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# An integrated model for dendrite growth simulation in selective laser melting

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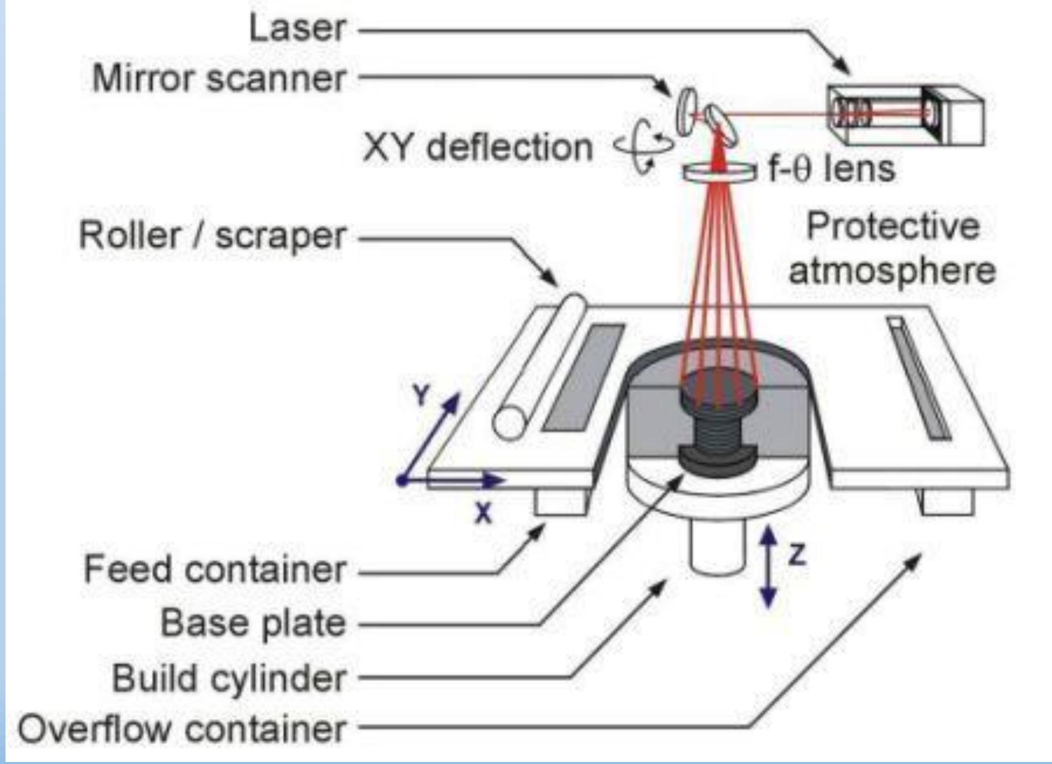
# OUTLINE

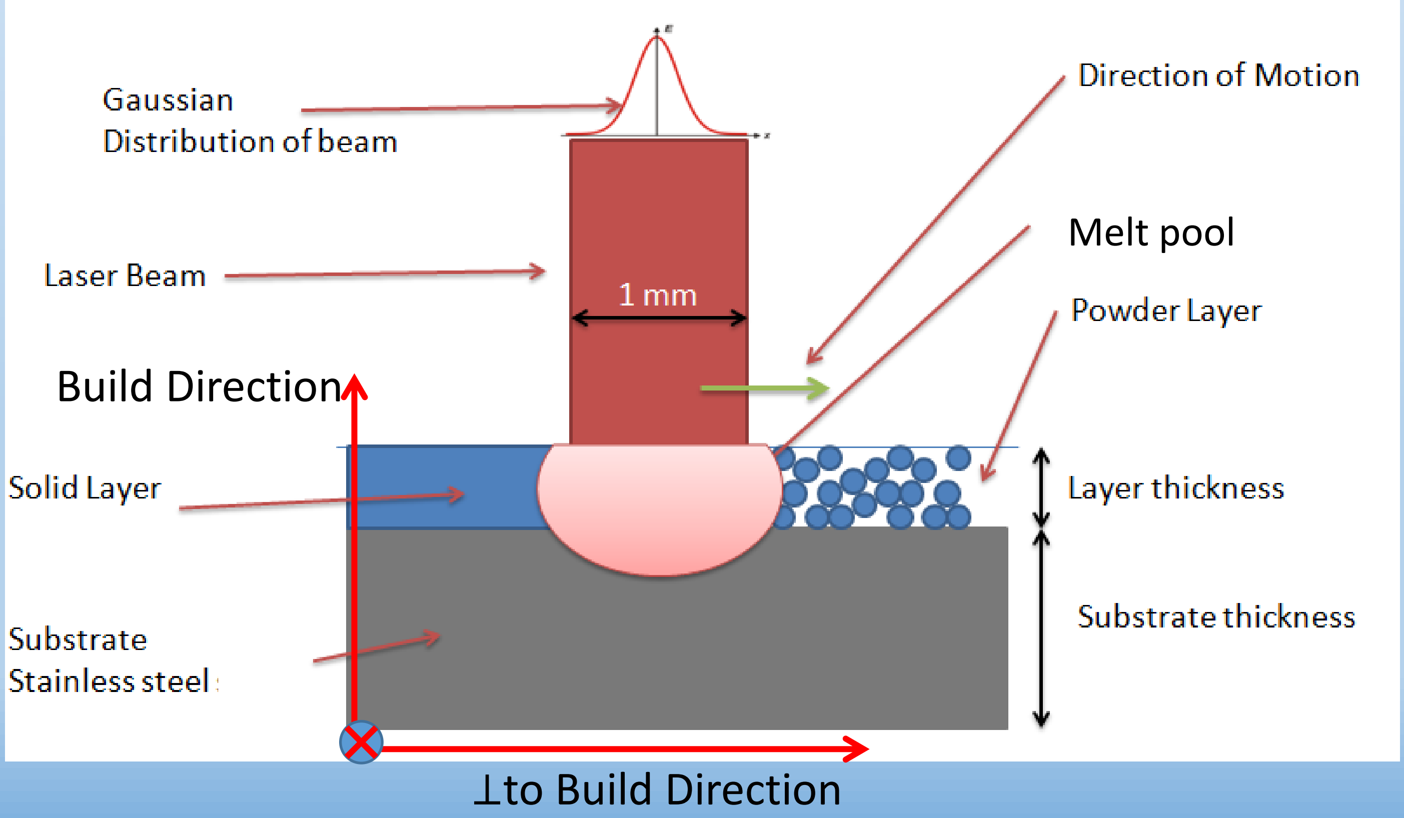
- Background and objective
- Model description
- Model validation with literature
- Conclusion



# Selective Laser Melting (SLM)

- Selective laser melting is an **additive manufacturing** process that uses a high-power laser beam, to create three-dimensional metal parts by fusing fine metal powders together.




http://sine.ni.com/cs/app/doc/p/id/cs-13103

# Rapid Cooling Rate and Dendrite Formation

- Reported cooling rate (steel)

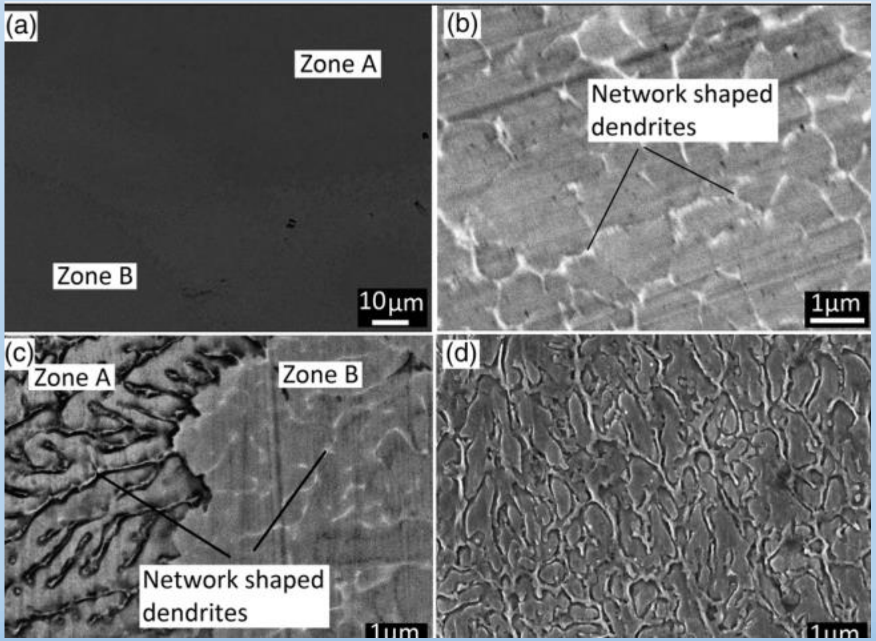
SLM: up to 40,000K/s

Water quench: 130K/s

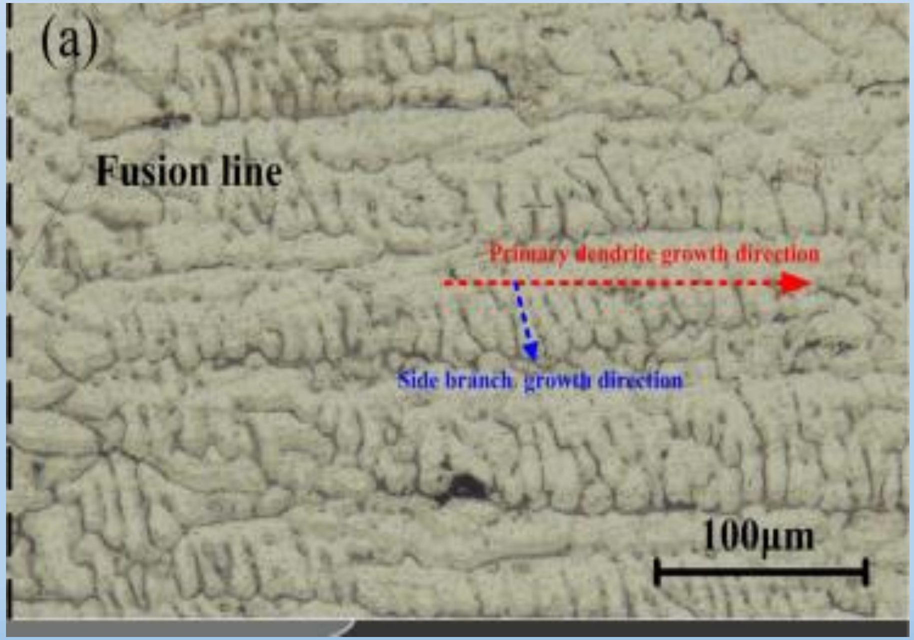
Benyounis, K. Y., Fakron, O. M., & Abboud, J. H. (2009). Rapid solidification of M 2 high-speed steel by laser melting. *Materials & Design*, *30*(3), 674-678.

Dhua, S. K., Mukerjee, D., & Sarma, D. S. (2003). Effect of cooling rate on the As-quenched microstructure and mechanical properties of HSLA-100 steel plates. *Metallurgical and Materials Transactions A*, *34*(11), 2493-2504.

- Dendrite is commonly observed for different materials under high cooling rate




M2
High speed steel




2A14
Aluminum alloy

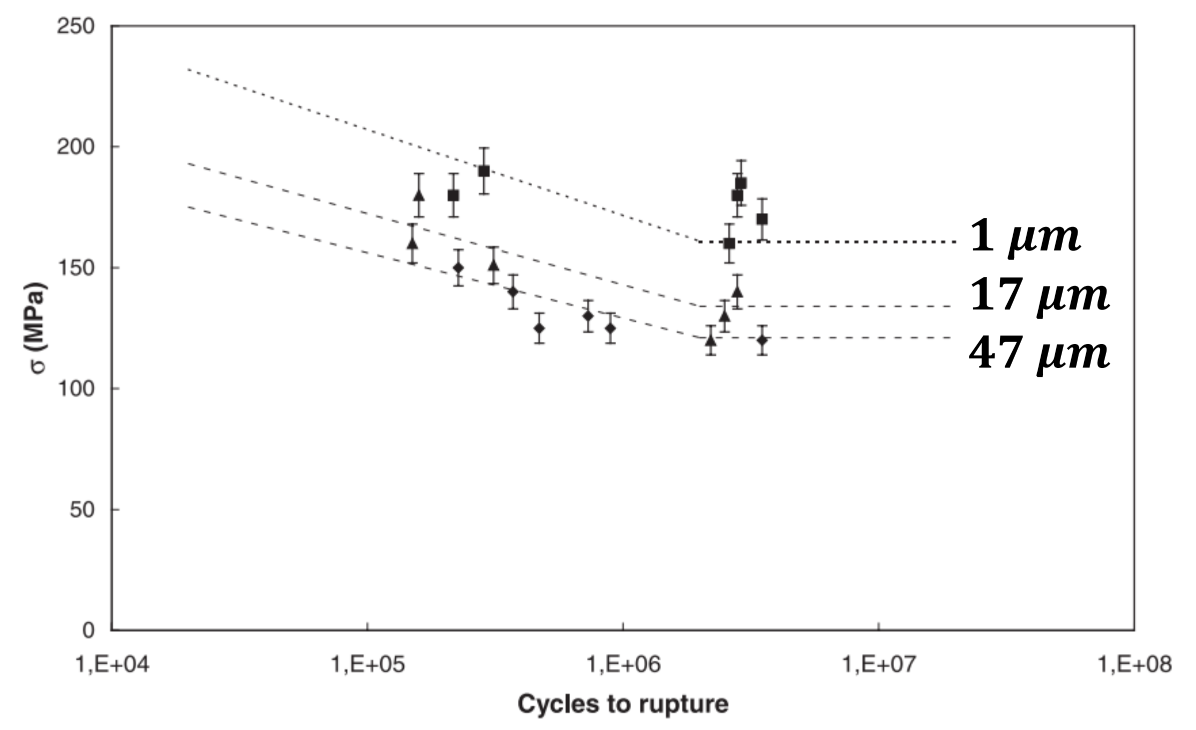
Liu, Z. H., Zhang, D. Q., Chua, C. K., & Leong, K. F. (2013). Crystal structure analysis of M2 high speed steel parts produced by selective laser melting.*Materials Characterization*, *84*, 72-80.

Zheng, W. J., et al. "Phase field investigation of dendrite growth in the welding pool of aluminum alloy 2A14 under transient conditions." *Computational Materials Science* 82 (2014): 525-530.

# IMPORTANCE OF GRAIN SIMULATION

- Grain morphology will influence mechanical properties
  - E.g. Material with smaller grain size → higher yield strength and higher fatigue strength

Hall-Petch Relationship : $\sigma_{ys} = \sigma_0 + \frac{k_y}{\sqrt{d}}$




S-N Curves for AISI 304 stainless steel

Model the grain evolution

↓

Generates optimal cooling conditions and SLM parameters

↓

Control of the mechanical properties

Di Schino, A., & Kenny, J. M. (2003). Grain size dependence of the fatigue behaviour of a ultrafine-grained AISI 304 stainless steel. *Materials Letters*,*57*(21), 3182-3185.



# INTEGRATED MODEL FOR GRAIN EVOLUTION SIMULATION

1. Thermal model: obtain temperature profile and cooling rate

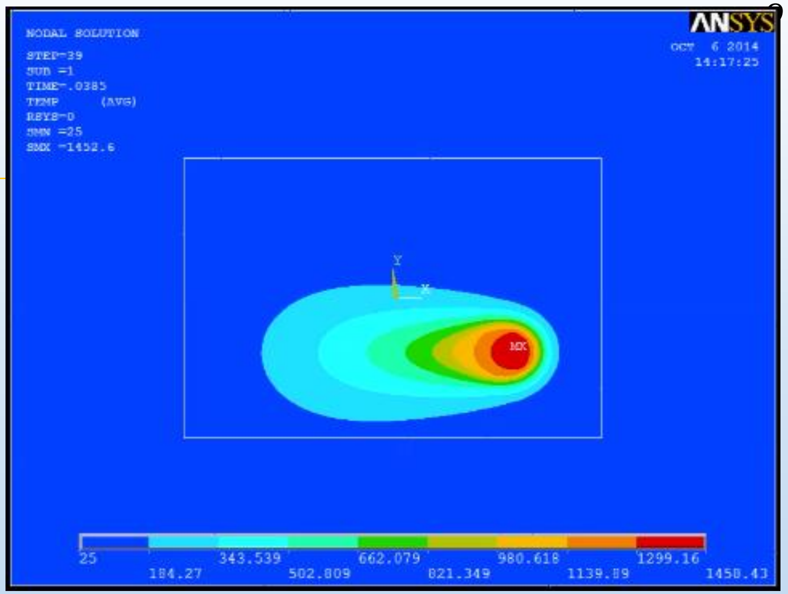
2. Nucleation model: generates grain nuclei

3. Growth model: simulate the growth of nuclei and hence the final microstructure

# 1. THERMAL MODEL

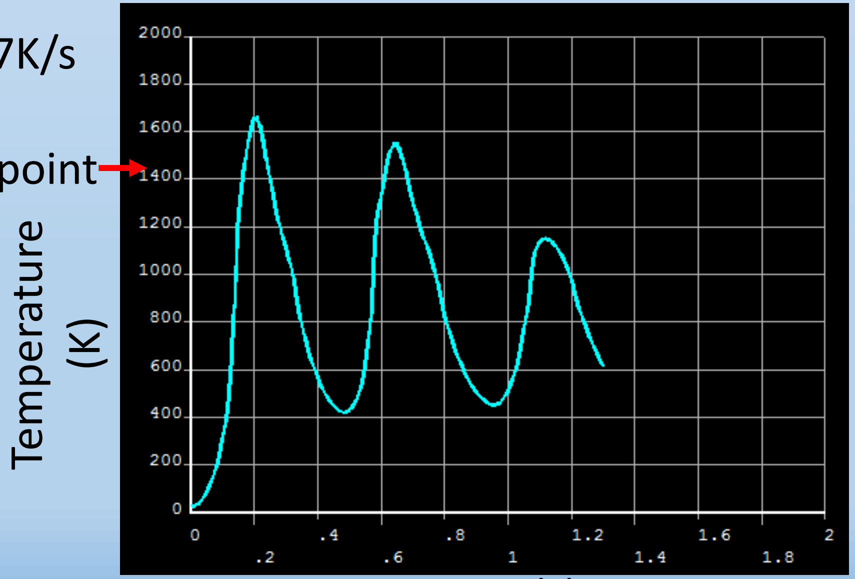
- ANSYS Finite Element Method

Material: stainless steel
Dimension: Substrate:50mm(L)X50mm(W)X60mm(H)
Powder: 0.1mm thickness
Mesh size: Substrate: 5mm
Powder: 0.02mmSpeed: 1cm/s
Spacing: 5mm
Time step: 0.01s
Power :100W

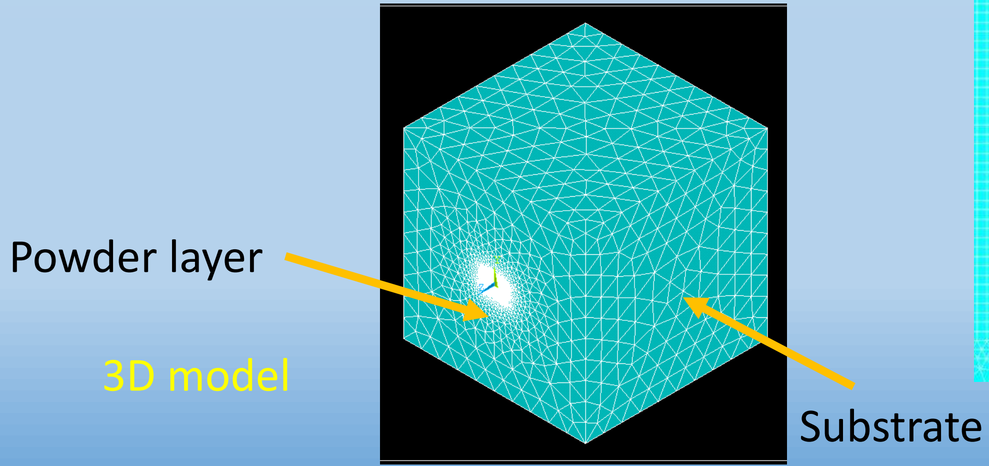



Temperature field at 0.04s

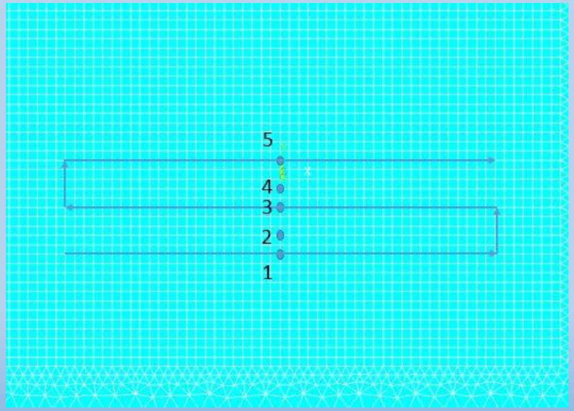
Cooling rate:5987K/s




Temperature vs Time curve

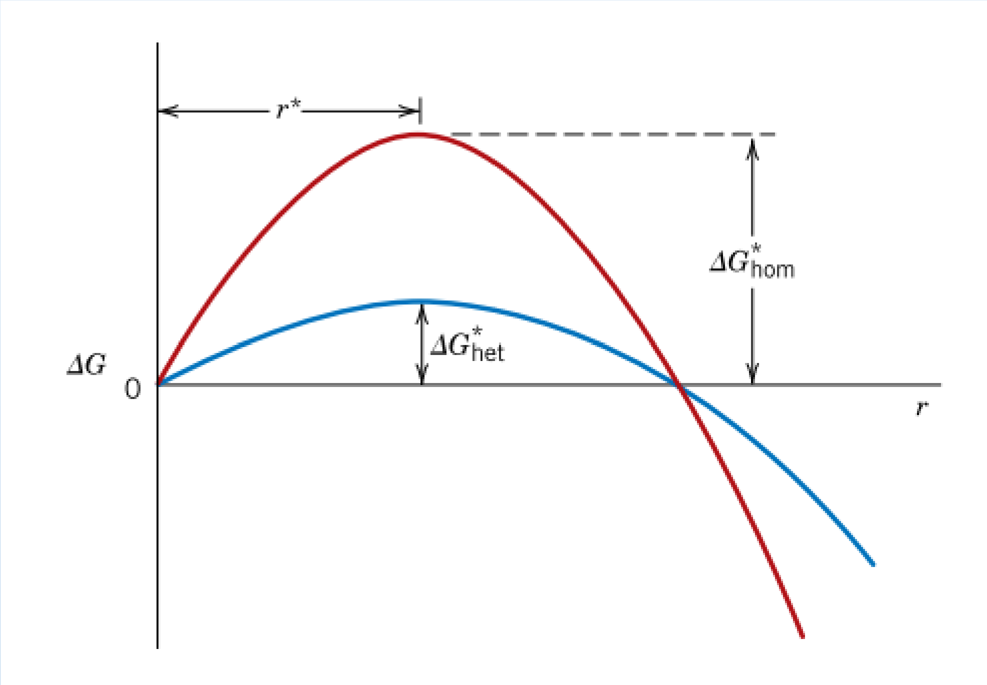



3D model

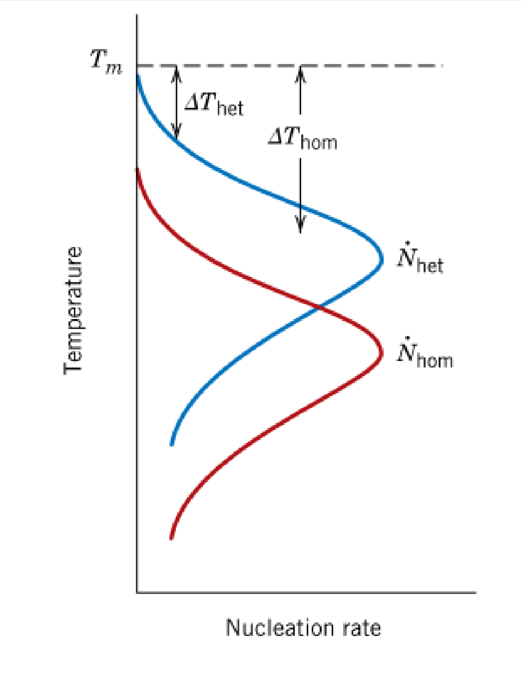



Scanning path

# 2.TEMPERATURE DEPENDENT NUCLEATION MODEL




Free energy of heterogeneous nucleation and homogenous nucleation




Relation of nucleation rate and temperature

Heterogeneous nucleation is easier to form than homogeneous nucleation

Nucleation rate

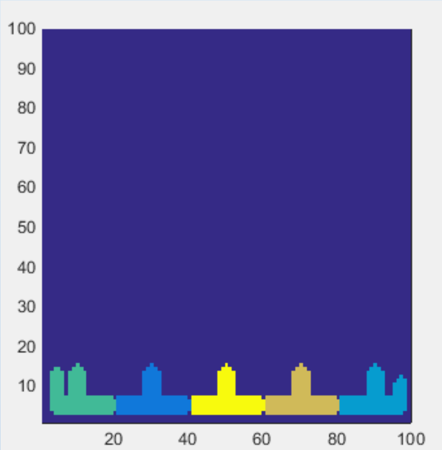
$$\dot{N} = K_3 n^* v_d = K_1 K_2 K_3 \left[\exp\left(-\frac{\Delta G^*}{kT}\right)\exp\left(-\frac{Q_d}{kT}\right)\right]$$

Callister, W. D., & Rethwisch, D. G. (2007). *Materials science and engineering: an introduction* (Vol. 7, pp. 665-715). New York: Wiley.

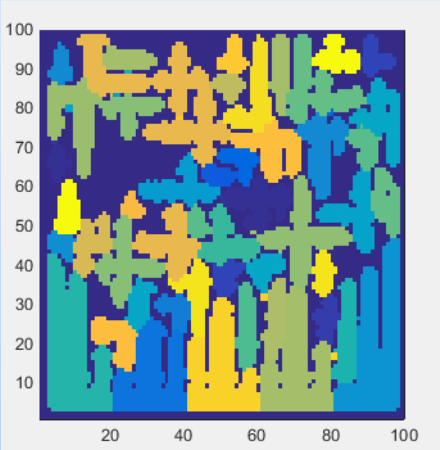
# 2. Nucleation model simulation example

## Simulation result

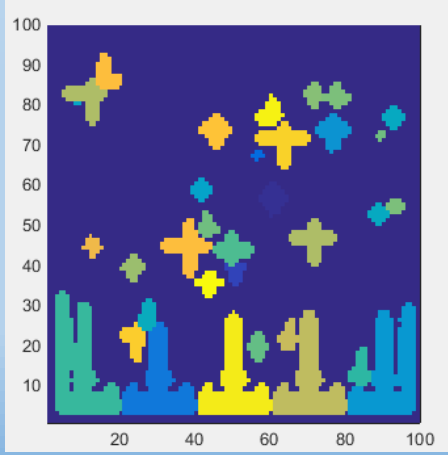
(1)



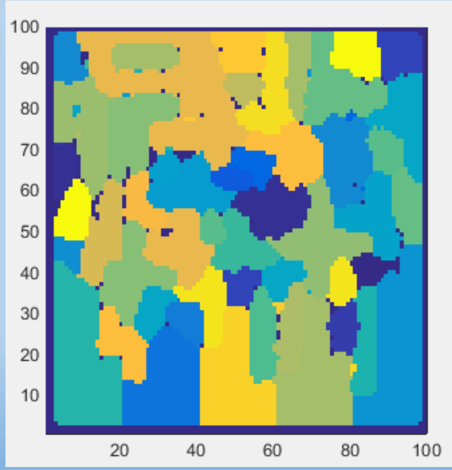
(3)



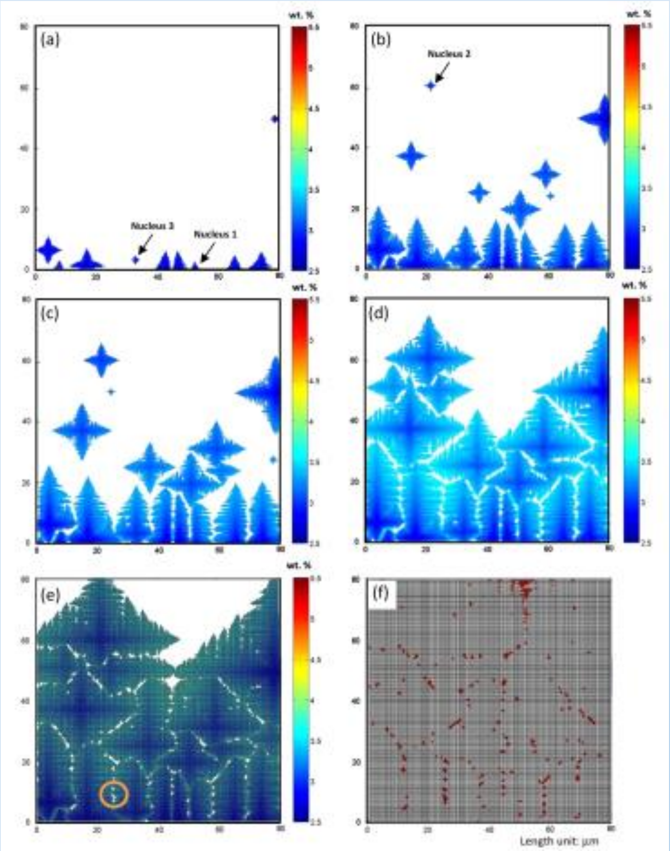
(2)



(4)



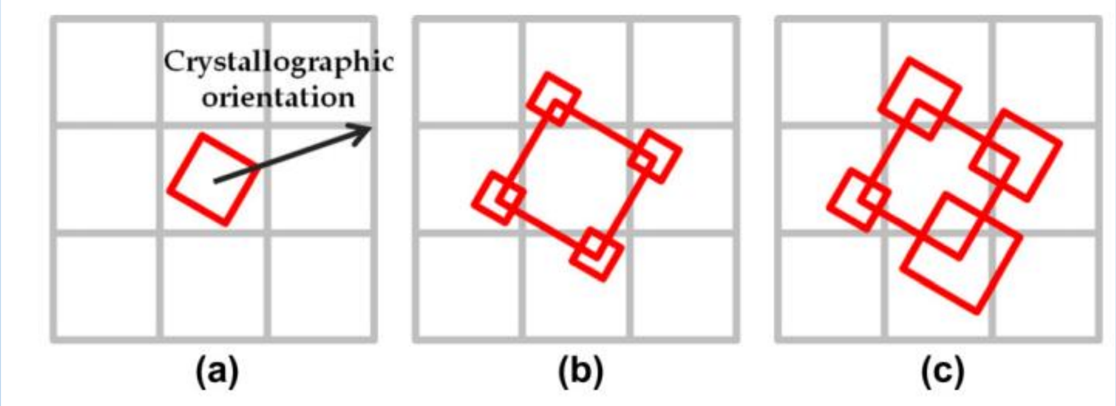
## Bechmark result



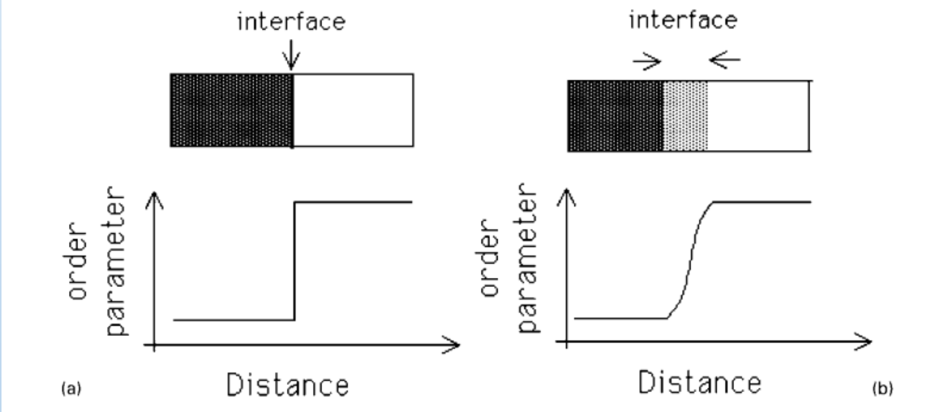

Nie P, Ojo OA, Li ZG (2014) Numerical modeling of microstructure evolution during laser additive manufacturing of a nickel-based superalloy. Acta Mater 77:85–95

# 3. Dendrite growth model

## Cellular Automata model + Phase Feld model =CAPF model




Cellular Automata algorithm




Sharp transition | Smooth transition

Phase field boundary

| | Cellular Automata | Phase field |
|---|---|---|
| Speed | Fast | Slow |
| Accuracy | Low | High |
| Computational cost | Low | High |

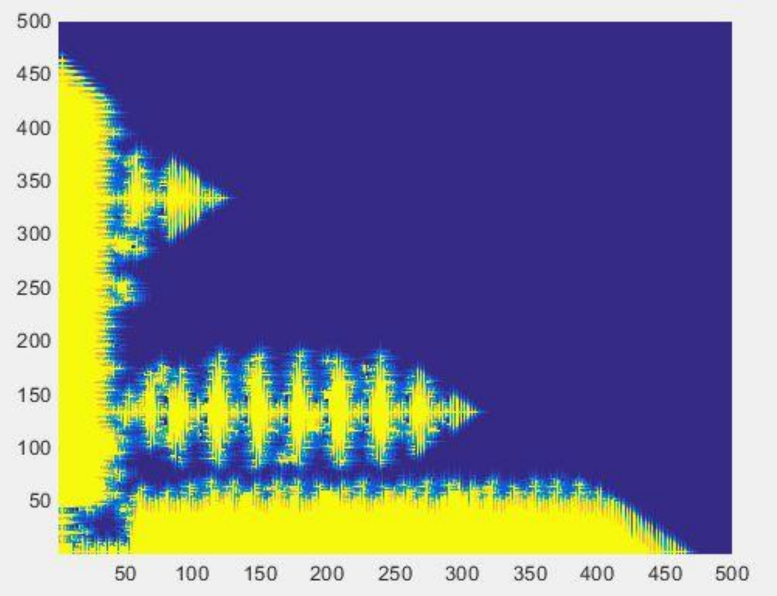

Tan, W., Bailey, N. S., & Shin, Y. C. (2011). A novel integrated model combining Cellular Automata and Phase Field methods for microstructure evolution during solidification of multi-component and multi-phase alloys.*Computational Materials Science*, *50*(9), 2573-2585.

Qin, R. S., & Bhadeshia, H. K. (2010). Phase field method. *Materials science and technology*, *26*(7), 803-811.

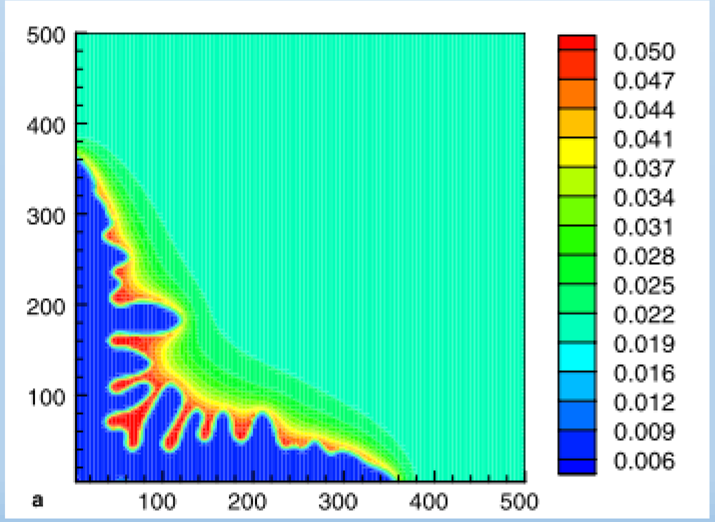



# 3. DENDRITE SIMULATION

| | Benchmarking | Ours |
|---|---|---|
| Material | Al-2at.%Cu-3.5at.%Mg alloy | |
| Grid size | $10^{-8}$ m | |
| Time step | $2x10^{-9}$ s | |
| Temperature | 900K | |
| Domain size | 500x500grid | |
| Total time | $6x10^{-5}$ s(30000step) | |
| Computational time | N/A | 10h |
| Grain size | 360 grids | 460 grids (27%more) |




Simulation result




Benchmark Result

Zhang, R., Jing, T., Jie, W., & Liu, B. (2006). Phase-field simulation of solidification in multicomponent alloys coupled with thermodynamic and diffusion mobility databases. *Acta materialia*, *54*(8), 2235-2239.

# CONCLUSION

- The integrated grain growth model, consisting 3 sub-models of Thermal model, nucleation model, dendrite growth model is promising in predicting grain evolution during the SLM process.
- Each of the sub-model is confirmed against results presented in the benchmarking model.
- Validation with our own 3D-printing experiment is in progress.



# THANK YOU

# Q&A