn_5 and Cu_3Sn were obtained by a nanoindentation tester. It indicates that with the Cu_6Sn_5 thickness increasing, its Young´s modulus and hardness have no significant change. The Young´s modulus of Cu_3Sn is greater than that of Cu_6Sn_5, but the hardness of Cu_3Sn is lower than that of Cu_6Sn_5. The nanoindentation experiments of the Sn3.0Ag0.5Cu/Cu interfacial zone show that the hardness of Cu, Cu_3Sn, Cu_6Sn_5 and Sn3.0Ag0.5Cu has an order of magnitude that is in sequence $Cu_6Sn_5 > Cu_3Sn > Cu > Sn3.0Ag0.5Cu$.

Key words: electronic packaging; intermetallic compound; nanoindentation; mechanical property

Improvement of corrosion resistance of friction stir welded joint of 7N01-T5 aluminum alloy by micro-arc oxidation LIU Wanhui[1,2], LIU Wenbin[1], BAO Ailian[2] (1. College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin 150001, China; 2. College of Materials Science and Technology, Heilongjiang Institute of Science and Technology, Harbin 150027, China). pp 29 – 32

Abstract: The ceramic coatings were prepared on surface of friction stir welded joint of 7N01-T5 aluminum alloy by micro arc oxidation technology. The morphology and phase constituent of the micro arc oxidation coatings were studied by SEM, XRD. The corrosion resistance of the friction stir welded joint oxidized and sealed was tested through the neutral salt spray (NSS) test. The results show that micro arc oxidation coating formed on the FSW joint is uniform, and there are many discharge micro-porous like crater and melting, sintering traces on the surface, and which are mainly composed of α-Al_2O_3 and γ-Al_2O_3 phase. Micro arc oxidation ceramic coating has excellent corrosion resistance. Boiling water seal treatment can generate a hydrated alumina, which makes the hole wall inflated and the pore size decreaed, the corrosion resistance of the coatings can be greatly enhanced, and the weight loss is only 2.6 mg after enduring 96 h in NSS test.

Key words: micro arc oxidation; aluminum alloys; friction stir welding; corrosion resistance

Influence of ultrasonic time and pre-clearance on gap-filling behavior of filler metal during ultrasonic-assisted brazing of magnesium alloy LI Hong[1], GENG Yuanyue[1], YAN Jiuchun[2], LI Zhuoxin[1] (1. College of Materials Science and Engineering, Beijing University of Technology, Beijing 100124, China; 2. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China). pp 33 – 36

Abstract: In order to investigate the influence of ultrasonic on flow behavior of filler metal when the filler metal propagates on the solid/liquid surface in brazing process, the gap-filling behavior of the molten filler metal during ultrasonic-assisted brazing of magnesium alloy was in-situ observed by high-speed video camera. Besides, the gap-filling behavior in unparalleled gaps and brazed joint properties were investigated. When the filler metal fills the gap in the direction parallel to the ultrasonic energy propagation, the dynamic curve of filling-gap distance appears linear relation with the ultrasonic time. And it shows that at the same ultrasonic time, good pre-clearance results in low filling velocity. Along the filler flow direction, the thickness of brazed joint decreases gradually. The filling-gap distance decreases as ultrasonic time increases when filler metal is placed at large gap side. The compactness of the joint is general. The filling-gap distance increases firstly and then decreases with the ultrasonic time increasing when the filler metal is placed at small gap side. In this case, the defects appear in the whole joint. The analysis

indicates that the flow behavior of filler metal in unparalleled clearance is influenced by the combined effect of ultrasonic induced gap-filling action and capillary action.

Key words: ultrasonic brazing; high-speed video camera investigation; gap; filling gap; dynamics

Effect of pre-oxidation treatment on thermal shock resistance and residual stress of thermal barrier coating LI Yajuan[1], DONG Yun[2], WANG Zhiping[1], LIU Shiqiang[3] (1. College of Science, Civil Aviation University of China, Tianjin 300300, China; 2. Department of Materials Science and Engineering, Northeastern University at Qinhuangdao, Qinhuangdao 066004, China; 3. School of Materials Science and Engineering, Hebei University of Technology, Tianjin 300130, China). pp 37 - 40

Abstract: The thermal barrier coating by taking MCrAlY as bonding coating and $ZrO_2 + 8\% Y_2O_3$ as top coating were deposited on the nickel-based super-alloy by air plasma spraying. Pre-oxidation treatment was carried out on the thermal barrier coatings by controlling the oxygen pressure in high vacuum sintering furnace. Then, the effects of pre-oxidation treatment on the thermal shock resistance and residual stress were investigated, respectively. The results show that pre-oxidation treatment improves the density of bonding coating, which makes it uniform and reduces the probability of complex stress caused by convex point in interface area. Meanwhile, pre-oxidation treatment interferes the growth process of thermally grown oxide (TGO), reduces the TGO growth rate and the stress concentration of coating. Residual stress increases with the increasing of thermal cycles. However, pre-oxidation treatment can slow down the increasing rate of residual stress. The residual stress of 650.1 MPa can be reached after 350 thermal cycles without pre-oxidation, while the residual stress is only 492.5 MPa after 400 thermal cycles with pre-oxidation.

Key words: pre-oxidation treatment; thermal barrier coating; thermally grown oxide; residual stress

Calibration of relative position and orientation between robot and positioner based on spheres fitting method ZHU Xiaopeng, ZHANG Ke, TU Zhiqiang, HUANG Jie (Shanghai Key Laboratory of Laser Manufacturing & Material Modification, Shanghai Jiao Tong University, Shanghai 200240). pp 41 - 44

Abstract: A method to calibrate the relative position and orientation between robot and positioner was presented by fitting sphere based on the least square method. Firstly, the positioner rotates or tilts to different positions, and the position data of TCP were recorded in the same time. The optimal sphere was fitted by the least square method, and the origin of base coordinate frame of the positioner was calculated. Secondly, several points were recorded in the same way to calculate the vectors of axis. In order to avoid the effects of causal factors, the concept of deviation rate was presented to verify the accuracy of the marked points. Experiments show that this method can reduce the random error and avoid the effects of causal factors, which has high precision.

Key words: robot; laser cladding; calibration; sphere fitting method; least square method

Spectrum of MIG arc at different welding parameters LI Zhiyong, ZHANG Wenzhao, LI Yan, DING Jingbin (Welding Research Center, North University of China, Taiyuan 030051, China). pp 45 - 48, 52

Abstract: The droplet transfer mode and arc length variation are the significant factors affecting the radiation intensity of arc plasma for MIG welding. It is critical to understand the regularity of the radiation fluctuation in application in industry control of the welding process. Therefore, the spectrum of MIG arc radiation was collected with a spectrometer based system. The spectrums of welding processes at different welding parameters were analyzed to study the regularity of the radiation variation. Based on the arc physics, the spectral information combining with the droplet transfer mode was used to get a better understanding of the arc radiation. The results show that the arc spectrum with its distinct distribution is different at different welding parameters. The MIG arc emits wavy radiation due to droplet transfer. The spectral signals in different spectrum bands, such as ultraviolet, visible and near infrared band, have totally different variation characteristics during different instance of the droplet transfer.

Key words: arc spectrum; welding parameter; MIG welding; droplet transfer

Microstructure and properties of diffusion bonded interface of titanium-copper interlayer-carbon steel composite tube LIU Deyi, CAI Jianwei, REN Ruiming (School of Materials Science and Engineering, Dalian Jiaotong University, Dalian 116028, China). pp 49 - 52

Abstract: The composite tube of titanium/steel was prepared by the drawing and inner pressure diffusion technique by using Cu foil as an interlayer. The interface microstructure, fractured surface and components were investigated with OM, SEM, XRD and EDS. The bonding strength of the interface was studied by shear test. The results show that the metallurgical bonding of titanium and steel was obtained by the drawing and inner pressure diffusion technique with copper foil as an interlayer. The interface components analysis show that the elements diffusion was found between the titanium/copper interface and the diffusion layer was formed. The thickness of the diffusion layer increased with increasing of diffusing time. The Fe-Ti brittle compound was prevented by using copper interlayer at lower diffusion temperature. The shear strength of titanium/steel interface firstly increased and then decreased with diffusion temperature increasing. Copper interlayer can improve the shear strength significantly, and the maximum shear strength can reach 310 MPa.

Key words: titanium/steel; interlayer; diffusion bonding; bonding strength

Effect of Zn on formation of voids on Sn*x*Zn/Cu interface YANG Yang[1], LU Hao[1,2], YU Chun[1], CHEN Junmei[1], CHEN Zhenying[1] (1. School of Materials Science and Engineering, Shanghai Jiaotong University, Shanghai 200240, China; 2. Key Laboratory of Shanghai Laser Manufacturing and Materials Modification, Shanghai Jiaotong University, Shanghai 200240, China). pp 53 - 56

Abstract: The effect of Zn on formation of Kirkendall voids on the interface was studied through the reaction between Sn*x*Zn solders ($x = 0, 0.2\%, 0.5\%, 0.8\%$) and the electroplated Cu substrate. During the thermal aging of Sn/Cu joints, a number of Kirkendall voids were formed in the Cu_3Sn layer and on the Cu_3Sn/EPC interface. With the increase of Zn content in solder, the growth of Cu_3Sn layer was greatly suppressed, and the formation of Kirkendall voids was effectively inhibited. The concentration of Zn on the reaction interface also significantly increased. Zn participated in the interface reaction, (Cu,