

TIG 电弧等离子体双温度数值模拟

黄 勇， 刘 林， 王新鑫， 陆肃中

(兰州理工大学 省部共建有色金属先进加工与再利用国家重点实验室, 兰州 730050)

摘 要: 基于连续性方程、动量守恒方程、电子能量守恒方程、重粒子能量守恒方程及麦克斯韦方程组, 建立了 TIG 电弧等离子体二维轴对称双温度数学模型. 等离子体的热力学性质及输运系数均为电子温度 (T_e)、重粒子温度 (T_h) 的函数, 采用 FLUENT 软件进行求解得到了 TIG 电弧等离子体的电子温度场、重粒子温度场、压力场、流场和电势场等, 重点比较了等离子体电子温度和重粒子温度的分布规律. 结果表明, TIG 电弧的外形为典型的钟罩形, 在电弧中心重粒子温度与电子温度几乎处处相等, 而在电弧边缘及阳极表面两者差异较大, 存在很明显的非平衡现象.

关键词: TIG 电弧; 双温度模型; 非平衡现象

中图分类号: TG 403 **文献标识码:** A **doi:** 10.12073/j.hjxb.2018390239

0 序 言

钨极惰性气体保护焊 (TIG) 焊缝质量高, 设备简单, 已在现代工业生产中得到较多应用. 但是, TIG 电弧是热等离子体, 通过试验研究其特性存在很多困难, 故而有必要借助于数值模拟技术对电弧等离子体进行深入研究. Hsu 等人^[1]首先基于磁流体动力学 (MHD) 理论建立了自由燃烧电弧数学模型. Kaddani 等人^[2]首先建立了三维轴对称电弧模型. Wu 等人^[3]对 TIG 焊电弧行为以及电弧阳极表面热流密度分布进行了研究.

在电弧等离子体体系中, 远离电弧核心的边缘处、阴极和阳极表面, 等离子体会偏离局域热力学平衡 (LTE) 状态, 出现电子温度远高于重粒子温度的现象, 这部分等离子体处于非局域热力学平衡 (NL-TE) 状态. 因此, 双温度模型 (2T) 通常被用来研究等离子体的非平衡特性. 在双温度模型中, 等离子体的物性参数与 LTE 状态下有较大差异, 文献^[4-5]采用不同方法对双温度等离子体成分组成及物性参数进行了计算. Hsu 等人^[6]建立了氩等离子体双温度模型. 李和平等人^[7]对圆形通道内双温度等离子体的传热与流动特性进行了二维数值模拟, 发现电子-重粒子非弹性碰撞过程会对通道中等离子体

温度分布和速度分布产生一定的影响. 王立军等人^[8]建立了小电流真空电弧的双温度磁流体动力学模型, 分析了不同电弧电流和不同纵向磁场强度对小电流真空电弧特性的影响. 钱海洋等人^[9]采用双温度化学非平衡模型, 模拟了直流电弧氩等离子体发生器, 发现在电弧边缘和阳极表面处非平衡现象强烈. 这些双温度模型大多针对真空电弧或是等离子体发生器, 有关 TIG 电弧等离子体的研究却相对较少. Tashiro 等人^[10]针对 TIG 电弧建立了双温度模型, 发现等离子体的非平衡特性与粒子碰撞频率有关. 但多数模型中使用了目前仍存在争议的反应热导率等参数. 张晓宁等人^[11]建立了一套完全自治的描述非平衡热等离子体中传热与流动等复杂过程的物理数学模型, 避免了对定压比热、反应热导率等参数的定义和计算.

文中以张晓宁提出的物理数学模型为基础, 仅考虑化学平衡状态对其进行简化, 将等离子体的热力学性质及输运系数视为电子温度 (T_e)、重粒子温度 (T_h) 的函数, 建立二维轴对称双温度数值模型, 并应用 FLUENT 软件研究 TIG 电弧等离子体的非平衡特性.

1 数学模型

1.1 基本假设

根据对 TIG 焊电弧等离子体的物理性质和流

动过程的分析, 模型所采用的基本假设为: 等离子体是连续、理想牛顿流体; 等离子体为定常、不可压缩层流流动, 等离子体是轴对称的; 等离子体处于非局域热力学平衡 (NLTE) 状态; 等离子体处于局域化学平衡状态, 满足准中性条件, 只考虑一次电离, 整个体系由电子、原子和一次电离的离子所组成; 等离子体光学薄, 即辐射的重新吸收和总的辐射损失相比可以忽略不计, 仅有体积辐射损失; 等离子体的热力学性质和输运性质仅为电子温度和重粒子温度的函数 (在给定压力下)。

1.2 控制方程组

根据上述假设得到二维柱坐标 (z, r) 下的磁流体动力学 (MHD) 方程组。

连续性方程:

$$\frac{\partial}{\partial z}(\rho v_z) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v_r) = 0 \quad (1)$$

轴向动量守恒方程:

$$\begin{aligned} \frac{\partial}{\partial z}(\rho v_z v_z) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v_z v_r) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \left(2\mu \frac{\partial v_z}{\partial z} \right) \\ + \frac{1}{r} \frac{\partial}{\partial r} \left[\mu r \left(\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right) \right] + j_z B_\theta \end{aligned} \quad (2)$$

径向动量守恒方程:

$$\begin{aligned} \frac{\partial}{\partial z}(\rho v_z v_r) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v_r v_r) = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right) \right] \\ + \frac{2}{r} \frac{\partial}{\partial r} \left(\mu r \frac{\partial v_r}{\partial r} \right) - 2\mu \frac{v_r}{r^2} - j_z B_\theta \end{aligned} \quad (3)$$

电子能量方程:

$$\nabla \cdot \left(\frac{5}{2} n_e k_B T_e \mathbf{v} + n_e \mathbf{E}_i \right) = \nabla \cdot (\kappa_e \nabla T_e) + \mathbf{j} \cdot \mathbf{E} + \frac{5}{2} \frac{k_B}{e} (\mathbf{j} \cdot \nabla T_e) - U_r - E_{ch} \quad (4)$$

重粒子能量方程:

$$\nabla \cdot \left(\frac{5}{2} n_h k_B T_h \mathbf{v} \right) = \nabla \cdot (\kappa_h \nabla T_h) + E_{ch} \quad (5)$$

轴向磁势方程:

$$\frac{\partial^2 A_z}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial A_z}{\partial r} \right) + \mu_0 j_z = 0 \quad (6)$$

径向磁势方程:

$$\frac{\partial^2 A_r}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial A_r}{\partial r} \right) - \frac{A_r}{r^2} + \mu_0 j_r = 0 \quad (7)$$

式中: v_z 和 v_r 分别为轴向 (z) 和径向 (r) 速度分量; j_z 和 j_r 分别为电流密度向量 $\mathbf{j}$ 的轴向和径向分量; T 为温度; p 为压力; ρ , μ , κ , n 和 U_r 分别为气体的密度、粘度、热导率、粒子数密度和单位体积的辐射功率; E_i 为电离能; 下标 e, i, h 分别表示电子、离子和重粒子; A_z 和 A_r 分别为磁矢量势分量; μ_0 为真空磁导

率。磁感应强度的切向分量可表示为

$$B_\theta = \frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r} \quad (8)$$

单位时间、单位体积中电子在和重粒子弹性碰撞过程中传递的能量为

$$E_{ch} = \frac{2m_e}{m_h} \frac{3}{2} k_B (T_e - T_h) n_e n_h \left(\frac{8k_B T_e}{\pi m_e} \right)^{\frac{1}{2}} Q_{ch} \quad (9)$$

式中: m 为质量; k_B 是玻尔兹曼常数; Q_{ch} 为电子与重粒子的碰撞截面, 详见文献[12-13]。为了简化模型, 未涉及粒子间的非弹性碰撞过程。

对于恒稳、不包含鞘层区、满足准中性条件假设的等离子体数值模拟而言, 可忽略位移电流、净电荷密度和感生电场的影响, 故电场守恒方程为

$$\begin{aligned} \frac{\partial}{\partial z} \left(\sigma \frac{\partial \varphi}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\sigma r \frac{\partial \varphi}{\partial r} \right) = 0 \\ j_z = -\sigma \frac{\partial \varphi}{\partial z}, \quad j_r = -\sigma \frac{\partial \varphi}{\partial r} \end{aligned} \quad (10)$$

式中: σ 为电导率; φ 为电势。

1.3 物性参数

文中模拟采用中国科学技术大学张晓宁博士^[11]计算所得标准大气压力下的双温度氩等离子体成分组成及输运系数。通过双线性插值法算出给定 θ 值 ($\theta = T_e/T_h$) 及电子温度 (T_e) 下的等离子体各组分数密度 n 、电导率 σ 、粘度 μ 、密度 ρ 、热导率 κ 等参数, 通过 UDF 将各数据加载到 FLUENT 软件中。

1.4 边界条件

电弧计算区域如图 1 所示, 阴极半径 1.6 mm, 锥角 60°, 电弧弧长 5 mm, 计算半径 15 mm。文中模拟采用的边界条件如表 1 所示。其中 $v_{z\text{given}}$ 为给定的轴向速度; J 为电流密度。

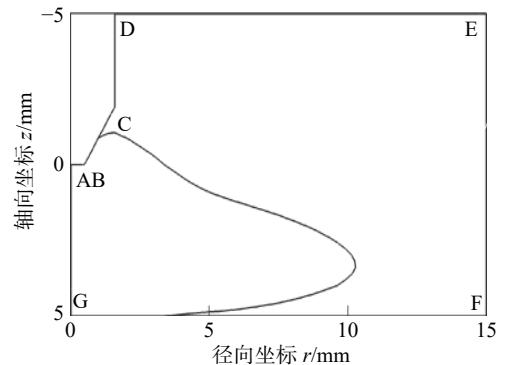


图 1 电弧计算区域示意图

Fig. 1 Arc arrangement and calculation domains

1.5 求解方法

模拟采用的计算网格如图 2 所示。文中 FLUENT 中对 MHD 方程的求解采用计算流体动力学软

表 1 数值模拟边界条件
Table 1 Boundary conditions

	轴向速度 $v_z/(\text{m}\cdot\text{s}^{-1})$	径向速度 $v_r/(\text{m}\cdot\text{s}^{-1})$	电子温度 T_e/K	重粒子温度 T_h/K	电势 φ/V	磁矢量势分量 $A_z/(\text{Wb}\cdot\text{m}^{-1})$
AB	0	0	3 000	3 000	$\frac{\partial\varphi}{\partial n}=0$	$\frac{\partial A_z}{\partial n}=0$
BC	0	0	3 000	3 000	$-\frac{\partial\varphi}{\partial z}=\frac{J}{\sigma}$	$\frac{\partial A_z}{\partial n}=0$
CD	0	0	$\frac{\partial T_e}{\partial n}=0$	1 000	$\frac{\partial\varphi}{\partial n}=0$	$\frac{\partial A_z}{\partial n}=0$
DE	$v_z=v_{z\text{given}}$	0	$\frac{\partial T_e}{\partial n}=0$	1 000	$\frac{\partial\varphi}{\partial n}=0$	$\frac{\partial A_z}{\partial n}=0$
EF	$\frac{\partial v_z}{\partial n}=0$	$\frac{\partial v_r}{\partial n}=0$	$\frac{\partial T_e}{\partial n}=0$	1 000	$\frac{\partial\varphi}{\partial n}=0$	$\frac{\partial A_z}{\partial n}=0$
FG	0	0	$\frac{\partial T_e}{\partial n}=0$	1 000	0	$\frac{\partial A_z}{\partial n}=0$
GA	$\frac{\partial v_z}{\partial n}=0$	$\frac{\partial v_r}{\partial n}=0$	$\frac{\partial T_e}{\partial n}=0$	$\frac{\partial T_h}{\partial n}=0$	$\frac{\partial\varphi}{\partial n}=0$	$\frac{\partial A_z}{\partial n}=0$

件(控制容积法),差分格式采用二阶迎风差分,以 $T_e=T_h=10\,000\text{ K}$, $v_z=v_r=0$, $\frac{\partial A_z}{\partial n}=0$ 作为模型各区域的初值,进行迭代求解.

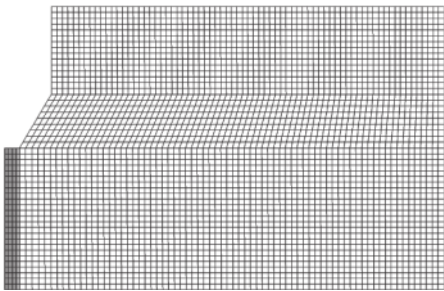


图 2 计算域网格划分示意图
Fig. 2 Schematic of geometry

2 模拟结果与讨论

2.1 等离子体的传热与流动特性

文中模拟采用的焊接参数为:电流 200 A,氩气流量 5 L/min. 由电子温度及重粒子温度分布(图 3)可以看出,电弧的外形是典型的钟罩形形状,阴极尖端附近,两者温度都在 20 000 K 以上,最高温度均达到 22 500 K 左右. 在等离子体电弧核心处,电子温度与重粒子温度几乎重合,即两温度处处相等,满足 LTE 假设,这一结果也与文献[14]结果相吻合. 但是,在阳极表面附近及远离弧柱中心的边缘区域,可看到电子温度超过重粒子温度,呈现非平衡现象.

图 4 为轴向不同位置上电子温度与重粒子温度随径向距离变化规律. 可见,在电弧中心电子温度与重粒子温度基本重合,满足 LTE 假设. 但随着

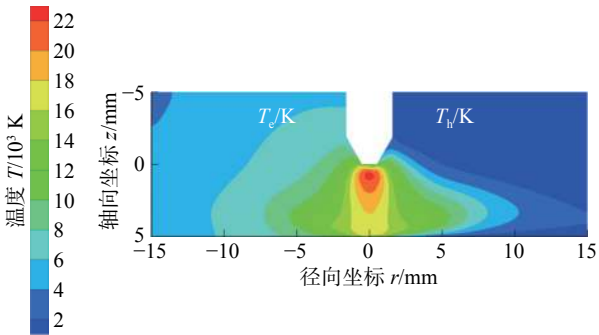


图 3 电子温度与重粒子温度分布
Fig. 3 Distributions of electron and heavy particles temperatures fields

径向距离增大,电子温度与重粒子温度逐渐分离,电子温度明显高于重粒子温度. 当轴向距离 $z=1.5\text{ mm}$ 时(图 4a),在距离中心轴线 5 mm 处分离度已达到 30%. 这是由于电弧周围的氩气(冷气流)从边缘吹过,使得此区域重粒子温度迅速下降,而电子因热运动依然保持较高温度. 由此可见,在电弧边缘区域,存在着强烈的非平衡现象,等离子体偏离局域热力学平衡状态. 另外,随着距钨极尖端轴向距离 z 增加,电子温度与重粒子温度在径向上的重合范围呈现先逐渐增大后逐渐减小的趋势. 在阳极表面附近,电子温度与重粒子温度的径向重合区域较小,满足 LTE 的区域较窄,非平衡现象明显.

图 5 为沿中心轴线从阳极表面到距阳极 0.5 mm 处电子温度与重粒子温度的变化关系. 可以看出,在距阳极表面 0.1 mm 附近,电子温度与重粒子温度开始出现分离,此时电子温度很高,而重粒子温度受阳极冷却作用的限制,在阳极表面迅速下降到阳极表面温度附近,有较大的温度梯度,且越趋向

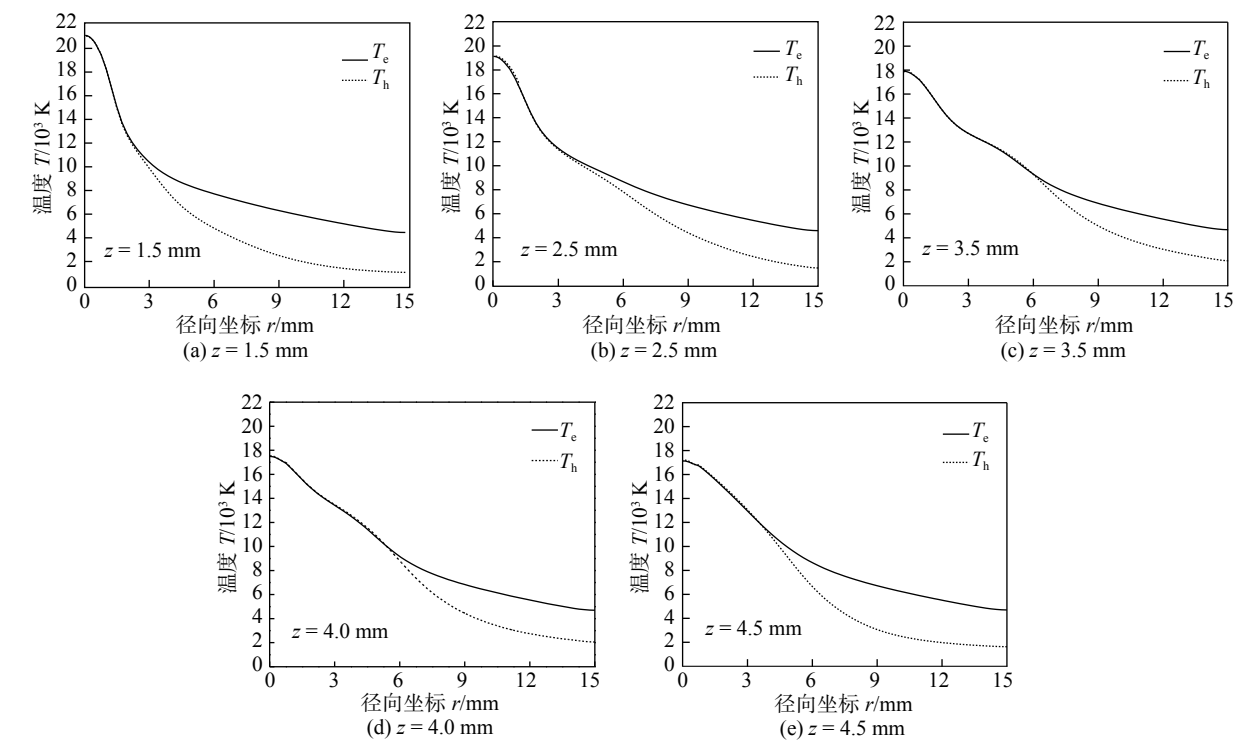


图 4 电子温度与重粒子温度随径向距离的变化

Fig. 4 Radial distributions of electron and heavy particles temperatures for axial positions

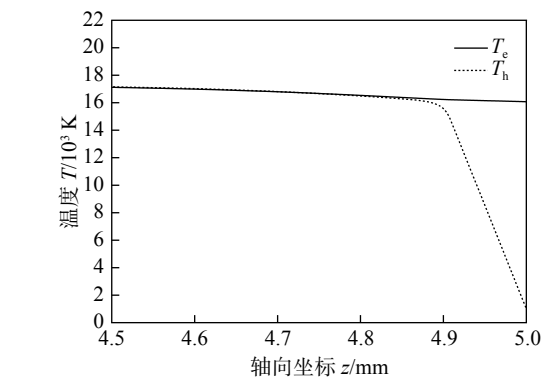


图 5 中心轴线上电子温度与重粒子温度的变化

Fig. 5 Distributions of electron and heavy particles temperatures along the arc axis

阳极电子温度与重粒子温度的分离现象越显著, 产生这一现象的原因是: 为使电流通过阳极表面, 维持电弧放电, 等离子体在阳极表面附近仍有很高的电导率, 故电子温度依然保持在很高的水平. 这种电子温度与重粒子温度的显著差别表明, 在阳极表面很薄的区域内存在着很强烈的非平衡现象, 即阳极边界层. 模型所得到的阳极边界层的厚度与其它文献相比较小^[10, 14], 是由于模型中未考虑阳极表面存在的化学非平衡现象.

图 6 为等离子体的流场, 对称轴左侧为速度矢量场, 右侧为速度云图. 等离子体沿轴向由阴极向

阳极高速流动, 当到达阳极表面时, 阳极的阻滞作用使气流沿阳极表面流向出口, 形成回流.

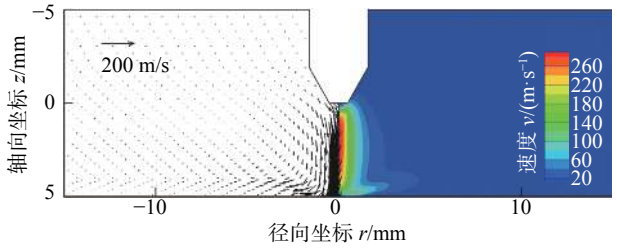


图 6 等离子体流场

Fig. 6 Flow field of TIG plasma

图 7 为等离子体的压力分布. 可以看出, 电弧的阳极区和阴极区有较大的压力分布, 远离这两个区域, 压力逐渐减小.

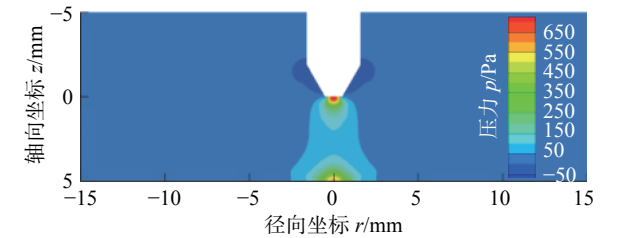


图 7 等离子体压力场

Fig. 7 Pressure field of TIG plasma

图 8 为中心轴线上等离子体压力和速度随轴向距离的变化. 在阴极尖端处压力梯度较大, 使得

等离子体的流速急剧增加, 等离子体的最大速度出现在对称轴附近, 可达 293 m/s, 压力和速度的变化趋势与文献[6]基本吻合。

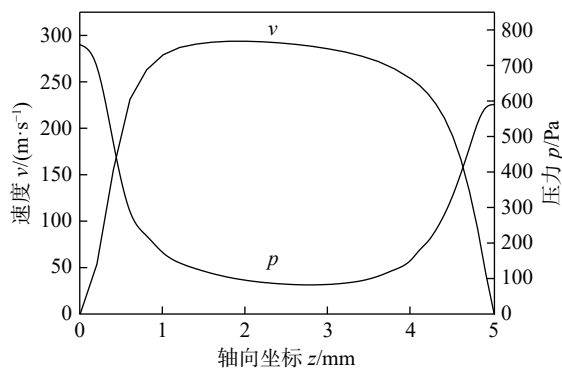


图 8 中心轴线上等离子体速度与压力的变化

Fig. 8 Variation of flow velocity (v) and overpressure (p) in the axis

2.2 等离子体的电特性

图 9 为等离子体的电势场, 电弧弧柱压降可达 11.4 V, 与文献[15]基本吻合。图 10 为中心轴线上电势与轴向电流密度随轴向距离的变化情况, 阴极尖端轴向电流密度可达 $-1.05 \times 10^8 \text{ A/m}^2$, 与文献[6]中计算所得数量级一致。

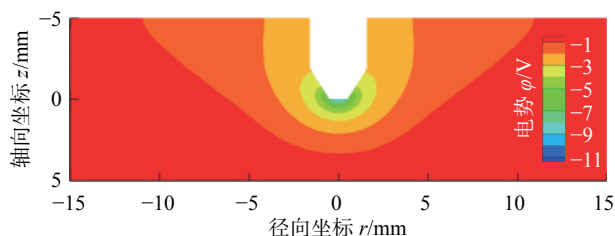


图 9 等离子体电势场

Fig. 9 Potential field of TIG plasma

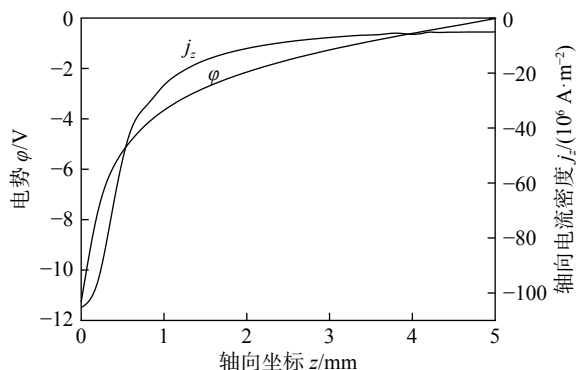


图 10 中心轴线上电势与轴向电流密度的变化

Fig. 10 Variation of the potential(ϕ) and axial current density (j_z) in the axis

3 结 论

(1) 针对 TIG 电弧等离子体建立了二维轴对称

双温度模型, 应用 FLUENT 软件进行求解, 模拟得到 TIG 电弧的电子温度场、重粒子温度场、流场、压力场等结果。

(2) 在 TIG 电弧等离子体的中心区域, 电子温度与重粒子温度几乎处处相等, 电弧处于局部热力学平衡状态 (LTE), 但在电弧的边缘区域与阳极表面区域出现电子温度远高于重粒子温度的情况, 电弧处于非局域热力学平衡状态 (NLTE); 距离阳极表面越近, 电子温度与重粒子温度分离越显著, 非平衡现象越明显。

致 谢: 感谢中国科学技术大学热科学与能源工程系张晓宁博士提供的双温度氩等离子体成分组成、热力学性质与输运系数数据。

参考文献:

- [1] Hsu K C, Etemadi K, Pfender E. Study of the free burning high intensity argon arc[J]. *Journal of Applied Physics*, 1983, 54(3): 1293 – 1301.
- [2] Kaddani A, Zahrai S, Delalondre C, *et al.* Three-dimensional modeling of unsteady high-pressure arcs in argon[J]. *Journal of Physics D: Applied Physics*, 1995, 28(11): 2294 – 2305.
- [3] Wu C S, Ushio M, Tanaka M. Analysis of the TIG welding arc behavior[J]. *Computational Material Science*, 1997, 7(3): 308 – 314.
- [4] 樊 丁, 黄 勇, 张瑞华, 等. 非平衡等离子体输运系数的数值分析[J]. *焊接学报*, 2006, 27(2): 31 – 34.
Fan Ding, Huang Yong, Zhang Ruihua, *et al.* Numerical analysis of the transport properties for no-equilibrium plasma[J]. *Transactions of the China Welding Institution*, 2006, 27(2): 31 – 34.
- [5] 王海兴, 孙素蓉, 陈士强. 双温度氦等离子体输运性质计算[J]. *物理学报*, 2012, 61(19): 317 – 323.
Wang Haixing, Sun Surong, Chen Shiqiang. Calculation of two-temperature transport coefficients of helium plasma[J]. *Acta Physica Sinica*, 2012, 61(19): 317 – 323.
- [6] Hsu K C, Pfender E. Two-temperature modeling of the free-burning, high-intensity arc[J]. *Journal of Applied Physics*, 1983, 54(8): 4359 – 4366.
- [7] 李和平, 陈 熙. 双温度通道电弧等离子体二维数值模拟[J]. *工程热物理学报*, 2006, 27(3): 481 – 483.
Li Heping, Chen Xi. Two-dimensional two-temperature simulation of plasma tube arcs[J]. *Journal of Engineering Thermophysics*, 2006, 27(3): 481 – 483.
- [8] 王立军, 贾申利, 史宗谦, 等. 电弧电流以及纵向磁场对小电流真空电弧特性影响的数值仿真[J]. *电工技术学报*, 2007, 22(1): 54 – 62.
Wang Lijun, Jia Shenli, Shi Zongqian, *et al.* Numerical simulation of effect of arc current and axial magnetic field on low current vacuum arc characteristics[J]. *Transactions of China Electrotechnical Society*, 2007, 22(1): 54 – 62.

[下转第 34 页]

tanium alloy electron beam weldments based on the different heat input conditions of the same line energy[J]. Vacuum, 2017, 146: 136 – 141.

[3] Wang T, Zhang B, Feng J, *et al.* Experimental study of electron beam welded titanium alloy to chromium bronze joint with a vanadium sheet[J]. China Welding, 2014, 23(2): 36 – 40.

[4] Schultz H. Electron beam welding[M]. Cambridge: Abington Publishing, 1993.

[5] Katarzyna O, Kazimierz F. Control of the electron beam active zone position in electron beam welding process[J]. Vacuum, 2004, 74(1): 29 – 43.

[6] Schauer D A. Thermal and dynamic effects in electron beam welding cavities[D]. USA: University of California, 1977.

[7] Luo Y. Bubble flow and the formation of cavity defect in weld pool of vacuum electron beam welding[J]. Vacuum, 2011, 86(1): 11 – 17.

[8] Tsukamoto S, Irie H. Melting process and spiking phenomenon in

electron beam welding[J]. Transactions of the Japan Welding Society, 1993, 24(1): 18 – 23.

[9] Armstrong R E. Spiking in partial penetration electron beam welds[C]// Electrochemical Society, Preceding Symposia of Electron and Ionbeam, 4th International Conference on Electron and Ion Beam Science and Technology, New York, 2014: 179-193.

[10] 石铭霄, 张秉刚, 马纪龙, 等. 钛合金电子束深熔焊钉尖缺陷形成的影响因素[J]. 焊接学报, 2012, 33(12): 32 – 36.

Shi Mingxiao, Zhang Binggang, Ma Jilong, *et al.* Affecting factors of forming spiking of titanium alloy electron beam deep penetration welding[J]. Transactions of the China Welding Institution, 2012, 33(12): 32 – 36.

作者简介: 高福洋, 男, 1986 年出生, 硕士, 工程师. 主要从事有色金属特种焊接方面的研究工作. 发表论文 10 余篇. Email: gaofuyang@126.com

[上接第 10 页]

[9] 钱海洋, 吴 彬. 直流电弧等离子体双温度化学非平衡数值模拟[J]. 核聚变与等离子体物理, 2011, 31(2): 186 – 192.

Qian Haiyang, Wu Bin. A two-temperature chemical non-equilibrium modeling of DC arc plasma[J]. Nuclear Fusion and Plasma Physics, 2011, 31(2): 186 – 192.

[10] Tashiro S, Tanaka M. Two-temperature plasma modeling of argon gas tungsten arcs[J]. Transactions of JWRI, 2008, 37(1): 7 – 11.

[11] 张晓宁, 李和平, Murphy A B, 等. 用于非平衡热等离子体数值模拟的物理数学模型[J]. 高电压技术, 2013, 39(7): 1640 – 1648.

Zhang Xiaoning, Li Heping, Murphy A B, *et al.* Physical-mathematical model used for simulations of non-equilibrium thermal plasmas[J]. High Voltage Engineering, 2013, 39(7): 1640 – 1648.

[12] Mitchner M, Kruger C H. Partially ionized gases [M]. New York:

Wiley, 1973.

[13] Dresvin S V, Donskoi A V, Goldfarb V M, *et al.* Physics and technology of low-temperature plasmas[M]. Iowa City, IA: University of Iowa Press, 1977.

[14] Baeva M, Kozakov R, Gorchakov S, *et al.* Two-temperature chemically non-equilibrium modelling of transferred arcs[J]. Plasma Sources Science and Technology, 2012, 21(5): 055027(13pp).

[15] Haidar J. Non-equilibrium modelling of transferred arcs[J]. Journal of Physics D: Applied Physics, 1999, 32(3): 263 – 272.

作者简介: 黄 勇, 男, 1972 年出生, 教授, 博士. 主要从事焊接物理和高效焊接技术研究. 发表论文 60 余篇. E-mail: hyorhot@lut.cn

MAIN TOPICS, ABSTRACTS & KEY WORDS

Multi-scale shape descriptor template matching algorithm based on weld points of interest CHEN Haiyong, CAO Junqi, REN Yafei, LIU Weipeng (School of Artificial Intelligence, Hebei University of Technology, Tianjin 300130, China). pp 1-5

Abstract: Aiming at welding many types of welds involved in car body, an identification method of weld type was proposed. The extraction algorithm of laser fringe was used to obtain the weld seam skeleton and the weld skeleton was linearly fitted to obtain the weld skeleton feature point as a point of interest. Using multi-scale shape descriptors to characterize the interest points, the shape information of the weld types was obtained. Selecting multiple types of weld templates and identifying weld types were achieved by the template matching algorithm. The results show that the correct classification rate of weld types can be achieved up to 95%, which means this type of weld identification method was feasible.

Key words: points of interest; multi-scale; shape descriptors; template matching

A two-temperature modeling of TIG arc plasma HUANG Yong, LIU Lin, WANG Xinxin, LU Suzhong (State Key Laboratory of Advanced Processing and Recycling of Non-ferrous Metals, Lanzhou University of Technology, Lanzhou 730050, China). pp 6-10,34

Abstract: A two-dimensional axisymmetric two-temperature mathematical model for TIG arc plasma is established based on the conservation equations of mass, momentum, electron energy and heavy particle energy, as well as Maxwell equations. The thermodynamic and transport parameters of the plasma are taken as a function of electron temperature and heavy particle temperature. The distributions of electron temperature, heavy particle temperature, pressure and velocity for TIG arc are obtained by FLUENT software. The results show that the arc plasma presents a bell shape. Temperatures of electron and heavy particle in the arc plasma show a near-LTE behavior in the core region. While a large deviation from LTE is observed in the near-electrode regions and outside the fringe of arc column, the plasma has a strong non-equilibrium characteristic.

Key words: TIG arc plasma; two-temperature model; non-equilibrium

Interface defects and mechanical properties in friction stir welded lap joint of thin aluminum alloy sheets LIU Wei^{1,2}, XIONG Jiangtao¹, ZHAO Huaxia², LUAN Guohong², LI Jinglong¹ (1. Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, China; 2. China Friction Stir Welding Center, AVIC Manufacturing Technology Institute, Beijing 100024, China). pp 11-15

Abstract: 2A12-T4 thin aluminum alloy sheets with different thickness were friction stir lap welded. The influences

of welding parameters on defects morphology and mechanical properties of lap joints were investigated in detail. The results show that the hooking defect displayed higher height and angle compared to cold-lap defect, as maximum defects height was 12.7% of the upper sheet thickness. With the increase of welding speed, height of both hooking and cold-lap defects decreased. The height of hooking defect rose to peak and then declined as improving rotation speed further, but the opposite result appeared in cold-lap defect. Highest strength value obtained under 950 r/min and 200 mm/min and joint efficiency can reach 84%. Vickers microhardness distribution exhibited W-shaped profile. Joint softening occurred in the upper sheet and hardness of the bottom nugget zone was higher than the upper zone. Cold-lap defect was the main factor that affected joint properties. All specimens in the tensile-shear test show shear fracture model along the lap interface, which could be attributed to relative low effective lap width.

Key words: defects morphology; microhardness distribution; effective lap width; shear fracture

Microstructure and strength of AlN/Kovar alloy joints brazed with two Ag-based active filler metals ZHU Chengjun^{1,2}, LI Chengsi¹, DONG Xuehua³ (1. School of Mechanical Engineering, Henan Polytechnical Institute, Nanyang 473009, China; 2. School of Mechatronics Engineering, Wuhan University of Technology, Wuhan 430070, China; 3. School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China). pp 16-19,40

Abstract: Ag-Cu-Ti and Ag-Cu-In-Ti active filler metals were used to braze AlN ceramic and Kovar alloy in the vacuum brazing furnace. The corresponding brazing parameters were 860 °C/10 min and 760 °C/10 min, respectively, and sound AlN/ Kovar alloy joints were obtained. The shear strengths of AlN/Ag-Cu-Ti/4J29 and AlN/Ag-Cu-In-Ti/4J29 joints were 126 and 113 MPa, respectively. The microanalysis results show that a continuous diffusion layer formed near the ceramic substrate. The TiN phase was detected in the layer by XRD. The thickness of the diffusion layer had obvious effect on the joint strength. Cu(s,s), Ag(s,s) and Ni(Fe, Co)-Ti compounds formed in the brazing seam matrix.

Key words: AlN ceramic; Ag-Cu-Ti; Ag-Cu-In-Ti; vacuum brazing

High frequency hybrid twin-electrode TIG welding process for stainless steel WU Tongli, WANG Kehong, KONG Jian, GAO Qiong (School of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing 210094, China). pp 20-24

Abstract: In order to solve the problems of small arc pressure and depth of weld in twin-electrode TIG welding, a new type gas tungsten arc welding process of high frequency hybrid twin-electrode TIG welding (HFHT-TIG) was put forward. A high frequency pulse current was added on one