

重力对全位置 TIG 焊熔池温度场与流场影响的有限元分析

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摘 要: 建立了全位置 TIG 焊接中平焊、45°下向焊、立焊下向焊的熔池温度场、流场数值计算模型, 计算了不同焊接位置以及不同重力加速度值情况下熔池的温度场和流场, 分析了重力方向和大小对熔池内流场和温度场的影响规律; 发现重力方向对熔池内液态金属的流场、温度场影响明显, 液态金属的流动影响温度场分布明显, 重力大小对熔池流场的分布形态没有影响, 但是对流动速度影响明显。得到的结论对于研究熔池失稳判定依据、指导设计全位置 TIG 焊乃至 MAG 焊工艺具有一定的参考价值。

关键词: 全位置焊接; 重力; 有限元; 温度场

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0 序 言

近年来随着国内能源需求的增长和能源工业的发展, 长输油管道等需要采用全位置焊接工艺的场合越来越多^[1,2]。全位置焊接过程中一个关键问题是熔池失稳, 液态金属易流淌, 影响焊缝稳定成形和焊接质量。为了解决这个问题, 一种方法是采取不同的方式促进熔池快速凝固, 如 Irving^[3] 通过控制燃弧和短路时的能量, 对汽轮机叶片进行全位置焊接; 曾惠林等人^[4] 在长管道焊接中采用激光-电弧复合焊接技术; 控制电流周期性变化, 对熔池间歇性加热^[5]。另外一种方法是改变熔池中力的作用形式, 抑制熔池内液态金属流淌。采用摆动焊接并保持焊枪与熔池成一定角度^[6] 是目前工程上广泛采用的一种方法; 通过外加磁场产生电磁力, 也可以用来减小重力对熔池失稳的影响^[7]。

造成全位置焊接过程中熔池内液态金属流淌的主要因素是重力。文中采用有限元方法, 研究了重力对全位置 TIG 焊过程中熔池流场和温度场的影响规律, 所得结论对于研究熔池失稳判定依据、指导设计全位置 TIG 焊乃至 MAG 焊工艺具有一定的参考价值。

1 TIG 焊熔池流场与温度场计算模型

建立 Q235 钢板平焊、45°焊接和立焊(图 1)的热传导、流动和熔化凝固模型, 计算熔池的温度场、流场。研究在不同焊接位置(即重力作用方向不同)对熔池内温度分布、速度分布的影响规律。改变重力加速度的大小, 分析重力大小对平焊位置温度分布、速度分布的影响规律。

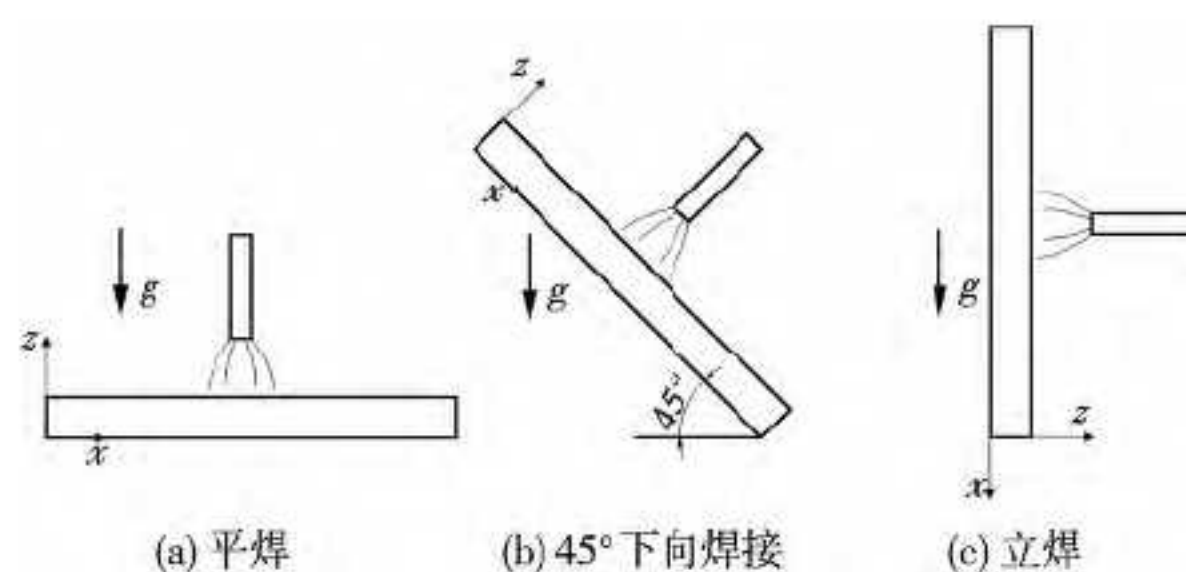


图 1 计算模型

Fig. 1 Calculation model

1.1 控制方程

为了研究重力对熔池流场的影响, 不考虑作用在熔池上的电磁力、电弧压力以及活性元素对表面张力系数的影响, 并满足: (1) 熔池中的液态金属为不可压缩流体; (2) 熔池表面没有发生变形; (3) 不考虑熔池金属的蒸发。基于此条件, 熔池的流场和温度场由以下方程控制。

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(1) 连续性方程(质量守恒方程)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \quad (1)$$

(2) $N-S$ 方程(动量守恒方程)

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho uu) + \frac{\partial}{\partial y}(\rho vu) + \frac{\partial}{\partial z}(\rho wu) \\ &= \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial u}{\partial z}\right) - \frac{\partial p}{\partial x} + S_x \end{aligned} \quad (2)$$

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(\rho vv) + \frac{\partial}{\partial z}(\rho wv) \\ &= \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial v}{\partial z}\right) - \frac{\partial p}{\partial y} + S_y \end{aligned} \quad (3)$$

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho w) + \frac{\partial}{\partial x}(\rho uw) + \frac{\partial}{\partial y}(\rho vw) + \frac{\partial}{\partial z}(\rho ww) \\ &= \frac{\partial}{\partial x}\left(\mu \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial w}{\partial z}\right) - \frac{\partial p}{\partial z} + S_z \end{aligned} \quad (4)$$

(3) 能量守恒方程

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho T) + \frac{\partial}{\partial x}(\rho u T) + \frac{\partial}{\partial y}(\rho v T) + \frac{\partial}{\partial z}(\rho w T) \\ &= \frac{\partial}{\partial x}\left(\frac{\lambda}{c} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda}{c} \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\lambda}{c} \frac{\partial T}{\partial z}\right) + S_h \end{aligned} \quad (5)$$

式中: t 为时间; T 为温度; ρ 为材料的密度; u, v 和 w 为 x, y 和 z 轴方向的速度; μ 为材料动力粘度; λ 为热导率; S_x, S_y, S_z 为动量源项; S_h 为热源项, c 为比热容。

为简化模型,把固相区并入流体区计算,通过加入适当的动量源强制固相区速度为0。熔池内较大的温度梯度引起各处密度不同因而产生自然对流,该浮力项也通过动量源 S 来处理,三个方向的动量源分别为

$$S_x = (\rho - \rho_{\text{ref}}) g_x = \begin{cases} 0 & \text{平焊位置} \\ \frac{\sqrt{2}}{2} g & 45^\circ \text{下向焊接} \\ (\rho - \rho_{\text{ref}}) g & \text{立焊位置} \end{cases} \quad (6)$$

$$S_y = (\rho - \rho_{\text{ref}}) g_y = 0 \quad (7)$$

$$S_z = (\rho - \rho_{\text{ref}}) g_z = \begin{cases} -(\rho - \rho_{\text{ref}}) g & \text{平焊位置} \\ \frac{\sqrt{2}}{2} g & 45^\circ \text{下向焊接} \\ 0 & \text{立焊位置} \end{cases} \quad (8)$$

式中: ρ_{ref} 为参考密度; g 为重力加速度; g_x, g_y, g_z 分别为重力加速度分量。

1.2 边界条件和初始条件

为了节约计算资源,考虑到模型的对称性,以焊

缝中心为对称面建立模型的一半,且焊缝中心为细密规则六面体网格,远离焊缝区域焊缝较粗糙,如图2所示。在对称面上,边界条件为

$$\frac{\partial u}{\partial y} = 0, \frac{\partial v}{\partial y} = 0, \frac{\partial w}{\partial y} = 0, \frac{\partial T}{\partial y} = 0 \quad (9)$$

除对称面以外的其它各面施加对流边界条件与无滑移壁面条件,即

$$u = 0, v = 0, w = 0, -\lambda \frac{\partial T}{\partial n} = h(T - T_w) \quad (10)$$

式中: h 对流换热系数; T_w 为环境温度; n 为外法线方向。

初始条件为

$$u = 0, v = 0, w = 0, T_w = 300 \text{ K}, p = \rho g l \quad (11)$$

式中: l 为沿重力加速度方向上表面到钢板内任意位置的距离。

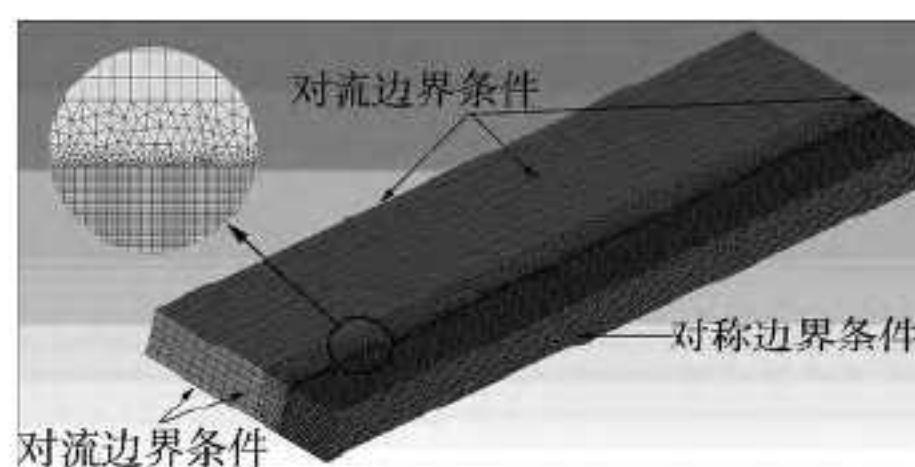


图2 边界条件

Fig. 2 Boundary conditions

2 数值求解与结果分析

选择 $100 \text{ mm} \times 50 \text{ mm} \times 6 \text{ mm}$ 的 Q235 钢板作为被焊材料,其热导率、比热容、密度以及钢液的动力粘度按文献 [8] 的数据写出分段函数形式;把潜热值转化为两相区的等效比热进行计算 [9];其它主要物理参数见表 1。

表1 Q235 其它物理参数

Table 1 Other physical parameters of Q235

固相线温度	液相线温度	潜热	对流换热系数
T_s / K	T_L / K	Q_m / kJ	$h / (\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1})$
1 765	1 795	270	10

采用文献 [6] 所述双椭球热源的模式,电弧电压 15 V,焊接电流 140 A,效率 0.8,热源模型参数见表 2。

采用流体力学软件 CFX 的求解器进行求解,压力与速度的耦合关系采用 SIM2PLEC 算法,主要关

表 2 热源模型参数

Table 2 Parameters of heat source model

前半椭球	后半椭球	前半椭球	后半椭球	双椭球	双椭球
热输入比例	热输入比例	x 半轴长	x 半轴长	y 向半轴长	z 向半轴长
f_f	f_r	a_f/mm	a_r/mm	b_h/mm	c_h/mm
0.6	1.4	2	4	2	1.5

注温度场与流场的分布规律,对计算结果不要求特别高的精度,残差设定为 1×10^{-4} 。

2.1 不同焊接位置的温度场与速度场

图 3 为 2 s 时刻,平焊、 45° 以及立焊的三维温度场与速度场。图 4 为焊缝中心面上各节点的速度分布。观察图 3 温度场,熔池深度没有变化,熔池上表面尺寸明显不同。在熔池上表面,平焊位置的熔池宽度最大为 5 mm (图 3a 中所示 2.5 mm 为焊缝的一半),立焊最小为 3.2 mm ;熔池长度稍有不同,平焊位置最小为 6.8 mm ,立焊位置最大为 7.1 mm 。

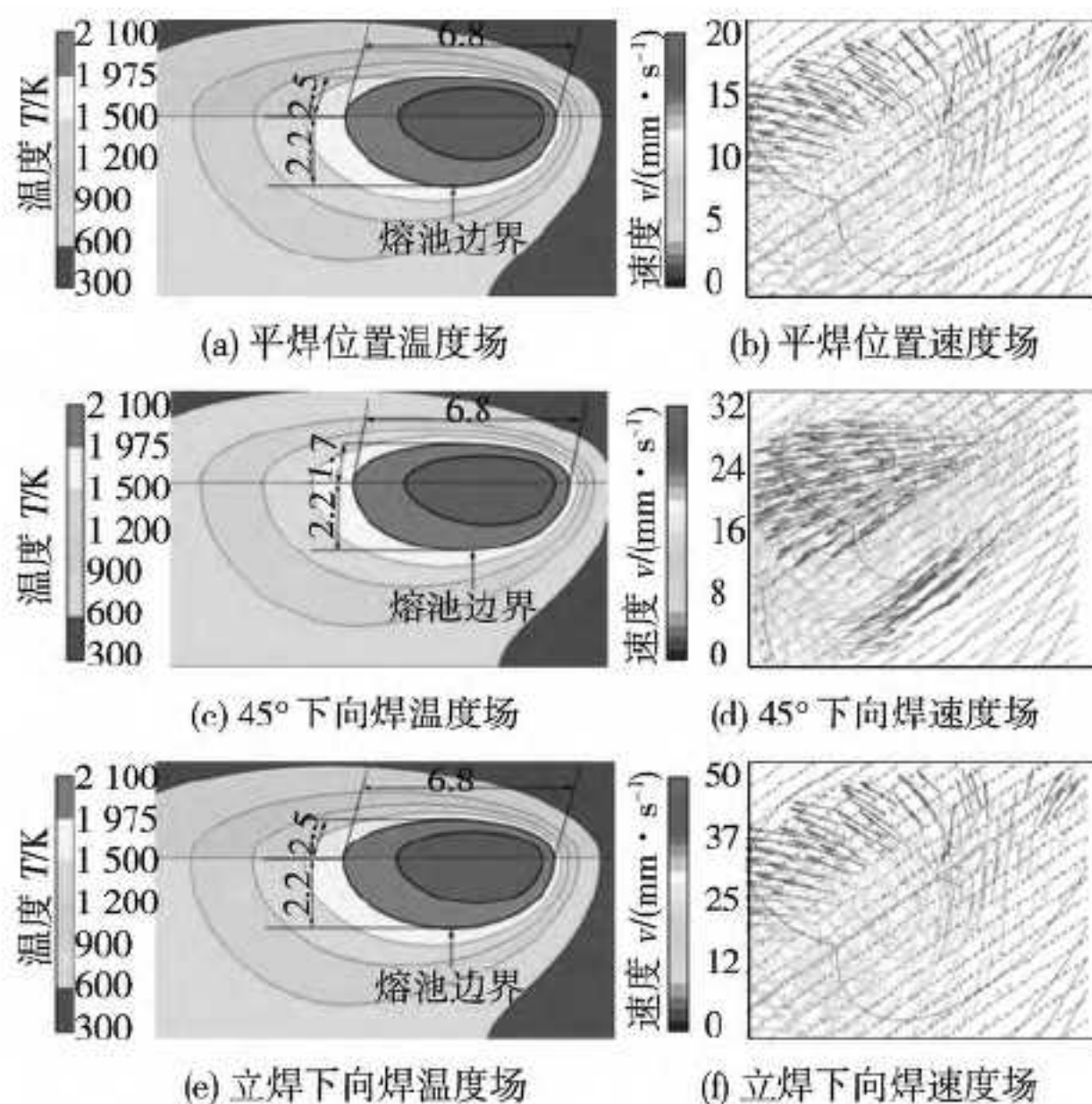
图 3 不同位置的三维温度场与速度场 (2 s 时刻)

Fig. 3 3D temperature and speed field

对比速度场分布,立焊位置速度最大,最大值为 49 mm/s ,位于熔池中心位置,液态金属在熔池表面从前往后流动,在熔池底部从后向前流动,导致熔池比较长。平焊位置最大速度小于 20 mm/s ,在熔池表面从中心流向两侧,在熔池底部从两侧流向中心,造成熔池较宽。 45° 焊接位置的速度场无论大小、方向及对温度场影响都介于平焊和立焊之间。

为了考察熔池内液态金属流动的剧烈程度,对熔池内各节点的速度 u 取绝对值再求平均值,得到 $|\bar{u}|$ 。见图 5,随着时间增加,熔池进入准稳态, $|\bar{u}|$ 趋

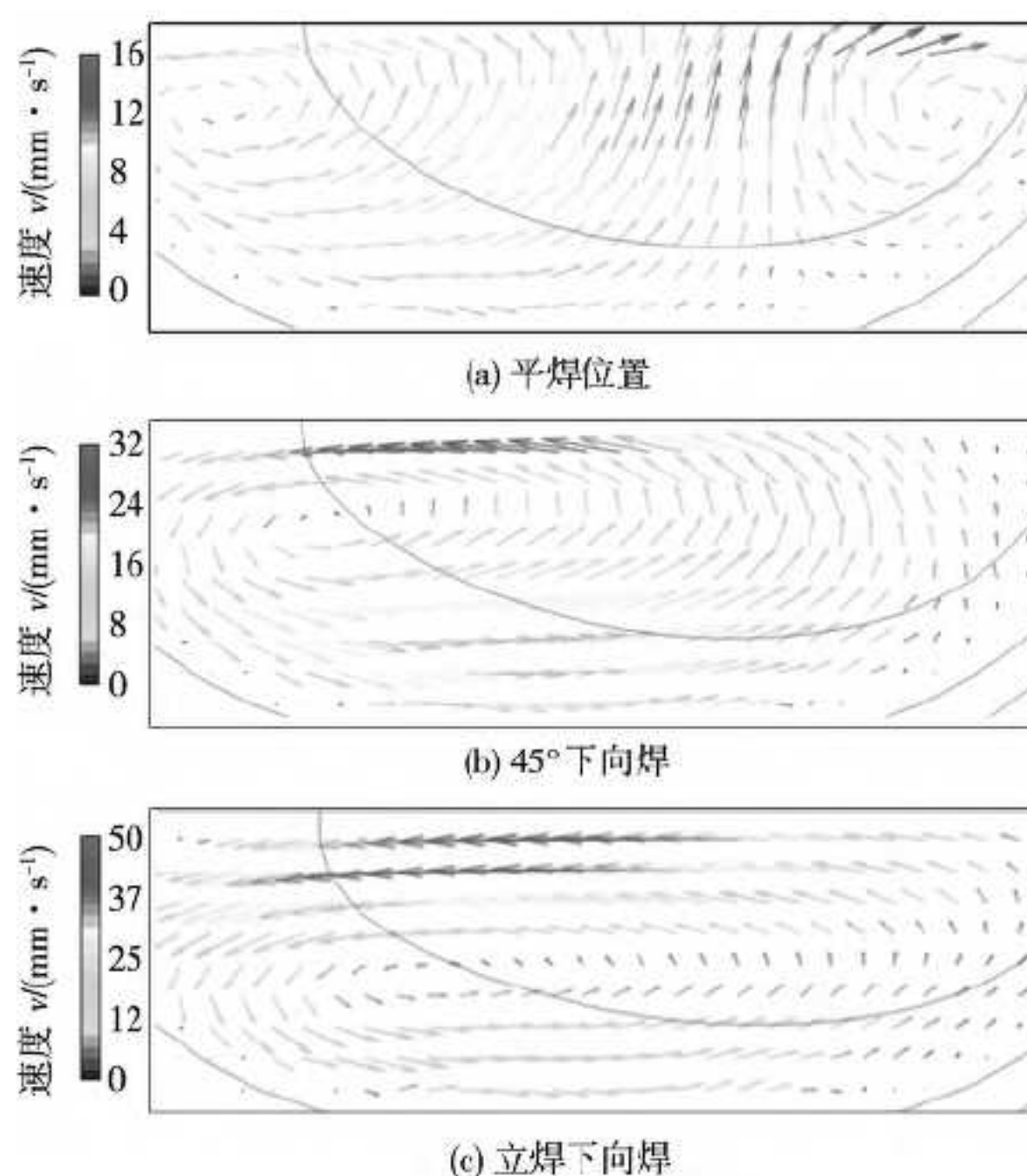
图 4 不同焊接位置的对称面速度场 (2 s 时刻)

Fig. 4 Speed field on symmetry plane

于一个固定值。立焊位置 $|\bar{u}|$ 值最大,说明熔池内存在明显的流动。

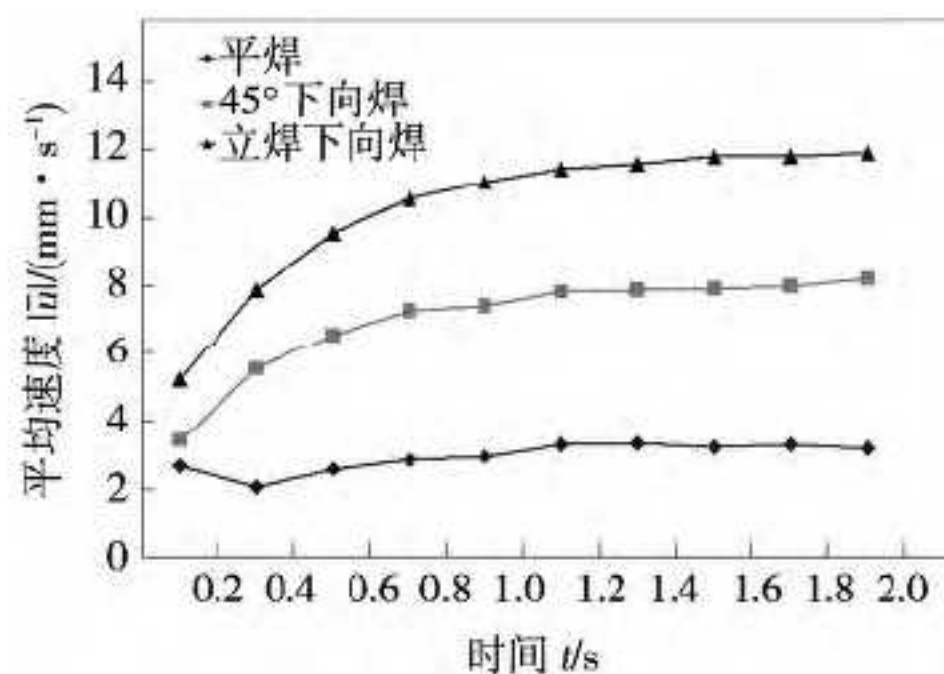


图 5 不同焊接位置的熔池速度平均值

Fig. 5 Average speed at welding pool

2.2 重力大小对平焊温度场和速度场的影响

为了进一步考察重力 g 的大小对焊接熔池产生影响,计算了微重力 ($0.2g$) 以及重力加速度等于 $5g$ 情况下的温度场与速度场。图 6 为 0.9 s 时刻平焊位置温度场,熔池深度、宽度以及长度均随重力加速度值的增加均有所增加。

重力加速度值的变化对三维速度场的分布形态没有影响,对速度大小影响显著:如图 7 所示,在对称平面上 0.9 s 时刻,当重力加速度值为 $0.2g$ 的时候,最大速度值仅为 4 mm/s ,而当重力加速度值增加到 $5g$ 的时候,最大速度增加到 36 mm/s 。

表 3 对比了 0.9 s 时刻不同重力加速度情况下

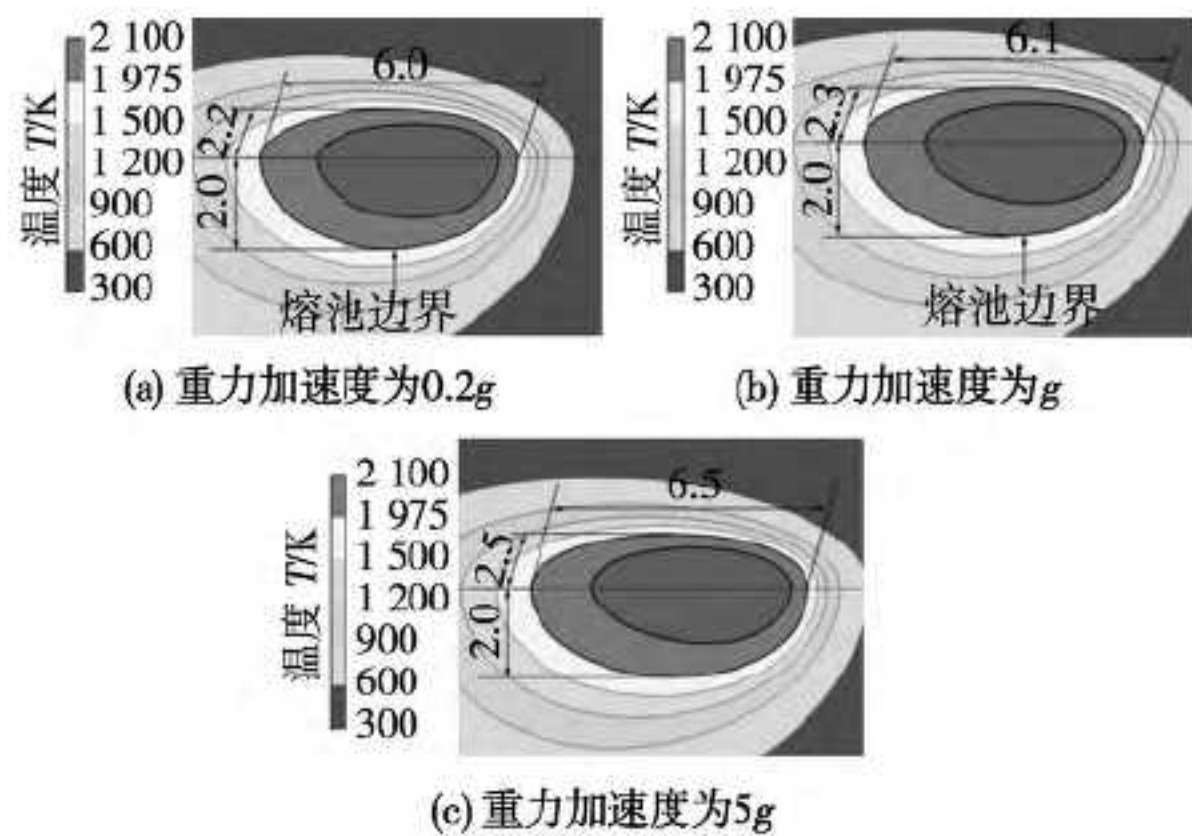


图6 重力加速度值对温度场的影响(0.9 s 时刻)

Fig. 6 affects of gravity value on temperature field

的计算结果。随着重力加速度值的增加, x, y, z 三方向的速度平均值 $|\bar{u}|, |\bar{v}|, |\bar{w}|$ 均显著增加, 但是只有熔池宽度 a 和熔池长度 b 随之增加, 熔池深度 h 并未发生变化。这是由于在平焊位置, 熔池内的液态金属在表面上从中心流向两侧, 在底部从两侧流向中心, 熔池表面过热金属的流动扩展了熔池尺寸。

表3 不同重力加速度情况下的计算结果(0.9 s 时刻)

Table 3 Results under different gravity value

重力加速度	x 向平均速度 $ \bar{u} / (\text{mm} \cdot \text{s}^{-1})$	y 向平均速度 $ \bar{v} / (\text{mm} \cdot \text{s}^{-1})$	z 向平均速度 $ \bar{w} / (\text{mm} \cdot \text{s}^{-1})$	熔池宽度 a / mm	熔池长度 b / mm	熔池深度 h / mm
0.2g	1.176	1.250	1.276	4.4	6.0	2.0
g	3.257	3.927	3.845	4.6	6.1	2.0
5g	8.615	10.080	9.353	5.0	6.5	2.0

3 结 论

(1) 平焊、45°下向焊以及立焊下向焊的速度场明显不同, 重力的作用方向对熔池内液态金属的流场、温度场产生明显的影响。

(2) 立焊下向焊接熔池内金属流动速度较大, 且主要从焊缝中心向前后流动(熔池上表面从前向后流动, 熔池底部从后向前流动)。相同条件下平焊位置熔池内的金属流动速度最小, 在熔池表面金属除了向后流动还向两侧流动, 造成熔池较宽。45°位置的速度场情况居于平焊和立焊之间。

(3) 在平焊位置, 随着重力加速度值的增加, x, y, z 三个方向的速度平均值均显著增加, 说明重力加速度的大小对流场影响明显。

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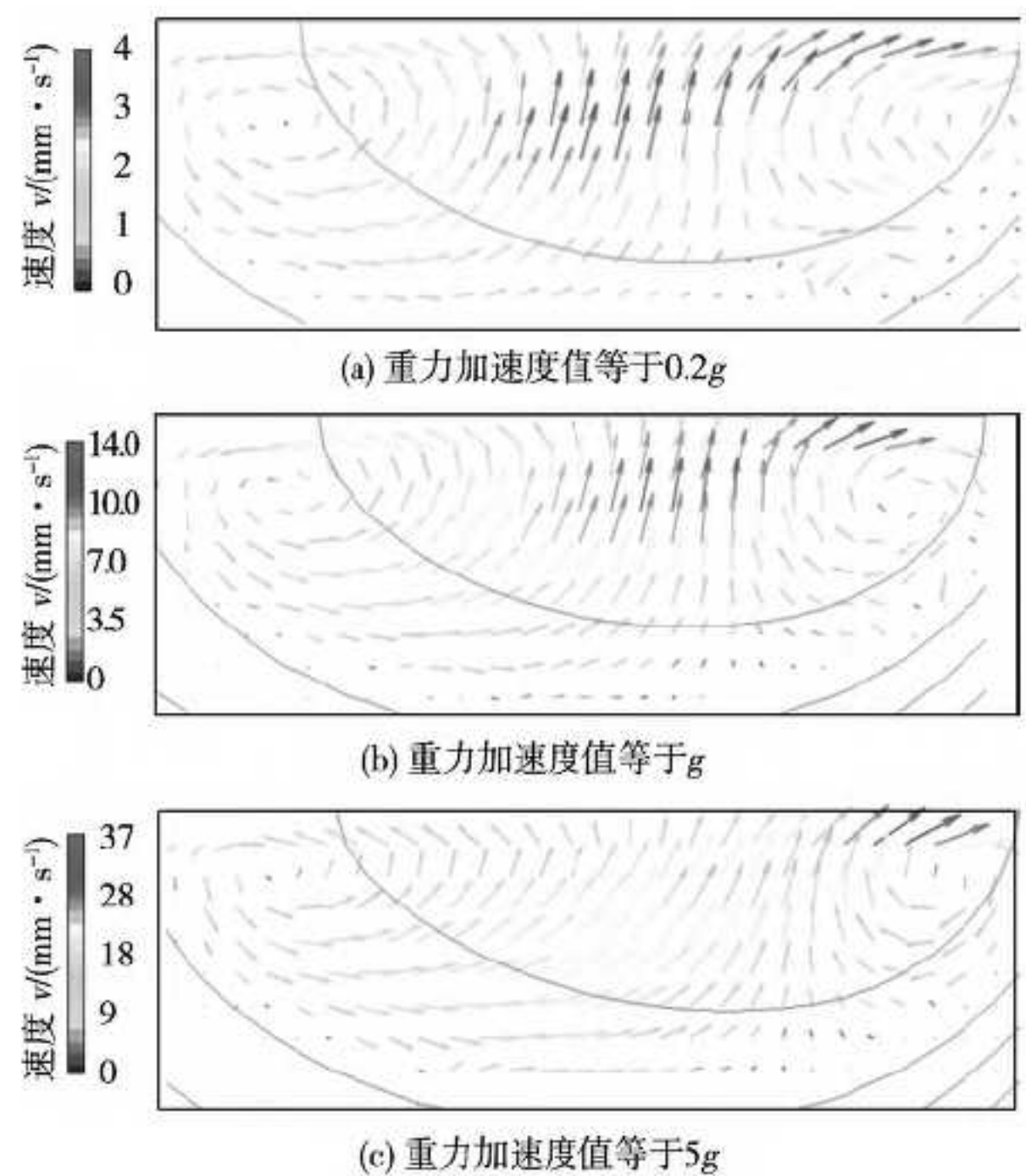


图7 重力加速度值对速度场的影响(0.9 s 时刻)

Fig. 7 Effects of gravity value on speed field

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strain rates (0.01 – 0.08 mm/s). The results show that dwell time of 1 – 20 s has little influence on fatigue life of solder joints at 25 °C. With the increasing of strain rates, the fatigue life of solder joints reduced gradually, and fracture mode was transformed from ductile fracture to brittle fracture. Fatigue cracks tended to initiate around the solder/IMC interfaces at the edge of the joints with different loading speeds, and then propagated within the solder proximately along the IMC interfaces. The fracture morphology of solder joints with different strain rates consisted mainly of propagation region and final fracture region.

Key words: low cycle fatigue; lead-free solder joints; dwell time; strain rate; crack

Effects of gravity on temperature field and fluid flow distribution of all-position TIG welding using finite element method

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Abstract: Numerical model of temperature field and fluid flow field was built to study the effects of gravity on different welding positions and different gravity values. Temperature field and fluid flow field of flat position, 45° position and 90° position with downward speed were calculated, respectively. The results showed that fluid flow of 90° position was far more intense than the one of flat position, which affected the temperature distribution and caused molten metal flowing downward. The presence of gravity had no influence on fluid flow distribution morphology, but affected the flowing speed significantly. Conclusions of this study can be used on the research of welding pool instability judgment basis and deciding parameters of all position TIG or MAG welding.

Key words: all-position welding; gravity; finite element method; temperature field

Void detection of BGA solder joints under complex X-ray imaging background

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Abstract: The void extraction method of solder joints based on global threshold segmentation is inaccurate. Moreover, once the solder joint in the image is shaded, the extraction of BGA solder joint's voids will become difficult. In order to detect the void defects of BGA solder joints under complex X-ray imaging background, it was detected that the unobstructed solder joints based on thresholding, solder roundness and solder area, and an interactive method of X-ray contour extraction to detect the obstructed solder joints was proposed. According to the characteristics of solder bubble, an integrated method of solder joint's void extraction was presented based on grayscale morphology, histogram stretching, fuzzy enhancement and BLOB analysis. The result of comparison experiment shows that the method presented in this research possesses high accuracy in detecting the

void defect of BGA solder joints.

Key words: BGA solder joints; ray contour extraction method; void detection

Microstructure and properties of joints of 600 MPa grade ultrafine grained steel obtained by friction welding

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Abstract: 13mm diameter bars of 600MPa grade ultrafine grain steel were welded by friction welding. Experimental results show that ultrafine grain steel has good weldability of friction welding when the friction welding process parameters were properly controlled. Ultrafine grain steel friction welding joint was mainly composed of four zones: welding seam, thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and base material. The grain size was about 9 – 11 μm in the HAZ, which was slightly larger than the one of the base metal. Mechanical properties results showed that joint strength of the ultrafine-grained steel friction welding was up to 715 MPa with 22% elongation and 68% contraction ratio of cross section, and impact toughness was about 98 J. Meanwhile typical ductile fracture was obtained for this kind of joint.

Key words: 600 MPa grade ultrafine grained steel; friction welding; microstructure; mechanical properties

Effects of post weld heat treatments on microstructure and mechanical properties of AZ91 magnesium alloy joints welded by TIG method with adding magnetic field

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Abstract: AC magnetic field was employed in welding of 5 mm thick AZ91 magnesium alloy plate by TIG method. The effects of post weld heat treatment on properties and microstructure of welded joints were studied through the analysis of the microstructure, mechanical properties and corrosion resistance. The results showed that the grain size was refined for AZ91 magnesium alloy joint with solution treatment, and more dispersed β-Mg₁₇Al₁₂ phase precipitates in α-Mg were found for the joint with solution and aging treatment, intermittent and dispersal precipitations of β-Mg₁₇Al₁₂ phase was smaller for joint with aging treatment. Meanwhile, the hardness, strength and plasticity of the weld joints were improved after heat treatment.

Key words: AC magnetic field; magnesium alloy; heat treatment; TIG welding; microstructure and properties

Growth model of hard phase in layer surfaced with Fe-Cr-Ti-C flux cored wire

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