



激光熔覆过程中传热传质的数值模拟

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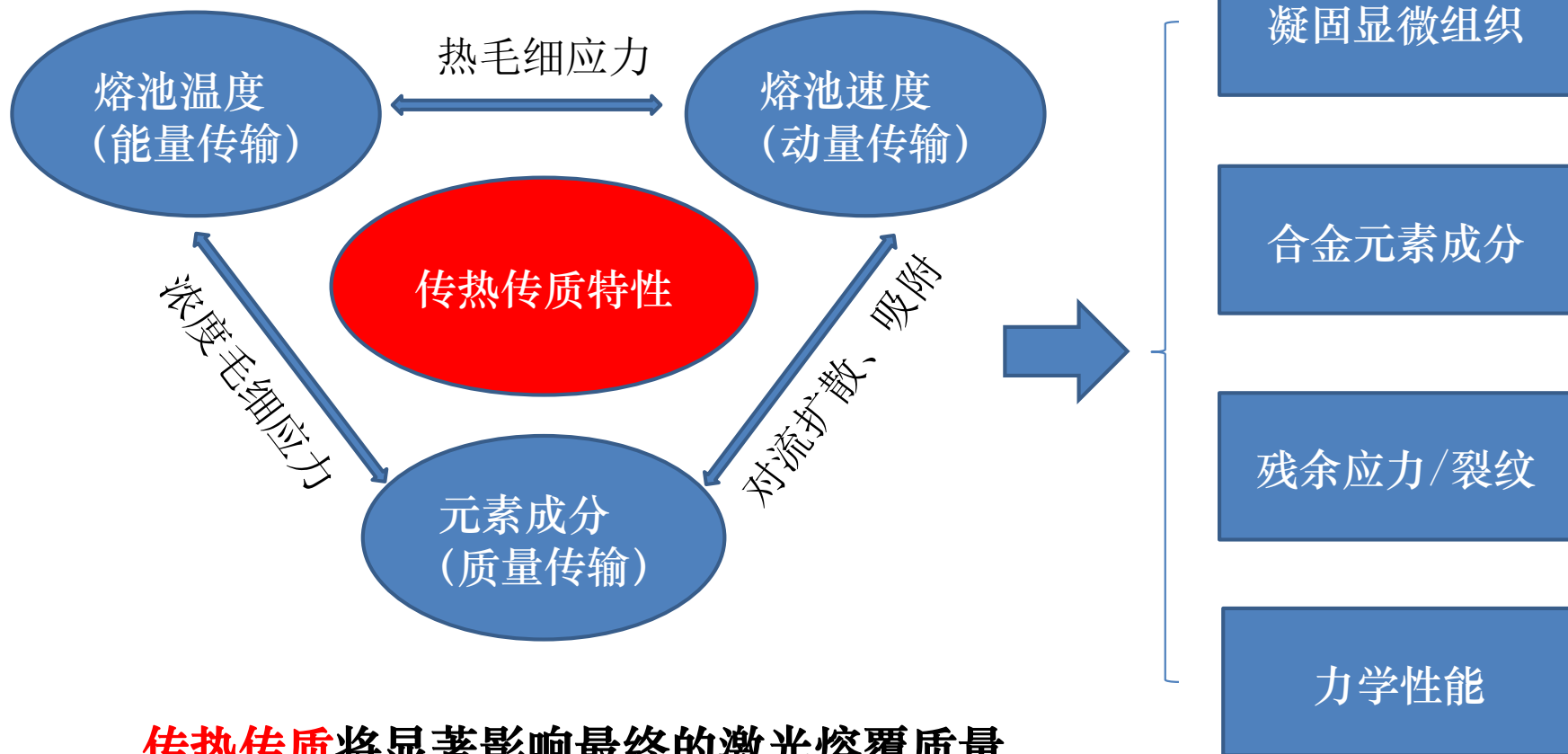
2015.11.4



- 一、熔池传热传质特性**
- 二、数学模型建立**
- 三、数值计算结果与实验验证**
- 四、分析与总结**



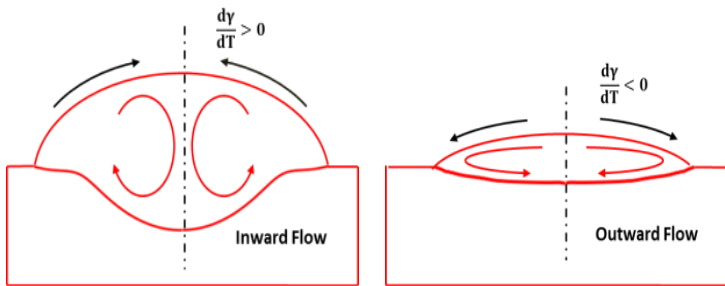
熔池传热传质特性



传热传质将显著影响最终的激光熔覆质量关注的核心问题

熔池传热传质特性

熔池中的主要流动形式是Marangoni对流:



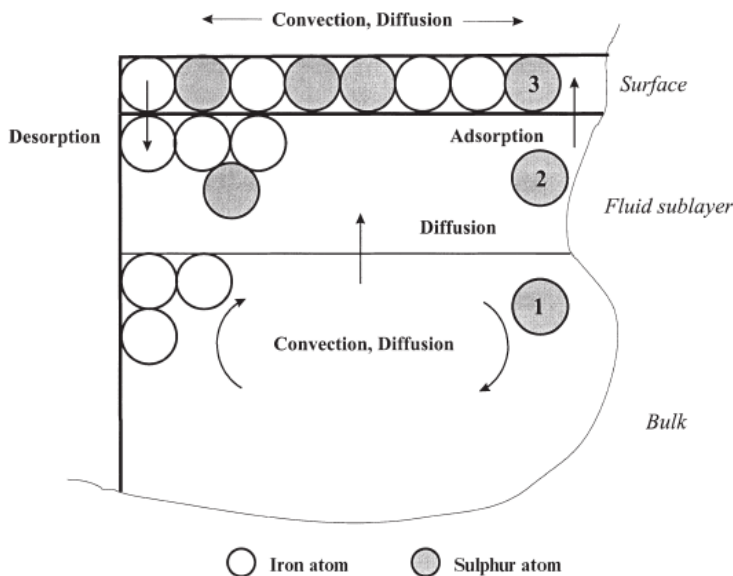
表面张力温度系数:

$$\gamma(T, a_s) = \gamma_m - A_\gamma(T - T_l) - R_u T \Gamma_s \ln(1 + K a_s)$$

$$K = k_1 \exp\left(-\frac{\Delta H^0}{R_u T}\right)$$

Inward Flow

Outward Flow



熔池**表面温度**和**表面活性元素** (S、O等) 会影响熔池的表面张力温度系数, 从而影响熔池流动状态和熔池形态

$$\frac{\partial \Gamma}{\partial t} + \nabla_s (\Gamma \mathbf{u}_s) = \frac{1}{Pe} \nabla_s^2 \Gamma + \frac{1}{Ca} S$$

$$S' = \beta' C'_s (\Gamma'_\infty - \Gamma') - \alpha' \Gamma' \quad \beta' = \beta'_0 \exp(-E'_a / R' T')$$

$$\alpha' = \alpha'_0 \exp(-E'_d / R' T')$$

$$\frac{\partial C}{\partial t} + (\mathbf{u} \cdot \nabla) C = \frac{1}{Pe_s} \nabla^2 C$$



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简化假设

- 固相和液相均考虑为连续介质，不考虑固相中的应力和变形。
- 熔池内金属液体为不可压缩流体，流动状态为层流。
- 激光束的分布假设为高斯分布，不考虑激光束在 Z 方向上的强度变化。
- 熔池驱动力只考虑浮力和表面张力梯度（Marangoni效应）。
- 粉末在作用区域假设为圆形，空间分布为高斯分布，假设当粉末接触到熔化金属将被吸收，接触到未熔化金属将被反弹。
- 活性元素（S）只存在于母材中，涂层粉末中的活性元素忽略不计。



使用的 COMSOL 接口

- 流体传热接口
- 层流流动，多相流（Level-Set方法）接口
- 成分传输接口

控制方程



质量方程:

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

动量方程:

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho \mathbf{u} u) = \nabla \cdot \left(\mu_l \frac{\rho}{\rho_l} \nabla u \right) - \frac{\partial p}{\partial x} + S_{S/L}^u,$$

其中:

$$S_{S/L}^u = - \frac{\mu_l \rho}{K \rho_l} u + \rho_r g_x \beta (T - T_r), \quad K = K_0 \frac{g_l^3}{(1 - g_l)^2},$$

能量方程:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) = \nabla \cdot (k \nabla T) - \nabla \cdot [\rho (h_l - h) \mathbf{u}].$$

其中:

$$h_s = \int_0^T C_{ps} dT = \bar{C}_{ps} T, \quad h_l = \int_0^{T_e} C_{ps} dT + L_m + \int_{T_e}^T C_{pl} dT = \bar{C}_{pl} T + \mathcal{L},$$

$$\mathcal{L} = (\bar{C}_{ps} - \bar{C}_{pl}) T_e + L_m = \Delta \bar{C}_p T_e + L_m, \quad h = \bar{C}_p T + f_l \mathcal{L},$$

活性元素浓度方程:

$$\frac{\partial c_i}{\partial t} + \mathbf{u} \cdot \nabla c_i = \nabla \cdot (D_i \nabla c_i) \quad \text{其中:} \quad \alpha_i = \frac{c_i - c_i^{1018}}{c_i^{200} - c_i^{1018}}$$



边界条件

Level-Set 方法捕捉气液界面:

$$\frac{\partial \phi}{\partial t} + F|\nabla \phi| = 0, \quad \text{其中: } \phi(\mathbf{x}, t) = \pm d, \quad F = F_p + \mathbf{n} \cdot \mathbf{u}(x, y, z, t), \quad \mathbf{n} = \frac{\nabla \phi}{|\nabla \phi|}.$$
$$F_p = N_s(r) v_p \frac{4}{3} \pi r_p^3, \quad r = \sqrt{(x - U_s t)^2 + y^2}.$$

焓-多空隙度方法捕捉固液界面:

$$\frac{\partial(\rho C_p T)}{\partial t} + \mathbf{u} \cdot \nabla(\rho C_p T) = k \nabla^2 T + S_{S/L}^T, \quad S_{S/L}^T = \frac{\partial(\rho f_s \Delta \bar{C}_p T)}{\partial t} - \frac{\partial(\rho f_l \mathcal{L})}{\partial t}.$$
$$f_l = \begin{cases} 0 & (T < T_s) \\ \frac{T - T_s}{T_l - T_s} & (T_s < T < T_l) \\ 1 & (T_l < T) \end{cases}$$

其他边界条件:

$$q_l(r) = \frac{2P}{\pi R_b^2} \exp\left(\frac{-2r^2}{R_b^2}\right), \quad \mathbf{F}_{L/G} = \sigma \mathbf{n}^* \kappa - \nabla_s T \frac{d\sigma}{dT}, \quad A_a = \alpha |\cos(\theta)|^{0.2}.$$
$$q_{L/G} = q_l(r) A_a + q_p - A_h (T - T_0) - \sigma \varepsilon (T^4 - T_0^4),$$

热物性参数和工艺参数



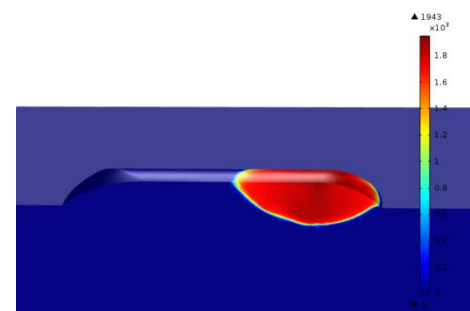
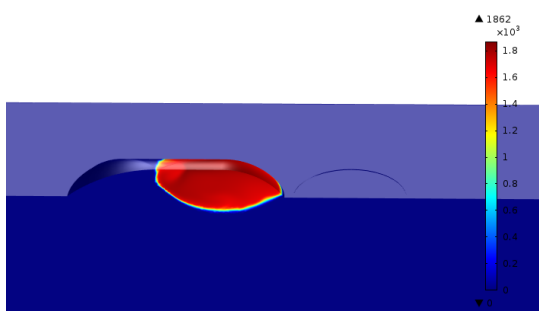
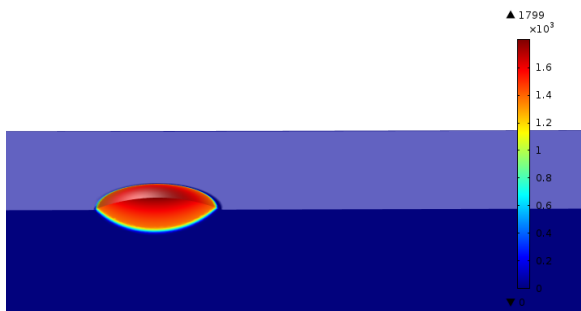
Parameters	Value
Solid thermal conductivity ($\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$)	24
Solid specific heat($\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$)	662
Solid density($\text{kg}\cdot\text{m}^{-3}$)	7400
Latent heat ($\text{kJ}\cdot\text{kg}^{-1}$)	270
Liquidus temperature (K)	1768
Solidus temperature (K)	1609
Laser beam radius at substrate(mm)	1
Laser power (W)	700
Laser scanning speed (mm/s)	2~9
Powder flow rate (g/min)	5
Powder jet radius at substrate (mm)	1.5
Initial concentration of sulfur in base(wt%)	0.04

Parameters	Value
Liquid thermal conductivity($\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$)	21
Liquid specific heat($\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$)	734
Liquid density ($\text{kg}\cdot\text{m}^{-3}$)	6890
Diffusivity (m^2/s)	2e-7
Convective heat transfer coefficient ($\text{W}/\text{m}^2/\text{K}$)	25
γ (N/m)	1.943
A (N/m/K)	4.3e-4
Tl (K)	1809
Ts (kmol/m^2)	1.3e-8
k1	0.00318
H0 (kJ/kmol)	1.66e8
Initial concentration of sulfur in power(wt%)	0.008

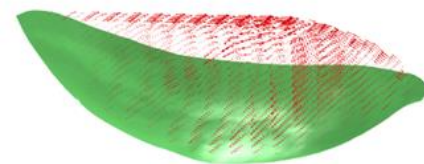
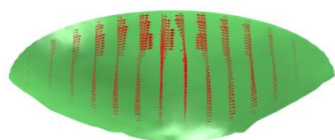


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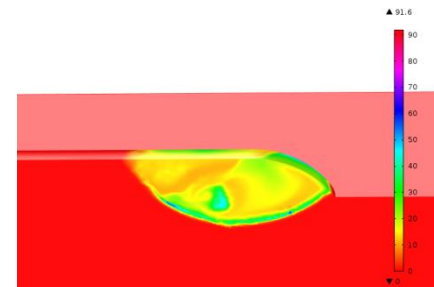
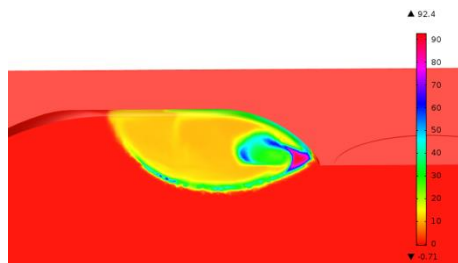
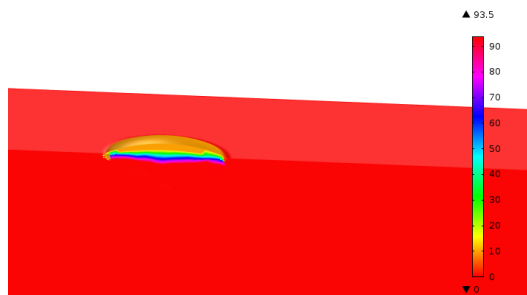
数值计算结果与实验验证



熔池温度场



熔池速度场



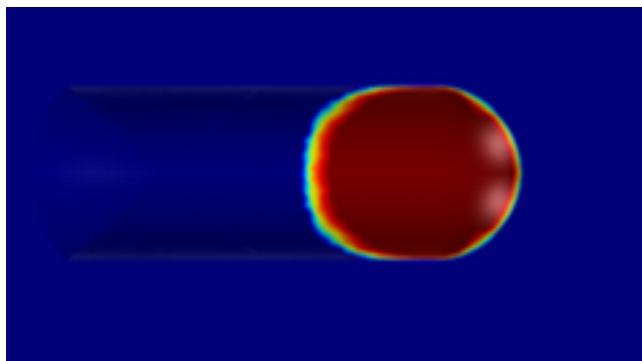
熔池浓度场

$t=100\text{ms}$

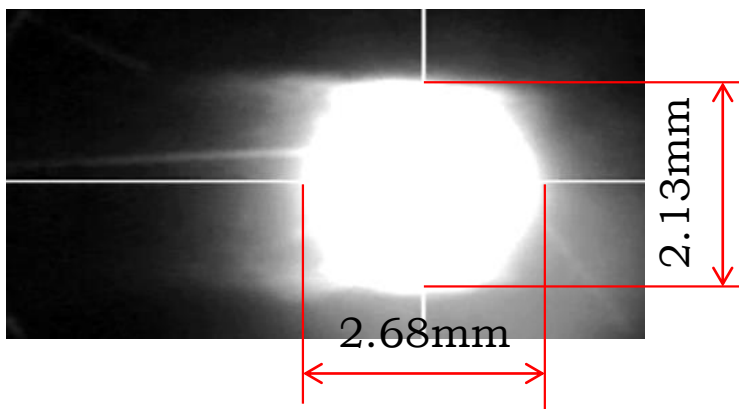
$t=500\text{ms}$

$t=1000\text{ms}$

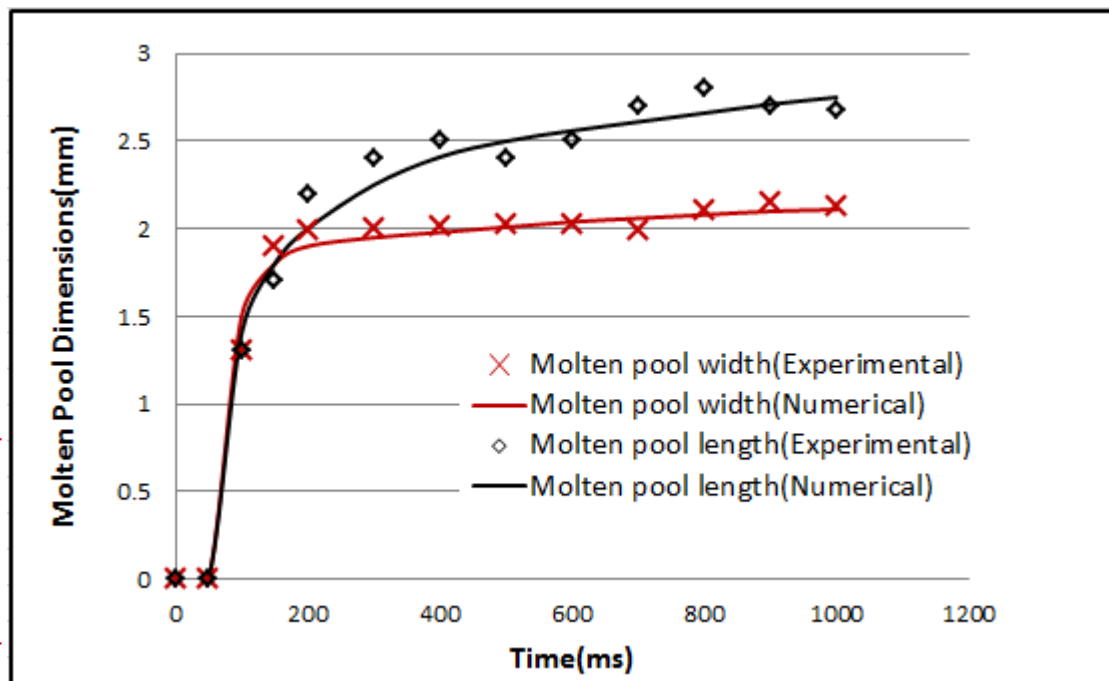
数值计算结果与实验验证



数值计算结果 t=1000ms



同轴CCD观测结果t=1000ms

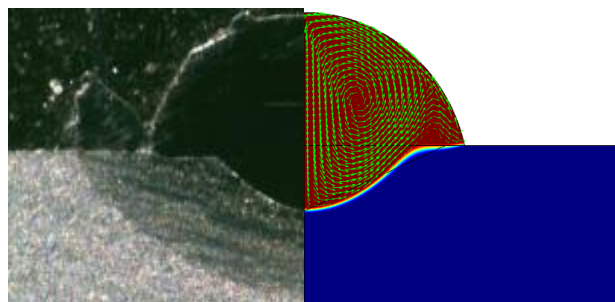


不同熔覆时间下的数值结果和实验结果的对比

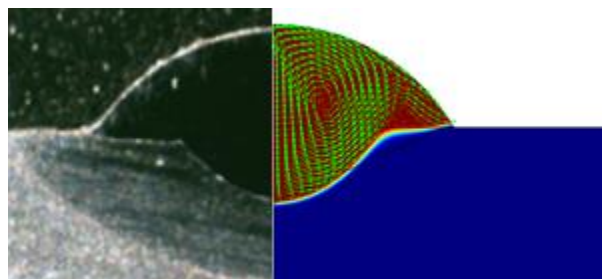
数值计算结果与实验验证



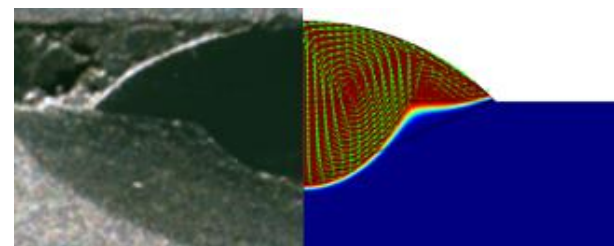
不同扫描速度 (2mm/s~10mm/s) 下的熔池横截面: 数值计算和实验结果



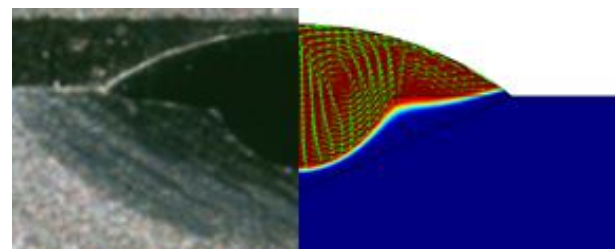
V=2mm/s



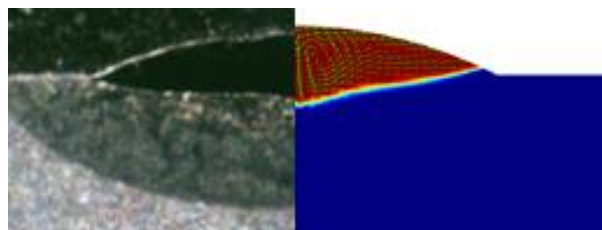
V=3mm/s



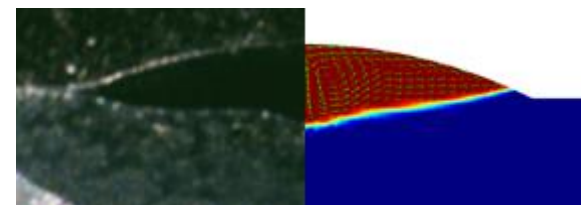
V=4mm/s



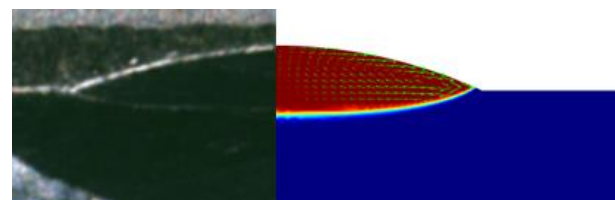
V=5mm/s



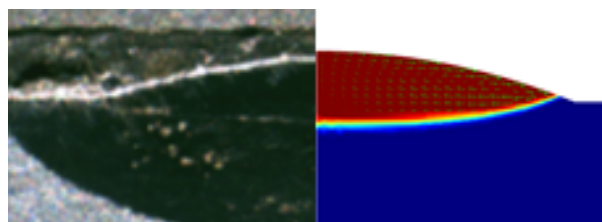
V=6mm/s



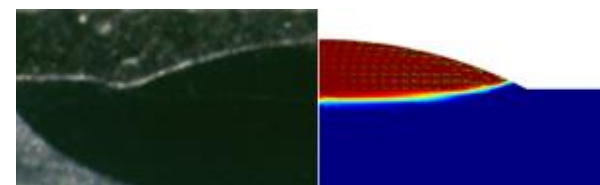
V=7mm/s



V=8mm/s



V=9mm/s

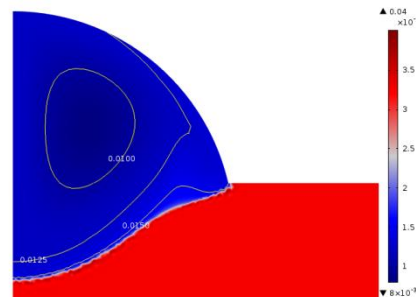


V=10mm/s

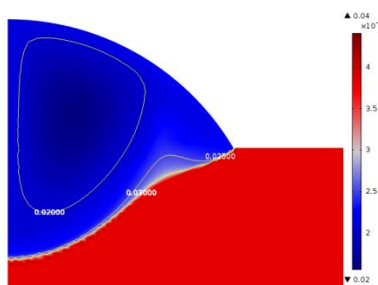
数值计算结果与实验验证



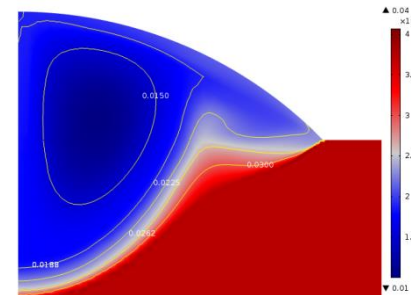
不同扫描速度下的熔池横截面活性元素 (S) 重量百分比 (wt%)



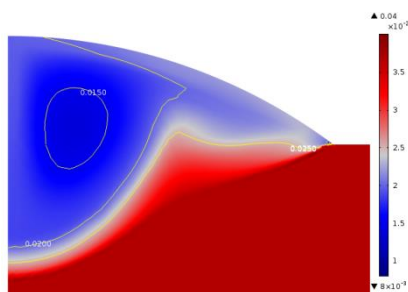
V=2mm/s



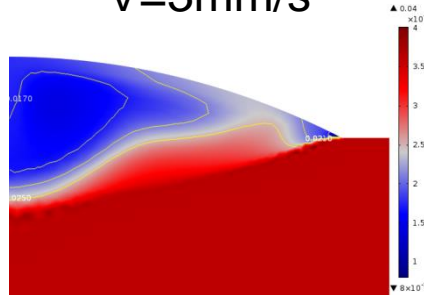
V=3mm/s



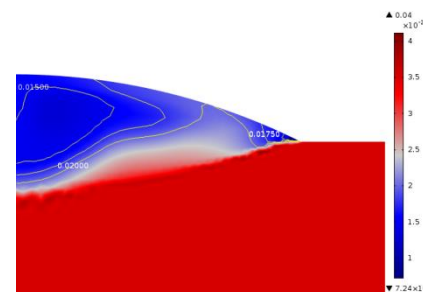
V=4mm/s



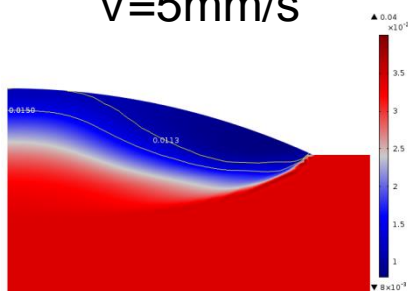
V=5mm/s



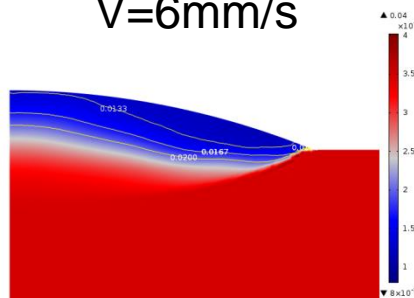
V=6mm/s



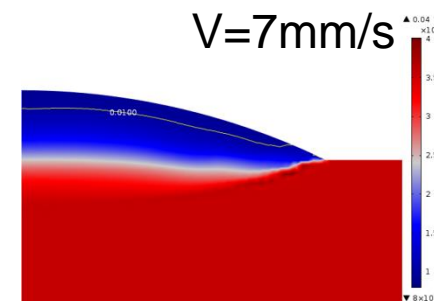
V=7mm/s



V=8mm/s



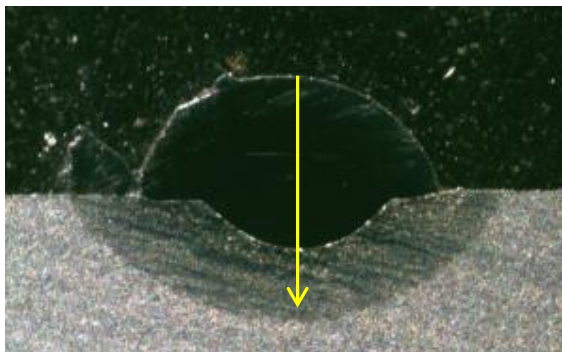
V=9mm/s



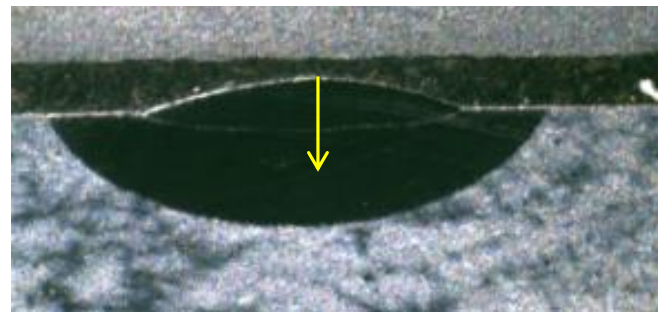
V=10mm/s

数值计算结果与实验验证

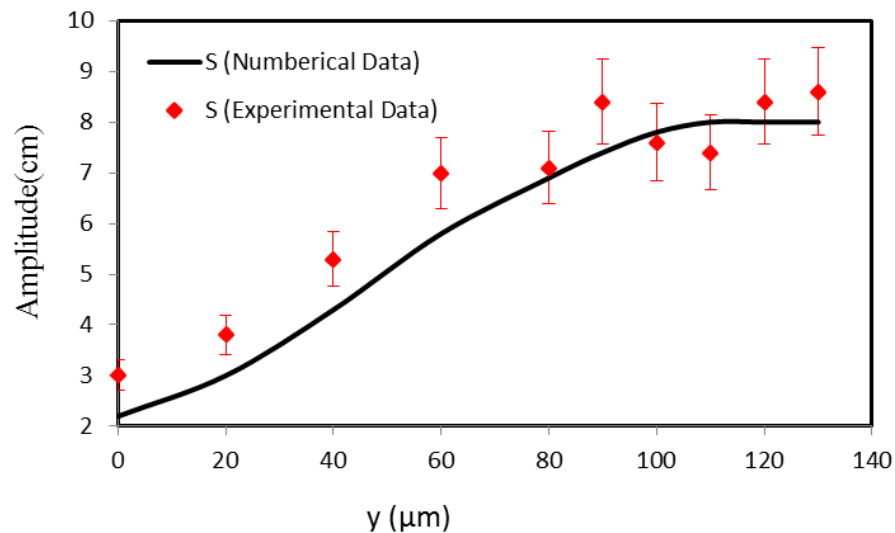
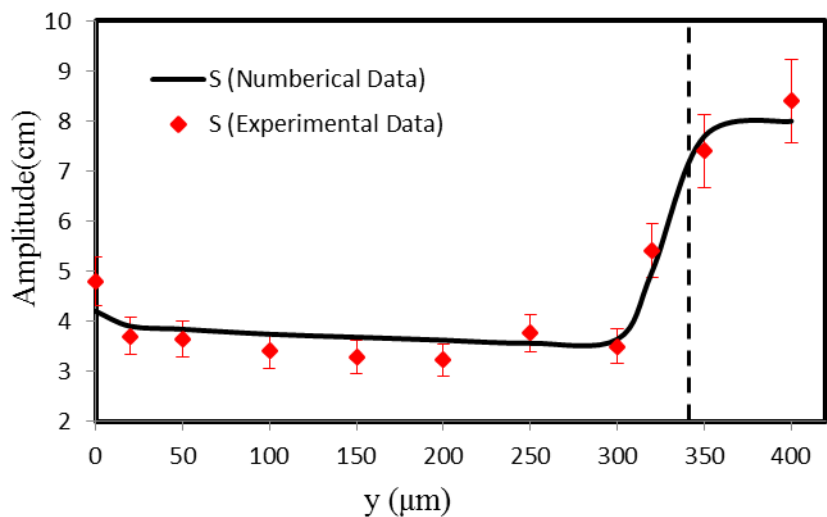
硫元素分布的AES检测结果和数值计算结果对比图



V=2mm/s

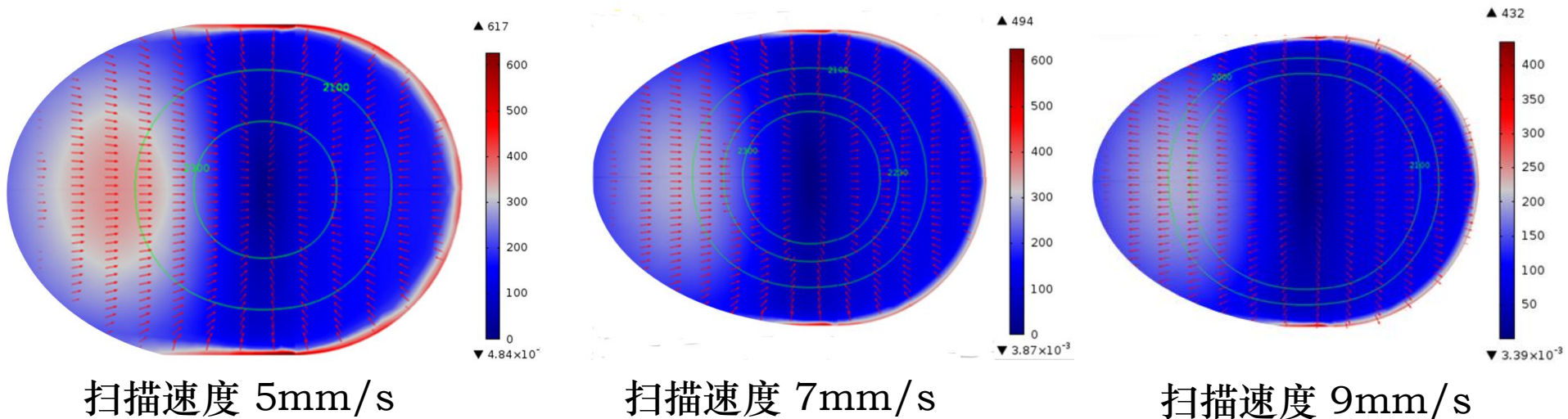


V=8mm/s



数值计算结果与实验验证

扫描速度为 5mm/s、7mm/s、9mm/s 下的熔池的表面应力分布：





- 一、激光熔覆过程中的力学问题
- 二、熔凝过程中的界面演化
- 三、数学模型建立
- 四、数值计算结果与实验验证
- 五、分析与总结

- 使用 COMSOL Multiphysics® 有限元软件模拟了激光熔覆的传热传质过程，考虑了质量添加、高温流动、传热、活性元素的传质等因素。
- 计算得到了不同扫描速度下的激光熔池传热传质规律，并通过实验结果验证计算结果的可靠性。
- 随着扫描速度的增加，由于熔池存在时间的减少，活性元素 (S) 出现不完全扩散，导致表面的 S 元素成分减少，使熔池表面张力温度系数变号，熔池流动方向由外向内转变为由内向外。
- 结合熔池的温度和成分分布，得到了不同扫描速度下的表面张力温度系数规律，结果显示在扫描速度 7-8mm/s 之间，表面张力温度系数跨过零点，出现流动方向转变点。



谢谢， 敬请批评指正