COMSOL Heat Transfer Simulation for Reliability Estimation of Additive Manufacturing Process

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Oct 6, 2016
Problem:

• Selective laser melting (SLM) is a popular additive manufacturing (AM) process
• Difficult to certify AM part as its final quality can largely vary
• A quantitative computational approach for uncertainty analysis is needed
• Simulation of complete and complex AM processes are hampered by long run-times

Goal:

• Develop a probabilistic physics-based numerical prediction approach to characterize the propagation of uncertainties due to material and process variabilities of SLM into the performance of manufactured components
Proposed Framework

1. Material/Process variability inputs
2. (AM Simulation) Fast Simulation
3. Analytical mechanical performance Calculation
4. Probabilistic Surrogate Modeling
   - Probabilistic Prediction / Uncertainty Quantification
5. Critical Supporting Experiments
6. Validation / Verification
AM Simulation Module

**Material uncertainty**
- Powder size distribution
- Chemical composition

**Process parameters uncertainty**
- Laser scan speed
- Power density

**Input**

**Microstructure module**
- Microstructure evolution modeling
- Thermal history
- Material thermal and mechanical properties

**Porosity / surface roughness module**

**Residual stress module**

**In-house thermo-mechanical simulation software + COMSOL**

**Macro-model**
- Temperature and melt pool distribution
- Roughness distribution

**Meso-model**
- Defect size distribution

**Micro-model**
- Residual stress distribution
- Grain distribution

**Performance Module**
- Mechanical performance module
  - Elastic modulus
  - Plastic properties, yield stress
  - Fracture toughness and fracture stress

**Mechanical performance distribution**: Elastic, plastic, and fracture properties distribution

**Validation**
- Experimental results on material properties and mechanical performance
Surrogate Modeling

Approach:

- We propose to demonstrate use of novel surrogate modeling approach which will provide good approximate answers to predict uncertainty overcoming run-time problems.

- The methodology employs Kriging, which is most suitable for highly parameterized contexts as in AM, and has the advantage of taking into account the nature of the distribution functions of the uncertainties in the data and provides estimates of the uncertainty of the predictions using information in only a few areas/hot spots of the component.

Advantage:

- Fast
- Simple
- Efficient
- Acceptable accuracy
The localized heating of powder is modeled by conductive heat transfer

\[
\rho C_p \frac{dT}{dt} = k_{xx} \frac{d^2T}{dx^2} + k_{yy} \frac{d^2T}{dy^2} + k_{zz} \frac{d^2T}{dz^2} + \varphi
\]

- \( T \) is the temperature, \( t \) is time, \( k_{xx}, k_{yy} \) and \( k_{zz} \) are thermal conductivities, \( \rho \) 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
- Thermal properties of material are dependent on temperature and the porosity of the randomly packed powder bed
• The heat transfer analysis of a single-layer multi-track AM process is modeled with and solved by COMSOL Multiphysics
• The material under consideration is Ti-6Al-4V
• We use COMSOL Livelink with Matlab to read a laser scan path input file and create the motion of the laser source
• COMSOL and Livelink with Matlab for analyzing the large database of temperature history results
Multi-layer Multi-track Simulation

- The heat transfer process is modeled with COMSOL Multiphysics.
- The material under consideration is Ti-6Al-4V.
- We use COMSOL Livelink with Matlab to read a laser scan path input file and create the motion of the laser source.
- The temperature history of the lower layers can affect the heat transfer process of the upper layers.
Monte Carlo Simulation (MCS):
- Sampling based method
- Well known and popular
- Dealing with complex limit states

Kriging method:
- An efficient Surrogate modeling to incorporate measures of error and uncertainty when determining estimations.
- Dealing with computationally demanding models.
- Taking into account the nature of the distribution functions of the uncertainties in the data and provides estimates of the uncertainty of the predictions.
Probability distribution functions were assumed for all random variables and five percent uncertainty was introduced to each parameter.

The training points were generated using the input distributions:

<table>
<thead>
<tr>
<th>Random Variable</th>
<th>Probability Distribution</th>
<th>Mean value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>Normal</td>
<td>120 (W)</td>
<td>6 (W)</td>
</tr>
<tr>
<td>Laser Beam Width</td>
<td>Normal</td>
<td>0.4 (mm)</td>
<td>0.02 (mm)</td>
</tr>
<tr>
<td>Chamber temperature</td>
<td>Normal</td>
<td>293.15 (K)</td>
<td>14.6 (K)</td>
</tr>
</tbody>
</table>
Initial Results

Simple geometry and selected locations

Temperature history – COMSOL results
The temperature history can have significant effects on part’s distortion and residual stresses.

Stresses and strains are induced by thermal loads.

The governing stress equation can be expressed:

$$ \nabla \cdot \sigma + f = 0 $$

$$ \sigma $$ is the stress tensor and $$ f $$ is the internal forces.

Elastic, plastic, and thermal strains are considered.
Concluding Remarks

- A quantitative computational approach for uncertainty analysis
- Combined physics-based and statistical-based modeling framework

- Heat transfer analysis of single- / multi-layer multi-track SLM AM process with COMSOL Multiphysics 5.2
- Monte-Carlo simulations for accessing uncertainty

- Temperature history and distribution useful for predict microstructure and mechanical properties
- Future works include prediction of residual stress for SLM AM process

- Any questions?