熔渣的溶氢能力与熔敷金属的扩散氢

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摘 要：分别改变碱性焊条熔渣中 CaO 和 MgO 与气保护药芯焊丝熔渣中 Al_2O_3 和 MgO 组元的相对含量，研究其对熔敷金属扩散氢的影响。结果表明，碱性焊条熔渣中，用同等质量 MgO 取代 CaO 导致熔敷金属扩散氢大幅度提高；药芯焊丝焊接熔渣中，脱氧产物若不是以 Al_2O_3 为主而是以 MgO 为主，熔敷金属扩散氢则大幅度提高。分析认为，熔渣成分的变化导致其溶氢能力的变化是这一结果的主要因素，即 Ca^{2+} 离子导致熔渣含氧量的提高及氢在 Al_2O_3 中具有较高的溶解度等提高了熔渣的溶氢能力。

关键词：焊接；熔渣；扩散氢；溶氢能力
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0 序 言

一般在分析对焊缝金属的扩散氢的作用因素时较少注意到焊接熔渣组成的影响。而对于采用渣保护的焊接过程，熔渣与熔滴、熔池直接接触，两者通过界面发生重要的传质过程，其中也包括氢。显然熔渣的组成对氢的转移是有重要影响的。CaO，MgO 和 Al_2O_3 是渣保护类焊接材料经常使用的氧化物，尤其是已有 MgO 碱性气保护药芯焊丝的研究报道[1]。作者分别改变焊条焊接熔渣中 CaO 和 MgO 与 CO_2 气保护药芯焊丝焊接熔渣中 Al_2O_3 和 MgO 组元的相对含量，研究熔敷金属扩散氢变化，分析焊接熔渣组成的作用。

1 试验方法

试验用碱性焊条直径为 φ4.0 mm，在 TL-25 液压涂粉机上制造。制作焊条所用钢芯化学成分见表 1，焊条药皮配方见表 2。

表 1 制作焊条所用钢芯化学成分（质量分数，%）
Table 1 Composition of core wire used in test electrodes

C	Si	Mn	S	P	Fe
0.060	0.025	0.350	0.010	0.015	余量

试验用 CO_2 气保护药芯焊丝直径为φ1.2 mm，在乌克兰制造的药芯焊丝轧机上制作，制作药芯焊丝所用钢带化学成分见表 3。焊丝原始成分见表 4。

表 2 焊条药皮成分（质量分数，%）
Table 2 Compositions of electrodes coating

焊条编号	CaF_2	SiO_2	CaO	MgO	Mn	Si	Ti	Ni＋Cr	CO_2	Fe
1	22	8	26.3	—	4.2	0.8	3	4.2	20.7	余量
2	22	8	28.0	—	4.2	0.8	3	4.2	22.0	余量
3	22	8	22.4	3.3	4.2	0.8	3	4.2	21.3	余量

表 3 制作焊丝所用钢带化学成分（质量分数，%）
Table 3 Composition of strip steel used in test flux cored wire

C	Si	Mn	S	P	Fe
0.030	0.025	0.250	0.010	0.015	余量

在制作过程中，三种焊条使用相同的药皮原材料和水玻璃粘结剂，且水玻璃粘结剂按粉料重量的加入比例一致，试验焊条的药皮外径也一样。在试验过程中的所有干燥制度、焊接工艺参数等均一致。两种药芯焊丝所使用的药芯原材料与填充率一致。三种焊条和两种药芯焊丝分别同时进行熔敷金属的扩散氢试验。

按照国家标准 GB 3965－83《电焊条熔敷金属中扩散氢测定方法》（甘油法）的要求，试验焊条与药芯焊丝熔敷金属扩散氢试块在平焊位置焊接而成。所用试块为连铸 12MnCrNi 钢板，其化学成分为（质量分数，%）：C 0.11，Mn 1.02，Si 0.48，S 0.005，P 0.014，Ni 1.16，Cr 0.40，Mo 0.12 及 V 0.03。每个试

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表 4　药芯焊丝成分(质量分数，%)

Table 4　Composition of flux cored wire

焊丝编号	CaF_2	SiO_2	CaO	Al_2O_3	Na_2O+K_2O	TiO_2	Mn	Al	Mg	C	Fe
1	0.43	0.32	0.12	1.34	0.12	3.91	2.49	0.280	0.049	0.026	余量
2	0.43	0.32	0.12	1.34	0.12	3.91	2.49	0.035	0.373	0.026	余量

块在试验前都进行了去氢处理。试块的尺寸为 130 mm×25 mm×12 mm。试验焊条采用直流电源焊接，焊条接正极，其统一的焊接工艺参数为：I=160～170 A，U=23～24 V。每种焊条焊四个试块。药芯焊丝也采用直流电源焊接，焊丝接正极，其统一的焊接工艺参数为：I=220 A，U=25 V，CO_2 气体流量为25 L/min。每种焊丝焊三个试块。每个试块焊后按标准要求进行熔敷金属扩散氢的收集、数据读取与计算。

2　试验结果

三种焊条的熔敷金属扩散氢试验结果见表 5。

表 5　三种焊条熔敷金属扩散氢量

Table 5　Diffusible hydrogen in deposited metal of electrodes

焊条编号	试验数据 w_H/(mL·100 g^{-1})			平均值 $\bar{w}_H$/(mL·100 g^{-1})	
1	0.90	0.78	1.09	0.92	0.92
2	0.83	0.83	0.94	0.85	0.87
3	2.61	2.87	2.42	2.65	2.64

两种药芯焊丝的熔敷金属扩散氢试验结果见表6。

表 6　两种药芯焊丝扩散氢量

Table 6　Diffusible hydrogen in deposited metal of cored flux wires

焊丝编号	试验数据 w_H/(mL·100 g^{-1})			平均值 $\bar{w}_H$/(mL·100 g^{-1})
1	2.49	1.65	2.89	2.34
2	6.95	5.65	7.06	6.55

3　分析讨论

3.1　熔敷金属扩散氢与焊条熔渣的溶氢能力

从三种焊条的药皮配方可见，其氧化还原条件基本一致，故冶金反应产物应基本一致。另外，这三种焊条药皮的氟化物脱氢条件、电弧气氛的氧化性也基本一致。三种焊条的制作和焊接条件也一致。而三种焊条的不同之处在于，焊接熔渣成分的 CaO 和 MgO 含量不同。对比 1 号和 2 号焊条，药皮中 CaO 的含量增加，由熔敷金属扩散氢的测定结果看出，这对降低熔敷金属扩散氢含量有作用，但不明显；而比较 1 号和 3 号焊条，药皮中用 MgO 部分取代 CaO，其熔敷金属扩散氢含量明显成倍增加。

可见，在总氢量一定的情况下，在碱性熔渣中用 MgO 代替 CaO，将显著增加熔敷金属的含氢量。这意味着，在碱性熔渣中用 MgO 代替 CaO，熔渣对氢的溶解能力降低了。

3.2　熔敷金属扩散氢与药芯焊丝熔渣的溶氢能力

由表 4 可见，两种药芯焊丝的差别在于强脱氧元素的安排不同，1 号焊丝主要用铝脱氧，而 2 号焊丝主要用镁脱氧。这两种元素在 CO_2 保护环境下几乎是 100%氧化。因此，这两种药芯焊丝的焊接熔渣的一个显著的不同在于前者含有较多的 Al_2O_3，而后者则含有较多的 MgO。

由于所使用的原材料、焊丝制作条件、焊接条件以及氟化物脱氢等方面的一致性，因此在焊接气氛中进入熔渣与熔敷金属系统的总氢量也基本一致。而对应的熔敷金属扩散氢测试结果表明，在焊接熔渣含有较多的 MgO 的情况下，其熔敷金属的扩散氢量显著增加。换句话说，在药芯焊丝的焊接熔渣中用 MgO 代替 Al_2O_3，熔渣对氢的溶解能力降低了，从而导致熔敷金属获得了较多的氢。

3.3　焊接熔渣溶氢能力本质的探讨

文献[2] 指出，酸性熔渣溶解的氢少于碱性熔渣。氢在熔渣中的溶解度随 CaO 含量的增大而上升。将碱性熔渣中的 CaO 用 MgO 代替，会显著降低氢的溶解度。这是导致碱性焊接材料熔敷金属氢较低的重要原因之一。同时，同是碱性材料，CaO 比 MgO 有较大的溶氢能力。

焊接熔渣结构实质是陶瓷结构。由于氢与氧的键合力比较大，因此，增加焊接熔渣(陶瓷)中的氧含量，将提高焊接熔渣对氢的溶解能力，从而在氢的来源不变的情况下，熔渣对氢的溶解能力的提高将减少氢向熔敷金属的分配，进而使熔敷金属的含氢量降低。

而焊接熔渣(陶瓷)的含氧量是受其阳离子的类型所支配的。Mg^{2+} 阳离子半径仅比理想值大

0.008 nm，接近下限，采取 6 个氧配位的 NaCl 结构十分稳定。而 Ca^{2+}，Sr^{2+}，Ba^{2+} 按理论计算采取 6 个或 8 个氧配位都有可能；但因离子半径太大，容易形成 12 配位的过氧化物 CaO_2，SrO_2，BaO_2[3]；因此，熔渣中用 MgO 代替 CaO，将大大减少其含氧量，从而降低其溶氢能力。

由于氢在 Al_2O_3 中有较大的溶解度和高的扩散系数[4]。因此，可以预期含有较多 Al_2O_3 的 1 号药芯焊丝熔渣比含较多 MgO 的 2 号药芯焊丝熔渣的溶氢能力要强，这无疑将成为 1 号药芯焊丝熔敷金属的含氢量下降的重要原因之一。

4 结 论

（1）提高焊接熔渣的溶氢能力将减少氢向熔敷金属的分配，进而使熔敷金属的扩散氢含量降低。

（2）在碱性焊接熔渣中，用 CaO 取代 MgO，将会显著地增加熔渣的溶氢能力，从而导致熔敷金属扩散氢的明显降低。其原因是熔渣中的 CaO 的 Ca^{2+} 半径较大，容易形成 12 配位的过氧化物 CaO_2，提高了熔渣的含氧量，从而增加了熔渣的溶氢能力。

（3）在焊接熔渣含较多 Al_2O_3（脱氧产物）的情况下，相比含较多 MgO（脱氧产物）的熔渣而言，其熔渣的溶氢能力因氢在 Al_2O_3 中有较大的溶解度而提高，这是导致熔敷金属的扩散氢降低的重要原因之一。

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[上接第 53 页]

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Key words: histogram equalization; welding seam; image binarization; edge extraction

The flowing behavior of weld metal in thickness of the plate and the formation mechanism of the onion ring KE Liming[1,2], PAN Jiluan[1], XING Li[2], HUANG Yongde[2] (1. Key Laboratory for Advanced Materials Processing Technology, Ministry of Education, Tsinghua University, Beijing 100084, China; 2. School of Materials Science and Engineering, Nanchang Hangkong University, Nanchang 330063, China). p39—42

Abstract: The plastic flow behavior of the weld metal during friction stir welding was analyzed by using the multi-plate piled up with several thin copper foils and aluminum sheets and the copper foils serves as a marker material. The results show that there is a serious material translation in the thickness of the weld along the screw thread if using a pin with screw threaded surface. These flowing materials will slough off from the thread at the tip or root of the pin and squeeze into the surrounding area, forming a solid ring with the center being the circle of tip or root of the pin. There is a distinct boundary between the solid ring and its surrounding parent metal. The onion ring is actually the projecting picture of the solid ring cut at the cross section of the weld. The driving force of the metal flow in the thickness of the weld is the pressure of the skew threads on the pin surface to its surrounding plastic metal. When the stir tool rotates clockwisely, the center of the onion rings deflect to the bottom of the weld in the case of the pin with left-hand skew thread on its surface, or deflect to the up surface of the weld in the case of the pin with right-hand skew thread on its surface.

Key words: friction stir welding; plastic flow; onion ring

Mathematical modeling and simulation on the lap welding groove of waving TIG HONG Bo, HUANG Mingcan, YIN Li, GONG Hai (Department of Mechanical Engineering, Xiangtan University, Xiangtan 411105, China). p43—46

Abstract: According to the character of the lap joint groove, the signal of the changing bulk of the column as the input signal was introduced into the mathematical model for the waving TIG welding of the lap joint groove, and the simulating model for the whole system accordingly was set up. Keeping the techniques parameters, the differences between the simulating results of this modeling, the traditional results which was made use of changing the height of the welding torch and the welding experiments results were analyzed and compared. It proves that the model reflectes the reality, and more accurate than the traditional ones.

Key words: TIG welding; lap welding groove; mathematical modeling and simulation; columned arc

Inspection of fillet weld shape dimension based on laser vision sensing FU Xibin[1], LIN Sanbao[1], YANG Chunli[1], FAN Chenglei[1], QIAN Xia[2] (1. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China; 2. Department of Industrial Engineering, Binzhou Vocational College, Binzhou 256603, China). p47—50

Abstract: In order to overcome the limitations of fillet weld shape dimension by manual inspection, an inspection method based on laser vision sensing is adopted. Firstly, a laser stripe image is acquired with a laser vision sensor based on principles of optical triangulation. Then the acquired laser stripe image is processed by medium filter, binary processing, laser stripe centerline extraction, and feature recognition algorithms. At last, the information about weld shape dimension is obtained. The experiments show that compared with manual inspection method, the method is much more accurate and reliable to inspect, convenient to use, and the inspection time is greatly shortened, the inspection items are increased obviously, the difference depending on user can be eliminated, and inspection data can be saved in PC.

Key words: laser vision; fillet weld; shape dimension; manual inspection

Effect of Ge on the SnAgCu/Cu soldering interface MENG Gongge[1], YANG Tuoyu[2], CHEN Leida[3], WANG Shizhen[1], LI Caifu[4] (1. School of Material Science & Engineering, Harbin University of Science and Technology, Harbin 150040, China; 2. Anhui Science and Technology University, Bengbu 233100, China; 3. Dalian University of Technology, Dalian 116024, China; 4. Institute of Metal Research Chinese Academy of Sciences, Shenyang 110016, China). p51—53, 56

Abstract: Germanium (Ge) is adjacent to Tin in periodic Table of the Elements; they are both in the main group Ⅳ and resemble each other in physical and chemical properties. A little element Ge was added into lead-free solder Sn2.5Ag0.7Cu (0.25, 0.5, 0.75, 1.0 wt%) and soldering interfaces were made up. The interfacial microstructure and photography were observed and analyzed with scanning electron microscope, the intermetallic compound thickness was measured with Auto CAD software, and interfacial composition was analyzed with energy dispersive X-ray analyzer. The results show that the pattern of IMC layer is pebble shape yet when adding element Ge, but displays a growth trend; the interface gets plainer and more regular with 150 ℃/100 h aging. The interfacial IMC layer is thicker with Ge in solder, but the ratio of getting thicker is smaller with 150 ℃/100 h aging. The addition of element Ge restrains the transformation of IMC Cu_6Sn_5 to Cu_3Sn and the growth during aging.

Key words: lead-free solder; interface; aging; Ge

Hydrogen dissolving capacity in slag and diffusible hydrogen in deposited metal GUI Chibin, WANG Zheng, WEN Jiancheng (Naval University of Engineering, Wuhan 430033, China). p54—56

Abstract: Effects of composition of the slag on the diffusible hydrogen content in deposited metals were studied by means of changing the content of CaO and MgO in the basic electrode slag and changing the content of Al_2O_3 and MgO in the CO_2 gas-shielded

FCAW slag. The results show that the same weight CaO replacing MgO has an obvious improvement on the hydrogen dissolving capacity in slag. It's because the radius of the Ca^{2+} is bigger than the radius of the Mg^{2+} which has 12 match places, and easy to form the peroxide CaO, which can improve the oxygen content in slag. Some Al_2O_3 replacing MgO in FCAW slag will improve the hydrogen dissolving capacity in slag; the reason is the hydrogen has better solubility and diffusion coefficient in Al_2O_3.

Key words: welding; slag; diffusible hydrogen; dissolve hydrogen capacity

Modeling method for pulsed GTAW welding process based on variable precision rough set LI Wenhang[1], CHEN Shanben[2], WANG Jiayou[1], YANG Feng[1] (1. Institute of Welding Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China; 2. Institute of Welding Engineering, Shanghai Jiaotong University, Shanghai 200030, China). p57—59, 63

Abstract: Considering the characters of welding process, a VPRS (variable precision rough set) modeling method is proposed for pulsed GTAW welding process. The VPRS model that can predict the backside width of welding pool is obtained. The main procedure of the modeling method and the key problems are expatiated. The result shows that the precise and complexity of the model is acceptable.

Key words: welding automation; modeling; variable precision rough set; GTAW

Calculation and discussion of welding plastic strain FANG Hongyuan, ZHANG Xueqiu, YANG Jianguo, LIU Xuesong (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p60—63

Abstract: Numerical simulation method is employed to discuss welding longitudinal plastic strain distribution. Residual compressive plastic strain presents in the weld from traditional views, but the new viewpoint supports that the tensile plastic strain presents in the weld. Based on the two different viewpoints, the welding longitudinal plastic strain distribution is analysed with and without the fusion phenomenon according to the calculation results. The simulated results show that there exists little different in the two situations, and compressive plastic strain in the heating process is larger than tensile plastic strain in the cooling process. When a fusion phenomenon is considered, the heat affected zone still keeps the compressive plastic strain all the time, and only the plastic strain value in the cooling process is smaller than the one in the heating process.

Key words: residual stress; compressive strain; numerical simulation; temperature field; fusion phenomenon

Wear resistance of TiB_2-316L stainless steel matrix composite coatings deposited by atmospheric plasma spraying CHENG Hanchi, LI Zhuoxin, AN Shuchun, WU Yongzhi, LI Hong, SHI Yaowu (College of Material Science and Engineering, Beijing University of Technology, Beijing 100022, China). p64—68, 80

Abstract: TiB_2-316L stainless steel matrix composite powders contained 10mass% and 40mass% TiB_2 were prepared by high energy ball milling and spray-drying processes respectively. Atmospheric plasma spraying deposited corresponding coatings and 316 L stainless steel coating. High velocity block-on-ring wear tester was used to test wear resistance of as-sprayed coatings. X-ray diffraction analyzed the constitution of as-sprayed coatings. Scanning electron microscope was employed to character as-sprayed coatings, feedstocks and the worn surface morphology. Results show that wear resistance of as-sprayed TiB_2-316L stainless steel matrix composite coatings is prior to 316L stainless steel coating. TiB_2 particles act as reinforcement component in the coating and oxides from tribo-oxidation of TiB_2 in the tribo contact, which possessed self-lubricating function, can reduce mass loss of the coatings during sliding wear.

Key words: titanium-diboride; 316L stainless steel; ball-milling; spray-drying; atmospheric plasma spray

Discussion on principle of welding stress and distortion (2) WANG Zhechang (Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China). p69—72

Abstract: Formation and relief mechanism of welding residual stress were addressed. Compressive plastic strain dose not play a role in the formation of welding residual stress. The residual stress is produced by the contraction of weld metal and its vicinity during the cooling process at the temperature below its "mechanical melting point". Residual stress elimination does not employ the tensile plastic strain to reduce, withdraw or compensate the compressive plastic strain, but to convert the residual elastic strain to a plastic one. The elimination of the inherent strain is not a prerequisite to eliminate welding residual stress. Partly removed or completely held inherent residual strains can also completely eliminated the residual stress. A new method is proposed to perform heating treatment following the welding torch to control stress-strain precisely, to realize the stress free welding or stress-free and non-distortion welding or even proper compressive stress and non-distortion welding or large compressive stress and minor distortion welding. The result is also compared with the traditional processing method and finite element analysis.

Key words: welding stress-strain; compressive plastic strain; inherent strain; non-stress welding; non-stress-deformation welding

Fe-Cr-V wear resistant hardfacing alloy GONG Jianxun[1], XIAO Yifeng[1], ZHANG Qinghui[1], Ma Mo[2] (1. School of Mechanical Engineering, Xiangtan University, Xiangtan 411105, China; 2. Faculty of Material and Photoelectronic Physics, Xiangtan University, Xiangtan 411105, China). p73—76

Abstract: The Fe-Cr-V hardfacing alloy containing 0.9%—1.5%C, 13%—15%Cr and 1.0%—2.0%V was prepared for flux cored wire of submerged arc welding. The microstructure of hardfacing alloy was researched by means of optical microscopy, scanning electron microscopy, X-ray diffraction, etc. The effect of