镀锌钢板脉冲电弧钎焊接头界面组织及性能分析

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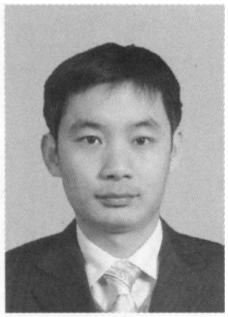
（上海工程技术大学 材料工程学院，上海 201620）



李瑞峰

摘 要：采用脉冲钨极氩弧钎焊使用 CuSi3 钎料对镀锌钢板进行了连接。主要研究脉冲频率变化对接头界面组织和力学性能的影响。结果表明，当电弧脉冲频率由 100 Hz 增加到 2 000 Hz 时，电弧钎焊熔池的搅拌和冲刷作用效果逐渐增强，促进了界面须状金属间化合物的破碎行为和熔池成分过冷区域的增加，使得钎料区域内部 Fe_5Si_3(Cu)强化相数量不断增多，弥散宽度变宽，由 40 μm 增加到 120 μm，接头显微硬度最大值也相应增加，由 175 MPa 增加到 204 MPa。

关键词：镀锌钢板；电弧钎焊；脉冲频率；界面组织
中图分类号：TG454 文献标识码：A 文章编号：0253－360X(2008)11－0093－04

0 序 言

电弧钎焊是一种利用电弧加热焊件和填充钎料的钎焊方法[1]，兼有钎焊和电弧焊的特点[1,2]。与普通电弧熔化焊相比，电弧钎焊具有接头的机械强度高，焊接热影响区小，成形美观，对表面光洁度要求不高，焊后不用清洗，节能高效易于实现自动化等优势。在对薄板、热敏感性高的金属材料、防磁隔磁部件或是存在金属表面涂层材料进行连接时能显示其独特的优点。日本、欧洲的一些厂家在汽车部件及电器制造上，已经大量采用了这种钎焊方法[3,4]。

目前很多相关研究已经发现采用铜基钎料电弧钎焊连接镀锌钢板时，接头的强度高于母材的强度[3,4]。但是这些研究只是针对其电弧钎焊设备及工艺进行研究，很少有研究涉及到电弧钎焊接头得到强化的原因。同时也未见针对脉冲频率变化对镀锌钢板连接时的微观组织和力学性能影响的相关报道。因此文中采用 CuSi3 作为填充金属连接镀锌钢板，其中着重研究脉冲频率变化时界面的显微组织以及接头的强化机理。

1 试验方法

试验中母材均为镀锌钢板，尺寸为 40 mm×40 mm×2 mm，钎料选用 CuSi3(质量分数：97% Cu，3% Si)，试验中称取 200 mg，并弯成环状，试验前所有材料用酒精和丙酮清洗干净。

在研究中，为获得电弧钎焊时 CuSi3 钎料和母材之间的界面反应情况，采用 TIG 电弧在镀锌钢板表面加热钎料使之熔化并在母材上润湿铺展和母材进行反应，即采用 TIG 钎焊方法。在 TIG 钎焊工艺中，焊接基值电流 I_0＝20 A，峰值电流 I_p＝80 A，占空比为 50%，即 t_0＝t_p，燃弧时间 t＝4 s，电压 U＝11.1～11.2 V，脉冲频率 f 分别为 100，500，1 000，2 000 Hz，基本参数如图 1 所示。电弧钎焊试验采用 Fronius 焊机(FK －2600)完成，电源采用直流正接方式，保护气体为纯氩，其流量为 12 L/min。

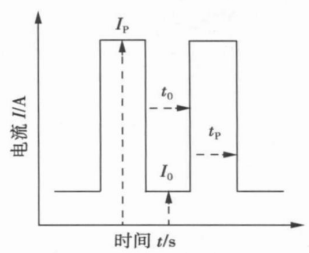


图 1 脉冲电流的基本参数

Fig. 1 Basic parameters of pulsed arc current

TIG 钎焊试样被割断后，打磨抛光，对界面分别进行扫描电镜(JXA840A)和能谱分析(OXFORD －7573)确定界面元素成分和显微组织。并且通过

收稿日期：2008－01－14
基金项目：上海市教委重点学科建设项目(J51402)

M400 — H1 显微硬度机(LECO)确定截面显微硬度。显微硬度测试时每个试样测量从钎缝到母材的区域,在每个测量点分别读取 5 次硬度值,然后取其平均值。试验中载荷皆为 0.098 N,载荷持续时间为 1 s。

2 试验结果及分析

2.1 微观组织分析

图 2 为镀锌钢板/CuSi3 钎料脉冲频率不同时的电弧钎焊接头显微组织形貌,其中左侧为镀锌钢板,右侧为 CuSi3 钎料。由图 2 可以看出在右侧的钎料区内部有呈球状或花状的深灰色颗粒相存在,前期研究已经证明此强化相为 Fe_5Si_3(Cu)相,并且发现由于此强化相的存在接头的强度得到了一定程度的强化[5]。

图 2a 是脉冲频率为 100 Hz 时的钎焊接头微观组织形貌。从图 2a 中可以看出,CuSi3 钎料与母材镀锌钢板之间有一道界面清晰的区域即为钎缝微观界面,在钎缝界面的右边大约 40 μm 的范围以内,零星的存在着几个球状或花状 Fe_5Si_3(Cu)金属间化合物颗粒,其数量较小,尺寸也不大。

图 2b 是脉冲频率为 500 Hz 时的钎焊接头微观组织形貌。相对图 2a 来说,图 2b 试验中所用频率略有增大,但钎缝微观界面组织中 Fe_5Si_3(Cu)强化相的分布仍然较少,且尺寸不大,呈小球状,个别呈花状,同样分布在靠近界面层的地方,主要集中在离界面层约 40 μm 的范围以内。

图 2c 是脉冲频率为 1 000 Hz 时的钎焊接头微观组织。从图 2c 中发现,在 CuSi3 钎料微观组织中分布着大量 Fe_5Si_3(Cu)强化相,相对图 2a, b 中的 Fe_5Si_3(Cu)强化相颗粒来说尺寸较大,数量多,呈小球状和星状,并且分布的宽度也有所增加,达到60 ~ 80 μm。

图 2d 是脉冲频率为 2 000 Hz 时的钎缝接头微观组织形貌。从图 2d 中可以明显发现,在右边 CuSi3 钎料区弥散分布着大量的 Fe_5Si_3(Cu)强化相,分布范围较广,不仅存在于靠近钎缝界面层,在远离界面层处也同样分布着大量 Fe_5Si_3(Cu)强化相,且个别 Fe_5Si_3(Cu)强化相颗粒的尺寸相比图 2a, b, c 明显的增大,呈花瓣状。

由图 2 可以看出 CuSi3 钎缝区内 Fe_5Si_3(Cu)强化相随脉冲频率增加时的分布和生长过程。在频率相对较低时(频率为 100, 500 Hz),钎料区域内部逐渐产生一定的 Fe_5Si_3(Cu)强化相,但 Fe_5Si_3(Cu)强化相的分布较少,且大多靠近界面层;当脉冲频率较大时(频率为 1 000, 2 000 Hz),Fe_5Si_3(Cu)强化相大量产生,数量增加很快,由刚开始的球状逐渐长大呈星状和花瓣状,且分布区域更广。

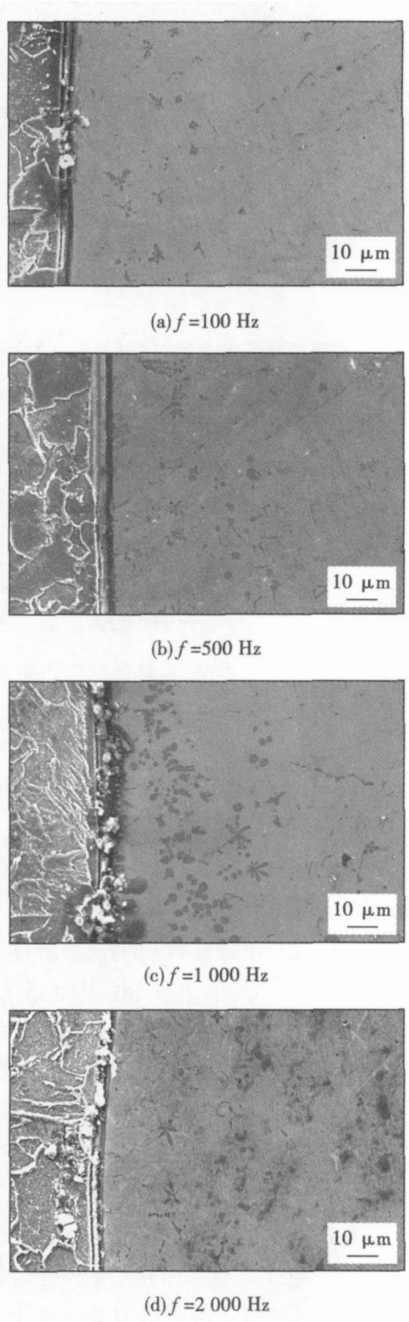


图 2 脉冲频率变化时电弧钎焊接头组织形貌

Fig 2 Effect of pulse frequency on microstructure of brazed joint

2.2 显微硬度分析

前期铜基钎料电弧钎焊连接镀锌钢板的接头拉伸试验结果已经表明,连接后的拉伸断口一般产生在母材一侧[5]。为表明电弧钎焊频率对接头钎缝区域力学性能的影响,研究采用了对钎缝区域进行显

微硬度测量的方法，结果如图 3 所示。由图 3 可知，对于采用 4 种脉冲电弧频率的电弧钎焊试样，都在界面附近显微硬度值达到最大值，也就是说界面的硬度高于熔化钎料区域和镀锌钢板母材区域。另外由图 3 也可看出，其它脉冲参数相同的条件下，当脉冲频率增加时其钎缝显微硬度的最大值不断增加，由 175 MPa 增加到 204 MPa，同时钎缝被增强的区域宽度也不断增加，由宽度为 40 μm 增加到 120 μm，也就是说随脉冲电弧频率的增加，钎焊接头的强化作用得到增强，这和前述界面微观组织的分析结果也是一致的。

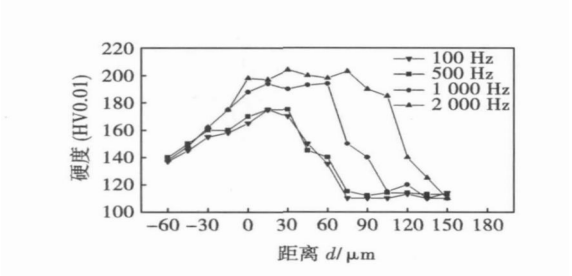


图 3　电弧钎焊接头显微硬度试验结果

Fig. 3　Micro-hardness test results of brazed joint

3　讨　　论

前期研究表明在镀锌钢板进行电弧钎焊连接时，当在接头的内部弥散分布 Fe_5Si_3(Cu)强化相时，镀锌钢板的电弧钎焊接头得到了一定的强化，使得接头的力学性能高于母材的力学性能。并且发现 Fe_5Si_3(Cu)的来源主要分为两个方面，分别为钎料/镀锌钢板界面须状金属间化合物破碎作用，以及钎料内部的 Fe 原子的溶解—析出作用[5,6]，作者认为在高频脉冲的作用下促进了以上两个作用。

在高频脉冲焊接电流作用下，由于脉冲电流在峰值电流和基值电流之间形成周期性变化，引起电弧压力也周期性变化，当峰值电流高时，电弧压力大，熔池表面的液体呈凹状；当处于基值电流时，电弧压力小，熔池表面呈凸状，从而导致熔池液体的上、下振动，使其发生强烈搅拌作用，远远大于未施加脉冲电流时的效果。并且随脉冲频率的增加搅拌作用的效果也不断增加[7,8]。

在脉冲电流作用下的熔池液体的搅拌作用一方面增强了熔池内原有的对流，增大了液体流动，降低了温度梯度，扩大了固液界面前沿的成分过冷区域，并使得 Fe 原子和 Si 原子有机会充分接触，因此增加了钎料区域内部形成 Fe_5Si_3(Cu)的机会，增加了形核核心，使得钎料区域内部的 Fe_5Si_3(Cu)增强相的数量不断增加。另一方面根据材料力学的基本理论可以看出，在交变应力作用下，材料的疲劳极限（$R_{-1}^{弯}$，$R_{-1}^{拉-压}$和 $R_{-1}^{扭}$分别为受弯曲，拉—压和扭转应力载荷条件下的疲劳极限）与其静强度极限 R_m 之间存在如下关系[9]，即

$$\left.\begin{aligned} R_{-1}^{弯} &\approx (0.4\sim0.5)R_m \\ R_{-1}^{拉-压} &\approx (0.33\sim0.59)R_m \\ R_{-1}^{扭} &\approx (0.23\sim0.29)R_m \end{aligned}\right\} \quad (1)$$

由上述关系可以看出，在交变应力作用下，材料抵抗破坏的能力显著下降。因此由脉冲电流产生的强交变对流作用可促进镀锌钢板/钎料界面上生长出的须状 Fe_5Si_3(Cu)金属间化合物发生低应力断裂。并且随着脉冲电流频率的增加也就是加载次数的增加，须状金属间化合物破碎的几率增加。这些破碎的金属间化合物在熔池搅拌的作用下将其带到固液界面前沿的成分过冷区中，促进了 Fe_5Si_3(Cu)相的非均质形核，因此增加了钎料内部 Fe_5Si_3(Cu)金属间化合物的形核核心，使得 Fe_5Si_3(Cu)增强相的数量分布增多。

4　结　　论

（1）界面微观组织和显微硬度分析结果表明，随脉冲频率的增加，接头的强化作用增强，Fe_5Si_3(Cu)强化相数量不断增多，弥散宽度变宽，其显微硬度值也相应增加。

（2）由于脉冲电弧的交变冲击作用下，电弧钎焊熔池的搅拌和冲刷作用效果增强，促进了界面须状金属间化合物的破碎作用和熔池成分过冷区域的增加，从而提高了钎料区域内部 Fe_5Si_3(Cu)强化相的数量和分布宽度。

参考文献：

[1] 林三宝，宋建岭. 电弧钎焊技术的应用及发展[J]. 焊接，2007(4)：19—21.

[2] 于治水，钱乙余，王凤江，等. Cu 基钎料电弧钎焊接头强度及断口分析[J]. 机械工程学报，2001，37(10)：88—92.

[3] Bouaifi B. Low-heat process enchance jointing of coated sheet metals [J]. Welding Journal，2003，82(1)：26—31.

[4] Quintino L，Pimenta G，Iordachescu D，*et al*. MIG brazing of galvanized thin sheet joints for automotive industry[J]. Materials and Manufacturing Processes，2006，21(1)：63—73.

[5] Yu Z S，Li R F，Zhou F M，*et al*. Joint evolution and strengthening mechanisms in arc brazed galvanized steels with Cu97Si3 filler[J].

Materials Science and Technology, 2004, 20(11): 1479－1483.
[6] Li R F, Yu Z S, Qi K, *et al*. Growth mechanisms of interfacial compounds in arc brazed galvanized steel joints with Cu97Si3 filler[J]. Materials Science and Technology, 2005, 21(4): 483－487.
[7] Lancaster J F. The physics of welding[M]. Oxford: Pergamon Press, 1986.
[8] 徐 强, 国旭明, 王宗杰, 等. 双脉冲 MIG 焊对 2219Al-Cu 合金焊缝组织及性能的影响[J]. 热加工工艺, 2004(10): 3－5.
[9] 单辉祖. 材料力学(Ⅱ)[M]. 北京: 高等教育出版社, 2004.

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(3) 根据错边预测模型能准确确定错边产生的主要原因, 对设备调整和保证生产质量有一定指导作用。

参考文献:

[1] 陈 炜, 吴毅明, 吕 盾, 等. 差厚激光拼焊板门内板的成形性能研究[J]. 中国机械工程, 2006, 17(11): 1188－1190.
[2] CEN. ISO 13919－1－1996 电子束和激光焊接接头质量缺陷及质量等级指南[S]. Switzerland, International Organization for Standardization, 1996.
[3] Xin L, Xu Z, Zhao M, *et al*. Analysis and design of a novel four-axis plane laser welding system[C] // In: Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation. Harbin, 2007: 2020－2025.
[4] 陈海洋, 俞建荣, 赵增慧, 等. 薄形焊件变形数值模拟的研究现状[J]. 焊接技术, 2006, 35(3): 4－7.

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different in the second specimen. One of them is 1 mm, and the other one is 2 mm. Meanwhile, the size of bridge between two hole are different. The former is 0.4 mm, and the later is 0.2 mm. Then the numerical resultes were compared with that of the experiment to verify the validity of Gurson damage models in describing the initiation and propagation of cracks during their evolution. The results show Gurson damage model give good results to the second specimen. Because the stress triaxiality of second specimen greater than 0.4.

Key words: aluminium alloy; double-hole test; damae; finite element method

Wear resistance of chromium carbides coating alloyed by vacaum electron beam LU Binfeng, LU Fenggui, TANG Xinhua, YAO Shun (Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiaotong University, Shanghai 200240, China). p77—80

Abstract: Fe/Cr/C powder mixtures were employed to modify the surface of a low carbon steel substrate by electron beam irradiation in vacuum condition. By optimizing the electron beam parameters, chromium carbide is in situ synthesized in the surface composite layer. The surface composite layer was analyzed with optical microscope, XRD analysis and trobological test. There are two main phases in the surface composite layer: chromium carbides as hard phase and austenite as tough phase. There are little typical hexagonal primary chromium carbides in the surface composite layer. Eutectic chromium carbides dispersively distribute between the interface of austenite phase to form a net like structure. It is metallurgical combination in the surface composite layer and the substrate. The existing of carbides in the composite layer provides a notable improvement on the wear resistant property of the surface layer.

Key words: surface composite layer; vacuum electron beam irradiation; chromium carbide; wear resistance

Offline automatic programming of arc prototype system based on arc welding robot DU Naicheng[1,2], HU Shengsun[1,2], DING Wei[1] (1. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin university, Tianjin 300072, China). p81—84

Abstract: At present, methods of graphic teaching for robot are mostly adopted in offline programming system to establish the path of robotic movement. However, for this programming of the approach complex path, the workload is still a large. Moreover, the robot procedure (JOB) is hardly formed by using the position data and welding instructions, which calculated directly by path planning. The offline automatic programming was researched for arc welding robots. The relative JOB is a data exchange interface of MOTOMAN robots. With this interface, the offline automatic programming module generates robots procedures. Through ODBC interface, offline automatic programming module queries the planning instructions and data in the corresponding database in the arc prototype system. The advantages of database are conducive to the expansion of offline programming system. The experiment results show that the researched offline programming operates stably, and the robot moves coherently, and the welding path is accordant to the design.

Key words: robot; arc prototype; offline automatic programming; relative job

Quantitative analysis method of geometrical precision quality on precision welding structure KONG Liang[1], YU Hailiang[1], JIN Xin[1], WU Yixiong[1,2] (1. School of Materials Science and Engineering, Shanghai Jiatong University, Shanghai 200030, China; 2. Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiaotong University, Shanghai 200240, China). p85—88

Abstract: Based on fussy set theory, a quantitative method for welding geometrical quality control of precision welding structure (PWS) is presented. The "Quality Differentiation Coefficient" which characterizes the relation between quality difference and effective quality essentials is adopted to formulate the qualitative linguistic variables of welding quality difference properties. The welding quality analysis model which could fully utilize experts experiments and historical data for PWS is established to quantificational analysis and decision-making.

Key words: precision welding structure; welding geometrical precision; quantification; quality analysis

Misalignment production and its prediction model in tailored blank laser welding XIN Liming[1,2], ZHAO Mingyang[1], XU Zhigang[1] (1. Shenyang Institute of Automation, Chinese Academy of Science, Shenyang 110016, China; 2. Graduate School of the Chinese Academy of Sciences, Beijing 100039, China). p89—92, 96

Abstract: Misalignment is an important quality evaluation standard in tailor welded blanks. The control of misalignment, especially for thinner blanks, is a difficult problem in tailored blank laser welding process. The production and control of misalignment is studied based on a tailored blank laser welding system. The influential factors of the misalignment are obtained after numbers of experiments: the deformation of the blanks before welding, the intensity of the clamping force, the uniformity of the clamping force, deformation of the clamping beam, flatness error of the based platform and the welding process. A mathematical model is established according to the analysis of misalignment. Experimental results indicate that the model provides an effective theorical guidance in improving welding quality.

Key words: tailored blank laser welding; misalignment; finite element analysis; misalignment prediction modeling

Interfacial structure and properties of galvanized steel sheet joined by pulsed arc brazing process LI Ruifeng, YU Zhishui, HE Jianping (College of Materials Engineering, Shanghai University

of Engineering Science, Shanghai 201620, China). p93—96

Abstract: The galvanized steel sheet was joined by pulsed arc brazing process, and the joint interfacial structures and properties of the joints at different pulse frequencies were studied, which the arc pulse frequencies are 100 to 2000 Hz. It can be seen that the agitation and brushing action of the molten pool is increaed with the increase of pulse frequencies, then the whisker-like intermetallic compound fragmentation behavior is strengthened and the constitutional supercooling zone is broadened from 40 μm to 120 μm. At last, the dispersal quantity and width of fine Fe_5Si_3(Cu) particles are increased in brazed joint, which strengthens the joint mechanical properties, and the maximum micro-hardness of the interfacial zone is improved from 175 MPa to 204 MPa.

Key words: galvanized steel sheet; arc brazing; pulsed frequencies; interfacial structure

Hardfacing material for impact wear-resistance with Fe-Mn-Cr-Mo-V alloy system LIU Zhengjun[1], ZONG Lin[1,2], SUN Jinggang[1], CI Honggang[1], SONG Xingkui[1](1. School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110023, China; 2. School of Mechanical Engineering, Shenyang Institute of Chemical Technology, Shenyang 110142, China). p97—99, 104

Abstract: Using H08A core wire, the TKCE50 electrode was compared with classical hardfacing electrode D256. The hardness, wear resistance, performance of work-hardening effect after impact and the effect of alloy elements on the hardfacing layers were studied by means of impact wear test, hardness test and microstructure analysis. The results show that the hardfacing electrode with Fe-Mn-Cr-Mo-V alloy system has high toughness, resistance to cracking and work-hardening properties, especially the performance of impact wear-resistantance is excellent. With the increase of contents of Cr, Mo and V, the hardness of hardfacing metal face increases, and when it reached some number, the degree of increasing becomes stable. After impact by 9000 times, the working-hardening degree reached its top, and the worn mass is the lowest and the wear-resistance is the best at this time.

Key words: hardfacing electrode; impact wear; Fe-Mn-Cr-Mo-V alloy system

Strength and fracture character of SiC_p/2009Al joint by composites reaction diffusion bonging with Al-Ag-Cu-Ti ZHAO Zude[1], SHU Dayu[1], HUANG Jihua[2], HU Chuankai[1], KANG Feng[1](1. No. 59 Institute of China Ordnance Industry, Chongqing 400039, China; 2. School of Materials Science and Engineering, Beijing University of Science and Technology, Beijing 100083, China). p100—104

Abstract: Reaction diffusion bonding of SiC_p/2009Al composites was carried out under vacuum conditions with Al-Ag-Cu-Ti as interlayer. The results show that the joint strength of SiC_p/2009Al composites is affected by the content of Ti, jointing temperature and holding time. When the optimum process is at 550 ℃ holding for 60 min with 3wt% Ti, the joint strength can reach to 120 MPa. The intermetallic compounds become as the crack source which propagate in the joint and result in the fracture of the joint.

Key words: SiC_p/2009Al composites; reaction diffusion bonding; joint strength; fracture analysis

Discussion on numerical simulation of multi-pass welding of thin-plate based on shell element ZHU Jindan[1], CHEN Hu[2,3], GONG Jianming[3], TU Shandong[3](1. School of Mechanical-Electronic and Information Engineering, Zhejiang Textile & Fashion College, Ningbo 315211, Zhejiang, China; 2. Technical Development Department, Ningbo Special Equipment Inspection&Test Center, Ningbo 315020, Zhejiang, China; 3. School of mechanical and power engineering, Nanjing University of Technology, Nanjing 210009, China). p105—108

Abstract: To solve the problem of low efficiency in simulation of multi-pass welding of thin plate by finite element method, a new method, which substitutes routine 3D solid element modeling with laminated shell element modeling based on the theory of thin-shell and composite layer, was used to thermo-mechanically simulate the single or multi-pass welding of thin plate and to predict the residual stress. For the laminated shell element, the shell section points with changeable material properties were used to describe the thickness of plate. A classic analytical model was used to solve the transient temperature distribution and then ABAQUS linking some extended user subroutine was used to analyze the stress. By comparing the residual stress obtained from this method with that based on the solid-element method, the simulation efficiency of this method is higher and the precision is equivalent to that of the solid element method.

Key words: shell element; multi-pass welding; finite element; residual stress

Effects of B_4C on mechanical properties of high carbon ferrochrome self shielded flux-cored wire WANG Qingbao[1,2], BAI Bo[1], LIU Jingfeng[1], LI Zhuoxin[2](1. Welding Research Institute, Central Research Institute Building & Construction, MCC, Beijing 100088, China; 2. School of Materials Science and Engineering, Beijing University of Technology, Beijing 100022, China). p109—112

Abstract: The effect of B_4C content on microstructures, hardness and wear resistance under multi-stress were researched respectively. The results indicated that the primary carbides grew directionally and the macrohardness of hardfacing layer was increased with the increment of B_4C content. The wear resistance of hardfacing alloys presented different characteristics under different stress. When a few primary carbides had broken off, its wear resistance was better than those of hardfacing alloys which lot of primary carbides broke off.

Key words: direction upgrowth; wear resistance; hardness; primary carbide