Modeling of Microstructure Evolution During LENS™ Deposition

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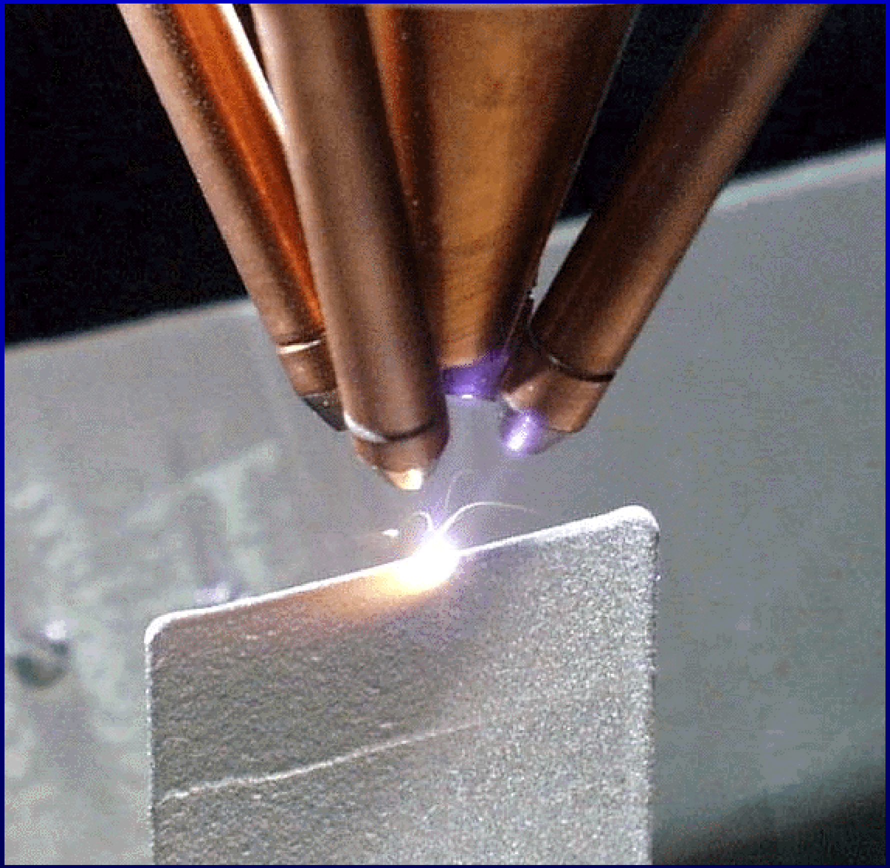
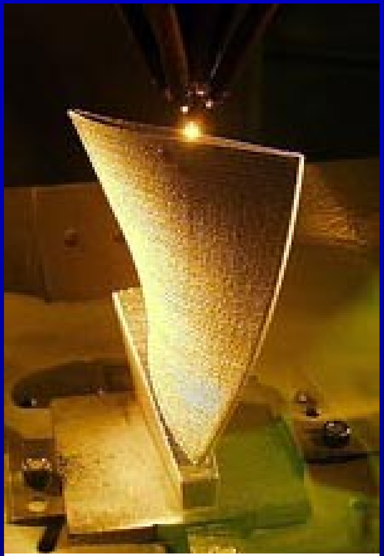


Laser Engineered Net Shaping (LENS)

Introduction

- A variety of materials can be used:
  - Steel Materials (4140, SS410, SS316)
  - Ti-based alloy (Ti-6Al-4V)
  - Inconel, copper, aluminum, etc.
- Application:
  - Aerospace repair & overhaul
  - Rapid prototyping and 3D structure fabrication
  - Product development for aerospace, defense, and medical markets, etc.
- Advantages:
  - Low cost & time saving
  - Enhanced design flexibility and automation
  - Highly localized heat-affected zone (HAZ)
  - Superior material properties (strength and ductility)



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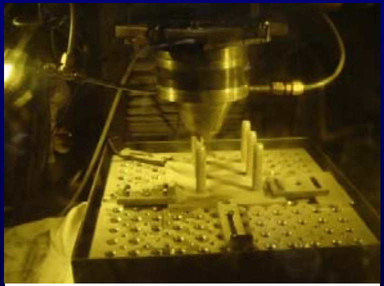


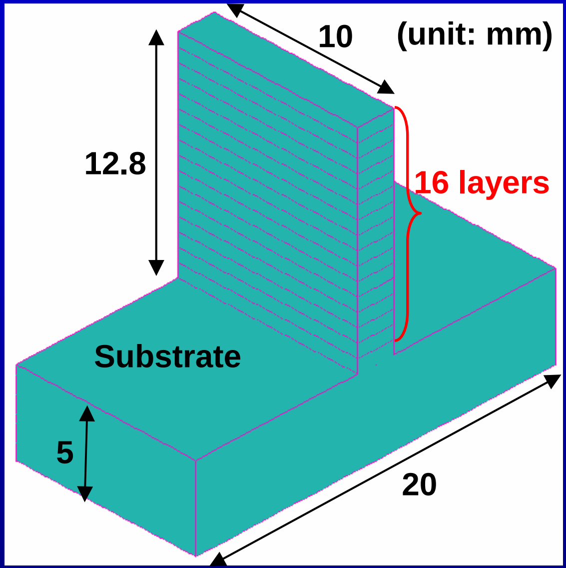
Processing Bar

Objectives

- Develop a 3-D thermal-metallurgical model to simulate 16-pass single build plate LENS deposition of 4140 steel powder with SYSWELD finite element code.
- Predict the thermal profiles, phase transformation, and hardness in the deposited part, and compared with experimental data
- Investigate the effect of the thermal cycles on the phase transformation and consequent hardness.

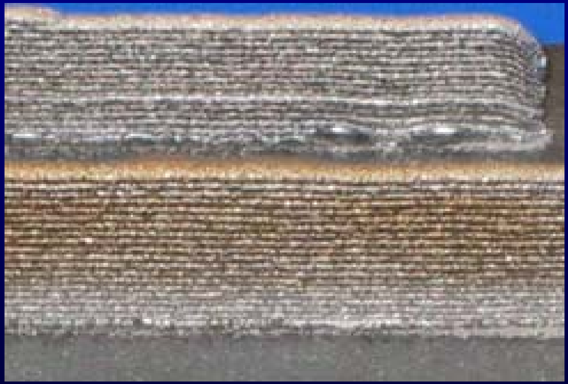
Geometry & Process Parameters

Process parameters	Values
Width of the part	2.0mm
Thickness for each layer	0.8mm
Laser beam travel velocity	8.5mm/s
Moving time of the laser beam for each pass	1.18s
Idle time of consecutive layers deposition	0.32s
Time to finish one layer	1.5s
Total time to finish the part	24s



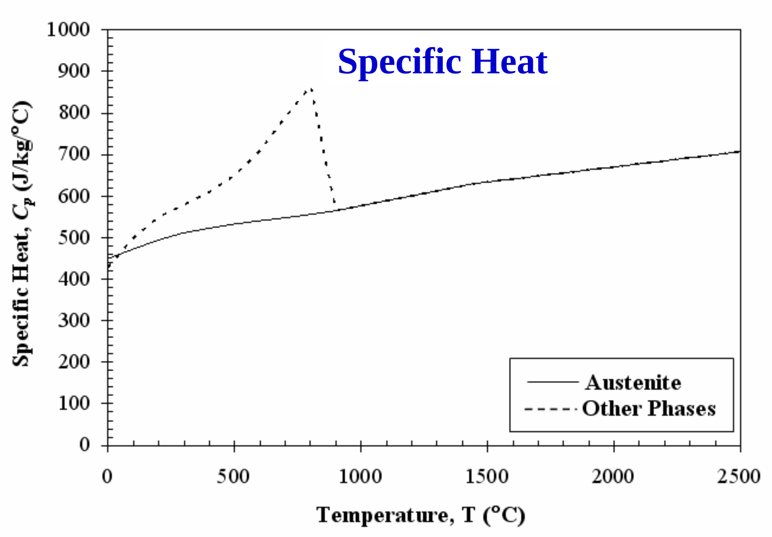
Chemical composition of 4140 steel (wt%)

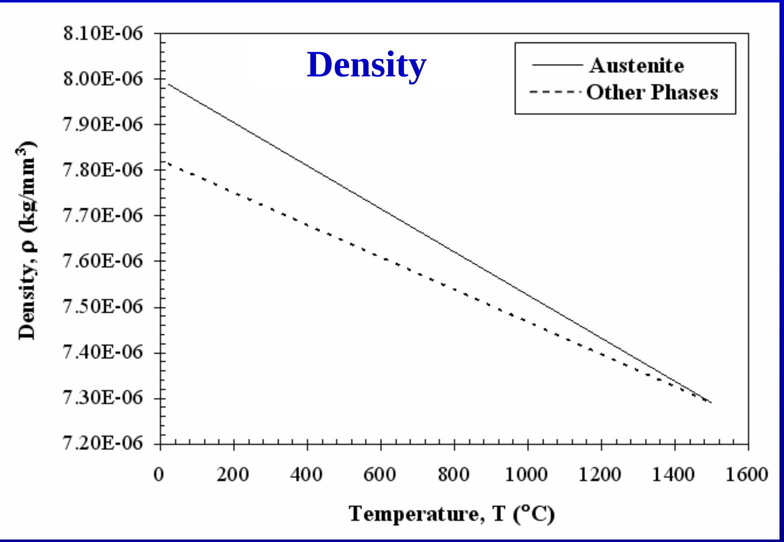
C	Si	Mn	Cr	Mo	P	S
0.38/0.43	0.15/0.30	0.75/1.0	0.8/1.1	0.15/0.35	<0.035	<0.04

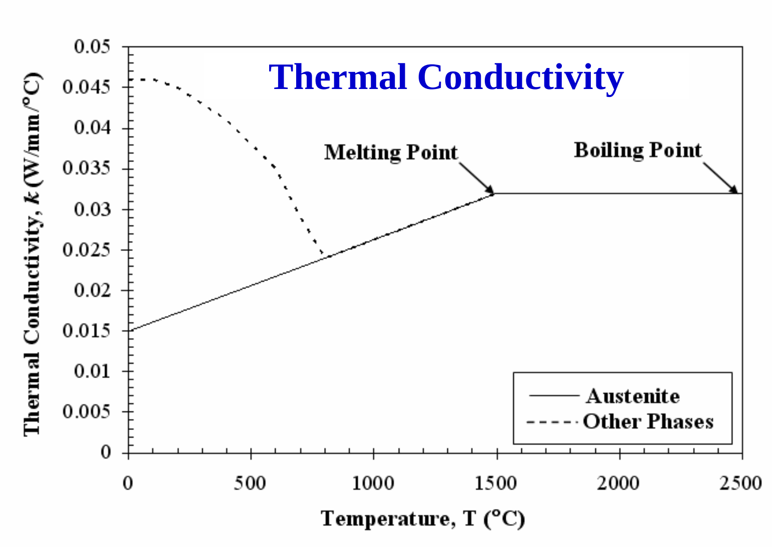


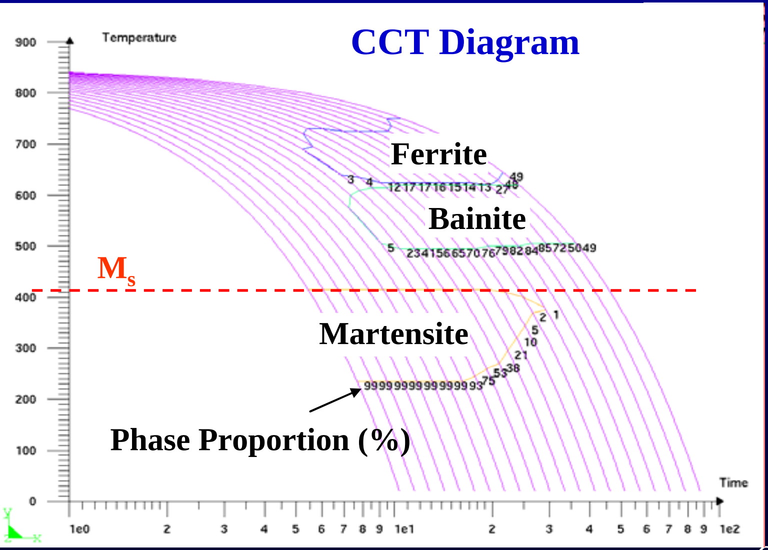
- Weld direction: Same direction for each pass
- Both the deposited part and the substrate are 4140 steel

Thermal Properties (4140)









Thermal-Metallurgical Model

- Modified heat conduction equation:

$$\left(\sum_i f_i(\rho C)_i\right)\frac{\partial T}{\partial t}-\nabla\left(\left(\sum_i f_i\lambda_i\right)\nabla T\right)+\sum_{i<j} L_{ij}(T)\cdot A_{ij}=Q$$

f - phase proportion

T - temperature

t - time

i, j - phase indexes

$L_{ij}(T)$ - latent heat of $i \to j$ transformation

A_{ij} - proportion of phase *i* transformed to *j* in time unit

ρ - mass density

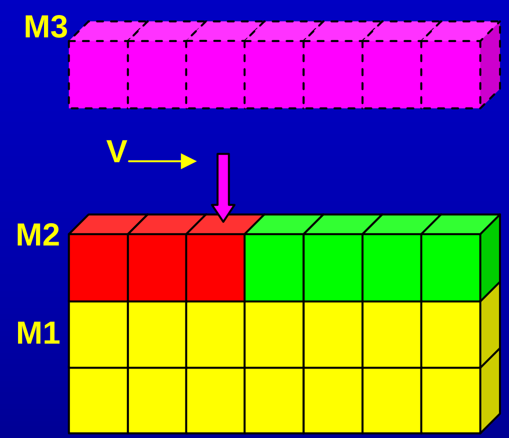
C - specific heat

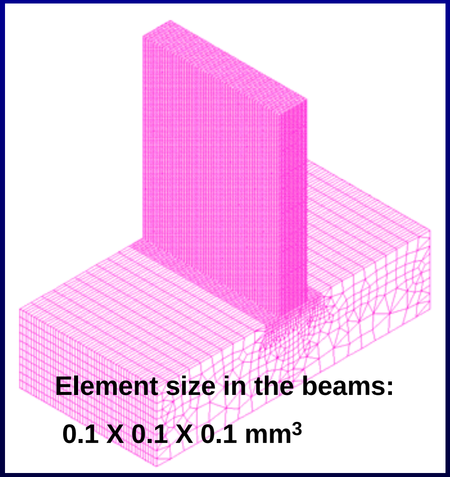
λ - thermal conductivity

Q - heat source

Element Activation Technique

- Dummy material method is applied to the element activation:
  - M1: Deposited layers + substrate
    - Material with actual thermal properties and phase transformation
  - M2: Layer being deposited
    - Material with actual thermal properties and starting with dummy phase
    - Dummy phase → Austenite phase ($T>T_{aus}$)
  - M3: Layers to be deposited
    - Material with dummy low thermal properties and without phase transformation





- Fixed mesh is used for the plate and substrate.

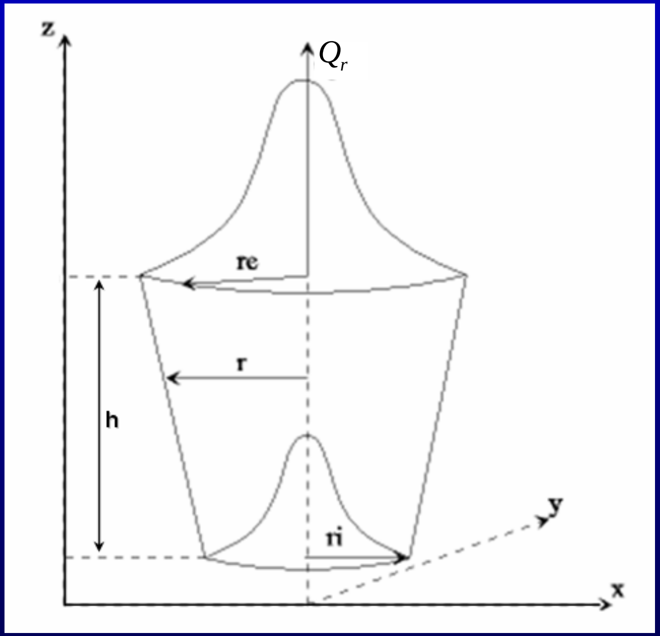
Heat Source

- 3D Conical Gaussian Function

$$Q_r = \frac{2P}{\pi r_0^2 h}\left(1-\frac{z}{h}\right)\exp\left(1-\left(\frac{r}{r_0}\right)^2\right)$$

$$r_o = r_e - \frac{(r_e - r_i)(h - z)}{h}$$

$$r^2 = (x - x_o)^2 + (y - y_o - v \cdot t)^2$$



Q_r - Input energy density (W/mm³)

P - Absorbed laser power (W)

Initial and Boundary Conditions

- Initial condition

$$T(x, y, z, t = 0) = T_0$$

- Boundary condition on the bottom of the substrate

$$T(x, y, z = 0) = T_0 \quad \text{for} \quad t > 0$$

- Boundary conditions for all other surface

$$k\left(\nabla T \cdot \vec{n}\right)\Big|_{\Omega} = h(T - T_a)\Big|_{\Omega} + \varepsilon\sigma\left(T^4 - T_e^4\right)\Big|_{\Omega} - Q_r\Big|_{\Omega Laser}$$

- As new layers are activated, the surfaces are increased and the boundary conditions are updated.

Model for Phase Transformation

- Evolution equation for austenitic, ferritic-perlitic, and bainitic transformation of steels:

$$\frac{df_j}{dt} = \frac{\bar{f}_{j_{eq}}^{ij}(T) - f_j(T)}{\tau^{ij}(T)}$$

f_j - proportion of phase *j* and $\sum_j f_j = 1$

$\bar{f}_{j_{eq}}^{ij}(T)$ - equilibrium fraction of phase *j* at temperature *T*

$\tau^{ij}(T)$ - characteristic time of the transformation (from *i* to *j*) at temperature *T*

These functions can be obtained by comparison of the prediction provided by the model with experimental results (i.e. CCT diagram).

Martensitic Phase Transformation

- Martensitic transformation by Koistinen-Marburger Law:

$$f_m(T) = f_\gamma(1 - \exp(-0.011(M_s - T))) \quad \text{for} \quad T \le M_s$$

f_γ - phase proportion of austenite before cooling down to Ms

M_s - initial transformation temperature

Hardness Calculation

- **Hardness of ferrite (229 HV)** (Blondeau et al., 1973)

  H_F (HV) = 42 + 223C + 53Si + 30Mn + 12.6Ni + 7Cr + 1Mo + logVr(10 - 19Si + 4Ni + 8Cr +130V)

- **Hardness of bainite (337 HV)** (Blondeau et al., 1973)

  H_B (HV) = -323 +185C + 330 Si + 153Mn + 65Ni + 144Cr + 191Mo + logVr(89+53C- 55Si - 22Mn - 10Ni - 20Cr -33Mo)

- **Hardness of martensite (H_{M0} = 800 HV)** (Miokovic et al., 2006)
- **Hardness of tempered martensite** (Costa et al., 2005)

$$H_M = H_{M0} - A\left\{\int_{t1}^{t2} \exp\left(-\frac{Q}{RT(t)}\right)dt\right\}^m$$

  - t1 is tempered martensite start time (the beginning of the thermal cycle in which martensite is tempered)
  - t2 is the final time when the part cools down to room temperature

Hardness Calculation

- For each thermal cycle
  - If Tmax > Ac3, then complete austenization
  - If Tmax < Ac1, then martensite tempered
- If there are n thermal cycles, the proportion of retained austenite in the final part:

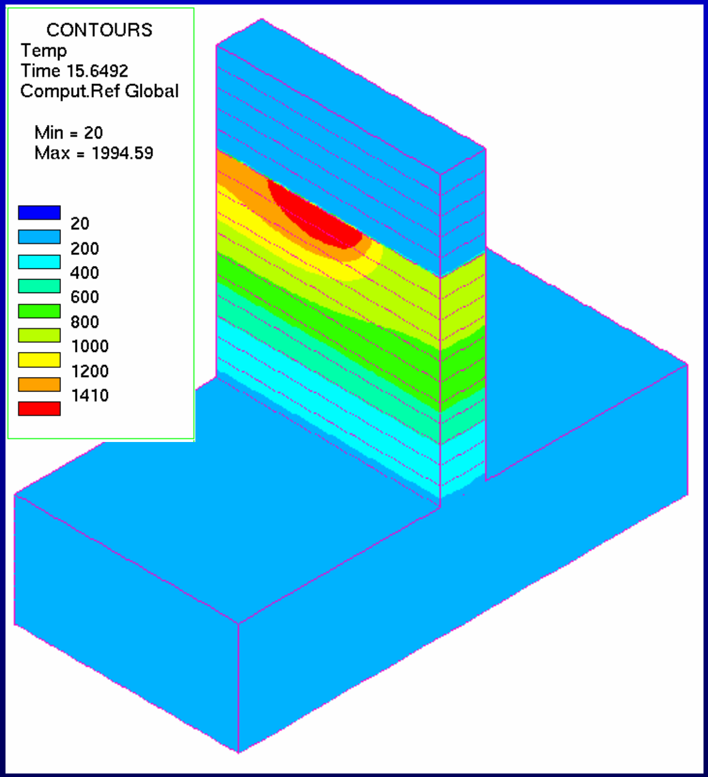
$$f_\gamma = f_{\gamma 0}\eta_1\eta_2\eta_3\ldots\eta_n$$

$$\eta_i = \exp\left(-\frac{(M_S - T)}{90.9}\right) \quad (i = 1,2,\ldots,n)$$

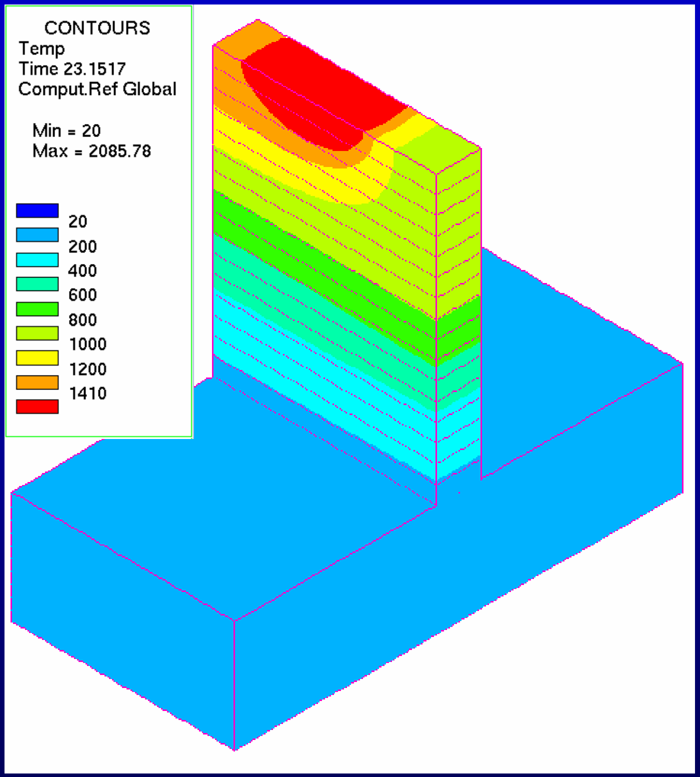
- **Hardness of the material:**

$$H = f_F \cdot H_F + f_B \cdot H_B + f_M \cdot H_M + f_{M0} \cdot H_{M0} + f_\gamma \cdot H_\gamma$$

Temperature Contours

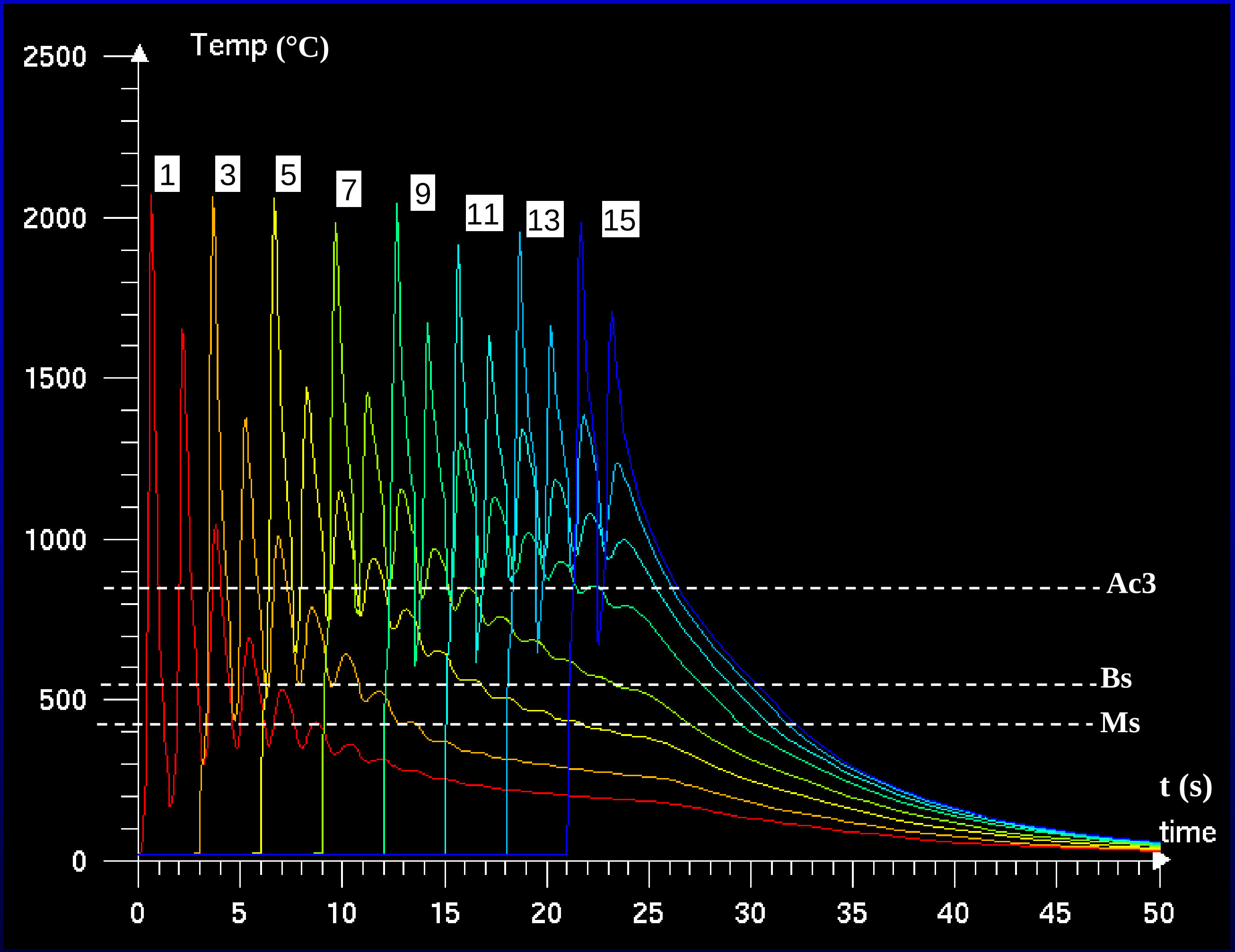


Deposition of 11th layer



Deposition of 16th layer

Thermal Cycles



Temperature profile at the center point of each layer

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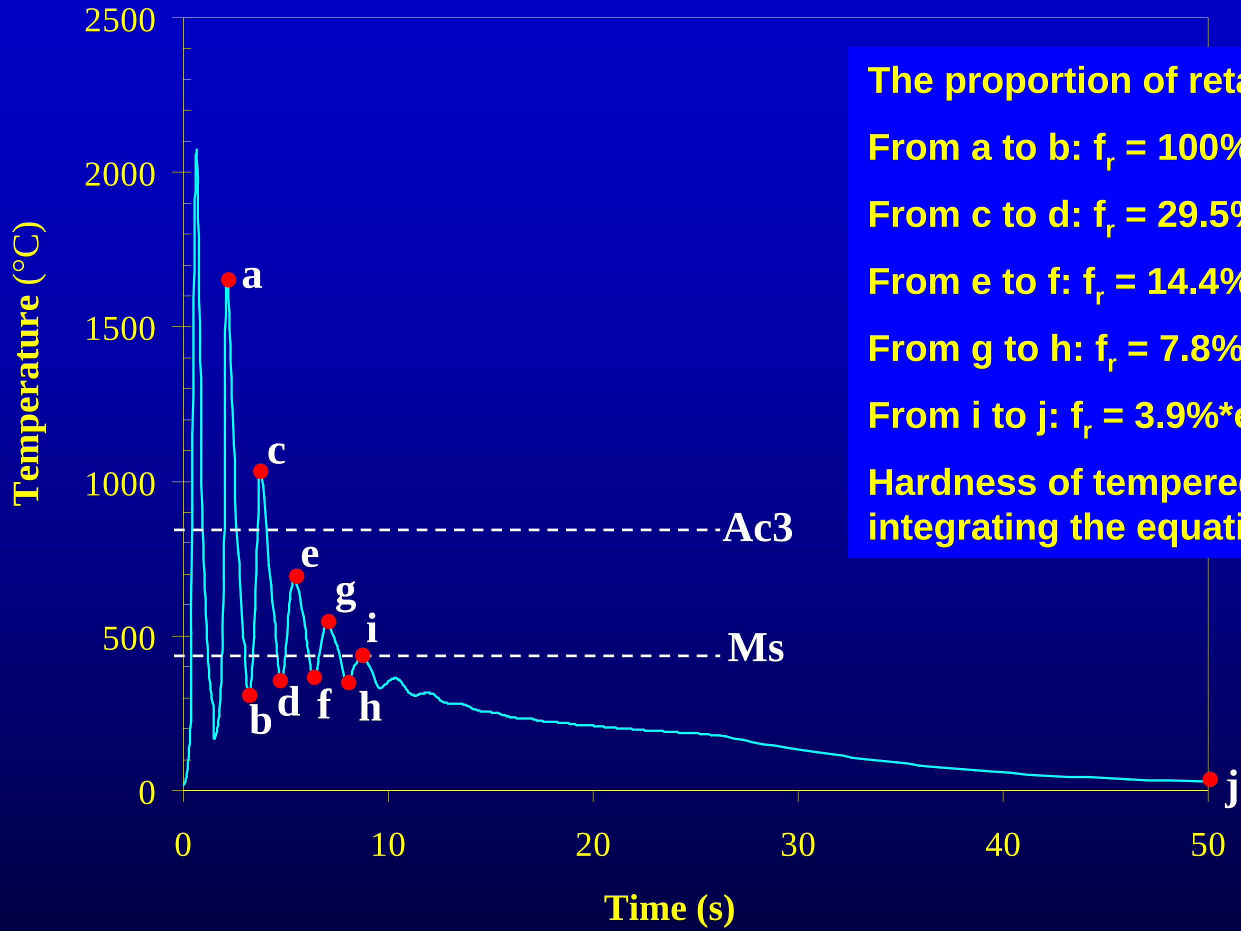
Thermal Cycle (1st layer)



The proportion of retained austenite is:

From a to b: f_r = 100%*exp[-(420-309)/90.9] = 29.5%

From c to d: f_r = 29.5%*exp[-(420-355)/90.9] = 14.4%

From e to f: f_r = 14.4%*exp[-(420-364)/90.9] = 7.8%

From g to h: f_r = 7.8%*exp[-(420-358)/90.9] = 3.9%

From i to j: f_r = 3.9%*exp[-(420-30)/90.9] = 0.0%

Hardness of tempered martensite is calculated by integrating the equation from point b to j.

- **Martensite is completely tempered at the first layer (H_M = 582HV)**

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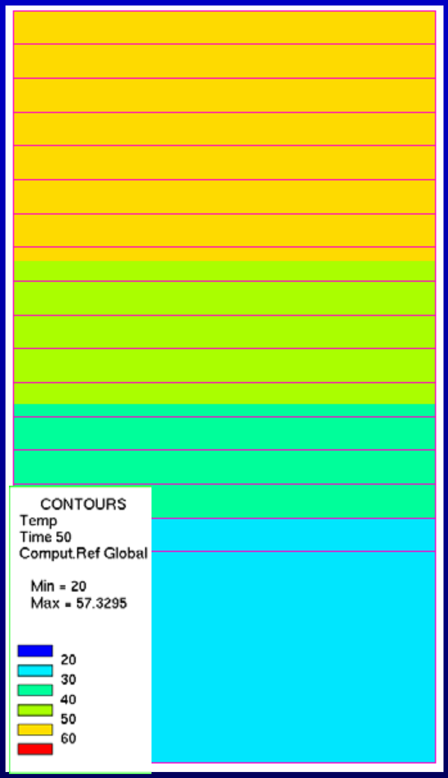
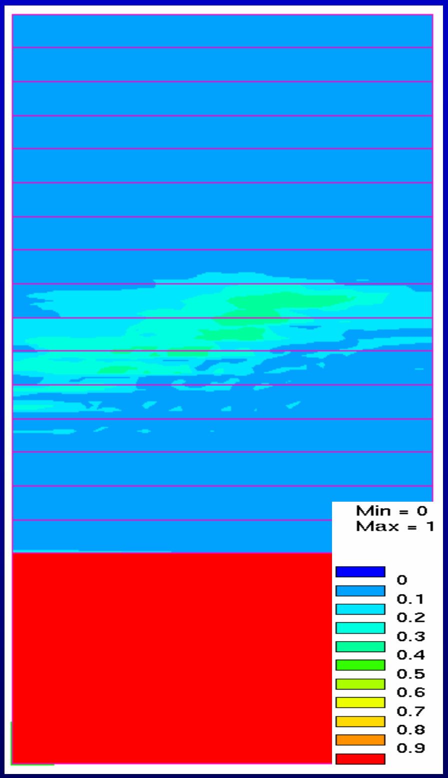
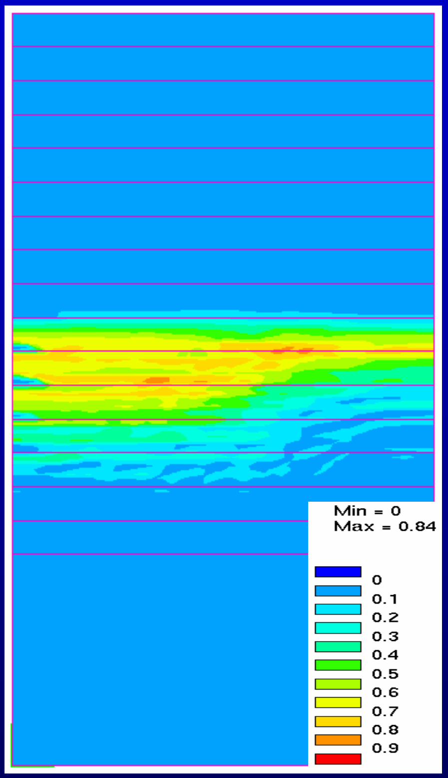
Phase Contours (t=50s)



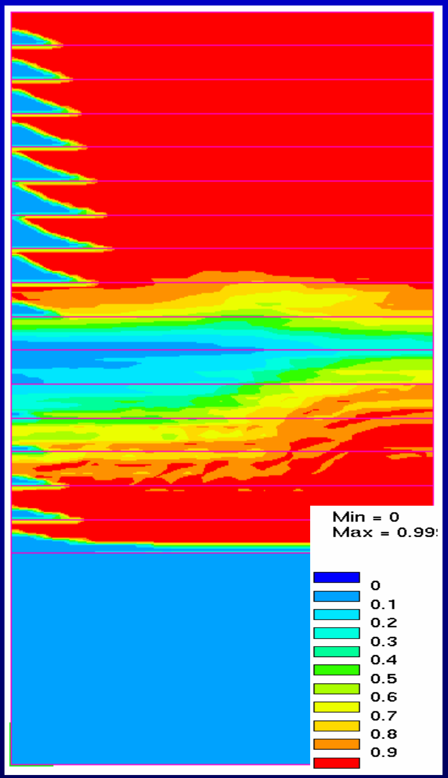
Temperature



Ferrite



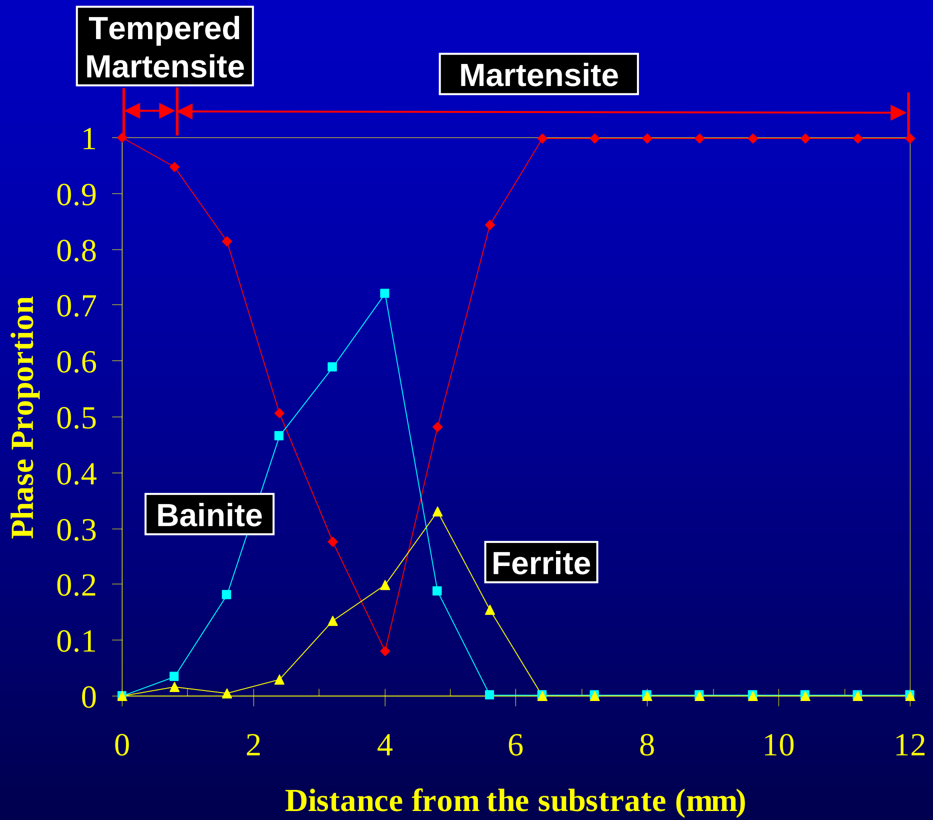
Bainite



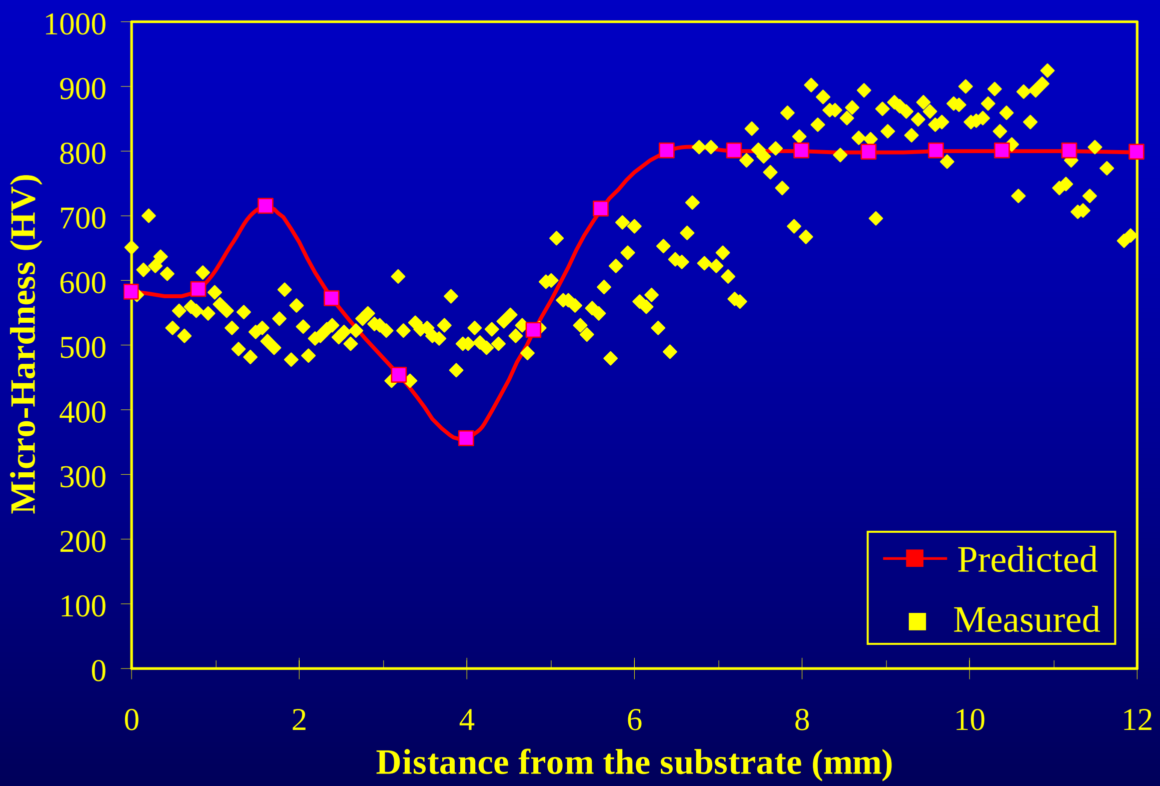
Martensite

Phase Proportions

- The first 2 layers are tempered martensite since the part cools down below the martensite start temperature (Ms) for each thermal cycle
- Starting from the third layer, the part never cools down to Ms and martensite is not tempered once it forms
- From the 3rd to 7th layers, bainite forms due to the slow cooling rate, then martenite forms afterwards with increasing cooling rate



Micro-hardness Measurement and Prediction



Conclusion

- 3-D model was developed to predict the thermal cycles, phase transformation, and hardness in LENS deposition process.
- The calculated hardness qualitatively agrees with the measured data
- The microstructure and hardness strongly depends on the thermal history in the deposited part.
- This model has the potential to control the process-property relationships for the component design optimization to meet the product attributes.