聚焦电流对电子束填丝焊接焊缝几何特征的影响

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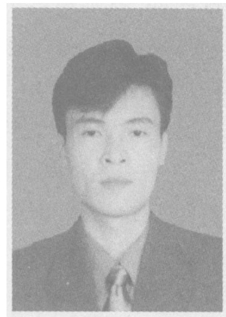
摘 要：通常情况下，电子束焊接工艺研究时将聚焦电流作为焦点位置的主要表征参数。电子束填丝焊接时，通过改变聚焦电流，可以控制束流的焦点位置。不同的焦点位置决定了束流到达工件表面时的能量分布，直接影响到焊丝及母材的熔凝状况，进而对电子束填丝焊接焊缝截面几何形状具有重要影响。通过改变聚焦电流、其余参数不变，能够得到聚焦电流与焊缝截面形状、焊缝横截面面积、熔深、表面熔宽、半熔深处熔宽、余高等焊缝截面几何参量之间的关系，对优化电子束填丝焊接工艺参数具有积极参考意义。

关键词：电子束焊；填丝；聚焦电流；截面形状
中图分类号：TG456 文献标识码：A 文章编号：0253－360X(2007)03－053－04



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0 序 言

与自熔性电子束焊接相比，电子束填丝焊接具有许多特殊优点。例如，可以改变焊缝的化学成分以得到特殊性能，改善电子束焊接时的间隙裕度等。同时电子束填丝焊接技术对许多新技术的发展有着重要的意义，如电子束快速成形、电子束熔覆等。

在电子束填丝焊接时，改变聚焦电流，可以控制束流的焦点位置，获得上焦点、表面焦点或下焦点。不同的焦点位置决定了束流到达工件表面时的能量分布，直接影响到焊丝及母材的熔凝状况，进而影响到焊缝的成形。文中通过试验考察了电子束填丝焊接时聚焦电流对焊缝横截面几何特征的影响规律。

1 试验方法

试验采用前送丝方式进行非穿透电子束焊。母材为Q235 钢，焊丝采用 ϕ1.0 mm 的 0Cr21Ni10。在试验中，固定其余参数，改变聚焦电流 I_f，使束流的焦点位置从工件表面以下逐渐过渡到工件上方。试验测得表面焦点聚焦电流 I_f 为 2 871 mA，小于此值为下焦点，大于此值为上焦点。以不同的聚焦电流分别焊出各条焊缝。焊后用扫描电镜测量焊缝横截面上熔深 h、余高 h_1、表面熔宽 b_1 及半熔深处的熔宽 b_{50}；用图像分析仪测量焊缝横截面的面积 S_w，焊缝截面各几何参量如图 1 所示。根据测试结果，建立焊缝横截面各几何参量与聚焦电流的关系。试验参数见表 1。

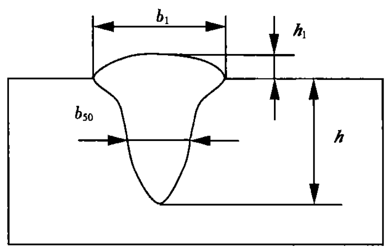


图 1 焊缝横截面示意
Fig. 1 Illustration of weld cross section

表 1 试验参数表
Table 1 Parameters of tests

加速电压 U_a/kV	焊接电流 I_b/mA	焊接速度 v_w/(m·min^{-1})	送丝速度 v_f/(m·min^{-1})	送丝角度 θ(°)	丝端伸出量 L_s/mm
140	12.5	0.6	0.96	15	8

收稿日期：2006－04－03

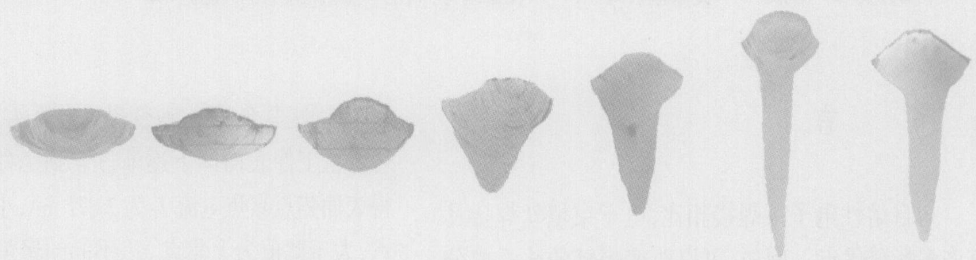
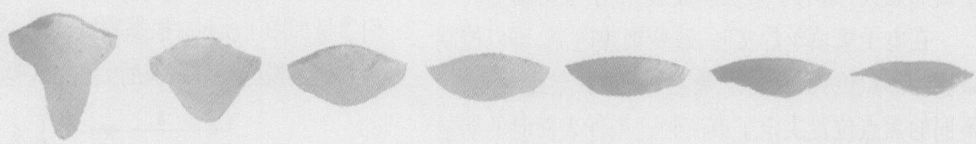
2　试验结果分析

2.1　聚焦电流对焊缝截面形状的影响

焊缝的截面形状随聚焦电流的变化如表 2 所示，聚焦电流逐渐增大的过程中，焦点位置也从工件内部移到了工件上方。在聚焦电流较小时，焦点位于工件内部，束流到达工件表面时呈下焦点散焦状态。同样功率条件下，束斑直径较大，能量密度较小，没有小孔效应，形成焊缝所需能量主要以热传导的方式获得[1]，因此焊缝截面较为扁平；随着聚焦电流增大，焦点上移，但仍在工件内部，束流的能量转化仍主要发生在工件表面。但束斑直径减小而能量密度增大，表现出一定的深熔效应，焊缝截面呈上宽下窄的漏斗形；焦点上移至工件表面附近时，束斑直径最小，能量密度最大，金属迅速熔化蒸发，产生小孔效应，焊缝截面呈“钉”形，深宽比较大。当聚焦电流继续增大，焦点向工件表面上方移动，相对工件表面形成上焦点散焦焊接的状态，与下焦点散焦类似，形成焊缝所需能量主要以热传导的方式获得[1]，焊缝截面轮廓又趋向扁平。总体而言，电子束填丝焊接时，焊缝的截面形状随聚焦电流的变化趋势与自熔性电子束焊接较为相似，在同样条件下，焦点离工件表面越远，焊缝就越趋向扁平化。

表 2　聚焦电流对电子束填丝焊接焊缝截面形状的影响

Table 2　Effect of lens current on cross section shape of EB welding with filler wire

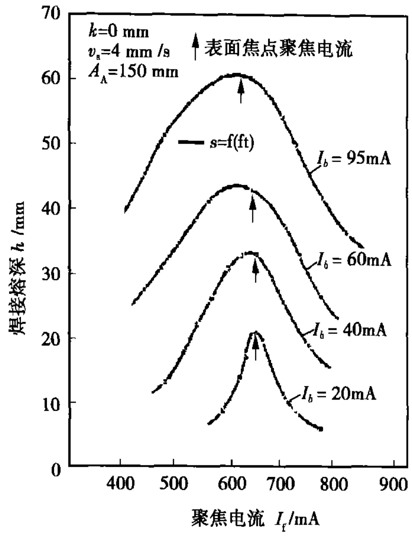
试样编号	1	2	3	4	5	6*	7
聚焦电流 I_f/mA	2 454	2 538	2 617	2 704	2 792	2 871	2 955
焊缝横截面形状							
试样编号	8	9	10	11	12	13	14
聚焦电流 I_f/mA	3 042	3 121	3 203	3 290	3 369	3 453	3 540
焊缝横截面形状							

注：　* 采用此聚焦电流时，焦点位于工件表面

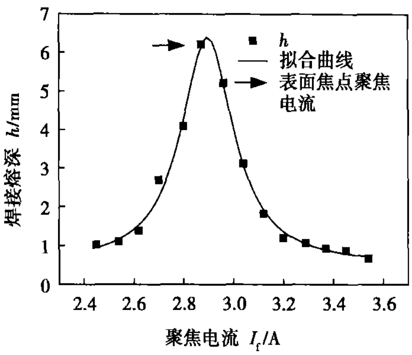
2.2　聚焦电流与焊缝截面几何参量的关系

自熔性电子束焊接时，根据图 2a[2] 所示规律，采用小束流焊接，利用表面聚焦状态可获得焊缝最大熔深，随着焊接束流的不断增大，焦点位置需下移至工件内部才可获得最大熔深。填丝电子束焊接时，对实测数据用 Lorentz 公式拟合：$y = y_0 + (2A/\pi)\dfrac{w}{4(x-x_c)^2+w^2}$，试验数据确定后，$y_0$、$x_c$、$w$、$A$ 均为常数项。由此可得到聚焦电流对焊缝熔深的影响曲线，其规律如图 2b 所示[2]。同图 2a 比较发现，小束流焊接时，无论填丝与否，聚焦电流对焊缝熔深的影响规律相近；焦点位于工件表面附近时，熔深最大，随着焦点位置远离工件表面，熔深逐渐减小。该曲线以表面焦点位置为中心呈对称衰减。

表面熔宽及半熔深处熔宽随聚焦电流的变化反映了束流能量密度的变化。图 3 及图 4 分别为聚焦电流对表面熔宽及半熔深处熔宽的影响曲线。电子束束斑的能量密度一般可认为呈高斯面分布，中心处较高，沿径向方向急剧衰减。焦点位于工件表面时，束斑直径最小，能量密度最高，焊缝表面熔宽也最小；聚焦电流增大或减小后，工件表面的束斑直径增大，焊缝表面熔宽也随之增大；但束斑直径的增大也将导致相同功率下能量密度降低，束斑边缘的能量密度已不足以熔化金属。因此，表面熔宽及半熔深处熔宽不会随束斑直径增大而无限增大，而是存在一个极值点，焦点进一步远离工件表面时，熔宽及半熔深处熔宽反而有减小的趋势。



（a）自熔电子束焊接聚焦电流对熔深的影响



（b）电子束填丝焊接时聚焦电流对熔深的影响

图 2　聚焦电流对电子束焊接熔深的影响

Fig. 2　Effect of lens current on penetration in EB welding with filler wire

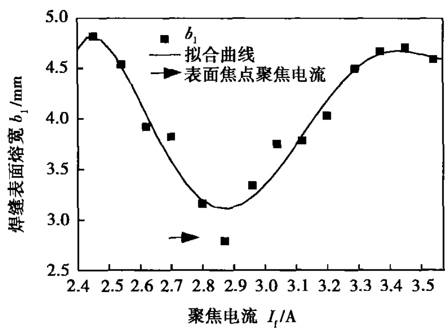


图 3　电子束填丝焊时聚焦电流对焊缝表面熔宽的影响

Fig. 3　Effect of lens current on weld width in EB welding with filler wire

聚焦电流对余高的影响如图 5 所示。无论上焦点还是下焦点焊接，焦点位置越接近工件表面，余高越大。与焊缝表面熔宽的变化相对应，熔宽越大，余高越小。

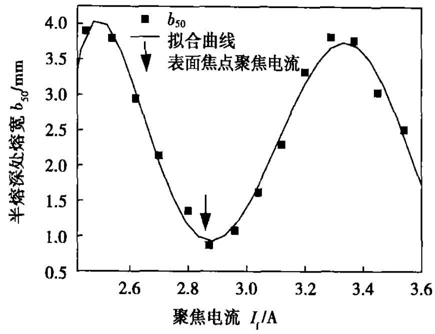


图 4　电子束填丝焊时聚焦电流对半熔深处熔宽的影响

Fig. 4　Effect of lens current on weld width in half of penetration in EB welding with filler wire

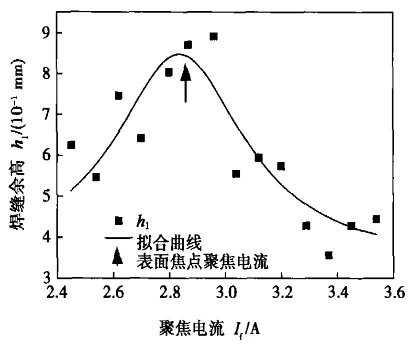


图 5　电子束填丝焊聚焦电流对余高的影响

Fig. 5　Effect of lens current on reinforcement in EB welding with filler wire

相同功率下，聚焦电流变化时，束斑能量密度随之改变，导致能量传递方式也发生改变，可以是热传导模式，也可以是“小孔”模式，或两种模式的结合。电子束的输出功率与工件吸收的功率之间有一个转化效率。不同聚焦状态导致转化效率发生改变，进而影响到焊缝的截面面积。电子束填丝焊缝截面面积随聚焦电流的变化关系如图 6 所示。焦点位置位

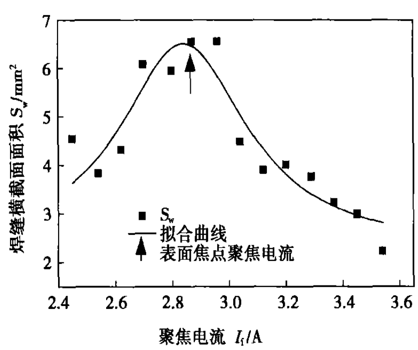


图 6　电子束填丝焊接时聚焦电流对焊缝横截面面积的影响

Fig. 6　Effect of lens current on cross section area in EB welding with filler wire

于工件表面附近时, 焊缝截面面积较大; 随着焦点远离工件表面, 焊缝截面面积随之减小。

由试验结果可见, 电子束填丝焊接时, 焊缝截面几何特征如形状、面积、熔深、余高、熔宽、半熔深处熔宽等在聚焦电流变化时, 以表面焦点处的聚集电流为中心, 均存在一定程度的对称性。利用这一结果, 可以较为方便地估计工艺裕度区间, 优化参数。截面几何特征在电子束填丝表面熔敷、电子束快速成型时是重要参量, 值得注意的是, 聚集电流对表面熔宽及半熔深处熔宽的影响并非单调变化, 而是存在对称的拐点, 因而, 不能单独依赖聚焦电流的变化来获得尽可能扁平的截面形态。

3 结 论

(1) 电子束焦点位于工件表面附近时, 焊缝截面呈“钉”形, 增大或减小聚焦电流, 焊缝截面形状均趋向扁平化。

(2) 熔深最大处对应的焦点位置处于工件表面附近, 聚焦电流增大或减小时熔深基本呈对称减小。

(3) 表面熔宽及半熔深处熔宽最小值出现在表面焦点状态下, 随着焦点位置远离工件表面, 表面熔宽及半熔深处熔宽分别出现极大值; 远离程度进一步增大, 二者反而有减小的趋势。

(4) 焦点位置越接近工件表面, 余高及焊缝横截面面积越大。

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parameter monitoring; partial least square

Effect of focusing current on weld section shape of electron beam welding with filler wire

SUO Hongbo, MAO zhiyong, Liu Fangjun, Li jinwei (Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). p53—56

Abstract: The electron beam welding with filler wire has been developed recent years in order to change the weld compositions to avoid the hot cracks, to strengen the joint, or to fabricate a complex metal object by overlaying. Weld section shape is considered as an important character in this processe. Thus, it is necessary to study the relationship between the welding parameters and weld cross section shape. Through careful control of the focusing current, and measuring the characters of weld section (section area, penetration, reinforcement, weld width, and weld width in the middle of penetration, etc.), the effect of focusing current on weld section shape was investigated. This is useful for optimizing the process.

Key words: electron beam welding; filler wire; focusing current; cross section shape

Transient liquid phase bonding of Al_2O_{3P}/6061Al metal matrix composite

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Abstract: The joint of transient liquid phase bonding of particle reinforced aluminium-based metal matrix composite with a pure metal interlayer contains a particle segregation region, which is deleterious to the joint strength. Decreasing particle segregation is one of effective approaches improving mechanical properties of the joint. The microstructure and mechanical property of aluminium-based metal matrix composite Al_2O_{3P}/6061Al joint by transient liquid phase bonding with Al/Cu/Al or Cu/Al/Cu multi-layer interlayer have been investigated. The experimental results show that bonding with the multi-layer interlayer is able to control the particle segregation region and improve the joint strength. Under the bonding condition of 600 ℃/60 min, with 10 μm Al/10 μm Cu/10 μm Al multi-layer interlayer, the particle segregation region is not evident in the joint, and the shear strength of the joint is 110 MPa; with 1.5 μm Cu/10 μm Al/1.5 μm Cu multi-layer interlayer, the particle segregation region is invisible in the joint, and the shear strength of the joint is further increased to 123 MPa.

Key words: multi-layer interlayer; aluminium-based metal matrix composite; transient liquid phase bonding

Group vontrol dystem for multi welding machines of membrane eater eall

ZHAO Zhangfeng, WANG Yangyu, ZHENG Xinrong (The MOE Key Laboratory of Mechanical Manufacture and Automation, Zhejiang University of Technology, Hangzhou 310014, China). p61—64

Abstract: A group control system of multi welding power supplies based on DSP was applied to membrane water wall welding machines. The group control strategy of different priorities was introduced to the system, and multi welding power supplies were adjusted in sequence according to this strategy when electric power network parameters changes. Consequently, the shorter time and less error of adjusting were obtained. At the same time, according to the welding area and the temperature field of welding-panel, the real-time adjusting strategy of welding parameters was put forward. On the basis of this strategy, the parameters of multi welding power supplies were adjusted dynamically at different striking places. The experiment results show that using the group control system, the quality of welding seam was improved, and the distortion of welded panel was effectly contralled greatly as well.

Key words: membrane water wall; welding; DSP; group control

Nonlinear finite element analysis of residual stresses and thermo-harm in direct welded K-joint of steel tubular members

LUO Yongchi (Department of Civil Engineering, Yangtze University, Jingzhou 434023, Hubei, China). p65—68

Abstract: It is necessary to study the residual stresses and thermo-harm of the direct welding joint of steel tubular members for researching the calculation of ultimate strength and fatigue life. According to the thermo-effect of welding process of tubular K-joint, the description of temperature field for welding process during heating and cooling, the mathematical model of heat transfer and physical model suitable to practical production, the coupling-calculation of temperature field and welding stress filed has been taken. The thermo-physical performance parameters and mechanical property parameters as the nonlinear functions of temperature were taken into consideration. The distributions of residual stresses and residual strains were in agreement with the experimental failure pattern of tubular K-joint. For the local buckling failure of brace tube in tubular K-joint experiment, the concept and principle of welding thermo-harm is presented.

Key words: welded joint of steel tubular members; residual stress; thermo-harm; finite element

Effect of alloy elements on properties of iron-base hardfacing alloy

LIU Zhengjun, ZHANG Guiqing, YIN Yijun, ZENG Xiebo (School of Material Science and Engineering, Shenyang University of Technology, Shenyang 110023, China). p69—72

Abstract: A kind of iron-base hardfacing alloy for carbon arc welding was developed, which is Cr—B—Ni—W—V poly-elements strengthening alloy system. The paper has studied the performance of grinding wear-resistant by analyzing the average degree of hardness, the abrasion weight loss and microstructure of deposited metal, and discussed the effect of alloy elements on the overlay's structure, degree of hardness and ability of wear-resistant, such as Cr, B, Ni, W, V. The best composition of the alloy system was confirmed. The results show that the mixture ratio of hardfacing alloy is suitable, and the hardness and wearing resistance of overlay is better when Cr con-