Optimal Design and Manufacturing of 3D Printed Metals with Smooth Transitions

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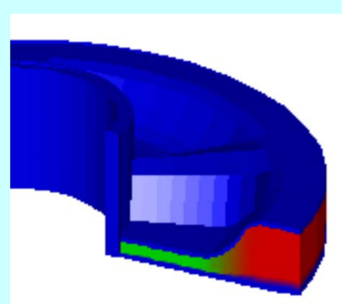
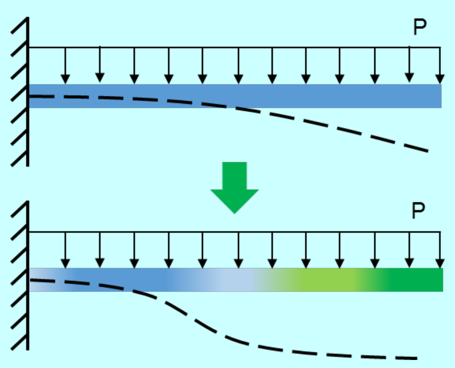
❑ INTRDUCTION and BACKGROUND

Motivation

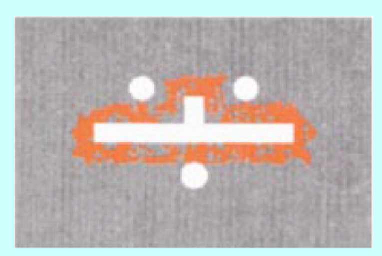
A heterogeneous object refers to an object with spatially distributed different material composition or structures, with smooth transitions between them. The potential application of heterogeneous objects has been demonstrated in different engineering fields.



Heterogeneous flywheel which stores more energy but weighs less



Heterogeneous cantilever beam which can deflect per design



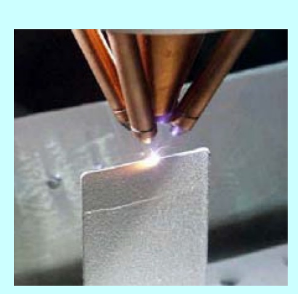
Heterogeneous injection mold to achieve fast and uniform cooling

Advantage of heterogeneous objects with smooth transitions

- Enhancement of the overall physical properties of the object: cost and weight reduction, achieve more than one design objective within a single object;
- Traditional composite materials have high internal stresses between discontinuous types, smooth transitions minimize these internal stresses.

Advantage of 3D printing of metals

- 3D printing minimizes retooling of machines;
- 3D printing allows for creating of complex geometries that would otherwise be impossible to manufacture;
- Laser Engineering Net Shaping (LENS) can vary the deposited material composition as a function of X,Y, and Z coordinates. This variability allows for customization of the composition of an object.



LENS process with powders injecting into the melt pool

Challenges

- Because LENS 3D printing allows for manufacturing of complex shapes with complex internal material compositions, how should these objects be modeled and designed?
- How should the LENS process be controlled to manufacture heterogeneous objects with smooth transitions?
- How does manufacturing process affect optimal object design?

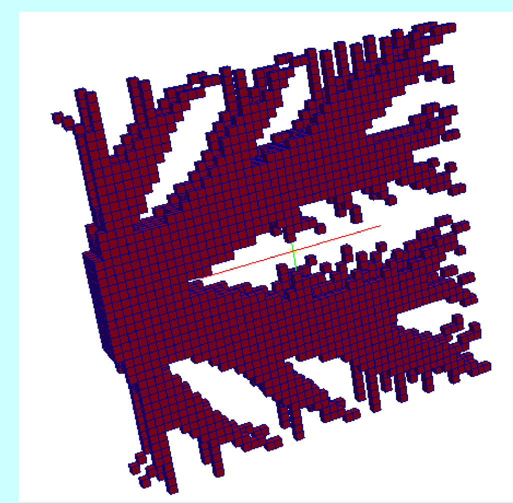
Objectives

- To find the best topology (outer shape and inner geometry) optimization and the material composition within the object in order to meet the design challenges;
- To model the material and outer geometry to allow for optimization;
- To model and optimize the LENS process in heterogeneous object fabrication;
- To control the LENS manufacturing of heterogeneous metal objects with smooth transitions.

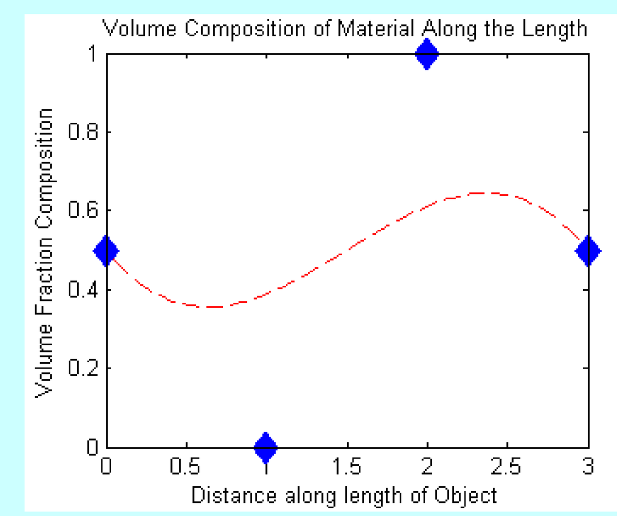
❑ DESIGN and MODELING

Representation

- A Voxel representation or the object geometry allows for topology optimization
- A 3D Bezier curve represents the volume composition of one material within the object



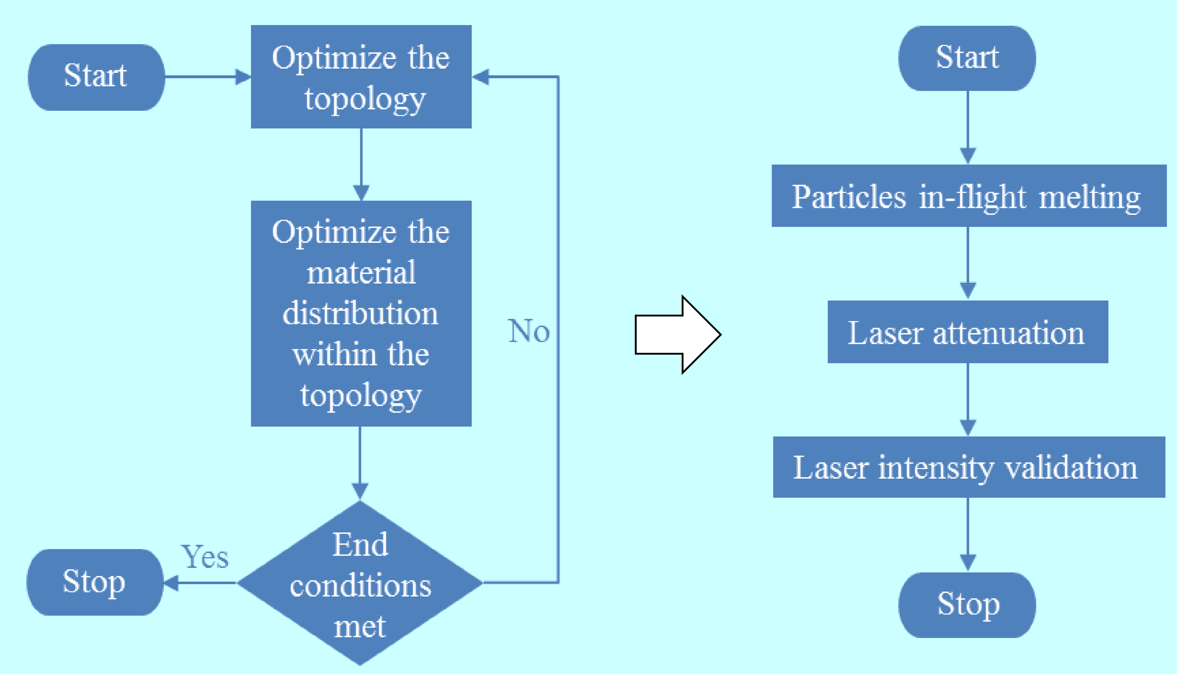
Topology optimization



Material variation

Design method

- For design, a two step iterative optimization process is used;
- A reversed optimization process combining with iterative and bisection method is used for manufacturing.



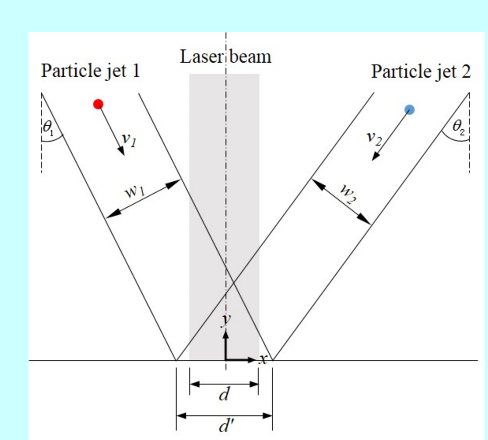
Object optimization

Manufacturing optimization

Governing equations

Particles in-flight melting:

$$m_p c_{pp} \frac{\mathrm{d}T_p}{\mathrm{d}t} = \alpha I \frac{S_p}{4} - hS_p\left(T_p - T_\infty\right) - \varepsilon\sigma S_p\left(T_p^4 - T_\infty^4\right) - \delta L_f \frac{\mathrm{d}m_p}{\mathrm{d}t}$$



Laser attenuation:

$$I = I_0 e^{-\mu y} = I_0 e^{-\varepsilon C(y) y}$$

Substrate heating:

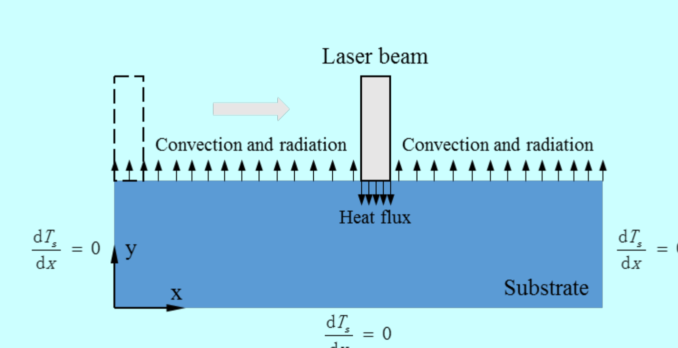
$$\rho_s c_{ps} \frac{\mathrm{d}T_s}{\mathrm{d}t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_s \frac{\partial T_s}{\partial y}\right)$$

Boundary conditions:

$$-k_s \frac{\mathrm{d}T_s}{\mathrm{d}y} = -\alpha I$$

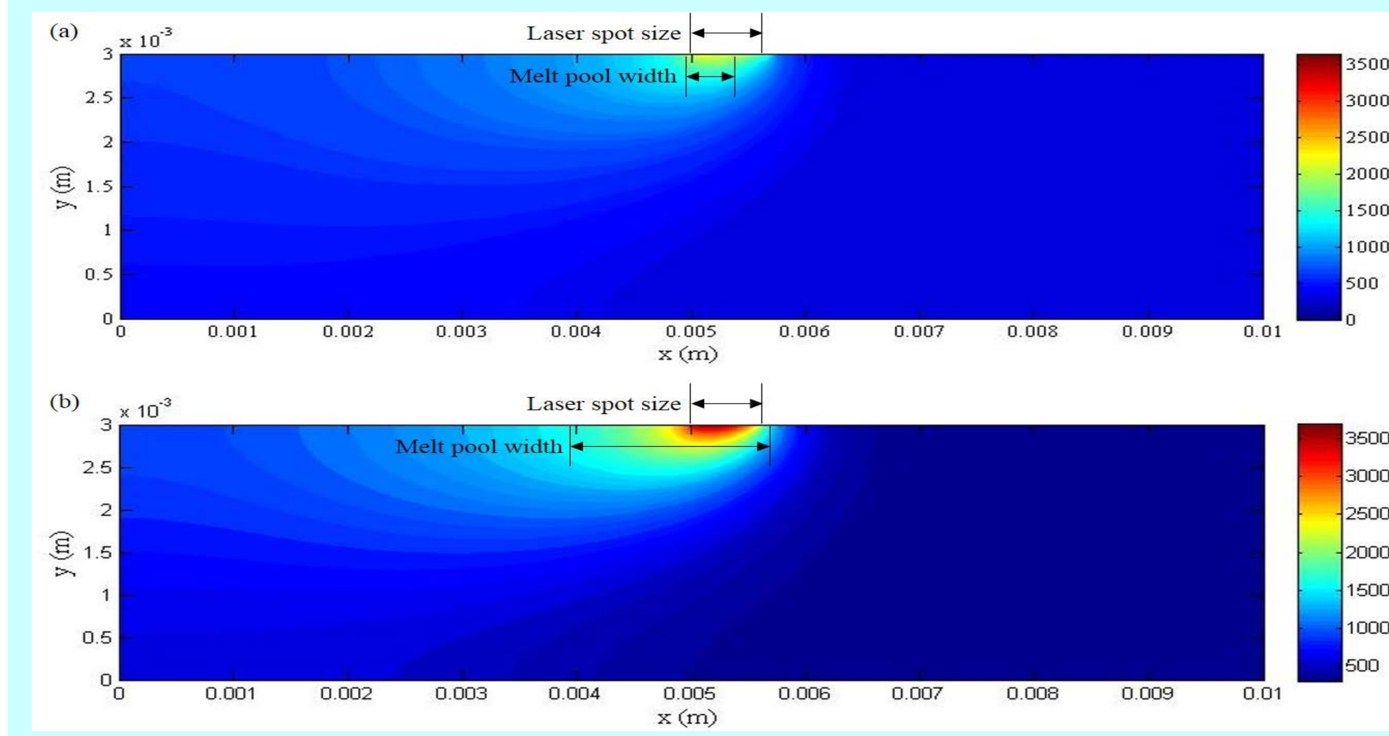
$$-k_s \frac{\mathrm{d}T_s}{\mathrm{d}y} = h\left(T_s - T_\infty\right) + \varepsilon\sigma\left(T_s^4 - T_\infty^4\right)$$

$$-\vec{n}\left(-k_s \frac{\mathrm{d}T_s}{\mathrm{d}\vec{n}}\right) = 0$$



❑ RESULTS and CONCLUSIONS

Substrate temperature distribution (2-D)

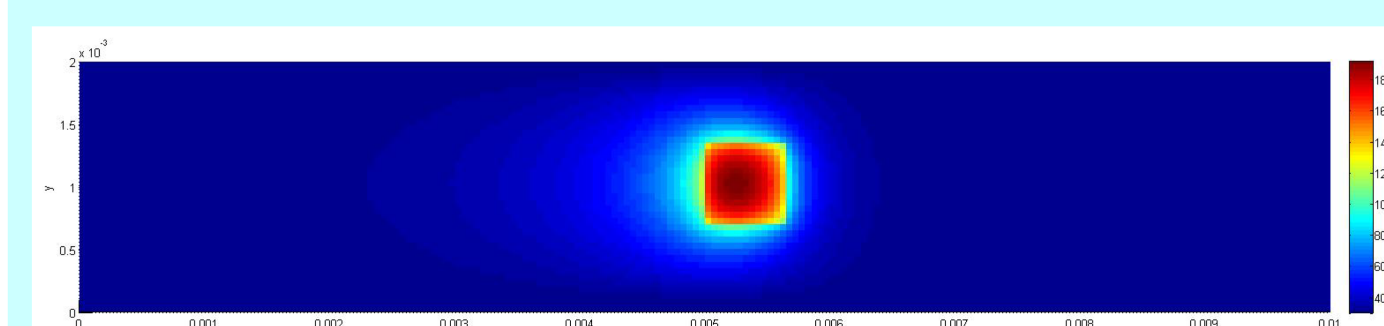


Laser moving at 10 mm/s on Inconel 718, with laser power: (a) 75 W, and (b) 150W

Parameter	Value
Laser parameters	
Laser power, P_l (W)	320
Laser spot radius, r_l (μm)	300
Laser moving velocity, v_l (mm/s)	10
Powder parameters	
Injection angle, θ_i (^{o})	20
Injection velocity, v_i (m/s)	1
Feeding rate, M_{pi} (g/min)	0.5
Particle radius, r_{pi} (μm)	10
Nozzle diameter, w_i (mm)	0.7

Optimized process parameters (materials: Inconel 718 and ceramics)

Substrate surface temperature (3-D)



Top view

Conclusions

- Designing objects with complex shapes and varying internal material compositions allows fully optimal designs that are locally optimal everywhere;
- The surface temperature can be controlled by controlling the laser properties and the injection of powders;
- An optimization approach is developed for the LENS fabrication of heterogeneous objects based on the 2-D models;

Future works

- 3-D modeling of materials deposition and cooling, prediction of cladding shape, to assess the effects of process parameters on printing efficiency;
- Experimental validation to substantiate the model;
- Building metal parts with smooth transition with process control.

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