Printability of alloys for additive manufacturing

Tuhin Mukherjee and James Scott Zuback II
Advisors: Prof. T. DebRoy and Prof. T. A. Palmer
The Pennsylvania State University

1. Background and problem statement

- Additive manufacturing (AM) is used to fabricate near-net shape metallic components used in aerospace, medical and automotive industries.
- All alloys are not equally printable or applicable for AM.
- Printability of various alloys are evaluated based on the relative susceptibility to three common defects of AM.

Printability
- Heating and cooling => Thermal distortion
- Selective vaporization => Composition change
- Inadequate bonding => Lack of fusion defect

2. Methods

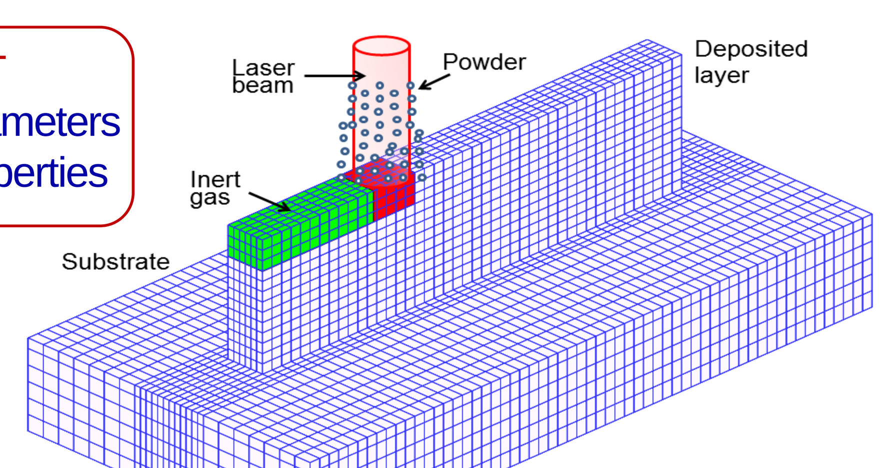
- Numerical and analytical calculations with experimental verifications.
- Main engine for computed results: transient, three dimensional heat transfer and fluid flow model.
- Thermo-physical and mechanical properties needed for the model are predicted using thermodynamic calculations.

Thermodynamic calculations → Alloy properties → Heat transfer and fluid flow model ← Process parameters, Boundary conditions
Heat transfer and fluid flow model → Temperature and velocity distributions, pool dimensions → Lack of fusion defect using LF index
Thermodynamic calculations → Alloy properties → Analytical calculations
Temperature and velocity distributions, pool dimensions → Dimensional analysis using Buckingham π-theorem → Thermal distortion
Analytical calculations → Dimensional analysis using Buckingham π-theorem
Analytical calculations → Langmuir equation → Composition change

3. Heat transfer and fluid flow model

Solves equations of conservation of mass, momentum and energy

INPUT
Process parameters
Material properties



OUTPUT
Transient temperature & velocity fields, solidification parameters …

- Calculation domain: about 250,000 cells
- Five main variables: three components of velocities, pressure & enthalpy
- 1.25 million algebraic equations (250000 x 5)
- 1000 time step => 125 billion total equations
- To validate the model, its results are compared to experimental data
- Heat loss to the substrate decreases with height
- Deposited cross-section may vary with build height

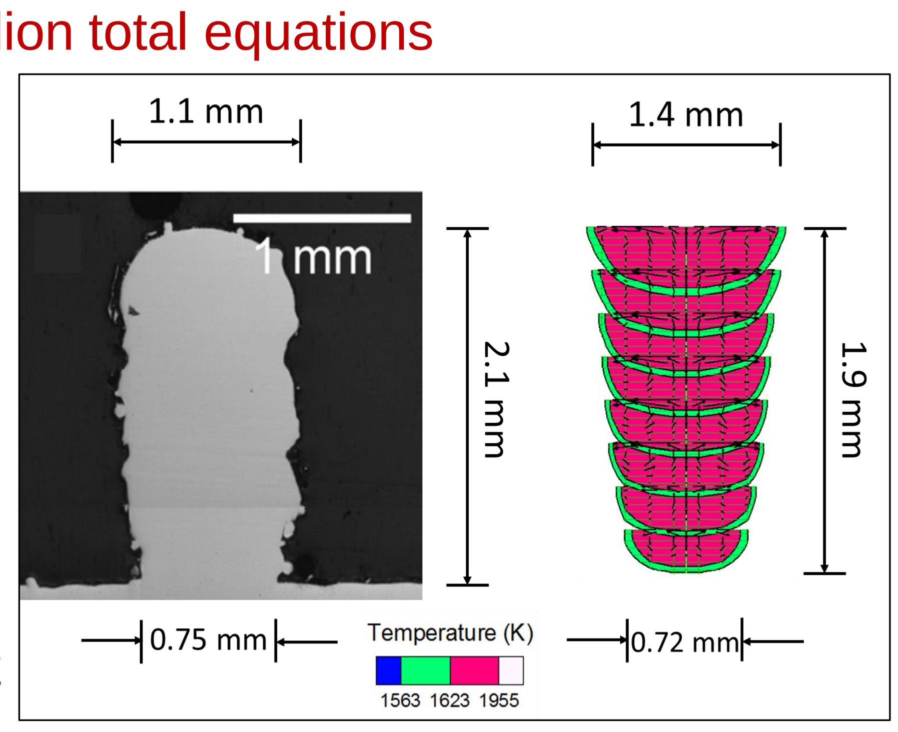


Figure: Experimental validation of the model using transverse section of a 8 layer IN 625 build using 300 W power and 15 mm/s speed.

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4. Results and discussions

Thermal distortion during deposition

$$\varepsilon^* = \frac{\beta \Delta T}{EI} \frac{t}{F\sqrt{\rho}} H^{3/2}$$

- ε* is obtained by dimensional analysis.
- ε* provides insight to thermal strain and distortion in AM.
- ε* does not consider any plastic deformation.

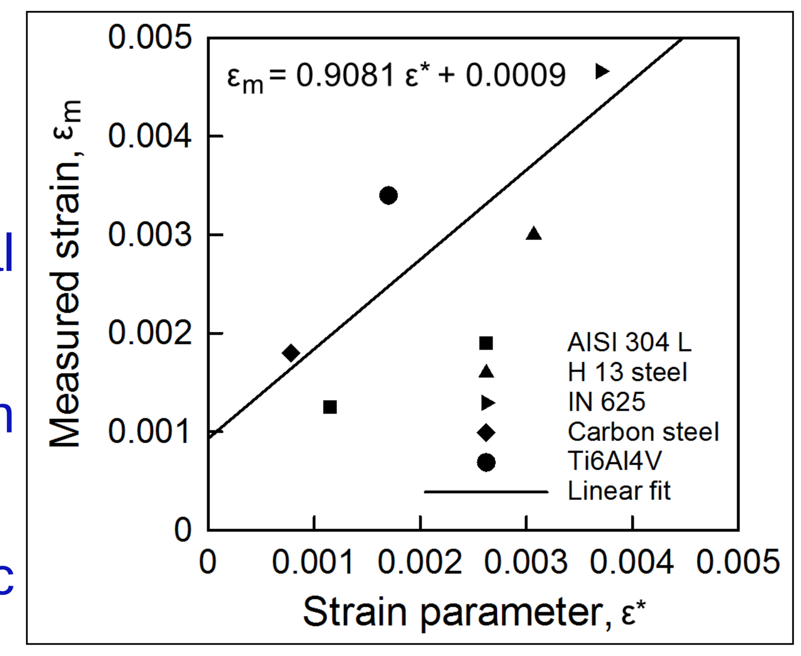

Figure: Relation between measured strain and ε*

Thermal expansion coefficient	β
Temperature difference	ΔT
Heat input per unit length	H
Total time	t
Flexural rigidity of substrate	EI
Density	ρ
Fourier number	F

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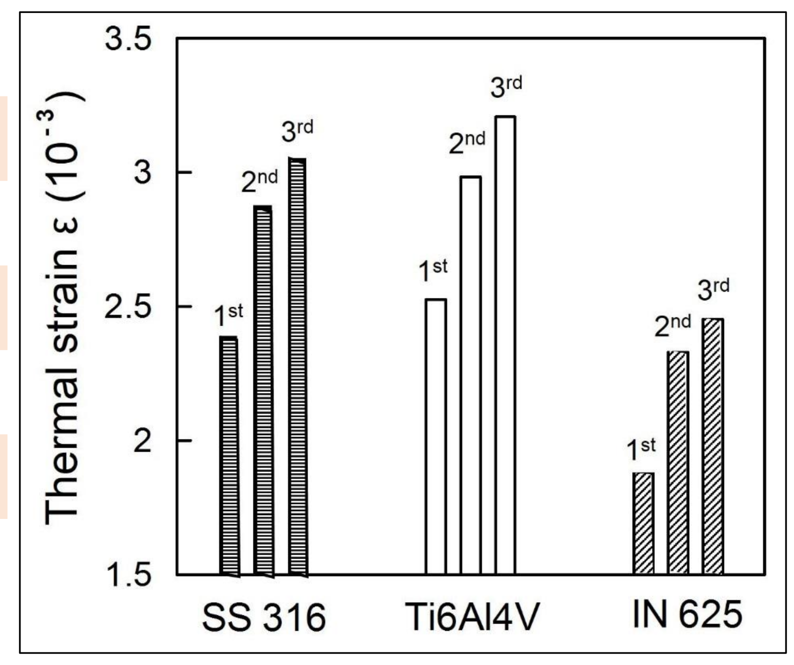

Figure: Thermal strain using 300 W laser power and 10 mm/s speed for 3 layers

Composition change due to evaporative loss

- Selective vaporization of volatile alloying elements change the composition of parts.
- Composition change is calculated from the temperature field using Langmuir equation.
- Ti-6Al-4V and IN 625 are most and least susceptible to composition change respectively

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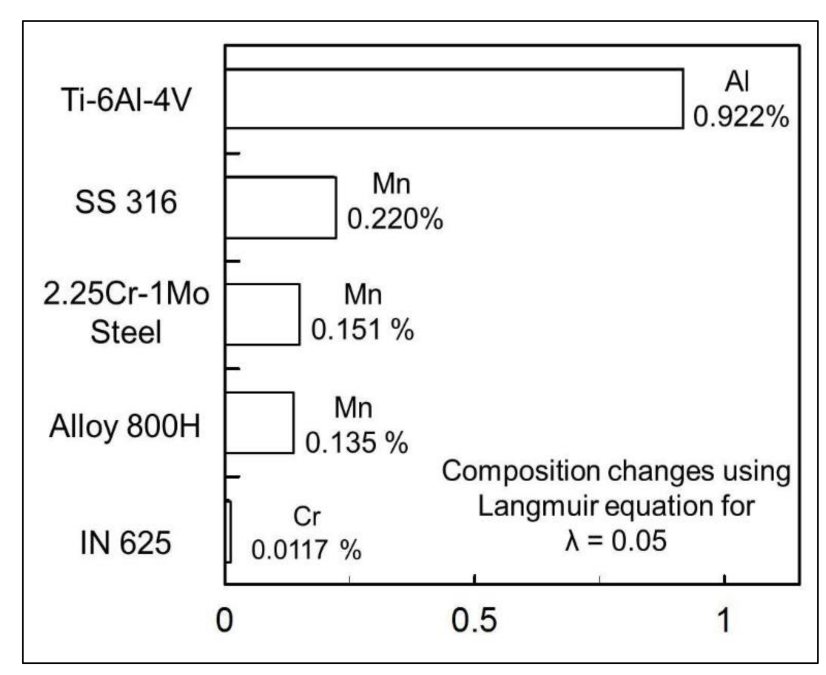

Figure: Composition change using 300 W laser power and 10 mm/s speed

Lack of fusion defect

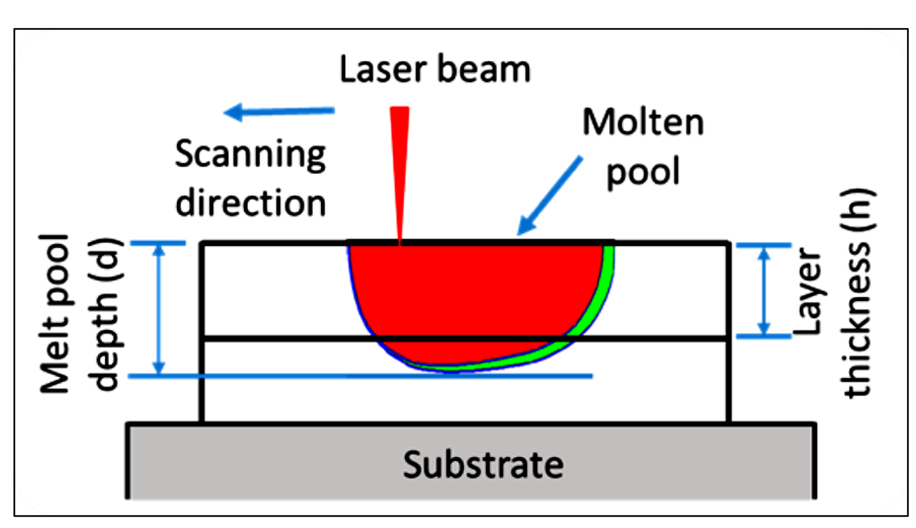

Figure: Longitudinal sectional view of molten pool. Lack of fusion occurs when d < h

$$\text{Lack of fusion index (LF)} = \frac{\text{Melt pool depth (d)}}{\text{Layer thickness (h)}}$$

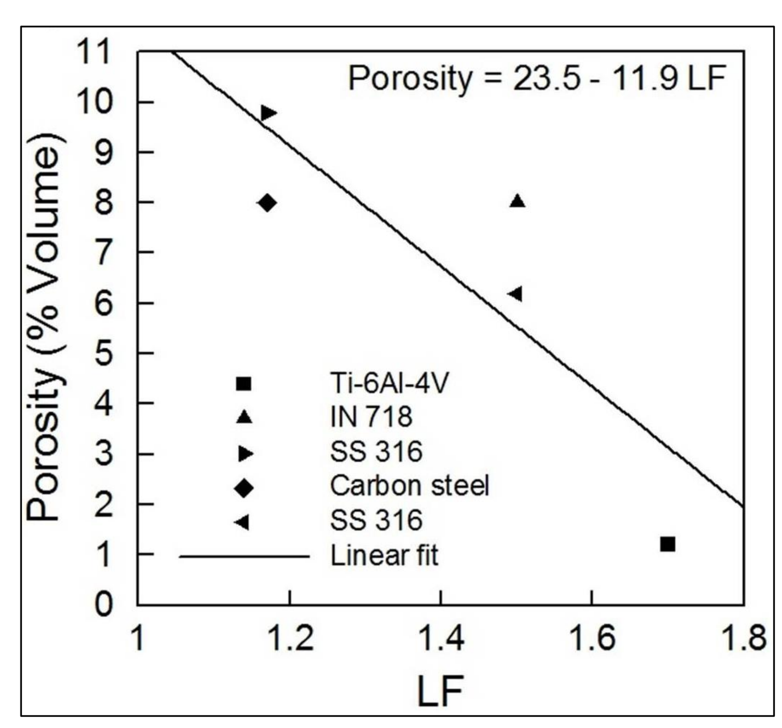

Figure: Volume % of porosity reduces with increase in LF index

5. Conclusions

- Susceptibility to distortion: Ti-6Al-4V (high) > IN 625 (low)
- Susceptibility to composition change: Ti-6Al-4V (high) > IN 625 (low)
- Vulnerability to lack of fusion defects: SS 316 (high) > Ti-6Al-4V (low)
- The results provide an understanding of the printability of various powder materials based on their physical properties and how they would behave under commonly used process conditions in AM.

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