干式高压环境对 TIG 焊接电弧温度的影响

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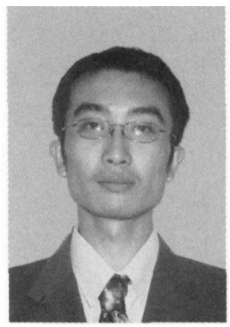

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摘 要：干式高压焊接时，环境压力对焊接电弧的影响不容忽视。电弧温度是焊接电弧物理特性的重要参数之一，测定高压环境下的电弧温度对于深入理解焊接电弧在高压环境下的物理特性，从而寻求改善水下干式高压焊接质量的新途径有重要意义。介绍了电弧等离子体光谱诊断方法，对高压环境下的 TIG 电弧光谱进行分析，建立了一套切实可行的高压环境电弧温度测量方法。对高压环境焊接电弧温度变化规律进行了分析，建立了环境压力与电弧温度的函数关系式，并对试验结果进行了讨论。研究结果对于高压环境焊接电弧物理特性的研究具有参考价值。

关键词：电弧；高压焊接；温度；光谱诊断

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0 序 言

对高压环境下的电弧行为进行研究，有助于了解干式高压焊接过程的特点，是开发相应的焊接设备及焊接材料，并最终获得良好焊接接头的重要理论基础。

电弧温度是描述电弧等离子体的重要参数，因而测定电弧温度对于深入理解焊接电弧在不同环境下的物理特性，从而寻求改善焊接接头质量的新途径具有重要意义[1]。Schmidt 等人[2]的试验表明，随着环境压力的增加，电弧温度下降。而王国荣等人[3]的研究却得到了相反的规律。因此有必要在干式高压焊接试验舱[4]中开展进一步研究工作。

1 试验原理与试验方法

1.1 试验原理

电弧的弧柱占电弧体积的绝大部分，它是一种等离子体，当等离子体满足局部热力学平衡（LTE）和光学薄条件时，元素特征谱线的发射率 ε_{mn} 和其频率以及等离子体温度之间满足关系为[5]

$$\varepsilon_{mn}=\frac{1}{4\pi}A_{mn}h\gamma_{mn}\frac{g_m}{Z(T)}n_0\cdot\exp[-\frac{E_m}{kT}] \quad (1)$$

式中：A_{mn} 为 m 能级原子跃迁到 n 能级的跃迁几率；h 为普朗克常数；γ_{mn} 为辐射谱线的频率；g_m 为 m 能级的统计权重；$Z(T)$ 为原子的配分函数；n_0 为该种原子的全部原子数的密度；E_m 为上能级 m 的激发位能；T 为电弧温度；k 为玻尔兹曼常数。

对于同种粒子任何两条谱线的发射率的比值为

$$\frac{\varepsilon_1}{\varepsilon_2}=\frac{\gamma_1A_1g_1}{\gamma_2A_2g_2}\exp(-\frac{E_1-E_2}{kT}) \quad (2)$$

式中：r_1 和 r_2 分别为两条谱线的频率；A_1 和 A_2 为两谱线的跃迁几率；g_1 和 g_2 为两谱线的统计权重。式(2)比值与配分函数 $Z(T)$、等离子体数密度 $n(T)$ 无关。而且，只要知道两条谱线跃迁几率的相对值，其误差比求跃迁几率绝对值的误差要小。

对于等离子体体积较小的焊接光致等离子体而言，发射系数之比可以用等离子体发射光谱的强度之比来表示。在此基础上，式(2)可以简化为[6]

$$T=\frac{0.624\,7(E_1-E_2)}{\lg\frac{g_1A_1}{g_2A_2}-\lg\frac{\lambda_1}{\lambda_2}-\lg\frac{I_1}{I_2}} \quad (3)$$

式中：E_1 和 E_2 分别为两条谱线的激发电位；λ_1 和 λ_2 为两线的波长；I_1 和 I_2 为其相对强度。测温用的物理参数可由相关资料查得[7,8]。

1.2 试验方法

在一般的工业传感和辐射检测中，是将电弧整体作为一个研究对象进行分析。光谱诊断法既可以对焊接电弧内部温度场进行分析，也可以将焊接电弧作为整体进行分析。由于仅对高压环境中将焊接电弧作为热源时的温度变化规律进行定量分析，未

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涉及电弧温度场的分布规律，又鉴于高压环境试验的可操作性，因此将焊接电弧作为一个整体进行研究。

需要指出的是，任何光源都有一定的形状和大小，只有当测试距离比光源本身的线度大得多，即光源的线度可以忽略时，才可以将光源当作点光源来处理。对于焊接电弧等离子体，当钨极到阳极距离为5 mm时，较亮发光区域不超过中心半径10 mm。整体光谱采集试验中光纤探头距离电弧大于200 mm，大大高于电弧本身尺寸的10倍，所以可以把电弧当作点光源来处理[9]。

对实际拍摄的焊接电弧进行分析，从中筛选出4条ArI（氩原子）谱线，并将其两两组合，得到4组测温谱线组（表1）。试验中，对拍摄的每一幅电弧光谱图计算出4组温度值，以便进行统计分析。

表1 用于焊接电弧温度诊断的4组谱线

Table 1 Four groups of spectrum lines used in arc spectral diagnostics

测温谱线组序号	谱线1波长 λ_1/nm	谱线2波长 λ_2/nm
1	675.283 4	714.704 2
2	675.283 4	727.293 6
3	687.128 9	714.704 2
4	687.128 9	727.293 6

2 试验结果及分析

试验在水下干式高压焊接试验舱中进行[4]，对0.1, 0.3, 0.4, 0.5, 0.6, 0.7 MPa压力环境下的电弧温度进行了分析。焊接工艺参数为：焊接电流100 A，电弧弧长3 mm，氩气流量20 L/min，曝光时间1～5 ms，钨极直径2 mm。

图1中的3幅图分别是在0.3, 0.4, 0.5 MPa压力环境下拍摄的TIG焊接电弧光谱图。图2为0.1, 0.3, 0.4, 0.5, 0.6, 0.7 MPa焊接电弧温度分析图，图中包括1～4组温度点描折线以及由4组温度值计算得到的平均温度线。从0.1 MPa温度图中可以看出，3谱线组计算出来的电弧温度最低，基本维持在10 100 K左右，其平均温度为10 145 K，2谱线组计算得到的电弧温度最高，平均温度值为12 469 K。4组谱线各自计算出来的10个温度值变化不大。至于4组谱线计算温度相互间存在的温差，主要是由于各条谱线的吸收率略有不同造成的，通过计算4组温度的平均值可以有效减少由此造成的误差。

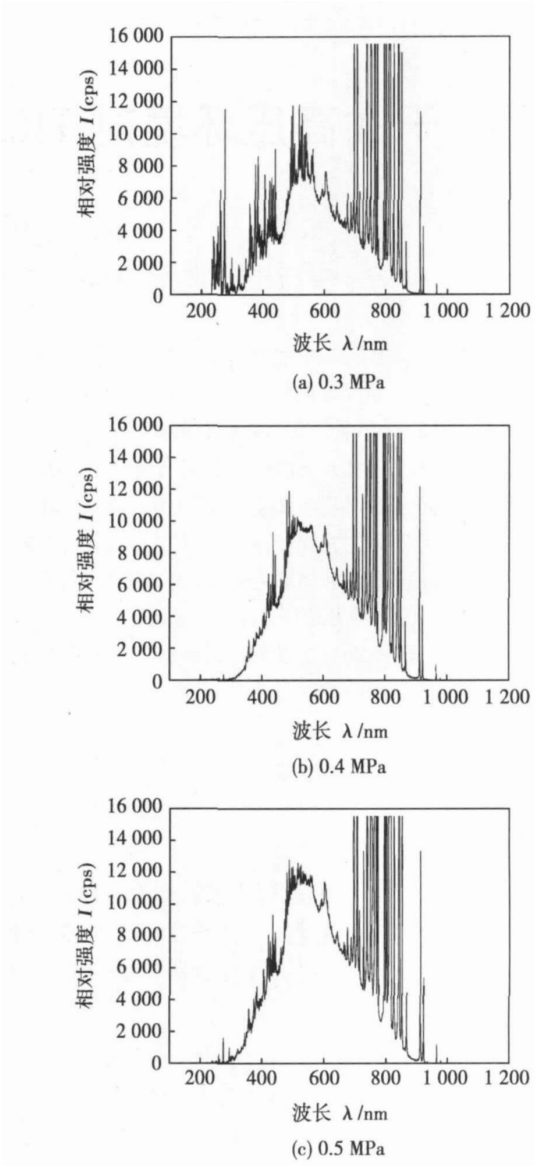

图1 不同压力环境下电弧光谱

Fig. 1 Arc spectrum in different pressure

0.3 MPa压力环境下使用4组谱线计算出来的电弧温度分布范围没有明显的差别，除了第4组计算温度离散程度较大以外，其它3组计算温度基本分布在8 000～9 000 K范围内。0.4 MPa压力环境下，4组谱线计算出来的电弧温度又开始略有分化，2谱线组计算出来的温度相对最高，3谱线组计算出来的温度相对最低，4组谱线各自计算出来的10个温度值变化不大。0.5 MPa环境压力下4组谱线计算出来的电弧温度平均值差异幅度继续增大，但各自计算的10个温度值波动幅度依然不大。

0.6 MPa压力环境下，4组谱线计算的温度值都出现较大幅度的波动，这说明在该压力环境下，电弧稳定性较差，这种结果可以用来解释实际焊接时在该环境压力范围内，引弧困难且容易熄弧的现象。正是由于在该压力下电弧在时域范围内的明显不稳

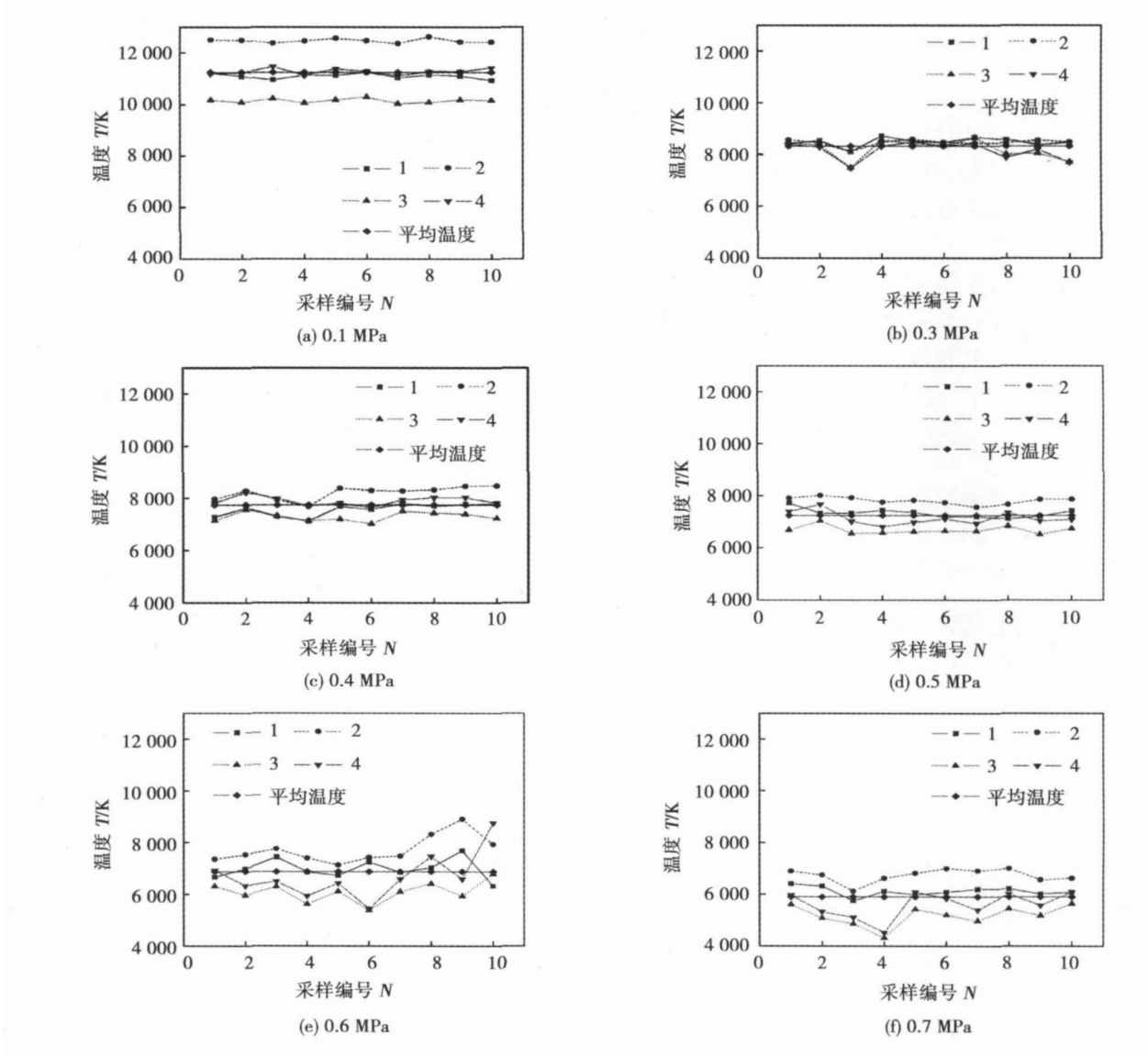

图 2　不同压力环境电弧温度统计曲线

Fig. 2　Graph of arc temperature in different pressure

定性导致了实际焊接时出现的上述问题。但此时 4 组谱线各自计算得到的平均温度高低次序依然没有改变。0.7 MPa 压力环境下,电弧温度在时域范围内仍然存在较为明显的波动,但与 0.6 MPa 时相比温度波动幅度略有下降。这说明通过 0.6 MPa 压力关口后焊接电弧又开始趋于稳定,实际焊接中,此时引弧较 0.6 MPa 时相对容易,焊接过程中电弧也不再容易熄弧。

以上6 组试验数据得到的电弧温度平均值见图3,从图中可以看出,随着环境压力的升高,电弧温度呈现下降趋势。从 0.1 ~0.3 MPa 这个过程中,电弧温度下降较为明显,从 0.3 ~0.6 MPa 这个过程中,电弧温度的下降逐渐趋缓。整体温度变化趋势可以认为符合指数衰减规律,对统计数据进行拟合,得到相同工况下焊接电弧温度与环境压力之间的函数关系式

$$T = 5\ 029 + 8\ 120\mathrm{e}^{-\frac{p}{0.36}} \tag{4}$$

式中:T 为电弧温度;p 为环境压力。

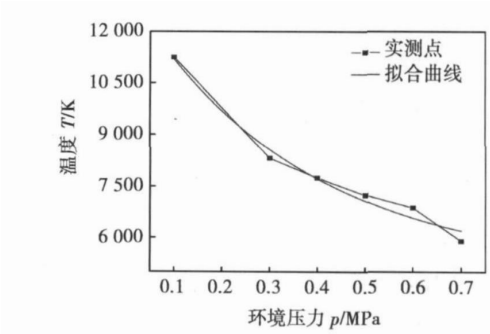

图 3　不同压力环境焊接电弧温度变化曲线

Fig. 3　Welding arc temperature curve in different pressure

3 结 论

(1) 0.6 MPa 压力环境下电弧温度波动剧烈, 由此可以说明, 在该压力环境下电弧稳定性下降。

(2) 随着环境压力的增大, TIG 焊接电弧温度呈现指数下降的趋势。

(3) 所建立的焊接电弧温度与环境压力之间的函数关系式能够反映实际规律, 该关系式对于研究高压环境焊接电弧物理特性具有普遍意义。

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Microsturctures and properties of Ti-Si intermetallic compound layers by arc cladding REN Zhen'an, ZHAO Jiyuan, FAN Jun, HONG He (Key Laboratory of Automobile Materials, Ministry of Education, Jilin University, Changchun 130025, China). p1—4

Abstract: The surface treatment technique of pre-placing silicon powders on the pure titanium substrate before arc cladding was applied to prepare Ti-Si intermetallic compound surface layers. Resulted in different fused amounts between pre-placing silicon powders and the pure titanium substrate prepare different surface layers by changing welding currents. The purpose was to strength the substrate metallurgically. The microstructures of the layers and the interfacial zone were investigated by optical microscopy, scanning electronic microscopy and X-ray diffraction. And the microhardness profiles and the abrasive resistance of the layers were measured. The experimental results showed that the microstructures of the arc cladded layers change from hypoeutectic, eutectic to hypereutectic with increasing welding currents. Ti_5Si_3 phase hardened the layers and made their abrasive resistance obviously higher than that of the pure titanium substrate.

Key words: arc cladding; Ti-Si intermetallic compound; commercially pure titanium; surface layer; abrasive resistance

Weld recognition based on texture feature WANG Shenghua, DU Dong, ZENG Kai, ZOU Yirong (Key Lab for Advanced Materials Processing Technology Ministry of Education, Tsinghua University, Beijing 100084, China). p5—8

Abstract: An automatic recognition and welding seam-tracking visual method was proposed. Different from the active vision method using the macrostructure feature of the workpiece, the passive vision method the gray gradient of the workpiece image is used. It uses the obvious difference of texture feature between welding seam region and base metal region. It has advantage to solve the weld recognition in the multi-layer welding, which is diffcult for the usual visual method. In the method, the textural feature of the image was firstly analyzed, and then the image was segmented by the difference of the image texture feature between the weld region and the base metal region; finally, the zone of the weld were recognized, and its position and the center could be found. Experiment showed the proposed method was effective for welding seam recognition in multi-layer welding.

Key words: weld recognition; texture feature; image processing

Effect of heat treatment on plasma arc welded joint of SiC_p/6061Al MMCs LEI Yucheng, ZHANG Zhen, CHEN Xizhang, NIE Jiajun (School of Material Science and Engineering, Jiangsu University, Zhenjiang 212013, Jiangsu, China). p9—12

Abstract: Heat treatment has much obvious effect on microstructure and properties of joint in plasma arc "in-situ" welding of SiC_p/6061Al MMCs. Prior to annealing process, the improvement effect of solution treatment and aging on microstructures and properties of the joint of SiC_p/6061Al MMCs is better. Massive bulky phases Al_3Ti turn into short rod-like, and intergranular segregation is eliminated, and more homogeneous particles are obtained; heat affected zone is refined, and strength of the joint was improved to 245 MPa.

Key words: SiC_p/6061Al MMCs; plasma arc; heat treatment; microstructure

Numerical simulation of residual stress and deformation on laser welding of "grooved-coat" structure YAN Dongyang[1], WU Aiping[1], JIAO Haojun[2], NING Liqing[2], ZHOU Liangang[2] (1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. Aerospace Research Institute of Materials and Processing Technology, Beijing 100076, China). p13—16

Abstract: Based on finite element analysis software MARC, the 3D numerical simulation on laser welding of "grooved-coat" structure was conducted. This research work concerned the application of hybrid heat source model of laser welding, the simplifications of the mechanical and thermal boundary conditions, the discussions on the computed results of temperature field and residual stress field, and that of the comparison between the shape and size of computed weld pool and the experimental results. The results of the comparisons show that the finite element model is reasonable. The effects of the welding sequences on the welding residual stresses and deformation of structure were investigated. The results show that different welding sequence can get the same distortion pattern, but their deformation have difference, and the distribution of the residual stress is different from each other. The deformation and the residual stress obtained with symmetrical welding from outer to inner is the lowest.

Key words: laser welding; numerical simulation; residual stress; welding distortion

Welding arc temperature in hyperbaric TIG welding ZHAO Huaxia[1], JIAO Xiangdong[2] (1. Mechanical and Electrical Engineering Institute, Beijing University of Chemical Technology, Beijing 100029, China; 2. OEJT, Beijing Institute of Petrochemical Technology, Beijing 102617, China). p17—20

Abstract: The effect of environment pressure on hyperbaric TIG (tungsten inert-gas) welding arc cannot be neglected. The arc temperature is one of the most important parameters. It has important significance to measure the temperature of hyperbaric TIG welding

arc in understanding physical property of hyperbaric welding arc and seeking improvement of the quality of underwater hyperbaric welding. The spectral diagnostics was introduced, and the TIG welding arc in high-pressure was analyzed. A set of feasible method of high-pressure arc temperature measurement was established. The welding arc temperature in high-pressure was analyzed, and the function between the environment pressure and the arc temperature was established. The experimental result was analyzed. This research is significant and valuable to the study of hyperbaric welding arc physics.

Key words: arc; hyperbaric welding; temperature; spectral diagnostics

Improvement on numerical analysis precision of surface deformation of molten pool in fully-penetrated GTAW ZHAO Ming, ZHAI Lei, SUN Yongxing (College of Mechanical & Electronic Engineering, China University of Petroleum, Qingdao 266555, China). p21—24

Abstract: The improvement was made to solve the problems existing in present numerical models of fully-penetrated GTAW (gas tungsten arc welding) weld pool surface deformation. Based on the complete and correct equations of both top and back surfaces deformations of molten pool and the more accurately predicted weld pool geometry, the fully-penetrated molten pool surface deformation at the quasi-steady state were numerically calculated and discussed. The calculated results were verified by experiments. The results indicate that this study solves the problems of the lesser predicted molten pool surface deformation in literatures, and improves the numerical analysis precision of molten pool surface deformation.

Key words: surface deformation; fully-penetrated molten pool; precision improvement; numerical simulation

Residual distortion of thin-plate weldments controlled by rotating extrusion LI Jun, YANG Jianguo, WENG Lulu, FANG Hongyuan (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p25—28

Abstract: A new technology was proposed to control residual distortion of thin-plate weldments with rotating extrusion. Extrusion force with is exerted by rotary action of an extrusion head on weld and zone near the weld to form the tensile plastic strain, which can counteract the welding-induced residual compressive plastic strain, and reduce or even eliminate the welding residual distortion. The surface of weld processed by this method is flat and smooth, and the stress concentration in the weld is decreased obviously. Experimental results showed that this technology can decrease the welding residual distortion of thin-plate weldments to below 3% of that of conventional weldments. The control effect of welding residual distortion has relation to some technical parameters. A good control effect of welding distortion can be acquired only when all kinds of technological parameters are matched properly.

Key words: rotating extrusion; welding; thin plate; distortion

Effect of supersonic fine particles bombarding on oxidation behavior of MCrAlY coating JI Zhaohui, WANG Minzhuan, FENG Ribao, WANG Zhiping (College of Sciences, Civil Aviation University of China, Tianjin 300300, China). p29—32

Abstract: MCrAlY bonding coating was deposited on GH99 high-temperature alloy using atmospheric plasma spraying (APS). The influence of supersonic fine particles bombarding on microstructure and thermally grown oxide of MCrAlY coating was investigated, and the interface, phase constituents and the evolution of the coating exposed at 1 100 ℃ for different times was evaluated by SEM, XRD and glow discharge spectroscopy. The experimental results showed that the oxide particles were fine through supersonic treating, then Al_2O_3 scale formed quickly on MCrAlY surface, and Ni and Cr were prevented from oxidizing. For this reason, the formation of $Ni(Cr, Al)_2O_4$ can be avoided and flaw decreases, so that the high-temperature oxidation resistance of coating is improved.

Key words: thermal barrier coating; supersonic fine particles bombarding; thermally grown oxide; plasma spraying; MCrAlY bond coat

Modeling on weld position and welding torch pose in welding of intersected pipes REN Fushen[1,2], CHEN Shujun[1], YIN Shuyan[1], GUAN Xinyong[1] (1. School of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100022, China; 2. School of Mechanical Science and Engineering, Daqing Petroleum Institute, Daqing 163318, Heilongjiang, China). p33—36

Abstract: The welding seam of intersected pipes is a typical and complicated space welding seam. The models of weld position and welding torch pose were founded for arc welding robot, and their position and pose were described precisely and quantificationally by coordinates. Then, the welding torch orientations were described by work angle, traveling angle and rotation angle, and the calculation methods were presented. A new simple method of calculation is put forward to establish the coordinate system of welding seam according to the characteristic analysis that any tangent through the point on intersection line coincides with the intersection line of two cylinder sections at this point. The model is general to the intersected pipes and it has significance for modeling on weld position and welding torch pose, simulating and off line programming for robot welding.

Key words: arc welding robot; intersection weld; model of weld position; model of welding torch pose

Analysis on microstructure and high temperature stability of nanostructured thermal barrier coatings WANG Hongying[1], HAO Yunfei[1,2], CHEN Hui[2], TANG Weijie[1] (1. Industry Center, Shenzhen Polytechnic, Shenzhen 518055, Guangdong, China; 2. Material Science and Engineering College, Southwest Jaotong University, Chengdu 610031, China). p37—40

Abstract: Nanostructured thermal barrier coatings (TBCs) have been prepared by air plasma spraying using reconstituted nano-