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微弧等离子喷枪电热特性分析

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摘 要: 等离子喷枪的电弧伏安特性和热效率等电热特性是影响等离子喷涂质量的重要因素，文中根据自行研制的微弧等离喷涂系统，开展等离子喷枪的电热特性研究，分析了不同进气方式下的电弧伏安特性以及微弧等离子喷枪的热效率. 结果表明，等离子喷枪在不同进气方式下均呈现下降的伏安特性，在相同电流和气体流量条件下，直流和切向混合进气方式下喷枪的电弧电压要高于单独采用直流和切向进气时电弧电压，电弧具有更高的能量密度. 微弧等离子喷枪热效率为56% ~76%，喷枪射流热焓为3.28 ~11.16 kJ/g.

关键词: 微弧等离子; 进气方式; 伏安特性; 热效率
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0 序 言

等离子喷涂是以等离子喷枪产生的压缩电弧作为热源，将送粉气载入的喷涂粉末加热至熔化或半熔化状态，并高速喷射在零件表面形成致密的层状涂层[1-3]. 等离子喷枪是产生等离子射流的发生器，其性能好坏对喷涂质量的关系很大. 工业上应用的等离子体炬的主要技术指标是功率、效率和连续使用寿命，因而对等离子喷枪电热特性的研究就显得至关重要[4].

等离子体伏安特性表示电弧稳定工作时电弧电压与电流之间的关系. 等离子喷枪伏安特性主要受阴极材料、结构和几何尺寸，电弧长度及工作气体种类和流量等因素的影响. 喷枪的热效率反应等离子电弧对工作气体加热的效果，等离子喷枪的热焓则直接影响喷涂粉末熔化效果. 国内外学者针对等离子喷枪的电热特性进行了许多有益的研究[5-9]. 等离子喷枪的电弧电压和电流根据不同的喷枪结构表现出下降的伏安特性[4,5,9]或者上升的伏安特性[8]. 而喷枪的热效率也有所区别.

目前研究多集中于通过对喷涂电流以及电弧工作气体的调节，实现对电弧功率的调节. 通过合理的喷枪设计以及进气方式的控制更有利于实现喷涂的稳定和热效率的提高. 文中根据自行研制的微弧等离子喷涂系统，开展等离子喷枪的电热特性研究，分析了不同进气方式下的电弧伏安特性以及喷枪的热效率. 微弧等离子喷枪在低功率条件下实现稳定的电弧输出和较高的热效率，这对提高等离子喷枪的性能和涂层质量均具有很现实的意义.

1 试验装置

试验系统为自行研制的多功能微弧等离子喷涂系统[10]. 主要由喷涂电源、喷枪、循环水冷机以及连接管路组成，如图1所示.

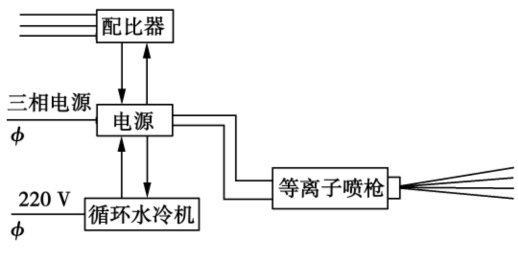

图1 微弧等离子喷涂系统示意图
Fig. 1 Schematic of micro plasma spray system

微弧等离子喷枪结构示意图如图2所示. 喷枪采用分段式结构，主要由阴极组件、阳极组件和绝缘体三部分组成，形成三段两腔两室结构，三段分别为前枪体、绝缘体和后枪体; 两腔分别为冷却水进水腔

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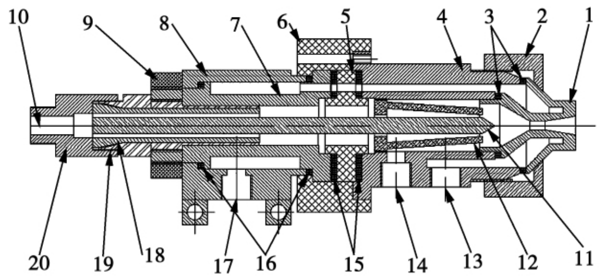
和回水腔;两室分别为主进气室和次进气室. 该结构不仅阴极固定方式简单,容易保证同心度,而且喷枪冷却效果好,等离子射流速度高,安装、拆卸和维护方便.



1 喷嘴; 2 前压盖; 3,16 密封圈; 4 前枪体; 5 绝缘体; 6 绝缘套; 7 后枪体内环体; 8 后枪体外环体; 9 压紧螺母; 10 主气进气嘴; 11 钨极; 12 高温隔热管; 13 回水嘴; 14 次气进气送粉嘴; 15 密封垫; 17 入水嘴; 18 阴极夹; 19 阴极套; 20 压紧螺帽

图2 微弧等离子喷枪结构示意图

Fig. 2 Schematic of micro plasma spray gun

微弧等离子喷嘴为拉瓦尔孔形结构,如图3所示. 等离子喷枪工作气体的进气方式可分为切向进气和直流进气两种. 切向进气是靠隔热环端面上开有两个切线方向的半圆孔实现的. 直流进气方式的气流是沿轴线方向推进的,直流进气是靠带内锥孔的隔热环来实现的.

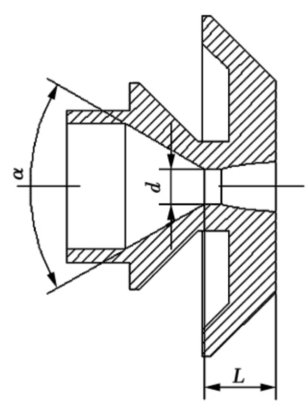


图3 微弧等离子喷嘴结构示意图

Fig. 3 Schematic of micro plasma spray torch

微弧等离子喷涂电源运用了二次逆变技术、软开关技术和智能控制技术等,很好地保证了电源的稳定性和可靠性. 电流可显示范围 0 ~ 350 A,电流连续可调,电弧电压使用数显万用表来测量. 工作气体是氩气和氮气,气体流量由流量计测得. 冷却水由系统自带的循环水冷机提供,冷却水的质量流量由冷水机控制,用温度计直接测量冷却水的进出口温度.

2 结果与讨论

2.1 电弧的伏安特性

图4为工作气体为 Ar + 10% N_2,流量为 20 L/min时,微弧等离子喷枪在不同进气方式下,电弧电压随电流的变化曲线. 可以看出,微弧等离子喷枪在不同进气方式下均呈现下降的伏安特性. 这是由于随着电流强度增加,电弧的热电离加强,电弧的截面积增加,导致电弧电阻的降低,而且下降速度比电弧电流增加速度要快,从而使得电压随着电流的增加而下降,保证了等离子电弧的稳定工作. 随着电流的继续增加,电压趋于稳定,这是由于在大电流条件下,电弧温度已经很高,这时再增加电流,电弧温度增高不多,电导率变化也不大,电流密度的增加速度超过了电导率的增加速度. 同时,等离子弧弧柱的截面积由于喷枪室壁的存在而受到限制,即弧柱的截面积变化不大,电弧中气体电离得更加充分,电流密度更大,电流增大对弧柱的压缩作用使弧长被拉长,因此在试验中,电弧电压在电流较大情况下呈现平特性.

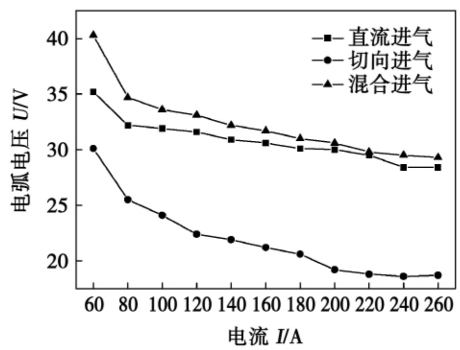


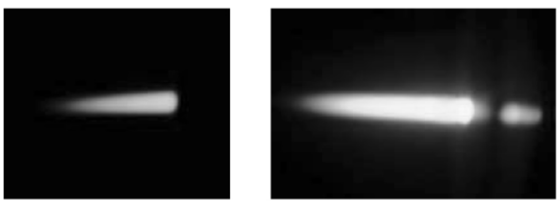
图4 不同进气方式下电弧电压和电流的关系

Fig. 4 Variation of arc current and arc voltage with different gas injection modes

在相同电流和气体流量条件下,直流或切向混合进气方式下喷枪的电弧电压要高于单独采用直流和切向进气时电弧电压,电弧具有更高的能量密度. 切向进气方式是使气流沿隔热环和喷嘴内壁流动,造成喷嘴的中心部位和壁面附近的气流形成压力差,在壁面附近出现一层冷气膜,并增强壁面附近"冷气膜"的厚度. 这不仅有利于保护喷嘴和阴极,使其承受更大的电流,而且有利于提高中心部位的电离度,实现电弧压缩和保证电弧的稳定性. 但是,切向进气方式也存在着以下缺点: 当等离子射流从

喷嘴喷出后，涡旋流动容易导致冷空气卷入射流，致使射流的温度和速度快速下降. 直流进气方式的气流是沿轴线方向推进，靠带内锥孔的隔热环来实现. 直流进气有利于等离子弧的起弧，但当气流向前推进时，受到阴极杆的阻挡，使气流很难达到均匀分布，会造成冷却气膜壁厚不均匀，将可能影响到等离子弧的稳定性能.

等离子喷枪设计的直流和切向混合进气方式不仅能够保持电弧的稳定性，而且还能够实施对阴极冷却和提高等离子弧焰流速度，保证等离子弧具有更高的电弧电压、较小的弧压波动幅值和较好的稳定性. 同时采用直流和切向相结合的进气时等离子弧被明显拉长（图 5），电弧的稳定性和射流速度明显提高，有超音速的特征出现，有利于电弧功率的稳定输出，更加均匀地加热粉末，提高涂层质量.



(a) 直流进气　　(b) 直流和切向混合进气

图 5　不同进气方式时微弧等离子射流形貌

Fig. 5　Plasma jet under different gas injection mode

2.2　喷枪热效率

等离子喷枪的热效率反应了等离子弧对气体的加热效果，在很大程度上也就决定了喷枪的能源利用率；等离子焰流的焓值，直接影响着粉末的熔化和沉积效率，它们都是喷枪性能的重要指标.

利用能量守恒原理，测量喷枪的输入功率和冷却水在单位时间内流经喷枪后的温差，以及工作气体的质量流量，然后按下式计算喷枪热效率 η 和总焓 H[11] 为

$$\eta = \frac{UI - m_w \cdot c_w \cdot \Delta T}{UI} \times 100\% \qquad (1)$$

$$H = \frac{UI}{W_g} \cdot \eta \qquad (2)$$

式中：U 为等离子弧电压（V）；I 为等离子弧电流（A）；m_w 为冷却水的质量流量（g/s）；c_w 为冷却水的比热（kJ/g/℃）；ΔT 为冷却水的温差（℃）；W_g 为气体的质量流量（g/s）.

图 6 为微弧等离子喷枪的热效率随电流变化曲线. 可以看出，在电流较小时，随着工作电流的增加，喷枪的热效率下降不明显；当电流增加到 140 A，工作电流继续增加，喷枪的热效率下降明显. 这是因为电流增加，功率增大，等离子弧温度升高，弧柱与周围气体的对流换热作用加剧，被冷却水带走的热量更多，所以热效率降低.

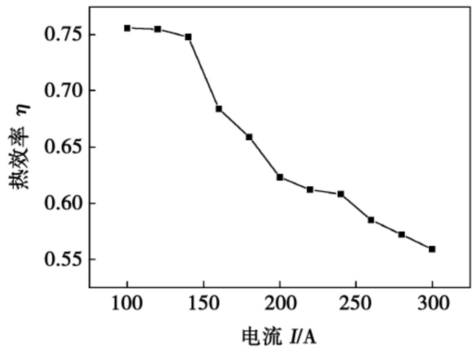


图 6　微弧等离子喷枪热效率图

Fig. 6　Influence of arc current on plasma thermal efficiency

喷枪的焓值随电流的变化如图 7 所示，焓流的焓值随工作电流的增大而增大. 电流增加，等离子弧功率增加，虽然热损失也随之增加，但等离子弧的净功率还是增加的，所以等离子弧的焓值会随电流的增大而提高.

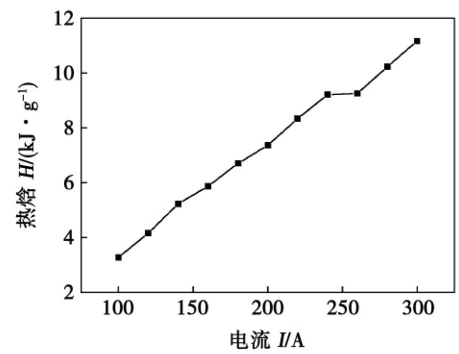


图 7　微弧等离子喷枪射流热焓

Fig. 7　Influence of arc current on plasma enthalpy

与传统等离子喷枪相比，微弧等离子喷枪的热效率得到显著提高. 这是由于传统等离子喷枪大部分电弧能量被冷却水带走，喷枪效率在 37% ~48% 之间变动[12]. 微弧等离子喷枪热效率为 56% ~76%，其主要与电弧的自磁压缩有关，自磁压缩能够保持电弧能量集中，防止能量的扩散. 传统等离子喷枪，电弧比较短，当等离子体流过阳极弧根，自磁压缩效应消失，从弧根至喷嘴出口较长的距离内，等离子体能量向喷嘴冷壁剧烈扩散，严重降低了喷枪的热效率；微弧等离子喷枪设计的拉瓦尔喷嘴，以及

采用直流和切向相结合进气方式，电弧被大大拉长，等离子体在喷枪内部较长距离内始终受到的自磁压缩效应，有效地防止了能量向冷壁扩散；同时，由于电弧工作比较稳定，没有大尺度的分流现象，等离子体流动比较平稳，有助于降低能量损失．因而提高了喷枪的热效率．

微弧等离子喷枪射流热焓为 3.28 ~ 11.16 kJ/g，基本达到传统大功率等离子喷枪的热焓值（传统大功率等离子喷枪为 4 ~ 20 kJ/g[11]）．这是由于等离子喷枪具有良好的压缩效应，使射流具有较高能量密度，有利于改善涂层质量．

3 结 论

（1）等离子喷枪在不同进气方式下均呈现下降的伏安特性，直流和切向混合进气方式下喷枪的电弧电压要高于单独采用直流和切向进气时电弧电压，电弧具有更高的能量密度，电弧的稳定性和射流速度提高．

（2）合理的喷枪设计以及采用直流和切向相结合进气方式有效地提高了微弧等离子喷枪的热效率和热焓值，等离子射流具有较高能量密度，有利于在小功率条件下制备性能优异的涂层．

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HUANG Wenrong, MO Zhonghai (Institute of Machinery Manufacturing Technology, China Academy of Engineering Physics, Mianyang 621900, China). p 93 – 96, 100

Abstract: Experimental investigations on the electron beam welding of aluminum alloy 2A14 are presented in this paper. Experiments are carried out to study the influence of welding parameters, such as beam current, welding speed, focal location, scanning graph, graph size and scanning frequency, on the penetration depth and width of welds based on an orthogonal test and analysis method. The results showed beam current and focal location had the greatest effect on penetration depth and width of welds, welding speed was next, and beam scanning parameters, such as figures, size and frequency, relatively affected much less. The joints welded by the optimum parameters are good appearance and quality. The microstructure of weld zone is composed of α phase and eutectic structure grains.

Key words: electron beam welding; aluminum alloy; orthogonal test and analysis; microstructure

Study of friction-stir-welded lap joint of aluminum and zinc-coated steel WANG Xijing, SHEN Zhikang, ZHANG Zhongke (State Key Laboratory of Advanced New Non-ferrous Materials, Lanzhou University of Technology, Lanzhou 730050, China). p 97 – 100

Abstract: Lap joint friction stir welding of dissimilar materials between DP600 dual-phase zinc-coated steel and industrial pure aluminum 1060 (the aluminum plate was on the top and the steel was under it) was researched in this paper. It can be found from microstructure morphology of the joint that the steel inserts the aluminum just like two nails in both the advancing side and return side. On the micro scale, the steel and aluminum fully mixed together like rivers. In the weld, nugget zone and heat affected zone, a layer of a certain width of the transition layer was formed by the two materials staggered together. Mechanical performance tests show that the hardness of transition layer is high, joint shear strength is about 77% of base metal, and the mechanical properties of the weld is good. Intermetallic compound $Al_{13}Fe_4$ is found on the fractured surface through XRD phase analysis.

Key words: friction stir welding; aluminum plate; zinc-coated steel; mechanical properties; intermetallic compound

Electric and thermal characteristics of micro-plasma torch LIU Gu[1], WANG Liuying[1,2], CHEN Guiming[1], YUAN Yuhua[3], WEI Wanning[1] (1. The 5th Staff of Second Artillery Engineering College, Xi´an 710025, China; 2. Key Laboratory of Electronic Ceramics and Devices of Ministry of Education, Xi´an Jiaotong University, Xi´an 710049, China; 3. Equipment Institute of the Second Artillery, Bejing 100085, China). p 101 – 104

Abstract: The voltage-current characteristic and thermal efficiency of a plasma gun are key factors influencing the quality of the plasma spraying process. The electric and thermal characteristics of the newly developed micro-plasma torch were investigated. As one of the factors effecting the plasma arc voltage, gas injection was also researched in this paper. The plasma arc voltage for the radial injection mode is much lower than that of axial injection mode and the integrated mode. However, the current-voltage characteristics of the plasma jet show a decreasing tendency in spite of the three gas injection modes. With the integrated mode, stable and long plasma jet with high heat energy was obtained. The thermal efficiency of the micro-plasma gun ranges from 56% to 76%, and the plasma enthalpy is 3.28 kJ/g ~ 11.16 kJ/g. With designed special plasma gun structure and integrated gas injection mode, the plasma gun shows a high thermal efficiency and plasma enthalpy which is suitable for the coating preparation with high qualities.

Key words: micro-plasma; gas injection mode; voltage-current characteristic; thermal efficiency

Microstructure and wear resistance of in-situ synthesis TiB_2-TiN particulates of composite coating reinforced titanium alloy surface by argon arc cladding WANG Zhenting, DING Yuanzhu, LIANG Gang (College of Materials Science and Engineering, Heilongjiang Institute of Science and Technology, Harbin 150027, China). p 105 – 108

Abstract: The composite coating reinforced by in-situ synthesized TiB_2 and TiN particulates was prepared on the surface of TC4 alloy by means of argon arc cladding using BN and Ni60A powders as raw materials. The microstructure of TiB_2-TiN composite coating were characterized by means of X-ray diffraction (XRD) and scanning electron microscopy (SEM). The wear properties of coating were examined using friction and wear tester. Experimental results show that three regions with different microstructures existed in the coating, the cladding zone, the binding zone and the heat-affected zone along the depth profile. There is a good metallurgical bonding between the composite coating and the substrate, the TiB_2 and TiN particulates are dispersively distributed in the coating. The composite coating exhibits its high microhardness and excellent wear resistance under dry sliding wear test condition. The wear mechanism of the coating is micro-cutting wear and adhesive wear.

Key words: argon arc cladding; in-situ synthesis; TiB_2 and TiN particulates; wear resistance

Effect of CeO_2 on microstructure and properties of Fe-based coating produced by plasma arc cladding process LI Diankai[1], LI Mingxi[1], HONG Haifeng[1], GAO Huhe[2], WANG Guilin[2] (1. School of Materials Science & Engineering, Anhui Key Lab of Metal Material and Processing, Anhui University of Technology, Ma´anshan 243002, China; 2. Anhui Taier Heavy Industry Co., Ltd., Ma´anshan 243000, China). p 109 – 112

Abstract: The effect of addition of 1% CeO_2 on the microstructure and wear resistance of high chromium cast iron coating produced by plasma arc cladding process was investigated by means of optical microscope (OM), scanning electron microscope (SEM), X-rays diffraction (XRD) and sliding wear testing. The results show that the phases composition of the alloy coating compared with the Fe-iron coating was not changed, both consisted of γ-(Ni, Fe) solid solution with a face-centered cubic lattice and M_7C_3 (M = Cr, Fe, Mo) carbides with a hexagonal structure. Heterogeneous nucleation of the alloy coating modified with rare earth oxide CeO_2 that leads to the microstructure refinement and restrains the growth of carbides. And it changes the crystal growth direction of γ-(Fe, Ni) solid solution from both {111} and {002} to single {002}. Meanwhile, the rare earth oxides homogeneously distribute in eutectic microstructure, thus improving the microhardness and wear resistance of the coating.

Key words: plasma arc cladding; Fe-based alloy; rare earth oxides; wear resistance