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钛合金电子束深熔焊钉尖缺陷形成的影响因素

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摘 要: 钉尖缺陷是电子束焊接所特有的缺陷，对焊接质量造成严重影响. 对于钉尖缺陷的形成机理，目前学术界还没有形成统一的认识. 为了对钉尖缺陷形成机理进行研究，采用正交试验法进行了钛合金电子束深熔焊接试验，焊后对每条焊缝进行了X射线探伤，探伤结果显示钉尖缺陷只存在于未熔透焊缝中，钉尖为不规则狭缝状，根部呈圆形. 利用光学显微镜和扫描电镜结合能谱分析对钉尖缺陷的形成机理进行了研究. 结果表明，电子束脉动是钉尖缺陷产生的直接原因，高饱和蒸气压金属蒸气的存在加剧了钉尖缺陷产生的倾向，是钉尖缺陷产生的重要内在动因.

关键词: 电子束焊; 金属蒸气; 钉尖
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0 序 言

电子束焊接由于具有焊接变形小、功率密度高、工艺可重复性好等优点，非常适合于大厚度材料的焊接. 但是电子束深熔焊在未熔透甚至微透的情况下容易出现钉尖缺陷[1]，钉尖缺陷会成为裂纹的萌生和扩展源，在焊缝根部造成应力集中，降低接头的疲劳性能，同时它也会降低焊缝的有效承载面积，弱化接头的力学性能[2].

国内外学者对钉尖缺陷的形成机理进行了大量的研究工作. 但是至今仍然没有形成一套被大家普遍接受的理论体系[3]，因此开展钉尖缺陷形成机理的研究就具有重要的理论意义和工程应用价值[4].

文中对20 mm厚的钛合金板材进行了电子束深熔焊接试验，对影响钉尖缺陷形成的原因进行了研究，进一步完善了对钉尖缺陷形成机理的认识.

1 试验方法

试验所用材料为TA15钛合金，试件尺寸为100 mm×50 mm×20 mm的平板.

在电子束焊接中，通常加速电压恒定不变，而电子束流、焊接速度、焦点位置是影响焊接质量的三个最主要的工艺参数，因此文中通过改变这三个参数进行电子束焊接试验，焊后对每条焊缝进行X射线无损探伤，确定焊缝中是否存在钉尖缺陷，并利用光学显微镜和扫描电镜结合能谱分析对钉尖缺陷形成机理进行研究. 显然这是一个多因素、多水平试验，因为正交试验法可以解决多因素、多水平以及多指标的试验问题，因此文中采用正交试验法进行试验.

在试验中选择了三个有关因素: 焊接速度、电子束流和焦点位置. 每个因素取五种水平，定义焦点在工件表面以下为负，在工件表面为零，在工件表面以上时为正. 所做因素水平如表1所示.

表1 因素水平表

Table 1 Table of factor and level

焊接速度(A) $v/(mm\cdot s^{-1})$	焦点位置(B) f/mm	电子束流(C) I/mA
5(A_1)	0(B_1)	40(C_1)
6(A_2)	2(B_2)	50(C_2)
8(A_3)	4(B_3)	55(C_3)
9(A_4)	−2(B_4)	35(C_4)
4(A_5)	−4(B_5)	30(C_5)

在因素及水平确定之后，就可以选择适当的正交表. 目前常用的五水平正交表为$L_{25}(5^6)$，将A，B，C三个因素依次放在$L_{25}(5^6)$表的第1，2，3列上，这样就可以得到表2，根据表2进行电子束堆焊试验.

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表2 正交试验表

Table 2 Table of orthogonal experiment

编号	A	B	C	组合水平
1	A_1	B_1	C_1	$A_1B_1C_1$
2	A_1	B_2	C_2	$A_1B_2C_2$
3	A_1	B_3	C_3	$A_1B_3C_3$
4	A_1	B_4	C_4	$A_1B_4C_4$
5	A_1	B_5	C_5	$A_1B_5C_5$
6	A_2	B_1	C_2	$A_2B_1C_2$
7	A_2	B_2	C_3	$A_2B_2C_3$
8	A_2	B_3	C_4	$A_2B_3C_4$
9	A_2	B_4	C_5	$A_2B_4C_5$
10	A_2	B_5	C_1	$A_2B_5C_1$
11	A_3	B_1	C_3	$A_3B_1C_3$
12	A_3	B_2	C_4	$A_3B_2C_4$
13	A_3	B_3	C_5	$A_3B_3C_5$
14	A_3	B_4	C_1	$A_3B_4C_1$
15	A_3	B_5	C_2	$A_3B_5C_2$
16	A_4	B_1	C_4	$A_4B_1C_4$
17	A_4	B_2	C_5	$A_4B_2C_5$
18	A_4	B_3	C_1	$A_4B_3C_1$
19	A_4	B_4	C_2	$A_4B_4C_2$
20	A_4	B_5	C_3	$A_4B_5C_3$
21	A_5	B_1	C_5	$A_5B_1C_5$
22	A_5	B_2	C_1	$A_5B_2C_1$
23	A_5	B_3	C_2	$A_5B_3C_2$
24	A_5	B_4	C_3	$A_5B_4C_3$
25	A_5	B_5	C_4	$A_5B_5C_4$

2 钉尖缺陷特征

图1为焊缝的X射线探伤形貌，每一个黑点代表一个钉尖缺陷. X射线探伤后发现钉尖缺陷只在未熔透焊缝中出现.

图1 X射线探伤形貌

Fig. 1 Photo of X-ray detection

图2为未熔透焊缝根部的钉尖缺陷，由图2中可以看出，钉尖为边缘圆滑的不规则狭长形缝隙，根部呈规则的圆形.

3 钉尖缺陷形成的影响因素

3.1 电子束脉动对钉尖形成的影响

图3所示为钉尖缺陷沿焊缝纵截面的分布情况. 从图3中可以看出在深度方向上钉尖的分布是参差不齐的，这主要是由电子束脉动造成的. 所谓

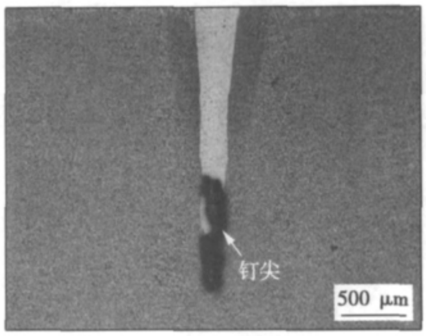


图2 未熔透焊缝根部的钉尖

Fig. 2 Spiking of weld root of incomplete penetration

电子束脉动是指由于网络电压波动及纹波系数的影响导致电子束焊接时束斑功率密度产生脉动周期性变化，这种变化与电子束焊接设备的性能相关且无法彻底消除. 电子束脉动会严重影响焊缝形状，使熔宽和熔深发生变化，尤其表现在熔深的不规则剧烈改变上.

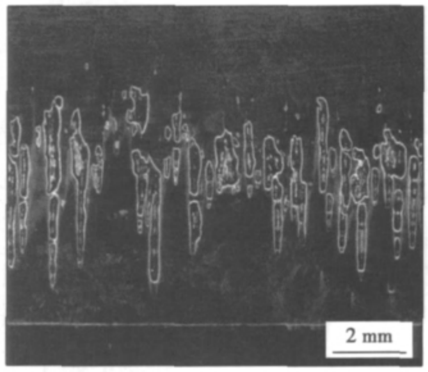


图3 钉尖沿焊缝纵截面的分布

Fig. 3 Distribution of spiking along longitudinal section of weld

由图4所示的钉尖缺陷形成示意图可知，当电子束移开后，液态金属开始填充匙孔，此时若电子束脉动使匙孔的熔深产生震荡变化，在焊缝根部形成脉冲空腔，在液态金属表面张力与高温金属蒸气的阻碍作用下，液态金属来不及流入填满脉冲空腔而在熔池的根部形成一个封闭的永久空隙，金属蒸气被阻隔在空隙中而不能逸出，在快速冷却条件下，液态金属凝固后形成钉尖缺陷. 可见电子束脉动是钉尖形成的直接原因.

3.2 金属蒸气对钉尖形成的影响

利用扫描电镜对钉尖缺陷的微观形貌进行了观察，如图5所示. 从图5中可以看出，钉尖内壁比较光滑，并且在内壁上附着着金属小颗粒. 造成这种现象的原因是因为在未熔透熔池匙孔尖端，由于距

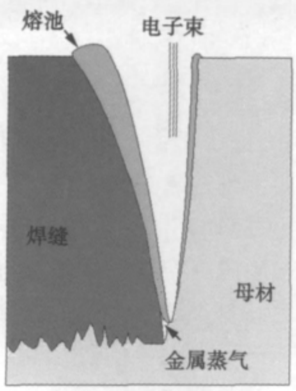
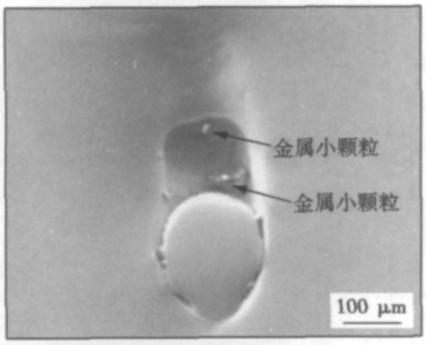


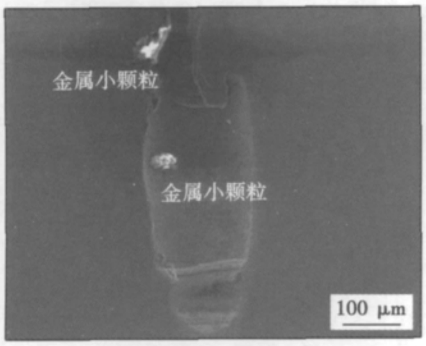
图 4　钉尖缺陷形成示意图

Fig. 4　Schematic of forming spiking

离熔池表面最远，高温金属蒸气不易逸出，对液态金属的相互流动和融合产生了较大的阻碍作用，同时因为电子束焊接热输入小，冷却速度快，还未等液流克服高温金属蒸气的阻碍作用而相互融合就已经凝固，从而将金属蒸气封闭在匙孔尖端，在焊缝根部形成了边缘圆滑的缝隙，即钉尖，在随后的冷却过程中，金属蒸气液化凝固形成金属小颗粒，附着在钉尖内壁上.



(a) 第一组试件



(b) 第一组试件

图 5　钉尖缺陷微观形貌

Fig. 5　Morphology of spiking

为了确定金属小颗粒的成分，对其进行了能谱分析，图 6 和图 7 的能谱分析结果如表 3 和表 4 所示. 由表中可以看出，和其它位置的成分相比，金属小颗粒的成分几乎全部为 Al 和 Ti 元素. 因为金属小颗粒就是由金属蒸气液化凝固形成的，所以能谱分析结果说明封闭在匙孔尖端的金属蒸气主要成分为铝和钛.

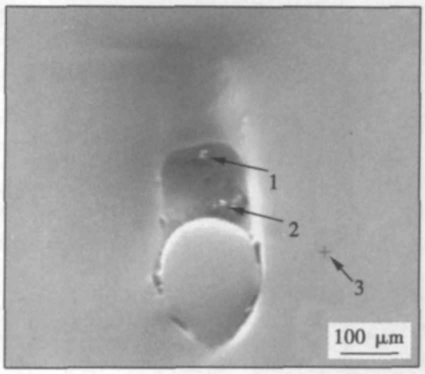


图 6　图 5a 钉尖缺陷能谱分析位置

Fig. 6　Position of EDS analysis of spiking of Fig. 5a

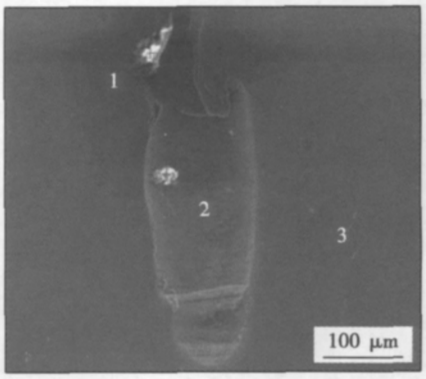


图 7　图 5b 钉尖缺陷能谱分析位置

Fig. 7　Position of EDS analysis of spiking of Fig. 5b

表 3　图 6 各点能谱分析结果（质量分数，%）

Table 3　Results of EDS analysis of different points of Fig. 6

打点位置	Ti	Al	Zr	Mo	V
1	66.7	33.3	0	0	0
2	71.77	28.23	0	0	0
3	83.96	7.78	3.50	3.13	1.63

表 4　图 7 各点能谱分析结果（质量分数，%）

Table 4　Results of EDS analysis of different points of Fig. 7

打点位置	Ti	Al	Zr	Mo	V
1	77.04	21.67	0	0	1.29
2	71.77	28.23	0	0	0
3	85.36	7.30	3.35	2.87	1.12

为了定量分析钛和铝高温金属蒸气对形成钉尖缺陷的影响,文中对它们的饱和蒸气压进行了计算.由文献[5]可知钛和铝的饱和蒸气压计算公式分别如式(1)和式(2)所示,即

$$\lg p = -3\ 085.6T^{-1} - 0.087\ 8\lg T + 1.561 \quad (1)$$

$$\lg p = -2\ 178.673T^{-1} - 0.133\lg T + 1.638 \quad (2)$$

式中:p 为压强;T 为温度.

在 Ti 和 Al 元素各自的熔点至沸点的温度范围内,饱和蒸气压计算结果如图 8 所示.

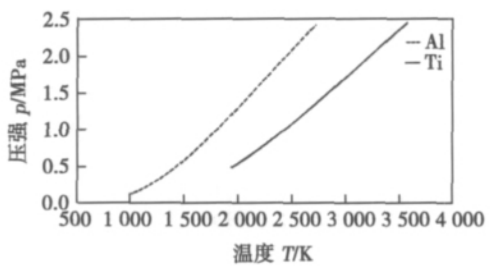


图 8 Al 和 Ti 元素饱和蒸气压与温度的关系

Fig. 8 Relation of saturated vapor pressure of Al element and Ti element

由图 8 可以看出,Al 元素的饱和蒸气压比 Ti 元素的饱和蒸气压要高出很多,并且因为铝的熔沸点低于钛的熔沸点,因此在冷却过程中铝蒸气液化凝固时间要晚于钛蒸气,这样在液态金属回填匙孔的过程中,铝蒸气会对液态金属产生较大的阻碍作用,在快速冷却条件下,还未等液态金属填充匙孔尖端就已经凝固,从而将铝蒸气封闭在匙孔尖端,最后液化凝固形成附着在钉尖内壁上的富含 Al 元素的金属小颗粒.

由以上分析可知,高饱和蒸气压金属蒸气的存在促进了钉尖缺陷的形成,而具体到 TA15 钛合金电子束深熔焊,高饱和蒸气压元素 Al 的汽化则是其形成钉尖缺陷的动因之一.

4 结 论

(1) 钉尖为边缘圆滑的狭长形缝隙,根部呈规则的圆形,主要出现在未熔透焊缝中.

(2) 电子束脉动在熔池根部形成一个封闭的空隙,金属蒸气被阻隔在空隙中而不能逸出,从而形成了钉尖缺陷,它是钉尖缺陷产生的直接原因.

(3) 高饱和蒸气压金属蒸气的存在加剧了钉尖缺陷产生的倾向,是钉尖缺陷产生的重要内在动因.

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joint; filling weld

Analysis and prevention of cracks in laser-welded joint of TiNi shape memory alloy and stainless steel LI Hongmei[1], SUN Daqian[1], DONG Peng[1], CAI Xiaolong[2] (1. School of Materials Science and Engineering, Jilin University, Changchun 130025, China; 2. State Key Laboratory of Rare Earth Resources Utilization, Changchun Institute of Applied Chemistry, Changchun 130022, China). pp 41 – 44

Abstract: Dissimilar metal joints of TiNi shape memory alloy wire and stainless steel wire were welded by laser welding method. The cracks feature and fracture surface morphology of joints were examined by using scanning electron microscopy (SEM) and confocal laser scanning microscope (CLSM). The mechanism of crack formation were analyzed, and some measurenents were taken to control the welding cracks. The results showed that the micro-cracks usually emerged in the center of the weld zone and fusion zone of TiNi alloy side. The existence of a large number of brittle compounds in the weld was internal cause of cracks, and the joint subjected to tensile stress was the necessary condition of cracks. The cracking susceptibility can be improved to a certain extent by adding Ni interlayer, Co interlayer, changing the laser beam position, applying an axial force to weld zone and optimizing the laser welding parameters. Adding metal interlayer was a more effective method. The tensile strength reached 372 MPa and 347 MPa respectively by using Ni and Co interlayer, and the joint strength increased by 98.9% and 85.6% respectively, compared with the joint without metal interlayer.

Key words: TiNi shape memory alloy wire; stainless steel wire; laser welding; cracks

Experimental analysis on fusion ratio and composition uniformity of laser hot wire welds ZHENG Shiqing[1], WEN Peng[1,2], SHAN Jiguo[1,2] (1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. Key Lab for Advanced Materials Processing Technology, Ministry of Education, Beijing 100084, China). pp 45 – 48, 72

Abstract: Ductile cast iron is welded with filling stainless steel hot wire in this article, then fusion ratio and distribution of elements are studied. The fusion ratio is as low as 38%-55%. The composition of filler wire distributes in welds uniformly. Nonuniform degrees of element Cr and Ni are 0.5% and 6%. Compared with laser hot wire welding, the fusion ratio of laser-MIG hybrid welds is 69%-77%, and the nonuniform degrees of element Cr and Ni are not less than 62% and 51%. The low electric energy input and its high utilization ratio for heating filler wire contribute to lower fusion ratio in laser hot wire welding compared to laser-MIG hybrid welding. The uniform distribution of filler wire in laser hot wire welds results from the low fusion ratio and solid filler wire transfer.

Key words: laser hot wire welding; laser-MIG hybrid welding; fusion ratio; distribution of elements; ductile cast iron

Joint microstructure and isothermal solidification modeling during transient liquid-phase bonding of a duplex stainless steel YUAN Xinjian[1], LUO Jun[1], TANG Kunlun[1], LI Jia[1], KANG Chungyun[2] (1. College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China; 2. Department of Materials Science and Engineering, Pusan National University, Busan 609735, Korea). pp 49 – 52

Abstract: An experimental investigation on transient liquid-phase bonding of a duplex stainless steel was carried by using Ni-based amorphous alloy as the interlayer. The microstructure of the bonded joint was observed with field emission scanning electron microscope (FE-SEM). The chemical compositions were analyzed by energy-dispersive X-ray spectroscopy (EDS) and wavelength-dispersive spectrometry (WDS). Phase structure of the bonded joint was identified by using X-ray diffraction (XRD). The results indicated that before the completion of isothermal solidification, the major secondary-phase precipitate present in the interface region between the insert and base alloy was BN. The dominating phases appeared in the interlayer zone were γ-Ni solid solution, Ni_3B and Cr-borides. Additionally, three diffusion models were employed to calculate the completion time of the isothermal solidification. By contrast to experimental results, the value obtained by solute distribution model was close to the actual value, and this model was considered to be suitable to the bonding process.

Key words: duplex stainless steel; Ni-based amorphous alloy; transient liquid-phase; microstructure; isothermal solidification

Affecting factors of forming spiking of titanium alloy electron beam deep penetration welding SHI Mingxiao[1], ZHANG Binggang[2], MA Jilong[2], CHEN Guoqing[2], FENG Jicai[2], FAN Ding[1] (1. State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China; 2. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China). pp 53 – 56

Abstract: The spiking is the unique defect of electron beam welding, which has a serious impact on the welding quality. The academia still hadn't had an unified understanding of the forming mechanism of spiking. To study the forming mechanism of spiking, the orthogonal test was used to carry out the experiment of titanium alloy electron-beam deep-penetration welding. The X-ray detection was done for each weld after welding The results of X-ray detection show that the spiking only exists in the partial penetration weld, and the spiking is the irregular-slited shape while the roots are round. The optical microscope and scanning electron microscope combined with energy dispersion spectroscopy were used to analyze the formation mechanism of spiking. The results show that the pulse of electron beam is the direct cause of spiking formation and the metal vapor with high saturated vapor pressure accelerates the tendency of forming spiking. It is important intrinsic motivation to the generation of spiking.

Key words: electron beam welding; metal vapor; spiking

Effect of trace calcium on performance of AgCuZn alloy BAO Li[1], LONG Weimin[1], ZHANG Guanxing[1], SUI Fangfei[2], LI Hao[2], MA Jia[2] (1. State Key Laboratory of Advanced Brazing Filler Metals and Technology, Zhengzhou Institute of