

COMSOL CONFERENCE 2017 BEIJING



激光增材制造中的热质输运

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工程背景

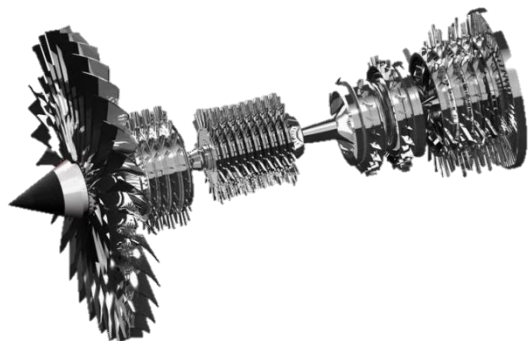
高温合金激光增材制造



飞行器承重结构
北航(中) 2011



航空发动机叶片
SUKHOI(俄) 2009



燃气轮机叶盘
TRUMPF(德) 2015

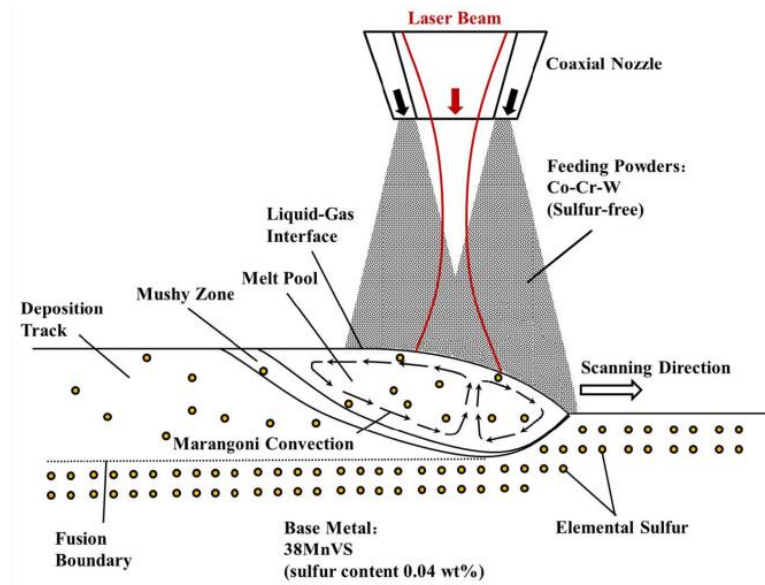


发动机喷嘴
NASA(美) 2009

熔池热质运输

• 数值模型基本假设：

1. 金属液体为不可压缩、牛顿流体，**层流**；
2. 材料热物性参数被假设为粉末和基体的线性插值；
3. 激光热流分布为超高斯分布；
4. 忽略蒸发导致的热流损失；
5. 粉末进入金属熔池立即被熔化，忽略粉末冲击动量；
6. **固相线和液相线之间的糊状区假设为各项同性的多孔介质**；
7. 忽略凝固过程中枝晶的微观偏析；
8. **凝固行为假设为伪二元合金系统凝固。**



激光增材制造中的热质运输

熔池热质输运

• 控制方程

连续性方程:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

动量方程:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] - \frac{2\mu}{3} (\nabla \cdot \mathbf{u})\mathbf{I} - K_0 \frac{(1 - f_l)^2}{f_l^3 + B} \mathbf{u}$$

糊状区中的动量耗散

能量方程:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) - \frac{\partial H}{\partial t} - \rho \mathbf{u} \cdot \nabla H$$

相变潜热

$$H = Lf_l$$

$$f_l = \begin{cases} 1, & T > T_l \\ \frac{T - T_s}{T_l - T_s}, & T_s \leq T \leq T_l \\ 0, & T < T_s \end{cases}$$

熔池热质输运

- 现状
- 二元组分传质模型(如Fe-Cr)

$$\frac{\partial(\rho c)}{\partial t} + \frac{\partial(\rho u_i c)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho D \frac{\partial c}{\partial x_i} \right) + \frac{\partial}{\partial x_i} \left(\rho D \frac{\partial (c_l - c)}{\partial x_i} \right)$$

Appl. Surf. Sci. (2011)

J. Phys. D Appl. Phys. (2009)

- 推广至多组分传质(Fe-Co-Cr-C):

The diagram shows the following equation on a blue background:

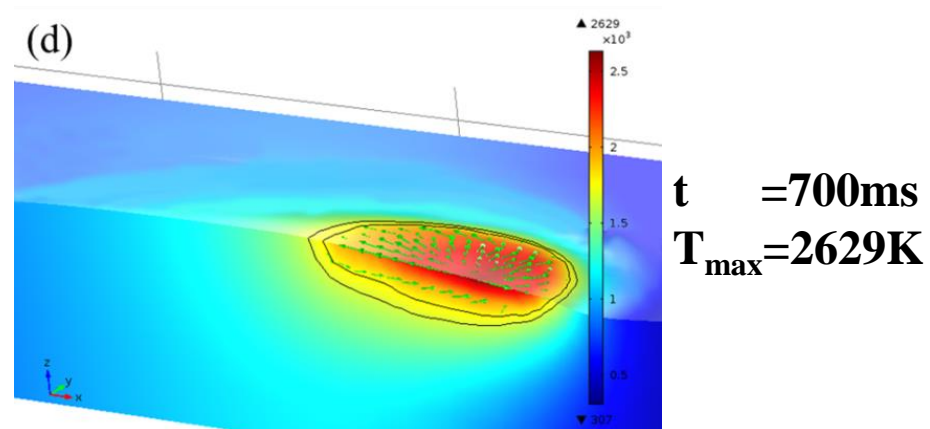
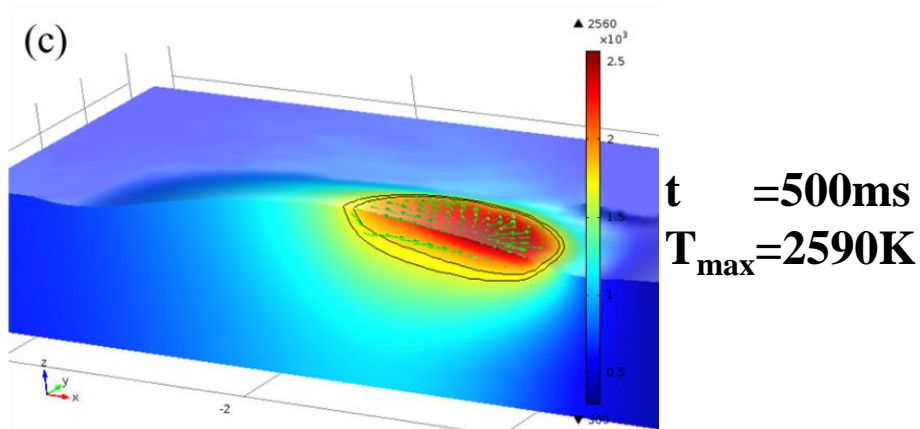
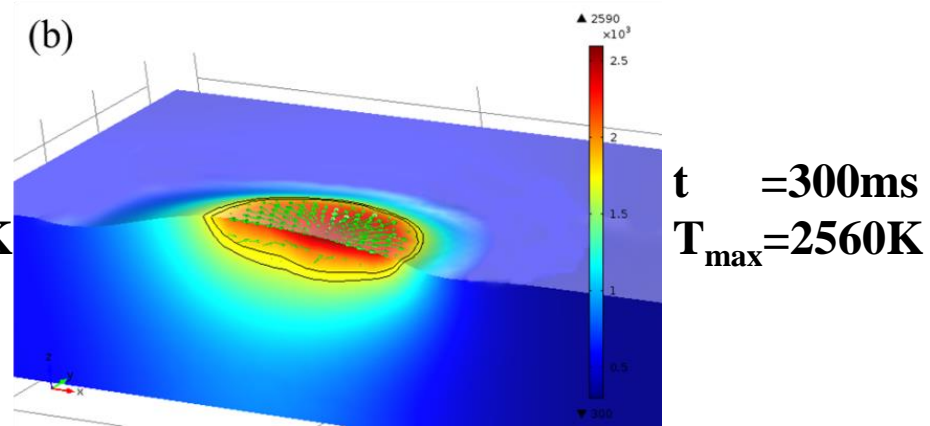
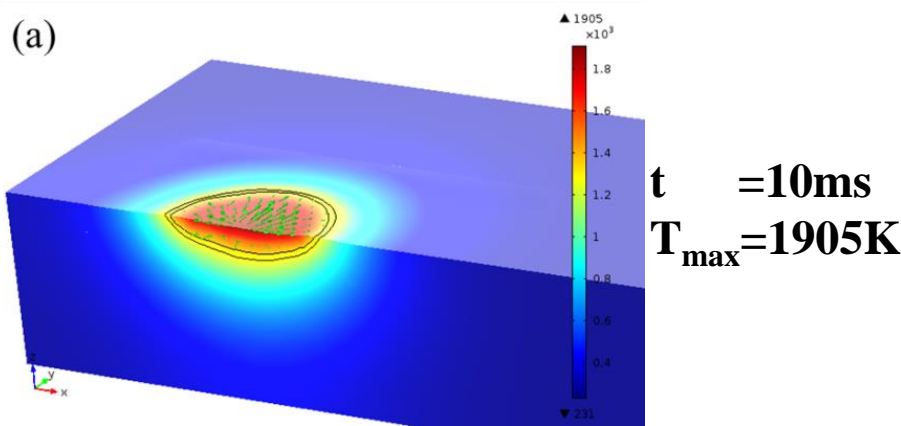
$$\rho \frac{\partial c_i}{\partial t} + \rho(u \cdot \nabla) c_i = \nabla \cdot \left(\rho D_i^m \nabla c_i + \rho c_i D_i^m \frac{\nabla M_n}{M_n} \right) + \nabla \cdot \left(\rho D_i^m \nabla (c_l - c) \right) - \nabla \cdot (\rho f_s \nabla (c_l - c_s) u)$$

Four terms are circled in yellow and labeled with arrows pointing to Chinese text below:

- $\rho(u \cdot \nabla) c_i$ is labeled 熔池对流 (Melting Pool Convection).
- $\rho D_i^m \nabla c_i$ is labeled 扩散 (Diffusion).
- $\rho c_i D_i^m \frac{\nabla M_n}{M_n}$ is labeled 组分间相互作用 (Inter-component Interaction).
- $\nabla \cdot (\rho D_i^m \nabla (c_l - c))$ is labeled 凝固溶质偏析 (Solidification Solute Segregation).

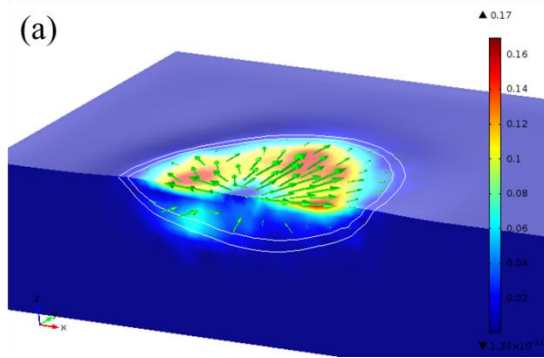
熔池热质运输

- 熔池温度场:

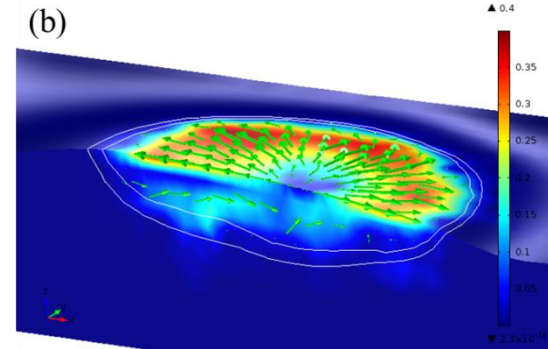


熔池热质输运

- 熔池速度场:

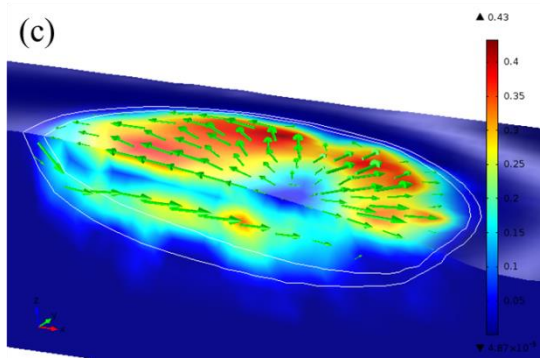


$t = 10\text{ms}$
 $V_{\max} = 0.17\text{m/s}$
 $Pe = 5$

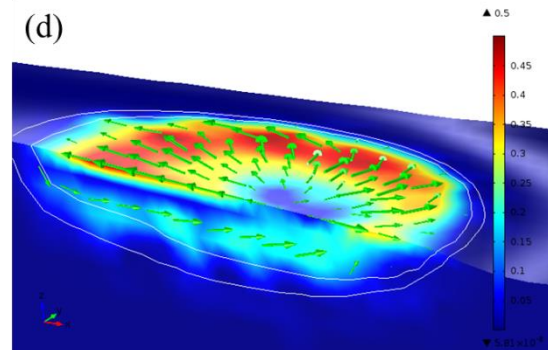


$t = 300\text{ms}$
 $V_{\max} = 0.4\text{m/s}$
 $Pe = 40$

$$Pe_T = \frac{uL_R}{\alpha}$$



$t = 500\text{ms}$
 $V_{\max} = 0.43\text{m/s}$
 $Pe = 80$

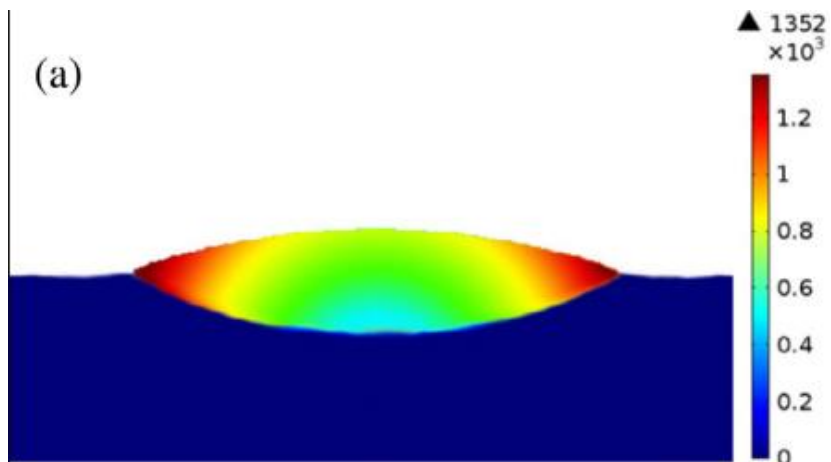


$t = 700\text{ms}$
 $V_{\max} = 0.51\text{m/s}$
 $Pe = 100$

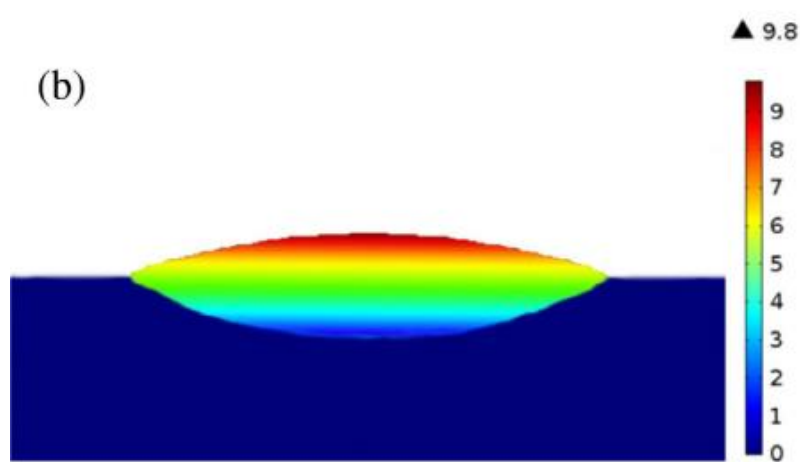
✓ 熔池充分发展后的传热行为主要由Marangoni对流主导

熔池凝固特征

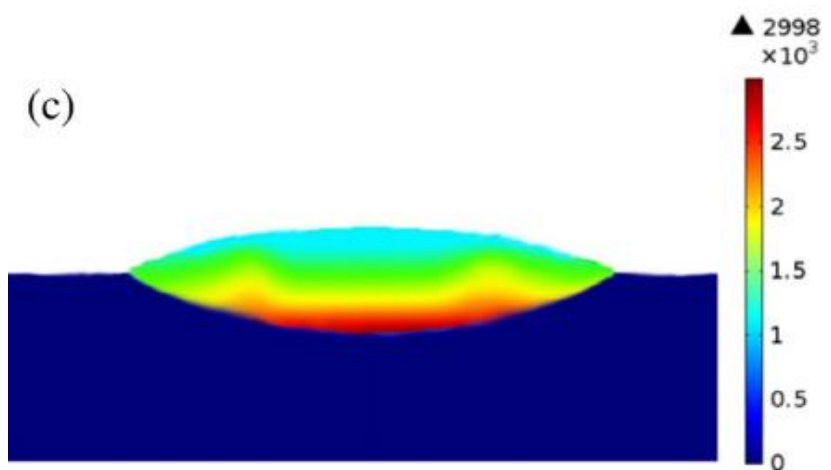
- 凝固参数G与R



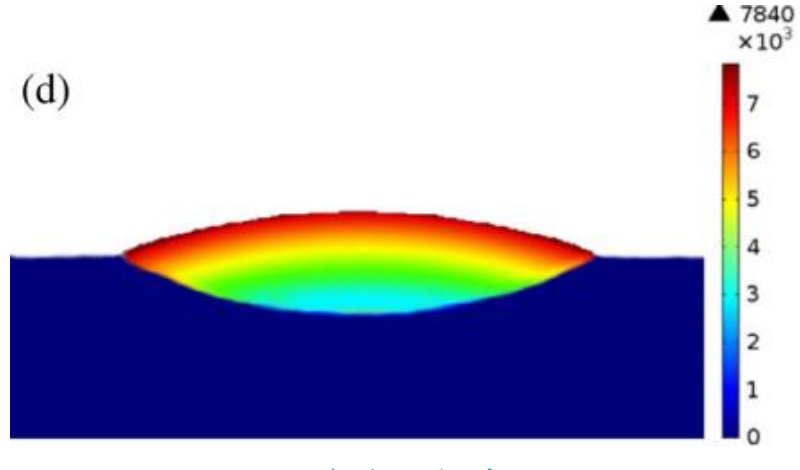
温度梯度G



凝固速率R



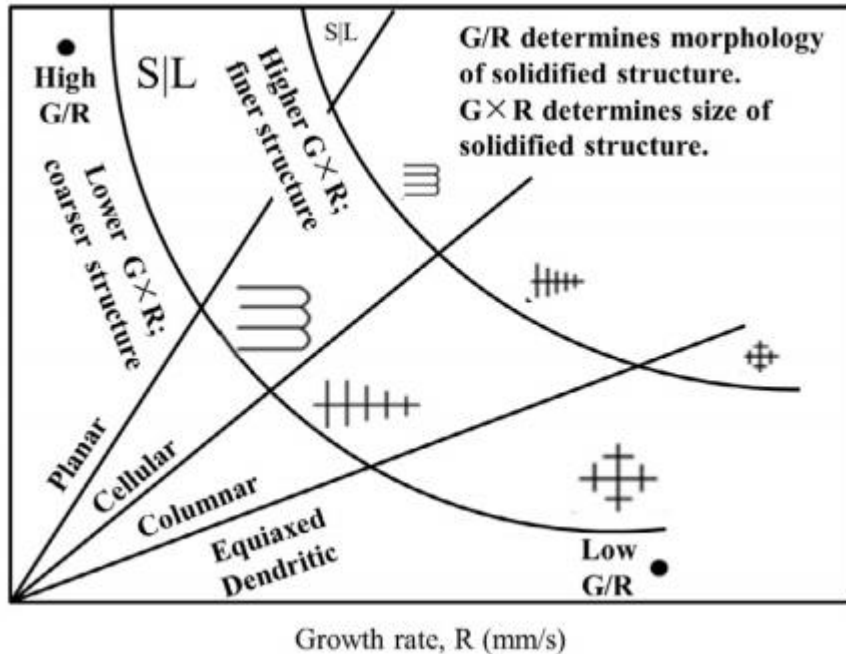
形态参数G/R



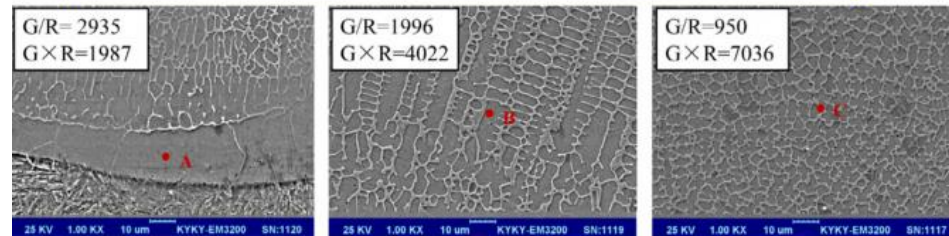
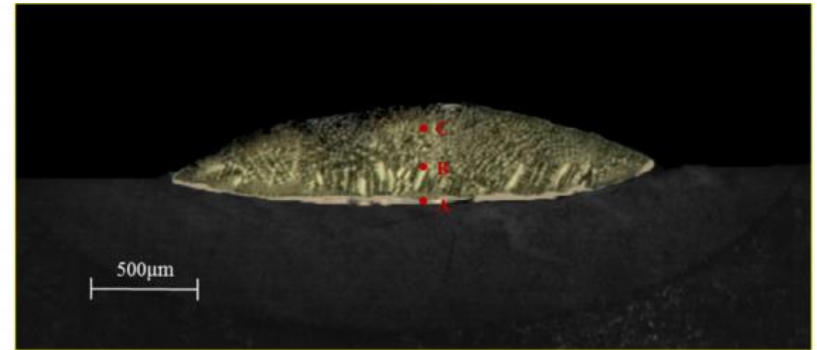
冷却速度G x R

熔池凝固特征

- 微观组织:



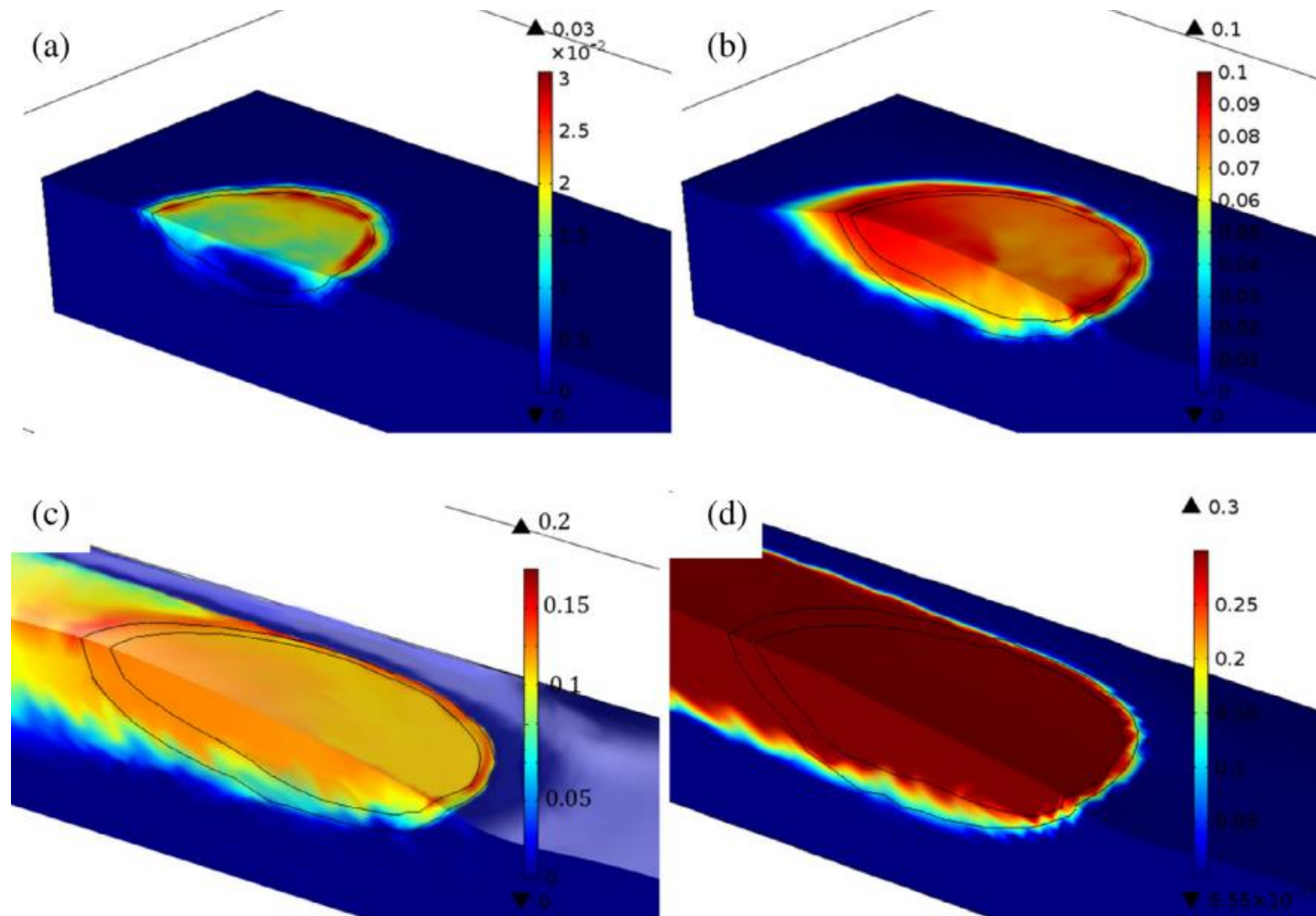
G和R对微观组织形态的影响规律



实验观察得到的微观组织

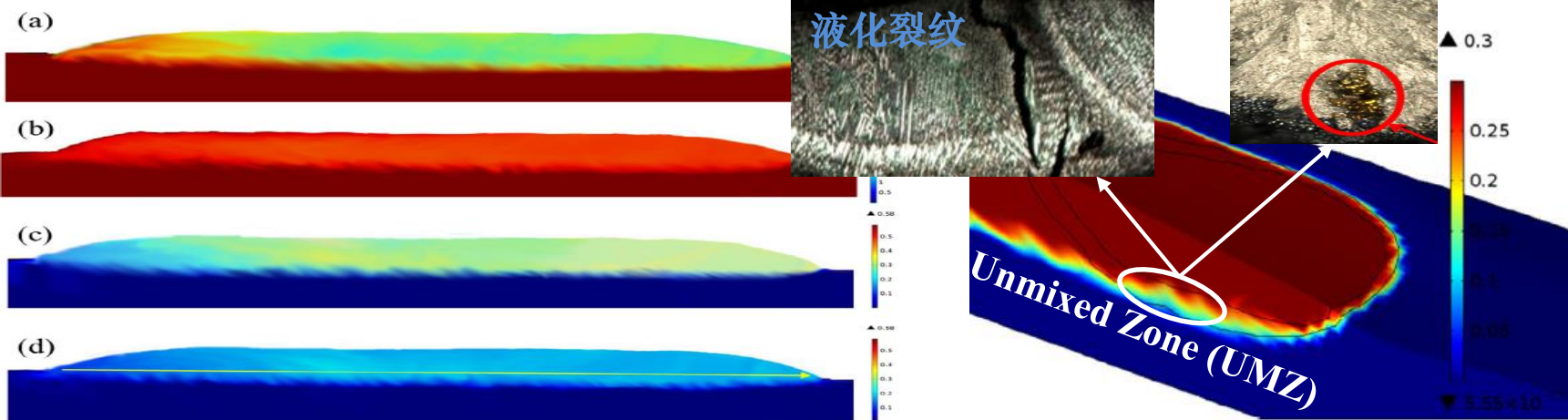
✓ 实验获得的特征点的微观组织，很好的验证了仿真结果

多组分传质

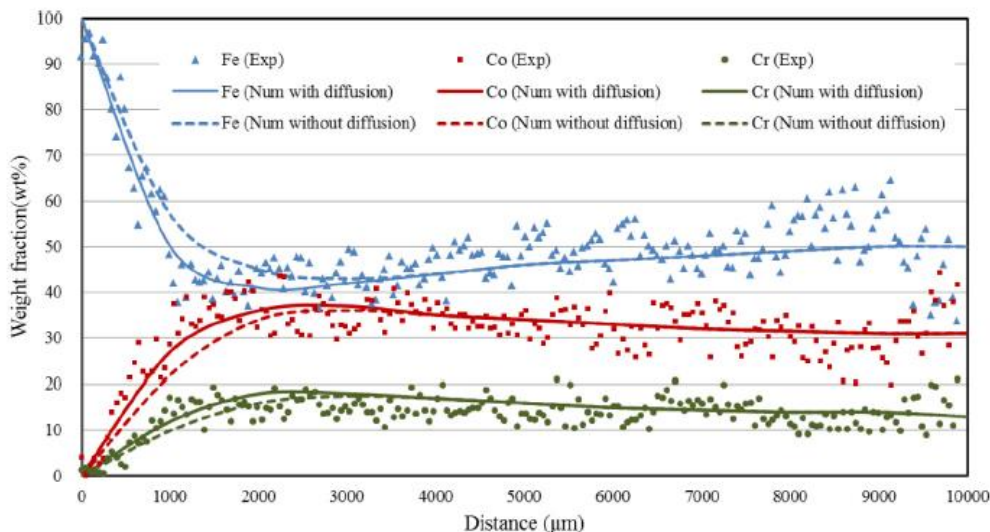


√ 不同时刻的Co元素成分分布 (a) 10ms(b)300ms(c)500ms(d)700ms

多组分传质



纵截面的多组分成分分布



扫描方向上合金元素浓度

- ✓ Fe的传质速率最大
- ✓ 扩散仅初始阶段起作用
- ✓ 熔池底部未混合区

谢谢！