Simulation of Laser Powder-bed Fusion Additive Manufacturing Process with the COMSOL Multiphysics® Software

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AM Simulation Module

Microstructure module
- Microstructure composition / Phase fraction
- Grain size distribution
- Porosity / density distribution
- Temperature and melt pool distribution
- Surface roughness distribution
- Residual stress distribution

In-house thermo-mechanical simulation software + COMSOL
- Heat transfer module
- Residual stress module

Performance Module
- Elastic modulus
- Plastic properties, yield stress
- Fracture toughness and fracture stress

Material parameters
- Powder size
- Chemical composition

Process parameters
- Laser scan speed
- Power density

Material thermal and mechanical properties

Experimental results on material properties and mechanical performance

Validation
• The localized heating of powder is modeled by conductive heat transfer

\[ \rho C_p \frac{dT}{dt} = k \nabla^2 T + \varphi \]

• \( T \) is the temperature, \( t \) is time, \( k \) is thermal conductivity, \( \rho \) is the density, \( C_p \) is the specific heat and \( \varphi \) is the heat source term

• The thermal interaction between the domain and surroundings can be represented as

\[ -k \frac{dT}{dn} = -h(T_{amb} - T) + \sigma \varepsilon (T^4 - T_{amb}^4) \]

• \( h \) is the heat transfer coefficient, \( T_{amb} \) is the temperature of the environment, \( \varepsilon \) is the emissivity of the material and \( \sigma \) is the Stefan-Boltzmann constant

\[ q(x, y, z, t) = \frac{6 \sqrt{3} \alpha P}{abc \pi \sqrt{\pi}} e^{-3 \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right)} \]
Dilip. Influence of processing parameters on the evolution of melt pool, porosity, and microstructures in Ti-6Al-4V alloy parts fabricated by selective laser melting.

**Melt Pool Simulation**
AM HEAT TRANSFER MODULE PREPROCESSING

Power = 195.00 W
Laser speed = 1200.00 mm/s
Laser beam radius = 0.000050 m
Ambient Temperature = 293.15 K
Absorptivity = 1.00
Efficiency = 0.50
a = 1.00
b = 1.00
AM Heat Transfer Module

Demonstration of heat transfer module
AM HEAT TRANSFER MODULE POSTPROCESSING

Melt pool half width along scan path (micron):
Average = 63.86.
Median = 64.00.
Standard deviation = 1.27.
Maximum = 66.00.
Minimum = 57.00.

Melt pool depth along scan path (micron):
Average = 63.84.
Median = 64.00.
Standard deviation = 1.25.
Maximum = 66.00.
Minimum = 57.00.

Melt pool depth to width ratio along scan path:
Average = 0.50.
Median = 0.50.
Standard deviation = 0.00.
Maximum = 0.50.
Minimum = 0.49.
Porosity Estimation

- No lack of fusion porosity
- Increase hatch spacing
- Increase layer thickness
- Increase scan speed

Lack of fusion porosity map
Porosity Estimation

\[ \rho = 0.91 + 18.3a - 904a^2 + 7590a^3 \]

\[ a = \frac{P}{vht} \]
Distortion and Residual Stress

- Residual stress built up in Ti–6Al–4V AM components produced by laser cladding process (CLAD) is compared with inherent strain method.
- In the experimental study of Szost et al., 65 layers of approximately 0.85 mm high and 250 mm long of Ti–6Al–4V were deposited on a 250 × 60 × 8 mm baseplate.
- Same geometry has been modeled in COMSOL software. Compressive inherent strain with magnitude equal to the half of the ratio of the yield stress over the modulus of elasticity, at room temperature, have been prescribed in the longitudinal directions.

\[ D_{\text{experimental}} = 3.5 \text{ mm} \]
\[ D_{\text{inherent strain}} = 1.5 \text{ mm} \]
AM Residual Stress Module
Demonstration of residual stress module
## Planned Experiments

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<th>Power (W)</th>
<th>Scan Velocity (mm/s)</th>
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- Hatch Spacing (H) = 140 μm
- Layer Thickness (T) = 30 μm

For each sample:
- In-situ monitoring to obtain melt pool depth, width and length, and temperature history (for tensile sample)
- CT scan of gage section to obtain porosity and size of defects (for tensile sample)
- Surface roughness measurement of gage section (for tensile sample)
- Microstructure analysis: phase fraction of α and β, α lathe size and prior β size (for tensile sample)
- Stress-strain curve (for tensile sample)
- Bridge samples to measure distortion (for bridge sample)
Experiments

On mechanical properties

Tensile properties

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<tr>
<th>Parameter</th>
<th>E (MPa)</th>
<th>σ_Y (MPa)</th>
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<th>σ_f (MPa)</th>
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Microstructure properties

Scan speed -> grain size

Grain size -> UTS, elongation